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Final Report

A Review of the Current State-of-the-Art Methodology for Handling Bias and Uncertainty in Performing Criticality Safety Evaluations

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Acknowledgment

Reviews of the site-by-site methodologies for handling of bias and uncertainty when calculational methods are used in criticality safety evaluations were possible due to the excellent and open participation of key site personnel during the review process conducted at each site. In cases where site visits were deemed unnecessary, contact via telephone with cognizant criticality safety personnel resulted in open discussions of methodology and approaches at various sites. The excellent cooperation of personnel contacted at the various sites is gratefully acknowledged. Efforts in organizing site visits, arranging interviews with key criticality safety personnel, identifying key criticality safety personnel at other sites, providing documents for later review, and timely response to numerous questions and requests for additional information or documents were greatly appreciated.

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1.0 Introduction

The methodology for handling bias and uncertainty when calculational methods are used in criticality safety evaluations (CSE's) is a rapidly evolving technology. The changes in the methodology are driven by a number of factors. One factor responsible for changes in the methodology for handling bias and uncertainty in CSE's within the overview of the U.S. Department of Energy (DOE) is a shift in the overview function from a "site" perception to a more uniform or "national " perception. Other causes for change or improvement in the methodology for handling calculational bias and uncertainty are; 1) an increased demand for benchmark criticals data to expand the area (range) of applicability of existing data, 2) a demand for new data to supplement existing benchmark criticals data, 3) the increased reliance on (or need for) computational benchmarks which supplement (or replace) experimental measurements in critical assemblies, and 4) an increased demand for benchmark data applicable to the expanded range of conditions and configurations encountered in DOE site restoration and remediation.

In response to these factors, a number of national actions have been undertaken to; 1) update the benchmark critical experiment database through expanded evaluations and improved documentation, 2) improve and/or standardize the documentation of criticality safety evaluations, 3) update and/or revise applicable standards related to criticality safety evaluations when calculational methods are used, and 4) improve and/or implement existing or new criticality analysis methods.

One of the standards activities which can change the current methodology is the "in revision" status of ANSI/ANS Standard 8.1 (Reference 1). The principal changes planned for the revisions of the current standard are minor changes in the current text and the addition of an appendix providing guidance on the development and application bias and uncertainty from the validation of calculational methods used in criticality safety evaluations. Section 3.1 of this report provides an overview of the draft changes currently planned for a revised standard.

A second activity which will impact the methodology of handling of calculational bias and uncertainty is the ongoing DOE funded documentation of a handbook of evaluated benchmark critical experiments planned for issuance in 1994. This handbook

(References 2 and 3) has evolved into an international effort providing detailed definitions of benchmark experimental configurations for use in validating criticality safety calculational methods. Section 3.2 of this report provides a summary discussion of the handbook, its content, and the potential impact of the handbook on the methodology for handling calculational method bias and uncertainty.

Section 3.3 is a discussion of recent efforts (References 4 and 5) undertaken to formalize the definition of area (range) of applicability and the effect of this effort on definition of calculational bias and uncertainty. Section 3.4 briefly describes the recent implementation or introduction of new and/or improved calculational methods for criticality safety evaluations. Features of these calculational methods which may contribute to improvements in the prediction of calculational bias and uncertainty are discussed.

The following sections describe the planned scope of work and technical approach for the contract effort.

Scope of Work

A review of the "The State-of-the-Art Methodology for Handling Bias and Uncertainty in Performing Criticality Safety Evaluations" shall be performed. After review is completed, the best technology(ies) shall be selected and developed into a full scale process.

The review shall be performed by an expert who is independent of the work being reviewed, and shall include an in-depth critique of the assumptions, calculations, extrapolations, alternate interpretations, methodologies, acceptance criterion employed, and conclusions drawn in the original work.

The scope of work for the review shall include, but not be limited to, all the necessary support activities and preparation of the final report and other deliverables.

The review criteria shall include, but not be limited to, the assessment of:

- Validity of assumptions

- Alternate interpretations
- Adequacy of requirements and criteria
- Appropriateness and limitations of the methods used to complete the work under review
- Adequacy of the application
- Validity of conclusions
- Uncertainty of results and impact of anticipated variations

In addition, the review shall recommend preferred technologies within the context of state-of-the-art practices. The recommendations shall include a set of assumptions, and a brief description of hypothetical non-technical and technical factors that may influence the selection of a preferred technology.

The final report is the primary product of the review process. The final report shall describe the work being reviewed, and clearly state the conclusion and recommendations of the review. Based upon the available alternatives, the final report shall recommend preferred technologies selected from those currently under evaluation. Each recommendation shall include a brief discussion of the rationale that lead to selection of the preferred technology.

In support of the review, the expert shall travel to the INEL, Hanford, Savannah River, Los Alamos, Oak Ridge, and Rocky Flats sites.

Technical Approach

The initial task in the contracted effort will be to identify the types or categories of criticality safety evaluations performed at the various sites which are the focus of the contracted effort. Agreement and concurrence on the scope of the study effort will be obtained from cognizant personnel at WINCO.

Based on the identified types or categories of criticality evaluations, the cognizant personnel to be contacted at various government laboratories and/or government contractor sites will be identified and agreed upon with WINCO personnel. Visits will then be setup and coordinated with the various sites to review the currently used practices specific to each site. The review process will identify, where possible, the current methodology used in applying bias and uncertainties to specific types/categories of criticality safety evaluations. The review will also identify the methods used to develop applied bias and uncertainties including the analytical modeling, the nuclear data used, the methods and approximations, and the interpretation of the predicted criticality results relative to the generation of biases and uncertainties. In addition, the current criticality safety evaluation methods used at each site for the specific types or categories of evaluations will be identified.

Based on the information collected from each site visit, currently used methodologies will be compared and evaluated and current state-of-the-art methodologies identified. Assessments of the validity of assumptions and alternate interpretations will be performed, when necessary, using the currently available methodologies, e.g., KENO V.a (SCALE-PC module), MCNP 4A, DOT/ANISN, or DORT. Additional site visits may be required to fully develop an understanding of the application of calculational methods used at specific sites.

Based on the results of the review and evaluation process, the best technology(ies) will be selected and a process for handling bias and uncertainties will be documented based on the selected technology(ies).

The final report of the contract will include, where possible, a summary documenting the "state-of-the-art" methodology used at each site visited. The summary will highlight the important features of the individual methodologies and will include a critique of the site methodology relative to the recommended methodology for handling bias and uncertainties developed in this study contract.

A review of the current state-of-the-art methodology for handling bias and uncertainty shall be performed.

The best technology(ies) shall be selected and developed into a full scale process.

Review shall include an in-depth critique of:

1) Assumptions
2) Calculations
3) Extrapolations

4) Alternate Interpretations
5) Methodology
6) Acceptance Criterion Employed
7) Conclusions Drawn In The Original Work.

Review criteria shall include, but not be limited to, the assessment of:

1) Validity of assumptions
2) Alternate interpretations
3) Adequacy of requirements and criteria
4) Appropriateness and limitations of the methods used
5) Adequacy of the application
6) Validity of conclusions
7) Uncertainty of results
8) Impact of anticipated variations

Review shall recommend preferred technologies within the context of state-of-the-art practices and based upon the available alternatives, the final report shall recommend preferred technologies selected from those currently under evaluation.

Recommendations shall include a set of assumptions, and a brief description of hypothetical non-technical and technical factors that might influence the selection of a preferred technology.

The final report shall describe the work being reviewed, and clearly state the conclusions and recommendations of the review.

Each recommendation shall include a brief discussion of the rationale that lead to selection of the preferred technology.

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2.0 Summary and Conclusions

A review of the site-by-site methodology for handling calculational bias and uncertainty in criticality safety evaluations has shown that current methodologies range from no formal methodology to methodologies based on rigorous statistical treatments involving linear and/or multiple regression techniques to correlate calculational bias to either physical or neutronic parameters. The most rigorous statistical treatments define calculational method bias and uncertainty as a function of a correlation parameter and the statistical analysis results are used to define an "upper safety limit" which incorporates the uncertainty in the bias and a statistically derived safety margin.

Approximately 50% of the sites reviewed in this scope of work use a statistical treatment to define calculational bias and uncertainty. The statistical treatments are similar with differences in the interpretation and application of the calculated bias and uncertainty to the evaluation of system upset conditions.

With one exception, the remaining site reviews showed that sites performed a validation process for calculational methods used within each CSE. In most cases, the CSE analyst either defined an enveloping bias/uncertainty value or determined that no bias was warranted. The determination of the calculational bias value at these sites relied heavily on the experience level of the CSE analyst or personnel in the site criticality safety organization. At the site where no formal methodology is currently used, criticality safety assessments are primarily handbook-based evaluations with calculational methods used as computational benchmarks to confirm subcritical limits derived for upset conditions for complex systems.

Key observations or findings from a review of CSE documents at the various sites were as follows:

- In general, CSE documents did not clearly demonstrate the area (range) of applicability of the calculational bias and uncertainty derived for use in evaluating upset conditions. Graphical and tabular illustrations of the area (range) of applicability versus the chosen correlation parameter, physical or neutronic, should be used in all CSE documents. In addition, reviewed CSE documents included only very limited demonstrations of the relationship of predicted upset conditions to the area (range) of applicability defined in the method validation sections of the CSE documents. As described before, graphical and/or tabular illustrations should be used to clearly demonstrate applicability of the defined calculational bias and uncertainty to the evaluated system conditions.

- In a limited number of CSE documents reviewed, the CSE analyst judged that no bias was warranted and uncertainty in the bias was not evaluated for the group of benchmark critical experiments included in the validation assessment. In some cases, only a very limited number of benchmark critical experiments were included. In other documents, the variance within the selected group of benchmark critical experiments was ignored and therefore, the uncertainties associated with computational methods (e.g., geometric/material modeling, neutron cross section data, Monte Carlo method) and the benchmark experimental specifications were not incorporated into the validation process. A zero (0.0) bias may be justified based on visual examination of the results. However, the within-group variance could be significant, real, and larger than the individual benchmark calculation variances.

- Continued development and/or improvements are required in the definition of area (range) of applicability methodologies. Recent developments in system categorization methods, as incorporated in the current MONK (Reference 16) methodology, may provide the basis for future developments which are applicable to all criticality safety calculational methods. Derivation of rule-based definitions, which provide physical/neutronic parameter values for each calculation, could be used to correlate predicted upset conditions to the area (range) of applicability of calculational method validation results.

- Based on the limited review of CSE documents in this contract scope, efforts should be undertaken to standardize the implementations of various calculational methods on the wide variety of computing platforms. The efforts should focus on eliminating or minimizing the effects of word length and random number generation on predicted results. In one case, the application of a statistical treatment to a CSE grouping of benchmark critical experiments results showed large differences (a factor of three larger standard deviation) in the variability of predicted results from two different workstations. This large variance is most likely attributed to random number generation techniques. The standard deviation value exceeded the uncertainty of the individual case results by a factor of 2.5.

Based on an intercomparison of the site-by-site methodologies, the implementation of a statistical treatment of calculational bias and uncertainty is recommended as a standard methodology for use in criticality safety evaluations. This conclusion is based on the fact that considerable insight and understanding of the method validation results is provided by a statistical process. In addition, a consistent approach is obtained when statistical methods are used by different CSE analysts. A statistical methodology provides the capability to incorporate uncertainty in the calculational method (neutron cross section data, method, modeling, and implementation) and the uncertainty in the specifications of the selected group of benchmark critical experiments used in the validation process.

The recommended statistical treatment should be a composite of the methods identified in the reviews. A multilevel statistical treatment should be incorporated into a methodology which provides the CSE analyst with statistical information and results for use in selecting appropriate bias and uncertainty for application to evaluations of upset conditions within each CSE. The statistical methodology should be based on a consensus of the currently used statistical methods and should be incorporated into a single computational method. Therefore, the level of detail used in each CSE would be selected by the CSE analyst based on the analyst's judgment of the quality of the group of benchmark critical experiments and the group's representation of the CSE system upset conditions.

Based on the various statistical methods currently used at the sites reviewed in this scope of work, the recommended statistical treatment would be a small or "exact" sampling theory method which is applicable to evaluations of large and small groups of benchmark critical experiments. The specific method recommended should be based on the use of a one-sided (or single-sided) lower tolerance interval technique. This method is the basis for the majority of current statistical treatments identified in the site reviews. The most rigorous statistical treatment recommended would be a linear regression technique based on either the ORNL/Y-12 method or the SRS method.

The ORNL/Y-12 method described in Section 3.4, predicts an "upper safety limit" from a linear regression analysis of a selected group of benchmark critical experiments. The method predicts a bias as a function of a correlation parameter and an uncertainty (standard deviation) of the linear fit to results from the selected group of benchmark criticals. The method can also be used to define a statistically derived "safety margin" based on the predicted uncertainties for the group of benchmark critical experiment results used in the statistical process. This technique has the desirable feature of incorporating the variability of the predicted results for the selected group of benchmark criticals into the width of the one-sided lower tolerance interval. For example, results from an application of the ORNL/Y-12 method clearly show the effect of variance in predicted critical conditions for a group of benchmark critical experiments. The ORNL/Y-12 method also incorporates additional conservatism in the "upper safety limit" by imposing a uniform width tolerance interval over the closed band of the independent (correlation) parameter. This uniform interval technique results in the "upper safety limit" based on the largest one-sided tolerance interval within the closed band.

The consistent use of a one-sided lower tolerance interval technique has the desirable feature that larger one-sided lower tolerance limits are predicted when fewer benchmark critical experiments are grouped in the validation process for a method.

As an integral part of the computational method, graphical illustrations of the area (range) of applicability of the validated method should be prepared for use by the CSE analyst in evaluating the bias and uncertainty representative to be applied in the evaluations of CSE system upset condition results.

The following observations or findings are based on the site-by-site reviews of methods used to apply calculational bias and uncertainty in the evaluation of system upset conditions:

- Application of the calculational method bias, when defined in the validation process of a CSE, was consistently performed at all sites. A majority of sites do not apply "positive" bias when evaluating upset conditions. However, some sites apply "positive" bias when the factors contributing to the predicted "positive" result are thoroughly understood. When "negative" bias is defined in the validation process, bias is consistently applied to reduce the Δk_{eff} margin in the evaluation process.

- Uncertainty in the calculational bias is not consistently applied at the various sites. At sites where uncertainty in the bias is defined by either linear or multiple regression analysis techniques, bias uncertainty is considered to be a correlated (or dependent) uncertainty and the bias uncertainty is combined additively with other defined uncertainties. At other sites which used a statistical treatment to define bias uncertainty, statistical combination of the defined uncertainties (root mean square of standard deviations) is used in the evaluation process.

- At the sites where a statistical treatment is not used in defining method bias and uncertainty, the magnitude of the bias is technically judged to be an enveloping value based on visual examination of predicted k_{eff}'s and uncertainties for selected benchmark critical experiments. At some of the sites in this category, it is technically judged that no bias and uncertainty is warranted based on capability of the chosen methods to closely predict the experimental k_{eff} ($\Delta k_{eff} \leq 0.01$) and the small predicted uncertainty of the result relative to the conservatism in the specification of upset conditions and the site-established allowable limiting neutron multiplication factor.

- The only uncertainties evaluated at the various sites included in this review are the following:

  * Bias uncertainty, defined by a statistical treatment on a group of benchmark critical experiment results or by a linear or multiple regression analysis of the group results.

  * Computational uncertainty (standard deviation), predicted by the Monte Carlo calculational method for either the system upset condition or for each of the benchmark critical experiment calculations used in the method validation process. The Monte Carlo calculated uncertainty or standard deviation is the only computational uncertainty considered in the CSE's reviewed.

* At a limited number of sites, uncertainties due to design fabrication/material tolerances are calculated and used in evaluating upset conditions.

Based on discussions with cognizant personnel and review of CSE documents, it is concluded that use of a statistical treatment to validate a calculational method results in a bias and uncertainty which incorporates uncertainties related to calculational method (including application, neutron cross section data, and modeling), experimental configuration definition and specification, and experimental measurements. In cases where no statistical treatment is used, the variance in the predicted critical conditions due to the prior factors is considered and the use of the chosen calculational method relies on assigned safety margins within each CSE or on the margin provided by the site-established allowable limiting neutron multiplication factor.

Based on review of the various methods of applying uncertainty in the evaluation process of system upset conditions, the following approach is recommended:

1. Uncertainty (standard deviation) from the Monte Carlo calculation of the upset conditions should be an additive value defined as a confidence interval at the appropriate confidence level, e.g., K_p=2.0 (95.45% confidence level).

2. Uncertainty in the calculational bias, if evaluated, should be an additive value defined as a one-sided lower tolerance interval at the appropriate confidence level and appropriate proportion of the population, e.g. at a 95% confidence level on a 95% proportion of the population for the number of degrees of freedom defined for the validation process.

3. Uncertainties (standard deviations) from each Monte Carlo calculation of the benchmark critical experiments used in the validation process may be included as a root mean square value of the individual values and subsequently combined statistically with the bias uncertainty. This approach is patterned after the ORNL/Y-12 method which implicitly includes this treatment in the evaluated upper safety limit. The rationale behind this approach as stated in OR03 is based on the inherent uncertainty associated with Monte Carlo methods. Further, it is this expert's opinion that Monte

Carlo calculations of upset conditions are generally more complex geometry calculations and may have different convergence conditions than the Monte Carlo calculations of benchmark critical experiments used in the validation process. The benchmark critical experiment calculations are normally more well defined and simpler than upset condition configurations. This approach will normally have a minor effect due to the fact that Monte Carlo calculations are normally converged to uncertainty levels much smaller than the standard deviation of the mean value of the group results or the linear fit of the group results.

4. In the case where additional uncertainties are evaluated for the upset condition, e.g., fabrication/material tolerances or degraded conditions, standard deviations should be statistically combined with the Monte Carlo calculated standard deviation for the upset conditions as defined in item number 1) above.

As discussed in Section 1.0, a number of DOE sponsored activities have focused on improving the validation process for calculational methods used in criticality safety assessments at DOE sites. Planned revisions to ANSI/ANS 8.1, when implemented, will provide expanded and improved guidance on the validation process for criticality safety calculations methods. Recently, documentation guidelines (Reference 6) for preparing criticality safety evaluation documents at DOE non-reactor nuclear facilities were issued and highlight the need for consistency in documentation. The most important effort in progress is the development of a handbook of evaluated benchmark critical experiments. The handbook will provide an extensive database of evaluated benchmark critical experiment specifications, evaluated uncertainties, and predicted critical conditions using standard calculational methods and will provide a standardized definition of benchmark critical experiments. Implementation of the handbook at the various sites will reduce and/or eliminate the often repeated site-by-site interpretation of benchmark critical experiments. Each of the activities when completed and implemented will improve and standardize the application of calculational methods to criticality safety evaluations and provide consistency in the DOE overview of criticality safety evaluations on a more uniform "national" perspective rather than a "site" perspective.

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3.0 Current Methodology for Handling of Bias and Uncertainty

Assessments of the current state-of-the-art practices for handling bias and uncertainty in performing criticality safety evaluations (CSE's) at the various sites have been based on one or more sources of information. During on-site visits to specific locations, interviews with key personnel were conducted to identify key elements in the development and application of bias and uncertainty in site CSE's. In addition, criticality safety related procedures and/or CSE documents provided by site criticality organizations were either reviewed on-site or hardcopies of documents were provided for independent review at a later time. A limited number of site reviews were conducted by telephone and both on-site and telephone reviews were subsequently confirmed, where required, by follow-up telephone conversations. In a number of cases, facsimile transmissions were used to confirm the expert's understanding of the individual site state-of-the-art processes or practices.

During the site review period, the scope of the review process was expanded to include the information required to develop a full understanding of the current processes of handling bias and uncertainty at the various sites. In addition to the definition of the current practices or processes for handling bias and uncertainty in CSE's, an understanding of the development of the bias and uncertainty associated with validation processes at the individual sites was required.

During the site visits, the evolutionary status of the treatment of bias and uncertainty in criticality safety evaluations was obvious. Key developments underway or recently completed which will have an impact or have already impacted the handling of bias and uncertainty are:

- Planned Revisions of ANSI/ANS 8.1: "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors"

- Planned Issuance of the DOE/HDBK-XXXX/YR: "Evaluated Criticality Safety Benchmark Critical Experiments"

- Recent Release of DOE-STD-3007-93: "DOE Standard: Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Non-Reactor Nuclear Facilities"

In addition to the above developments, the activity related to the definition of areas (range) of applicability for analysis methodologies and the recent implementation of new or existing methodologies have the potential to effect and/or improve the methodology for handling of calculational bias and uncertainty in criticality safety evaluations.

One of the key developments discovered in the early stages of the review process was the "in-revision" status of ANSI/ANS 8.1, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors". During the site visit to the Oak Ridge National Laboratory (ORNL), Elliott Whitesides of the ORNL staff described in detail the planned revisions to ANSI/ANS 8.1 and provided a draft copy of the revisions. The principal change to the current standard is the addition of an Appendix C to define the validation process for calculational methods used in criticality safety evaluations. The revisions to ANSI/ANS 8.1 are patterned after the information on the same subject in the currently approved ANSI/ANS 8.17, "Criticality Safety Criteria for the Handling, Storage, and Transportation of LWR Fuel Outside Reactors," standard (Reference 7).

In addition to the above developments, the on-site reviews and review of documents provided by site personnel identified efforts to revise, update, and/or issue site procedures dealing with the verification and validation of calculational methods used in criticality safety evaluations. At a number of sites, considerable effort has been expended to complete and/or update validation of the current calculational methods used in criticality safety. The updated validations also reflect the improved documentation guidelines of Reference 6.

3.1 ANSI/ANS 8.1 Revisions

Planned revisions to ANSI/ANS 8.1 involve minimal rewording of the current approved standard which is called out as a requirement in DOE Order 5480.24. An appendix, Appendix C, is planned to provide guidance related to the validation processes when calculational methods are used in criticality safety evaluations. Planned modifications to the current standard which were reviewed in draft form are;

- Section 4.3.4 of the current standard has an additional statement identifying ANSI/ANS 10.4-1987 as guidance material for use in the verification and validation efforts for computer programs used as calculational methods in criticality safety evaluations.

- Section 4.3.6 has been revised to reflect the addition of an Appendix C addressing the validation process when calculational methods are used in criticality safety evaluations.

- Item (2) of Section 4.3.6, which provided documentation guidance when calculational methods are used, has been moved to Appendix C. The item moved is as follows;

  "State computer programs used, the options, recipes for choosing mesh points where applicable, the cross section sets, and any numerical parameters necessary to describe the input."

- Items (3) and (4) of Section 4.3.6 have been renumbered to reflect the movement of item (2) to Appendix C.

- Item (5) of Section 4.3.6 has been revised and renumbered to Item (4). The planned revision of Item (4) is as follows:

  Original: "State the bias and the prescribed margin of subcriticality over the area(s) of applicability. State the basis for the margin."

  Revised: "State the bias in the prescribed criticality and the margin of subcriticality over the area(s) of applicability. State the basis for the margin."

The major planned revision in ANSI/ANS 8.1 is the addition of Appendix C. Appendix C provides an expanded discussion of the requirements of Section 4.3 when calculational methods yielding k_{eff} are used in criticality safety evaluations. The draft version of Appendix C is patterned after a similar discussion included in the currently approved ANSI/ANS 8.17 Standard (Reference 7).

The draft version of Appendix C defines the purpose of using calculational methods in criticality safety as either a substitute for experimental data or to provide an estimate of criticality conditions and margin of subcriticality for systems under evaluation.

Key definitions included in Appendix C are:

- Verification - A process to confirm correct installation of a computer based method.
- Benchmark - An evaluated criticality experiment used to establish reliability of methods.
- Validation - A process to determine method applicability and establish a conservative bias.

Key relevant elements in the Appendix C draft address the evaluation process to be used when calculational methods are applied to predict k_{eff} for safety assessments. The suggested evaluation process is:

$$k_p + |\Delta k_p| \leq k_a$$

where: k_p = Calculated k_{eff} of the system for normal/upset conditions,

Δk_p = An allowance for;

a) statistical/convergence uncertainties,

b) material/fabrication tolerances,

c) uncertainties due to limitations in geometric/material representations.

k_a = The established allowable limiting neutron multiplication factor.

The established k_a is the result of a validation process and is defined as:

$$k_a = k_c - |\Delta k_c| - |\Delta k_m|$$

where; k_c = Mean k_{eff} from calculations of benchmark criticals with a particular method.

Δk_c = A margin for uncertainty in k_c which includes an allowance for;

a) uncertainties in the benchmark critical experiments,
b) statistical/convergence uncertainties,
c) uncertainties due to extrapolation outside of range (area) of applicability,
d) uncertainties due to limitations in geometric/material representations,
e) uncertainty in the bias.

k_m = An arbitrary margin to ensure the subcriticality of k_a.

As stated in the Appendix C draft, if k_c exhibits a trend with a parameter, k_c shall be determined from a best fit to the calculated values of k_c for the applicable benchmark criticals. Further guidance provided in the draft Appendix C is:

- Benchmarks should be similar to the system being evaluated.
- The difference between the experimentally measured k_{eff} and k_c is defined as the bias.
- Independent uncertainties may be combined statistically.
- Correlated uncertainties should be combined additively.

The planned revisions to ANSI/ANS 8.1 described above, if approved and implemented as discussed, have the potential to impact the current methodology for handling calculational method bias and uncertainty in criticality safety evaluations. Criticality safety organizations at sites under the DOE overview process will be required to address the use of statistical methods to evaluate calculational method bias and uncertainty and the application of results in the assessment of criticality safety of normal/upset conditions of systems evaluated. In addition, the implementation of a revised ANSI/ANS 8.1 Standard will require that the area (range) of applicability issue be addressed in a more formal manner. As discussed later in the reviews of the bias and uncertainty handling process at the individual sites, one key element missing from almost all CSE's reviewed was a clear and definitive demonstration of the applicability of the bias (or lack of bias) in the CSE validation sections. From discussions with some criticality personnel during site visits, the definition of area (range) of applicability has proven to be a difficult task. Later sections discuss activities within the DOE criticality safety organizations to address the issue of area (range) of applicability.

3.2 DOE Handbook: Evaluated Criticality Safety Benchmark Experiments

The DOE funded effort to compile benchmark critical experiment data into a comprehensive handbook (References 2 and 3) is expected to have a positive impact on the methodology for handling bias and uncertainty in criticality safety evaluations. The scope of the DOE funded effort is described in Reference 2. The focus of the handbook is on documenting, in a standardized format, details of a large collection of benchmark critical experiments. The evaluations of the benchmark experiment specifications are being compiled and verified from a current review of existing documentation supplemented by reviews of archived information or interviews with cognizant personnel associated with the performing experimental facility or the experimenters. Additional information being compiled into the handbook are sample input setups and predicted critical conditions, k_{eff} and Δk_{eff}'s, for the experimental configurations and the identified uncertainties in the experiment specifications. As described in References 2 and 3, the primary purpose of the document is to compile benchmark critical experiment data into a standardized format allowing criticality safety analysts to easily use the data to locally validate calculational methods and associated neutron cross section datasets. The current draft of the handbook states that the predicted critical conditions for the benchmark experiments do not constitute a validation of any of the calculational methods. Further, the handbook contains a statement that input setups and predicted results are to provide guidance for criticality safety analysts in the analytical modeling and method application to the specific benchmark experiments and further that predicted results are provided for comparison purposes only. Consistent with DOE Orders, the criticality safety organization at a DOE site is responsible for validating calculational methods for use in site criticality safety evaluations.

One of the primary benefits of the benchmark critical experiment handbook relative to the development of calculational methods bias and uncertainty is the standardization of the specifications and the consensus-based interpretation of the experimental configurations. Use of the handbook data will provide for a consistent definition of the experiments and eliminates the often repeated research, evaluation, and interpretation of the experiment specifications and modeling. In addition, the sample input setup for each of the commonly used criticality safety calculational methods will eliminate or minimize modeling differences introduced by local interpretations of specifications. The geometric/material modeling the input file setup for the each sample calculation of a benchmark critical experiment is provided as guidance information for interpretation and enhancement of modeling consistent with local site practices.

3.3 Definition of Area(s) or Range of Applicability

Definition and use of the area(s) or range of applicability in criticality safety analyses was the topic of a seminar/workshop conducted in 1992 (Reference 4). The results of a workshop subgroup of criticality safety specialists were incorporated in a draft document describing key physical parameters which define area (range) of applicability. The document from the 1992 workshop proceedings has been revised and issued in draft form as Appendix E of Reference 5. As discussed below, the latest version of one of the criticality analysis methods has incorporated a system categorization method which attempts to characterize the neutronic conditions of the system configuration based on predicted results and a basic set of rules. Reference 8 discusses the features and the possible use of the categorization method in defining area (range) of applicability.

Based on the review of current CSE documents within this scope of work, the use of area(s) or range of applicability has been limited to the engineering judgment of the criticality safety analyst. Selection of a group of benchmark critical experiments representative of the system under evaluation is based on the physical similarities, e.g., fissile element(s), moderator-to-fissile ratio (H/X), fissile concentration, moderator type and configuration (bare, reflected, sphere, cylinder, slab). Characterization or categorization of benchmark critical experiment results versus predicted neutronic parameters have primarily been limited to correlation's to the average energy group (AEG) causing fission (a KENO predicted result) with only limited use of second order correlation parameters. Further efforts in development and implementation of an area (range) of applicability method are required. Development of a area of applicability method could have a beneficial impact on the methodology of handling bias and uncertainty. Definition of a standardized set of rules which categorize predicted conditions could form the basis for a consistent interpretation of benchmark critical experiment results. Application of the predicted bias and uncertainty would then rely on the CSE analyst's interpretation of the values relative to the system upset conditions.

3.4 Recent Implementations/Improvements in Calculational Methods

The increased use of existing methodologies at some sites and the increased activity to improve the utilization of existing methodologies are developments with the potential to influence and improve the methodology for handling calculational method bias and uncertainty.

As described in Reference 9, continued improvements in the KENO methodology is focused on providing easy-to-use, yet accurate, analysis capabilities. The three primary improvement or enhancement efforts are system portability, user interface, and system performance. System portability focuses on the implementation of the SCALE (Reference 10) methodology on the wide variety of mainframes, workstations, and personal computers. As discussed elsewhere in this report, system portability should address the word length and truncation differences as well as the random number generation methods. Standardization of these techniques or methods should be investigated to provide for precise certification of analysis methods at various sites. Development and implementation of a graphical user interface is focused on providing interactive input processors and graphical displays of geometric modeling to improved checking and visual verification of geometric model information. System performance enhancements are focused on improvements in the neutron cross section data and SCALE processes to enhance the analysis capabilities. Improved geometric modeling capabilities are also planned in the next version of KENO, KENO VI. The primary benefit of the SCALE/KENO enhancements to the methodology of handing bias and uncertainty is the improvements and enhancements in geometric modeling and the ability to model more accurately complex geometry system conditions. Therefore, more accurate models can be generated, hence, expanded and more detailed analyses are possible.

Use of the MCNP Monte Carlo methodology in criticality safety analysis has increased due to a number of factors. The current version of MCNP, MCNP 4A (Reference 11), has enhanced geometry modeling capabilities and provides the ability to accurately model complex geometries including arrays. The embedded capability to check and visually verify complex geometric models has been a desirable feature of MCNP.

Another factor contributing to the increased use of MCNP is the extensive neutron cross section library (Reference 12). The neutron cross section library exists as pointwise data for a large number of elements and isotopes based on the ENDF/B nuclear data files. The increased use of MCNP 4A as a primary criticality analysis method has resulted in improvements and enhancements in the statistical treatments used in estimating k_{eff} (References 13 and 14). In addition, the current users manual (Reference 10) contains an expanded discussion of the use of MCNP 4A for criticality calculations and a primer (Reference 15) on the use of MCNP 4A for criticality calculations has been recently issued. Improvements in the statistical analysis methods within MCNP 4A enhances the analyst's ability to assess the validity of the predicted k_{eff} values and the uncertainty (variance) of the predicted k_{eff}.

The MONK criticality analysis methodology (Reference 16) is currently used by two of the sites visited, and is the primary criticality analysis method at one of the sites. The current version, MONK 6B, is a preferred methodology due to the relatively easy-to-use input preparation modules (including geometric modeling capability) combined with an alternative Monte Carlo method and neutron cross section data library. The MONK alternative Monte Carlo method uses a superhistory technique which was developed to eliminate potential problems in the application of Monte Carlo methods to predict critical conditions of complex configurations. The superhistory technique has been shown in Reference 17 to minimize source convergence errors and eliminate bias in predicted eigenvalues. An additional feature in the MONK method is the system categorization techniques. As described in Reference 8, system categorization techniques provide neutronic characterization data which could be applicable to defining area (range) of applicability for MONK 6B calculations. In addition, the MONK methodology uses and independently evaluated neutron cross section data library.

In addition to the changes and improvements being implemented in the Monte Carlo methodologies, utilization of an enhanced TWODANT-SYS discrete ordinates transport methodology (Reference 18) as a deterministic methodology for criticality safety evaluations has been documented in the literature. A number of sites have implemented either ONEDANT or TWODANT in criticality safety evaluations with the primary application in performing trend or sensitivity analyses.

As described above, continuing improvements and new implementations of calculational methods in the criticality safety analysis arena have provided for an increased capability to eliminate or minimize computational uncertainties. During the site reviews, efforts were made to define computational method uncertainties associated with applied Monte Carlo methods. A number of documents (References 17 and 19-26) were identified in discussions with key criticality safety personnel and subsequently reviewed. The current implementations of Monte Carlo methods provide the capabilities to assess the validity of individual case results using techniques and results inherent to the various methods. Therefore, with proper and consistent use of the methods, no significant computational errors exist beyond the predicted statistical uncertainty of the k_{eff} inherent to the Monte Carlo methods. Enhanced geometric modeling capabilities of current methods provide for more accurate models of either benchmark critical experiments used in validation efforts or for system upset condition evaluations. Improvements in the Monte Carlo methods which eliminate or minimize convergence errors and improved statistical treatments included in the Monte Carlo methods provide the user with valuable information for assessing validity of predicted k_{eff} and standard deviations or relative errors. With the increased use of MCNP 4A and MONK 6B coupled with continuing use of KENO V.a, there exists second and independent methods to provide results necessary to extend or extrapolate the area (range) of applicability in validation efforts.

3.5 Site Reviews/Contacts

The purpose of the on-site reviews at the various nuclear installations was to interview key personnel involved in criticality safety evaluations (CSE's). The review process included personnel interviews, on-site reviews of site procedures and recent CSE's, and identification of site procedures and CSE documents which show recent or current "state-of-the-art" practices at each site. Reviews of the methodology for handling of calculational bias and uncertainty also required that the review include examination of the calculational methods and applications in criticality safety evaluations at each site. Table 2-1 lists the sites either visited or contacted via telephone and identifies the personnel contacted and interviewed. Key personnel involved in either the development and/or application of bias and uncertainty are noted by underline in Table 2-1. The order of the site visits in Table 2-1 is the order of the site reviews provided in the following discussion.

Table 2-1
Site Visits and Personnel Contacts/Interviews
(Personnel Interviews Noted by Underline)

Site Visited	Contacts	Personnel Contacts
Savannah River Site	On-Site	<u>Jim Mincey</u>, Courtney Apperson, Jr., <u>Hugh Clark</u>
Y-12 Plant @ Oak Ridge	Telephone	Dick Vornehm, <u>Chris Robinson</u>
Oak Ridge National Laboratory	On-Site	Mike Westfall, <u>Howard Dyer</u>, <u>Curtis Jordan</u>, Calvin Hopper, <u>Trent Primm</u>, Lester Petrie, <u>Elliott Whitesides</u>
WINCO	On-Site	<u>Todd Taylor</u>, <u>Paul Sentieri</u>, Ed Lipke
EG&G Idaho	On-Site	Dave Nigg, Jim Lake, Blair Briggs (Telephone)
Westinghouse-Hanford	On-Site	Denelle Friar, <u>Jim Daugherty</u>, <u>Charles Rogers</u>, <u>Alan Hess</u>, <u>Ed Miller</u> <u>Hans Toffer</u>, <u>Warren Wittekind</u>, <u>Kevin Schwinkendorf</u>, <u>Duane Erickson</u> <u>Lee Carter</u>, <u>Bob Morford</u>, Jess Greenborg
Battelle-PNL	On-Site	<u>Les Davenport</u>, <u>Andy Pritchard</u>, <u>Ann Doherty</u>
Los Alamos National Laboratory	On-Site	<u>Tom McLaughlin</u>
Rocky Flats Plant	On-Site	<u>Paul Felsher</u>
W-Nuclear Manufacturing	Telephone/On-Site	Al Casadei, <u>Chris Savage</u>, <u>Bill Newmyer</u>
B&W-Nuclear Fuel	Telephone	<u>Francis Alcorn</u>

Savannah River Site (SRS)

Review of the SRS methodology for handling bias and uncertainty when calculational methods are used in criticality safety evaluations is based on discussions with cognizant criticality safety analysts and a historical review of the handling methodology at SRS. Subsequent contacts with SRS cognizant personnel were used to define in more detail the current methodology and obtain additional documentation of the current methods. Due to the diverse nature of criticality safety evaluations at the SRS site, the application of a variety of calculational methods has evolved. In addition, the handling methodology for calculational method bias and uncertainty at SRS has a strong historical background (References 27-32). The following discussion addresses the current calculational methodology and handling of calculational method bias and uncertainty and is based on discussions with cognizant personnel and review of documents (SR01-SR10).

Calculational Methodology

Calculational methods used in a production mode at SRS include both the original versions of industry standard methodologies and the currently distributed standard versions distributed by the Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory. The SRS calculational methodology for CSE's is evolving from a technology based on local implementations of standard methodologies to the implementation of methodologies distributed by RSIC. Due to the diverse nature of CSE's at SRS, numerous studies of data uncertainties, trends, and sensitivities are performed to more fully understand calculational bias and uncertainty.

The calculational methods currently used in a production mode at SRS include the following:

- KENO-IV/JOSHUA
- KENO-CG/JOSHUA
- ANISN/JOSHUA
- TWOTRAN/JOSHUA
- KENO V.a/SCALE-III
- KENO V.a/SCALE-4.2
- TWODANT-SYS

- MCNP 4A

The first five methodologies are the local implementations of program versions integral to the JOSHUA system or in the case of SCALE III restricted to use with JOSHUA nuclear data. JOSHUA is the standard reactor design methodology at SRS and incorporates both the reactor design and criticality safety methodologies. The last three methodologies are the standard RSIC distributed versions. Each program system is certified on a periodic basis and maintained under configuration control on computer systems per site procedures. Earlier versions of the criticality safety methods are maintained to provide continuity with prior CSE and validation efforts.

The current KENO V.a module is maintained as both a SCALE III and SCALE 4.2 program module. The SCALE packages from RSIC are distributed as CCC-545 (Reference 10). KENO V.a (SCALE III) is the current primary calculational method used in criticality safety evaluations at SRS and the SCALE 4.2 version of KENO V.a has undergone only limited validation and applications. The TWODANT-SYS code system (Reference 18), a deterministic, multigroup, discrete ordinates transport methodology includes both the one-dimensional capability, ONEDANT, as well as two-dimensional capabilities. The TWODANT-SYS code system is used as a secondary or independent method and has undergone only limited validation. ONEDANT and TWODANT are used primarily in uncertainty, trend and sensitivity studies of neutron cross sections, modeling, and methodology. MCNP 4A, the current version of the general purpose Monte Carlo program with enhanced capabilities for criticality analysis, is implemented as the current version distributed by RSIC as CCC-200 (Reference 11). MCNP 4A has undergone only limited validation at SRS and is used in scoping and preliminary design applications.

Neutron cross section data currently used at SRS includes:

- JOSHUA System Processing
    - ⇒ Hansen & Roach (16 group)
    - ⇒ ENDF-IV (84 group, GLASS Module Process)
- SCALE 4.2 Processing
    - ⇒ ENDF-IV (218 group & 27 group)
- AMPX Processing
    - ⇒ ENDF/B-V and VI (ORNL/TM-12370, LAW 238 group)
- MCNPDAT ENDF/B-V (Pointwise)

Neutron cross section data processed within the JOSHUA system maintains continuity with prior criticality safety evaluations and validations. The SCALE 4.2 and MCNPDAT neutron cross section data files are the standard data files distributed by RSIC for use in the SCALE 4.2 system and the MCNP 4A program. In addition, recent investigations have required limited validation and implementation of the 238 group ENDF/B-V and VI data which is locally processed using AMPX modules to prepare cross section data for use in TWOTRAN-SYS. Current production KENO V.a/SCALE III applications use cross section data processed from JOSHUA libraries. Neutron cross section data used in MCNP 4A is the pointwise ENDF/B-V data files distributed by RSIC as the DLC-105C data library (Reference 12).

Bias Development

The SRS development of calculational bias and uncertainty is based on a global (or generic) validation and in special cases, where necessary, bias and uncertainty are defined specifically for each CSE. Current SRS techniques used in the analysis of calculational bias include statistical treatments up to and including multiple regression fits to the predicted results from a group of benchmark critical experiments.
Both multiple regression analysis and selective grouping of benchmark critical experiment results with subsequent linear regression analysis have been used to correlate bias to either physical or neutronic parameters. Current SRS practice is to use either a one-sided tolerance interval or a confidence interval based on the understanding of the physics of the system under evaluation and the availability of benchmark critical data. Generally, only a limited number of benchmark criticals are available to define bias and uncertainty, therefore, one-sided tolerance interval techniques are used. In cases where sufficient understanding of the physics and adequate numbers of benchmark critical experiments are available, multiple regression techniques are used to identify correlations and confidence interval techniques are used. The statistical treatments used at SRS are derived based on References 33, 34, and 35 and the methodology is partially implemented in SR11.

The primary correlation parameter for bias and uncertainty evaluations at SRS is moderator-to-fissile atom ratio, H/X. Other correlation parameters (i.e., second order effects) identified in SRS CSE's are excess nitric acid, reflection (media and thickness), isotopics (e.g., high/low ${}_{93}Pu^{240}$ content), absorbers, and low enriched uranium (LEU) enrichment or rod size.

Development of bias and uncertainty is based on predicted criticality conditions for each of the selected benchmark criticals. Statistical analysis of the results is performed to correlate the mean k_{eff} (or mean of the differences in the predicted k_{eff} and the experimental k_{eff}) and standard deviation of the predicted values for either the overall group or as a function of the correlation parameter. The calculated value of the difference is defined as the method bias and the standard deviation is a product of the statistical process. As described by cognizant SRS personnel, the experimental uncertainties and the standard deviation from the benchmark critical Monte Carlo analysis are combined as a root mean square value and used as weighting factors in the linear or multiple regression analysis based on the methods of Reference 34 to obtain the calculational bias and uncertainty. As described by cognizant personnel, groups of benchmark criticals are selected to cover the area (range) of applicability. SRS experience with the use of area (range) of applicability guidelines as described in References 4 and 5, has shown that the guidelines are difficult to apply in practice.

Bias Application

The current handling of calculational bias and uncertainty in evaluating normal/upset system conditions is either based on a one-sided tolerance interval or a confidence interval. At SRS, the established allowable limiting neutron multiplication factor, k_a, is specified for each CSE based on the site area and the quality of the validation database. Typically, the range of k_a is 0.90 to 0.98 for the SRS site. The evaluation process for the normal/upset condition is as follows;

$$k_p + K_p*\sigma_p < k_a + \Delta k_b - K_b*\sigma_b$$

where: k_p = predicted k_{eff} for normal/upset condition,
K_p = factor defining confidence interval of predicted k_{eff},
σ_p = standard deviation of predicted k_{eff} for the normal/upset condition,
k_a = established allowable limiting neutron multiplication factor,
Δk_b = calculational method bias

K_b = factor defining one-sided tolerance interval <u>or</u> confidence interval from method validation,

σ_b = standard deviation from calculation method validation.

The SRS practice is to use a multiplicative factor, K_p= 2 or 3, corresponding to either a 95.45% or 99.73% confidence level depending upon the complexity and understanding of the system condition being evaluated. The multiplicative factor, K_b, applied to the calculational bias uncertainty is based on either the one-sided tolerance interval at a confidence level of 95% on a 95% proportion of the population defined in Reference 35 or on a confidence interval at a confidence level of 95.54% or 99.73%, where K_b = 2.0 or 3.0, respectively.

The SRS practice is to not apply "positive" calculational bias, except in special well understood cases.

Summary

Comments and conclusions drawn from the review of the current SRS handling of calculational bias and uncertainty follow:

1. The SRS methodology for applying bias uncertainty assumes that the bias standard deviation and the predicted standard deviation of the Monte Carlo predicted k_{eff} for the normal/upset condition are additive. The assumption is made that the uncertainties are not independent. (At a number of other sites, these uncertainties are treated as independent values and are combined as the root mean square of the values.)

2. The above practice results in an increased conservatism in the evaluation process and could be justified on a case-by-case basis. For well understood systems and a consistent application of the calculational methods, use of the root mean square value is valid.

3. Use of linear or multiple regression fits to define bias and uncertainty at SRS utilize combined benchmark experimental and calculation uncertainties to "weight" each benchmark k_{eff} value used in the fitting process. This technique captures not only the variability of the benchmark critical experiments but also considers the quality or uncertainty of the benchmark experiment values and predicted standard deviation in the fitting process of individual benchmark critical results.

4. The SRS methodology for handling of bias and uncertainty is appropriate and valid. The use of multiple or linear regression fits provides the analyst with visual information for judging applicability, trends, and sensitivities of benchmark critical data versus upset condition predictions for the system in evaluation. In addition, as discussed in the overall summary, improvements in CSE documents would result from graphical illustrations of correlations of bias and uncertainty data.

In summary, the SRS practices of handling calculational bias are consistent with the requirements of the current ANSI/ANS 8.1 standard and would meet the requirements of the planned revisions to the standard. The SRS methodology provides the flexibility to adapt handling of bias and uncertainty consistent with the available database and provides for consistent handling of bias and uncertainty within CSE's.

Y-12 Plant @ Oak Ridge, TN

Review of the Y-12 Plant methodology for handling calculational bias and uncertainty is based on the on-site interviews with Oak Ridge National Laboratory (ORNL) personnel cognizant of the development of the Y-12 methodology. Additional sources of information were numerous telephone conversations with cognizant Y-12 criticality safety personnel and documents provided by Y-12 and ORNL personnel (References 35-40 and YP01-YP13).

Calculational Methodology

Calculational methods used in a production mode at the Y-12 site are the computer code versions distributed by the Radiation Shielding Information Center (RSIC) at Oak

Ridge National Laboratory (ORNL) and the proprietary United Kingdom computer program, MONK 6B.

Calculational methods used at Y-12 include the following:

- KENO V.a (SCALE 4.2)
- MCNP 4A
- MONK 6B

KENO V.a is the primary calculational method used for criticality safety analyses at Y-12. Both MCNP 4A and MONK 6B are currently employed as second and independent methods. Currently, only limited validations exist for specific applications of either MCNP 4A or MONK 6B. Each program system used in criticality safety evaluations is certified on the Y-12/ORNL computer systems per site procedures and each code version is maintained under site configuration control.

The current KENO V.a is maintained as the SCALE 4.2 program module (Reference 10). MCNP 4A, the latest version of the general purpose Monte Carlo program with enhanced capabilities for criticality analysis, was implemented from the latest version distributed by RSIC, computer code package CCC-200 (Reference 11).

The MONK calculational methodology was recently licensed for use at Y-12. Version 6B is the current version of the methodology distributed by the ANSWERS Service of the United Kingdom (Reference 16).

Neutron cross section data currently used at Y-12 are the following data libraries:

- SCALE 4.2 ENDF-IV (27 group)
- MCNPDAT ENDF/B-V (Pointwise)
- MONK (Pointwise)

The SCALE 4.2 and MCNPDAT neutron cross section data files are the standard data files distributed by RSIC for use with the SCALE 4.2 system and the MCNP 4A program. MONK neutron cross section data is a pointwise data library processed from the United Kingdom evaluated nuclear data files. Neutron cross section data for use in the SCALE 4.2 module of KENO V.a is obtained using the CSAS25 process of

SCALE 4.2. Current KENO V.a applications use 27 group cross section data processed from ENDF/B-IV data files. Neutron cross section data used in MCNP 4A, are the pointwise ENDF/B-V data files distributed by RSIC as the DLC-105C data library (Reference 12). MONK neutron cross section data exists as a pointwise library with more than 8000 data points for each element or isotope in the data library.

Bias Development

The methodology for handling of bias and uncertainty at the Y-12 Plant was developed in collaboration with Oak Ridge National Laboratory and is described in Reference 36 and YP09. Bias and uncertainty for calculational methods are based on either a global (or generic) validation over a large database of benchmark critical evaluations or in special cases, where necessary, bias and uncertainty are developed specifically for the system undergoing criticality safety evaluation. The Y-12 technique used to determine calculational method bias and uncertainty is based on a linear regression analysis of the predicted results from a group of benchmark critical experiments. Correlation of the bias is primarily to the neutronic parameter, average energy group (AEG) causing fission, which is provided as an output result from a KENO V.a analysis. Current Y-12 practice is to require a very high confidence level in the statistical process used to analyze the benchmark data, and let the statistical analysis technique provide the equations for the calculational method bias and the upper safety limit (USL) as a function of the correlation parameter, AEG. The USL equation includes the uncertainty (standard deviation) in the linear fit of the bias and the safety margin to ensure subcriticality of a system. A bias value is not specifically used in the Y-12 method, but rather an upper safety limit is used as a function of the correlation parameter, AEG. As described by Y-12 and ORNL personnel, results from the statistical technique include the calculational method bias and "safety margin" is derived from the results of the fitting process.

The statistical process used at Y-12 is defined as a single-sided (or one-sided), lower tolerance interval technique as described in Reference 36 and documents YP09, OR01, OR02, and OR03 include more detailed information on the implemented method. The Y-12/ORNL technique uses a uniform width tolerance interval over a closed band (range) of the independent variable, the correlation parameter AEG. The statistical techniques used are derived from References 37 and 38.

As described above, the primary correlation parameter used at Y-12 is the KENO V.a predicted neutronic parameter, AEG. For special cases, the limits of the closed interval on AEG are limited to define a USL line over the limited range of AEG. In Y-12 applications, the LTB becomes the upper safety limit (USL) acceptance criteria for evaluating normal and upset conditions for systems. As described by cognizant Y-12 criticality safety personnel, bias and uncertainty are generally based on predicted criticality conditions for a large group of the benchmark criticals focusing on highly enriched uranium (HEU) systems. The results of the statistical process are equations for;

1. the linear fit to the predicted k_{eff}'s for the group of benchmark criticals,
2. the one-sided, uniform width, lower confidence interval for a single future calculation at a 95% confidence level on a 95% proportion of the population,
3. the one-sided, uniform width, lower tolerance interval at a 95% confidence level on a 99.9% proportion of the population.

Selection of a confidence level and the proportion of the population at Y-12 is based on a requirement for a very high confidence level in the statistical process. The calculational bias is defined on the basis of a critical condition as follows:

$$\Delta k_b = k_f(x) - 1.0$$

where; Δk_b = calculation bias at the AEG of the normal/upset system condition,

$k_f(x)$ = k_{eff} value from linear fit of benchmark critical results at the specific value of the independent variable x,

x = specific value of the independent variable, AEG.

The Y-12 "safety margin" is explicitly defined as the difference between values from the equations for the lines (1) and (2) defined above at a specific value of AEG.

In the Y-12 application, the confidence and tolerance intervals defined for lines (1) and (2) above are based on a "pooled" standard deviation which is the root mean square of the estimated standard deviation of the linear fit to the benchmark criticals k_{eff}'s and the estimated standard deviation of the predicted k_{eff}'s for benchmark criticals as follows:

$$\sigma_b = (\sigma_f^2 + \sigma_c^2)^{1/2}$$

where; σ_b = estimated standard deviation, "pooled" value, used to define the confidence interval or lower tolerance interval,

σ_f = estimated standard deviation of the linear fit, and

σ_c = estimated standard deviation from individual benchmark critical experiments (root mean square value of the individual standard deviations, σ_i's)

σ_c = $(\sum \sigma_i^2)^{1/2}$

The closed band on the independent variable, correlation parameter AEG, defines the area (range) of applicability in Y-12 CSE's.

At Y-12, case specific evaluations have used trend and/or sensitivity studies to isolate or eliminate anomalies identified by the linear regression analysis for groups of selected benchmark criticals.

Bias Application

The current methodology at Y-12 of applying calculational bias and uncertainty in evaluating system normal/upset conditions is based on the use of the upper safety limit described above. The technique of calculating the USL captures the uncertainty within the group of benchmark criticals and incorporates the uncertainty in the individual result of each benchmark critical prediction. At Y-12, the established allowable limiting neutron multiplication factor, k_a, is defined as the USL for the normal/upset condition to be evaluated. The evaluation process for the normal/upset condition is as follows:

$$k_p + K_p * \sigma_p < \text{USL}$$

where: k_p = predicted k_{eff} for the normal/upset condition,

K_p = multiplier to define the confidence interval on the predicted k_{eff} of a normal/upset condition,

σ_p = standard deviation of predicted k_{eff} for normal/upset condition.

The Y-12 practice is to use a confidence interval based on a 95% confidence level, $K_p = 2.0$. As discussed by cognizant ORNL, ORNL/Y-12 statisticians do not require the application of the standard deviation of the predicted k_{eff} for the individual benchmark critical results, however, ORNL/Y12 includes the value because of the inherent uncertainty in the Monte Carlo method. Normally, the individual calculation standard deviations are much smaller that the standard deviation from the linear fit and therefore statistically combining the values does not significantly increase the "pooled" standard deviation.

Summary

Review comments and conclusions drawn from the review of the current Y-12 handling of calculational bias and uncertainty in CSE's follow:

1. The Y-12 methodology for applying bias uncertainty assumes that the calculational bias standard deviation and the predicted standard deviation of the Monte Carlo predicted k_{eff} for the normal/upset condition are additive and therefore correlated values. The Y-12 technique of calculating a "pooled" standard deviation which includes the root mean square value of the standard deviations of the benchmark critical k_{eff}'s differs from the techniques used at other sites. The current Y-12 practice provides an additional conservatism in the acceptable safety limit (USL).

2. The use of a uniform width tolerance band to define the USL based on the linear fit of the benchmark critical data provides additional margin over part of the area (range) of applicability or closed band. Because of the technique used to define the lower tolerance interval as a uniform width, the Y-12 USL equation cannot be used to extrapolate beyond the limits of the closed band. The Y-12 technique could be used to extrapolate by parametrically examining the uniform width size as a function of the upper or lower limits of the closed band.

3. Use of the Y-12 technique of establishing a USL based on the statistical treatment of the benchmark critical data eliminates the need to define a safety margin based on intuition or judgment of the analyst (or criticality safety organization). The technique relies on the variability in the benchmark critical predictions to set the size of the safety margin. Therefore, a well defined group of benchmark critical data would approach using a Monte Carlo method as a computational benchmark in place of a benchmark critical experiment.

4. For well understood systems and consistent application of the calculational methods, the practice of including the "within-group" or individual benchmark critical experiment standard deviations as the root mean square value of the standard deviations may not be necessary. However, at the convergence level of current applications on Monte Carlo calculational methods, the added conservatism is small and most probably inconsequential in evaluations of upset conditions in CSE's.

5. The Y-12 technique of developing the USL will capture not only the variability of the benchmark critical experiments but can also include a measure of the quality of the benchmark experiments and predictions in the calculational bias. In contrast to SRS techniques, the current Y-12 technique cannot include the variability of the predicted and experimental uncertainties in determining the linear fit and the uniform width of the lower tolerance interval.

6. Examination of results from application of the Y-12 technique to a sample set of benchmark critical data indicates that the Y-12 technique provides results similar to the one-sided lower tolerance interval technique used at other sites when the benchmark critical data is grouped into a single set of data.

7. The Y-12 methodology for handling of bias and uncertainty is appropriate and valid and includes some conservatism beyond techniques used at other sites. The use of a linear regression fit provides the analyst with visual information for judging applicability, trends, and sensitivities of benchmark critical data versus upset condition predictions for the system in evaluation. In addition, as discussed in the overall summary, improvements in CSE documents would result from inclusion of graphical illustrations of correlations.

In summary, the Y-12 practice of handling calculational bias is consistent with the requirements of the current ANSI/ANS 8.1 standard and would meet the requirements of the planned revisions to the standard. The Y-12 methodology provides the flexibility to adapt handling of bias and uncertainty consistent with the available database and provides for a consistent methodology for handling of bias and uncertainty in CSE's.

Oak Ridge National Laboratory @ Oak Ridge, TN

In the prior discussion summarizing the review of the Y-12 methodology for handling bias and uncertainty, a primary source of information was discussions with ORNL criticality safety personnel and documents and information provided by ORNL personnel (References 36-41 and OR01-OR03). ORNL personnel provided a FORTRAN program (OR01) for evaluation purposes which incorporates the Y-12/ORNL statistical methodology. ORNL personnel collaborated with Y-12 and were principal contributors to the development of the statistical treatments used at Y-12. The following discussion addresses the current ORNL calculational methodology used in criticality safety evaluations. The ORNL methodology for handling of bias and uncertainty in criticality safety evaluations is the same as the Y-12 methodology. Differences in the ORNL versus Y-12 applications are due to a much broader scope of criticality safety evaluations at ORNL. As described in prior sections, the Y-12 Plant focus is on criticality safety evaluations of highly enriched uranium (HEU) systems. In contrast, ORNL's scope of criticality safety evaluations includes evaluations of systems involving a majority of fissile isotopes, e.g., U^{233}, Pu, and actinides.

Due to the diverse nature of criticality safety evaluations at ORNL, the calculational methods and the applications are expanded versus the Y-12 scope. The following discussion addresses the current ORNL calculational methods.

Calculational Methodology

Calculational methods used in a production mode within the ORNL criticality safety organization are maintained under site configuration control procedures. Due to the diverse nature of CSE's at ORNL versus Y-12's focus, the deterministic methods in SCALE 4.2 are used to conduct studies of data uncertainties and trend and sensitivity analyses. Discussions with ORNL criticality safely personnel and reviewed documents identified studies using deterministic methods to reduce or more fully understand calculational bias and uncertainty and expanded evaluations of area (range) of applicability. Technique discussed during the site visit included the analysis approach used to extend the area (range) of applicability by extracting a trend, e.g., reflection, for use in extending the validation for a second group of benchmark criticals. References 39 and 40 are examples of ORNL analyses which establish, extend, or extrapolate area (range) of applicability.

Calculational methods used at ORNL include the following:

- KENO V.a (SCALE 4.2)
- XSDRN-PM (SCALE 4.2)
- DORT

KENO V.a is the primary calculational method used for criticality safety analyses at ORNL. The XSDRN-PM module of SCALE 4.2 is used as the one dimensional deterministic transport method for evaluating trends and sensitivities and evaluation of data uncertainties. DORT (Reference 42) is the current ORNL version of a deterministic transport methodology. DORT, a multigroup discrete ordinates transport methodology, includes both a two- and one-dimensional capability. The DORT code system, distributed by RSIC as CCC-543, is used in special cases to investigate trends and sensitivities and to assess uncertainties of neutron cross sections, modeling, and methodology. Each code system is certified on the ORNL/Y-12 computer systems per site procedures and each code version is maintained under site configuration control.

KENO V.a and XSDRN-PM are maintained within the SCALE 4.2 methodology and are included in the RSIC distribution package CCC-545 (Reference 10).

Neutron cross section data currently used at ORNL are ENDF-IV data in either a 218 group or 27 group format. In addition, for special studies, ENDF/B file data has been processed to provide cross section data for use in SCALE 4.2 processes. The SCALE 4.2 neutron cross section data files are the standard data files distributed by RSIC for use in the SCALE 4.2 system.

Bias Development

Development of calculational bias and uncertainty at ORNL is the same as described in the Y-12 site review. Due to the diverse nature of the criticality safety evaluations, the applications of the statistical treatment are more varied and generally incorporate smaller groupings of benchmark critical data. In general, ORNL practices are to develop the USL limits on a case-by-case basis with added emphasis on evaluating area (range) of applicability and correlations other than the average energy group (AEG) causing fission.

Bias Application

The ORNL technique for applying calculational bias and uncertainty are the same as described earlier in the Y-12 site review. As described earlier, the ORNL criticality safety evaluations are more diverse than Y-12's applications. ORNL CSE's involve a wide variety of physical/neutronic parameters to evaluate calculational bias and uncertainty. However, the methodology for handling the calculation bias and uncertainty based on the determination of an upper safety limit (USL) is the same as the Y-12 method except the independent variable may be different. As discussed with ORNL personnel, the primary correlation parameter is the average energy group (AEG) causing fission.

Summary

The Y-12 site review summary in the prior section includes an assessment of the current Y-12/ORNL methodology for handling bias and uncertainty in criticality safety evaluations and therefore is not repeated here.

Westinghouse Idaho Nuclear Co. (WINCO)

Review of the WINCO methodology for handling calculational bias and uncertainty is based on the on-site interviews with cognizant criticality personnel, review of criticality procedures, review of recent CSE documents, and telephone conversations with cognizant criticality safety personnel. Documents provided for later review are identified as References 43-49 and WI01-WI17.

The following discussion addresses the current WINCO calculational methodology and the methodology for handling of bias and uncertainty in criticality safety evaluations.

Calculational Methodology

At the WINCO site, the CSE calculational methods currently used in a production mode are:

- KENO V.a
- MCNP 4A
- TWODANT-SYS

Each of the methodologies has been implemented in the standard RSIC distributed format without local modifications. Each program system is certified and placed under configuration control on the WINCO computer systems per site procedures. Site procedures (WI01-WI10) were reviewed to ascertain the site implementation of standards and the requirements relative to calculational bias and uncertainty.

The KENO V.a module used at WINCO is the program module distributed with the SCALE 4.2 package from RSIC as CCC-545 (Reference 10). The MCNP 4A version implemented at WINCO is the current version distributed by RSIC as CCC-200 (Reference 11). Each of these program systems has been used in a number of the reviewed criticality safety evaluations. The applications have been consistent with the capabilities of each of the methodologies. CSE and validation documents were reviewed to determine the program options used to predict criticality conditions.

The TWODANT-SYS code system (Reference 18) was implemented in one of the CSE's reviewed and both the ONEDANT and TWODANT modules of the TWODANT system were used.

Neutron cross section data files currently used at the WINCO site are the standard distributed data associated with either the SCALE 4.2 system or the MCNP ENDF/B-V data files distributed by RSIC. The current neutron cross section data files used in validation and CSE applications of KENO V.a and TWODANT are derived using the

CSAS1 or CSAS25 processes within SCALE 4.2. Current applications at WINCO use the neutron cross section datasets from the ENDF/B-IV data files in the multigroup format with 27 groups. Twenty seven (27) group data in SCALE 4.2 has been collapsed from 218 group ENDF/B-IV data. The 27 group data is distributed as part of the SCALE 4.2 code package (Reference 10). In the ONEDANT/TWODANT applications, the multigroup cross section data is processed with the CSAS1 process in SCALE 4.2 and are used as multigroup P_ℓ scattering approximation neutron cross section data.

Neutron cross section data used in MCNP 4A is the pointwise ENDF/B-V data files distributed by RSIC as the DLC-105C data library (Reference 12).

Bias Development

Based on the discussions with cognizant criticality safety analysts and review of available CSE documents (WI11-WI16), the development of calculational method bias and uncertainty is generally performed within the CSE analyses. Most cases use information from a series of generic validation documents for KENO V.a or MCNP 4A. Generic validations of the KENO V.a and MCNP 4A methodologies for the WINCO site have been documented in References 43-49. The KENO V.a validations are documented in References 43, 44, and 45 for highly enriched uranium solutions, highly enriched uranium metal systems, and highly uranium oxide systems, respectively. Each of the KENO V.a validation runs was made with 203 generations and 300 source particles per generation. The validation reports include predicted k_{eff}'s for three different cross section data libraries, i.e., the 27 group ENDF/B-IV data, the 16 group Hansen and Roach and 123 group GAM/THERMOS data as distributed with SCALE 4.2. All neutron cross section data were processed within a CSAS25 sequence and used directly in KENO V.a. In each of the documents, suggested biases based on the 27 group analyses are discussed on a generic basis. No statistical process or treatment is used to support the suggested use of no bias being necessary. The basis for the assumption of no bias being necessary is the fact that the majority of the KENO V.a runs predicted k_{eff}'s greater than the corresponding experimentally measured k_{eff}. As described in the documents, the only case where bias may be suggested is the case for boron poisoned highly enriched uranium solutions. Later discussions will address the validity of the assumptions and the use of the generic validation data in individual

CSE's. The generic MCNP 4A validation (References 46-49) uses the same geometric and material data and experiment specifications as used in preparing the input files for the KENO V.a validation calculations. The MCNP 4A generic validation calculations are all run with 100 generations and with 1000 source particles per generation. The ENDF/B-V pointwise data files distributed with Reference 12 were used in all cases.

The generic validation documents for both KENO V.a and MCNP 4A are summary documents and contain the predicted k_{eff}'s, standard deviation or relative error of the predicted k_{eff}, and an input file listing for each calculation. None of the documents define the computing platform, mainframe or workstation, used to predict criticality conditions for each of the benchmark critical experiments. Only minimal dimensional or material concentrations information is provided for each entry in the tabular information.

In the reviews of CSE documents, no calculational method biases or uncertainties were defined for use in assessing the safety of predicted critical conditions for the systems under evaluation. In general, the analysts judged that the predicted k_{eff}'s for the benchmark criticals were all approximately unity (1.0), therefore, no bias was necessary. Also, WINCO analysts generally judged the uncertainty of the individual benchmark critical results as small (< 1%) and therefore no uncertainty in the bias was warranted.

Bias Application

The current WINCO methodology for handling calculational bias and uncertainty in evaluating system normal/upset conditions is based on reviews of recent CSE's. At WINCO, the established allowable limiting neutron multiplication factor, k_a, is defined for the site as $k_a = 0.95$. The evaluation process for the normal/upset condition is as follows:

$$k_p - \Delta k_b + K_p \sigma_p < k_a$$

where:
- k_p = predicted k_{eff} for the normal/upset condition,
- Δk_b = calculational method bias,
- K_p = multiplier to define the confidence interval on the predicted k_{eff} of a normal/upset condition,

σ_p = standard deviation of predicted k_{eff} for normal/upset condition.

The WINCO practice is to use a confidence interval based on a 95.45% confidence level or $K_p = 2.0$. As described in the previous section and based on reviews of WINCO CSE's, the calculational bias, Δk_b, was generally judged to be small and assigned a zero (0.0) value. In discussions with cognizant criticality safety analysts, calculational bias has been used in prior analyses with an enveloping value estimated by visual inspection of predicted k_{eff}'s (or differences in predicted and experimental k_{eff}'s). As shown by the above evaluation equation, the uncertainty (or standard deviation) of the calculational bias is not defined in WINCO CSE's and was generally judged to be small relative to the safety margin afforded by the site established limiting neutron multiplication factor ($k_a = 0.95$), the conservatism in the choice of upset conditions, and the predicted subcritical margin for system upset conditions.

Summary

The following critique items address the handling of calculational bias and uncertainty based on the review of documents WI11-WI16.

1. It is assumed that the predicted k_{eff} is the multiplication factor for the benchmark critical experiment. Predicted k_{eff}'s from a Monte Carlo calculation are the estimated mean value with a confidence interval about the mean value defined by the standard deviation or relative error of the Monte Carlo calculation.

2. The assumption is made that the selected benchmark criticals represent the normal and upset conditions evaluated in each CSE. Only limited discussions of a correlation parameter, e.g., moderator-to-fissile atom ratio or H/X, are documented to identify area (range) of applicability for the selected benchmark critical experiments. Correlation parameter values for the evaluated normal/ upset condition are not generally included in the documents and area (range) of applicability is not demonstrated.

3. Certain CSE's define the computing platform used, however, comparisons of the program options and computing platform used in the CSE's versus validation documents are not mentioned or evaluated. This approach is appropriate if no statistical analysis is performed.

4. Variability in the Monte Carlo predicted k_{eff} values for the selected group of benchmark criticals used for validation is generally judged to be small (≤ 1.0%) with small predicted standard deviations (or uncertainty). In discussions with cognizant personnel, variability and uncertainties in Monte Carlo results are judged to be small in comparison to the margin Δk_m of 0.05 for the WINCO site, and normal and upset criticality conditions are either far below the site-imposed allowable limiting neutron multiplication factor of k_a = 0.95 or that evaluated upset conditions are conservatively specified.

5. Only a limited number of benchmark critical experiments were identified in each document. Correlation of the experiments to a physical/neutronic parameter was only verbalized and no graphical or tabular data was provided to evaluate the correlation parameter(s) used to judge the area (range) of applicability for the selected benchmark critical experiments

6. Program options used in the CSE and benchmark critical experiment validation were not stated in the reviewed documents.

In summary, WINCO CSE analysts do not generally use calculational method bias or uncertainty is assessing criticality safety of systems. Calculational bias is generally judged by analysts to be small, Δk_b <1%, with all predicted benchmark critical k_{eff}'s~ 1.0 and small predicted uncertainties based on the predicted standard deviation (or relative error) of the Monte Carlo result. Reviewed WINCO documents did not use statistical techniques to evaluate the mean k_{eff} and standard deviation and to estimate the variance of uncertainty of the selected group of benchmark criticals. Within the sections of documents assessing normal/upset conditions, trend and/or sensitivity studies were performed to define "worst case" scenarios for systems. However, correlations of normal/upset conditions to the area (range) of applicability for the group of benchmark criticals are not shown in the documents.

The documented WINCO methodology for handling bias and uncertainty relies heavily on the expertise level of the criticality safety organization and personnel. Use of a statistical treatment for handling bias and uncertainty at an appropriate level of detail could be used to assure a consistent approach within CSE's and further could be used to demonstrate the validity of criticality safety evaluations relative to area (range) of applicability. At a minimum, illustrations and tabulations of the correlation of predicted upset conditions to benchmark critical experiment conditions should be included in CSE documents to demonstrate how validated methods are representative of the evaluated system upset conditions per ANSI/ANS 8.1 guidance.

EG&G Idaho

The review of the methodology for handling calculational bias and uncertainty in criticality safety evaluations at EG&G Idaho is based on an on-site interview with cognizant criticality personnel, review of criticality safety procedures, review of recent CSE documents, and telephone conversations with cognizant criticality safety personnel. Documents provided for later review are identified as documents EI01-EI05. The EG&G Idaho criticality safety group provides criticality safety services for outside customers with minimal in-house support. EG&G Idaho is the lead organization in the development of the Evaluated Criticality Safety Benchmark Experiments Handbook (Reference 3). Criticality safety evaluations for external customers are performed to requirements defined by the customer. The review of three CSE documents showed that in one document, a customer defined calculation bias was applied in the criticality safety evaluations of upset conditions in the document. In the other two documents, specific method validations for selected groups of benchmark critical experiments are discussed. In both of the latter CSE's, the analyst judged that no calculational bias or uncertainty was necessary for the Monte Carlo method used. The analyst judged that the predicted k_{eff}'s for the selected benchmark criticals indicated that a calculational bias in addition to the statistical uncertainty associated with the Monte Carlo calculation method is not warranted. One of the documents reviewed included an excellent example of an approach used to extended the area (range) of applicability with an independent methodology, i.e., calculational method and neutron cross section data.

Based on the limited review, the EG&G methodology for handling calculational bias and uncertainty is a non-statistical treatment with the use of a bias and uncertainty judged to be small and not warranted. Normally, the Monte Carlo predicted uncertainty, i.e., standard deviation for the upset condition calculation, is the only uncertainty included in the evaluation process.

The following discussion addresses the current EG&G Idaho calculational methods and the methodology for handling calculational method bias and uncertainty.

Calculational Methodology

EG&G Idaho criticality safety calculational methods used in a production mode are:

- KENO IV
- KENO V.a (SCALE 4.2)
- SCAMP
- MCNP 4A

The KENO IV, KENO V.a, and MCNP 4A methodologies have been implemented in the RSIC distributed format. Each program system is certified and placed under configuration control on the EG&G Idaho computer systems per site procedures. Site procedures (EI01,EI02) were reviewed to ascertain site implementation of standards and requirements relative to calculational bias and uncertainty.

KENO IV, an earlier version of the KENO Monte Carlo criticality analysis program, is used is a stand-alone version for special applications using original Hansen & Roach neutron cross section libraries. KENO V.a is the current version of the KENO program distributed by RSIC within the SCALE 4.2 package (CCC-545, Reference 10). The MCNP 4A version implemented at EG&G Idaho is the current version distributed by RSIC as computer code package CCC-200 (Reference 11). The SCAMP computer program is a local implementation of a multigroup discrete ordinates transport method. SCAMP, a deterministic transport method, was used in special applications. Each program was used in the documents reviewed (EI03-EI05) and applications are consistent with the capabilities of each methodology.

Neutron cross section data files currently used at EG&G are the standard distributed data associated with either the SCALE 4.2 system and the MCNP ENDF/B-V data files distributed by RSIC. Both the CSAS25 and CSAS1 processes of SCALE 4.2 are used to prepare both Hansen & Roach (16 group) and ENDF/B-IV (27 group) neutron cross sections for use in either KENO or SCAMP. In addition, older versions of the Hansen & Roach neutron cross section library are used in special cases using KENO IV. Neutron cross section data used in MCNP 4A is the pointwise ENDF/B-V data files distributed by RSIC as the DLC-105C data library (Reference 12).

In addition to the above cross section data, EG&G maintains an independent cross section processing methodology, COMBINE/PC, which provides the capability to process ENDF/B-IV, ENDF/B-V, and ENDF/B-VI nuclear data files. COMBINE/PC is used to prepare neutron cross section data sets for used in SCAMP, KENO IV, or KENO V.a. COMBINE processed cross section data is prepared in a multigroup format and provides neutron cross section data for use in trend or sensitivity studies.

Bias Development

Based on the discussions with cognizant criticality safety analysts and review of available CSE documents (EI03-EI05), the evaluation of calculational method bias and uncertainty is performed within each CSE. In one of the reviewed documents, a KENO IV and KENO V.a calculational bias of Δk_b=-0.02 is referenced to a customer document and used to assess the CSE system criticality conditions. In other documents, calculational bias and uncertainty were judged to be small in relation to the conservative assumptions used in specifying upset conditions in the CSE and the evaluation versus the site-imposed allowable limiting neutron multiplication factor (k_a) of 0.95. Therefore, no bias was warranted.

Bias Application

The current methodology for handling calculational bias and uncertainty in evaluating system normal/upset conditions at EG&G Idaho is inferred from document reviews and limited discussions with EG&G personnel. At the INEL site, the established allowable limiting neutron multiplication factor, k_a, is defined for the site as k_a = 0.95. The evaluation process for the normal/upset condition is as follows:

$$k_p - \Delta k_b + K_c * \sigma_p < k_a$$

where: k_p = predicted k_{eff} for the normal/upset condition,
Δk_b = calculational method bias,
K_c = multiplier to define the confidence interval on the predicted k_{eff} of a normal/upset condition,
σ_p = standard deviation of predicted k_{eff} for normal/upset condition, and
k_a = the established allowable limiting neutron multiplication factor.

The EG&G Idaho practice is to use a confidence interval based on a 95.45% confidence level or $K_c = 2.0$. As described in the previous section and based on the review of CSE's, the calculational bias, Δk_b, and the uncertainty, σ_b, were generally judged to be small and assigned zero (0.0) values.

Summary

The following items address the handling of calculational bias and uncertainty based on a review of a limited number of documents. In general, the methodology for handling bias and uncertainty is similar to that described in the WINCO site review section and no additional critique relative to the methodology for handling bias and uncertainty is warranted.

In summary, EG&G CSE documents do not generally use calculational method bias or uncertainty is assessing criticality safety of systems. Calculational bias is generally judged by analysts to be small, Δk_b <1%, with all predicted benchmark critical k_{eff}'s ~ 1.0 and small uncertainty based on the predicted standard deviation (or relative error) of the Monte Carlo result. Reviewed EG&G documents did not use statistical techniques to evaluate the mean k_{eff} and standard deviation of the benchmark critical data for method validation. Therefore, the definition of a bias or uncertainty for a calculational method is left to the analyst's judgment. The use of trend and/or sensitivity studies was included in EG&G documents and were performed to assess "worst case" scenarios for systems. However, correlation of normal/upset conditions to the area (range) of applicability for the group of benchmark criticals is not illustrated in the documents.

The current EG&G methodology for handling bias and uncertainty relies heavily on the level of expertise of the criticality safety organization and personnel. As discussed above in the WINCO site review section, the use of a statistical treatment for handling bias and uncertainty at the appropriate level and interpretation can provide for consistency within CSE's and would demonstrate validity of criticality safety evaluations versus the area (range) of applicability of the benchmark critical experiments selected to be representative of the CSE system conditions.

Westinghouse-Hanford

The methodology for handling calculational method bias and uncertainty when calculational methods are used in criticality safety evaluations at the Westinghouse Hanford site is based on interviews with cognizant criticality safety analysts and information provided for later review (WH01-WH07). At the W-Hanford site, criticality safety evaluations are performed by two separate groups with a third group providing specialized support services. One of the groups has the responsibility for criticality safety evaluations other than the N-Reactor Area. The second group is primarily responsible for N-Reactor Area criticality safety evaluations, and the third group provides specialized support services in Monte Carlo applications, where necessary. Site procedures require that the CSE review process be conducted by independent organizations. As described later, although the two organizations use different and independent calculational methods in evaluating criticality safety of systems, the methods of handling calculational bias and uncertainty are similar. The following discussions address the methodology of handling bias separately since the application of calculational methods are different and diverse.

The following sections address the criticality safety evaluations outside of the N-Reactor Area.

Calculational Methodology

The calculational methodology currently used in the organization responsible for all CSE's except for the N-Reactor Area is the proprietary United Kingdom Monte Carlo criticality analysis system, MONK (Reference 16). The current version of the MONK system, MONK 6B, is licensed for use at W-Hanford from the ANSWERS Service in the United Kingdom.

MONK 6B has been certified on the W-Hanford computer systems per site procedures and the current version is maintained under configuration control.

Neutron cross section data used is the pointwise data library distributed with the MONK system. MONK neutron cross section data is a pointwise data library processed from the United Kingdom evaluated nuclear data files. MONK neutron cross section data exists as a pointwise library with more than 8000 data points for each element or isotope in the data library.

Bias Development

The W-Hanford development of calculational method bias and uncertainty relies on the global (generic) validation database distributed with the MONK methodology, (Reference 16), supplemented by benchmark critical experiment predicted results specific to the CSE. The process to define the bias and uncertainty is a straightforward calculation of the mean k_{eff} (or mean difference between the predicted k_{eff} and the experiment k_{eff}) and the standard deviation of the k_{eff}'s (or differences) for the selected group of benchmark critical results.

The group of benchmark critical experiments is selected to be representative of the system condition to be evaluated and is assumed to span the area (range) of applicability. The calculated value of the differences in k_{eff}'s is defined as the calculational bias and the standard deviation of the differences is applied in the evaluation equation shown in the next section.

No correlations of the predicted benchmark critical k_{eff}'s to a physical or neutronic parameter were used in the CSE's reviewed. Generally, the selected group of benchmark criticals is chosen to be representative of the system under evaluation. As described by cognizant personnel, groups of benchmark criticals are selected to cover the area (range) of applicability and by including a sufficient range, a conservative calculational bias is defined.

Bias Application

Application of the calculational bias and uncertainty is by a straightforward statistical process, i.e., a confidence interval at a specified confidence level. The calculational bias and the bias standard deviation are used to evaluate the predicted normal/upset condition as follows:

$$k_p - \Delta k_b + \Delta k_m + K_c * (\sigma_b^2 + \sigma_p^2)^{1/2} < k_a$$

where:
- k_p = predicted k_{eff} for normal/upset condition,
- Δk_b = calculational bias,
- Δk_m = margin to ensure subcriticality of system,
- K_c = multiplier to define a confidence interval at a specified confidence level,
- σ_p = standard deviation of the Monte Carlo result for system,
- σ_b = standard deviation of k_{eff}'s (or differences) of benchmark criticals,
- k_a = the established allowable limiting neutron multiplication factor.

At the W-Hanford site, $k_a = 0.95$, is a site requirement for all criticality safety evaluations outside of the N-Reactor Area. In addition, Δk_m is assigned a value of 0.0. It is W-Hanford practice to use a 95% confidence level, i.e., $K_c = 1.96$, to define the confidence interval. The confidence interval is based on the root mean square of the standard deviations for the predicted k_{eff} from the MONK 6B run and the standard deviation of the group of benchmark criticals. The standard deviations from the individual MONK 6B calculations of the benchmark criticals are not used. This assumption is based on a consistent application of the MONK 6B method to predict the system condition subcriticality and the benchmark criticals and further assumes that the MONK 6B method will converge in a similar manner such that any computational biases would be the same for all MONK 6B calculations.

The normal practice at W-Hanford is to not to apply "positive" calculational bias. Positive bias occurs when the mean value of differences, predicted k_{eff} minus experimental k_{eff} is greater than 0.0. Therefore, the W-Hanford practice of not including positive bias increases conservatism in the criticality safety assessment when a "positive" value is predicted.

The following items address the current methodology for handling calculational bias and uncertainty in the W-Hanford areas other that the N-Reactor Area.

1. The assumption is made that the standard deviation of the normal/upset condition is the only computational method uncertainty used in the evaluation equation. The basis for this assumption is that all MONK 6B calculations are performed with the same program options and that MONK predicted results are based on normally distributed results.

2. The prior assumption is only valid if the analyst has assured that the MONK results are based on a properly converged source distribution and that the convergence pattern to the predicted k_{eff} is as expected and does not show any abnormalities indicating errors in the solution.

3. W-Hanford practice is to use ANSWERS recommended stages, cycles, and particles per stage and convergence criteria on the predicted k_{eff} for all calculations. This approach is valid and consistent and provides the capability to use the individual ANSWERS validation results in the determination of calculational bias within a CSE. This approach is only valid for calculations performed on the same computing platform.

4. W-Hanford use of a statistical process based on a confidence interval at the 95% level may not be valid if the group of selected benchmark criticals is small or does not closely representative the system being evaluated. A more valid approach would be to use a one-sided lower tolerance interval technique for all CSE's except for the case where a well-characterized and correlated group of benchmark criticals are available which closely represent the evaluated system conditions.

5. The group of benchmark criticals selected is assumed to span the area (range) of applicability. The use of a straightforward statistical analysis treating the overall group and using a confidence interval is therefore assumed to capture the uncertainties in; a) the benchmark critical specifications, b) the extrapolation

or extension of the area (range) of applicability, c) the limitations in the geometric/material representations of the benchmarks, and d) the calculational bias.

6. Use of a mean value of the k_{eff}'s for the group of benchmark criticals has the potential to be conservative or non-conservative if the calculational bias is a function of a physical or neutronic parameter. At the limits of the parameter which defines a range (area) of applicability, the bias could be larger or smaller than the mean value.

7. The use of a linear (or multiple) regression fit versus a group mean value can provide the analyst the ability to visualize and better understand the trends and sensitivities of the bias and the possible correlation of bias to a physical or neutronic parameter.

In summary, the W-Hanford methodology for handling calculational bias and uncertainty is consistent with the requirements of the ANSI/ANS 8.1 standard. If the planned revisions to the standard are approved as currently drafted, the practice of using a group mean value and standard deviation may require extension to a higher order regression fit. In addition, the use of a 95% confidence band is less conservative than other sites which use a statistical approach. The use of a technique based on a one-sided lower tolerance interval at a 95% confidence level on a 95% proportion of the population may be more appropriate for cases which have a limited number of representative benchmark criticals or a less than desirable understanding of the physics in the area (range) of applicability.

However, the W-Hanford practice is a valid approach to handling bias and uncertainty and reviewed documents indicated a consistency in handling of bias and uncertainty in CSE's.

Westinghouse-Hanford (N-Reactor Area)

The W-Hanford (N-Reactor Area) methodology for handling calculational method bias and uncertainty relies on benchmark critical experiment evaluated results specific to a CSE (WN01). A statistical treatment to define the calculational bias and uncertainty is used by estimating the mean value of the predicted k_{eff}'s (or mean of the difference in predicted and experimental k_{eff}'s) for a selected group of benchmark critical experiments. The uncertainty in the bias is then defined as the standard deviation from the mean value. Due to the reactor physics background of the N-Reactor group, the use of trend/sensitivity studies are relied on to define "worst case" conditions for system criticality safety evaluations.

Calculational Methodology

The calculational methodologies used in the N-Reactor Area are as follows:

- WIMS-E
- MCNP 3B
- MCNP 4A

The primary tool for evaluating "worst case" configurations is the deterministic methodology, WIMS-E. The MCNP methods are used both to evaluate "worst case" conditions and either MCNP 3B or MCNP 4A are the primary tools used to evaluate upset conditions which require modeling of complex geometry configurations.

The process to define the bias and uncertainty is a straightforward calculation of the mean value and standard deviation for the selected group of benchmark criticals. The group of benchmark critical experiments is selected to be representative of the system condition to be evaluated and is generally assumed to span the area (range) of applicability. The calculated value of the differences in k_{eff}'s is defined as the calculational bias and the standard deviation of the differences is applied in the evaluation equation shown in the next section. No correlations of the predicted benchmark critical k_{eff}'s results to a physical or neutronic parameter are used in the CSE's reviewed.

Bias Application

Application of the calculational bias and uncertainty is by a straightforward statistical process, i.e., a confidence interval at a specified confidence level. The calculational bias and the bias standard deviation are used to evaluate the predicted normal/upset condition as follows:

$$k_p - \Delta k_b + \Delta k_m + K_c * (\sigma_b^2 + \sigma_p^2)^{1/2} < k_a$$

where: k_p = predicted k_{eff} for normal/upset condition.
Δk_b = calculational bias,
Δk_m = margin to ensure subcriticality of system,
K_c = multiplier to define a confidence interval at a specified confidence level,
σ_p = standard deviation of the Monte Carlo result for system,
σ_b = standard deviation of k_{eff}'s (or differences) of benchmark criticals,
k_a = established allowable limiting neutron multiplication factor.

At the Hanford site, $k_a = 0.98$, is a site requirement for criticality safety evaluations within the N-Reactor Area. As described by cognizant criticality safety personnel, a k_a value of 0.98 is specified based on the fact that fissile materials in the N-Reactor Area are limited to LEU materials. In the above equation, the safety margin, Δk_m, is assigned a value of zero (0.0). It is W-Hanford practice to use a 95% confidence level, i.e., $K_c = 1.96$, to define the confidence interval on the Monte Carlo predicted k_{eff} for upset conditions. The confidence interval is based on the root mean square of the standard deviations for the predicted k_{eff} from the MCNP Monte Carlo calculation of the system upset condition and the standard deviation estimated from the group benchmark critical experiments results. Standard deviations from the individual MCNP calculations of the benchmark criticals are not included in the bias uncertainty estimate. This assumption is based on a consistent application of the MCNP method to predict the system upset conditions and the individual benchmark critical experiments and further that the MCNP method will converge such that any computational bias would be approximately the same value for all MCNP calculations. In cases where the WIMS methodology is used to predict criticality conditions, the convergence criterion used in the deterministic WIMS method is assumed to be the uncertainty estimate for the predicted k_{eff}.

The normal practice at W-Hanford is not to apply "positive" calculational bias. Positive bias occurs when the mean value of differences, predicted k_{eff} minus experimental k_{eff} is greater than 0.0. Therefore, the W-Hanford/N-Reactor Area practice of not including positive bias increases conservatism in the criticality safety assessment.

Summary

Discussions and review of the methodology for handling calculational bias and uncertainty in the N-Reactor Area at the W-Hanford site clearly showed a strong reliance on the reactor physics background. Extensive use of the WIMS methodology was evident. Application of independent methodologies to assess "worst case" criticality conditions of complex configurations was evident in the reviewed documents.

Prior discussions of the W-Hanford methodology for handling calculational method bias and uncertainty are applicable to the N-Reactor Area and are not repeated in this discussion.

Los Alamos National Laboratory

Review of the methodology for handling bias and uncertainty at Los Alamos National Laboratory was limited to discussions with cognizant criticality safety personnel and review of a CSE document (LA01). As discussed with LANL personnel, criticality safety evaluations are generally based on criticality handbook values with calculational methods only used to confirm handbook based evaluations. The approach is justified on the basis that the majority of CSE's are in support of research or development activities or projects. Therefore, a methodology for handling calculational method bias and uncertainty has not been implemented at LANL. The following discussion addresses the calculational methods identified in reviews with LANL personnel and review of CSE documents.

Calculational Methodology

The calculational methods used in criticality safety evaluations at LANL are:

- KENO V.a (SCALE 4.2)
- MCNP 4A
- TWODANT-SYS (ONEDANT, TWODANT)

- THREEDANT

The KENO V.a program is the version distributed by RSIC in the SCALE 4.2 package. The SCALE package is distributed by RSIC as computer code package, CCC-545 (Reference 10). The general purpose Monte Carlo program, MCNP, with enhanced capabilities for criticality analysis is implemented as the current version, MCNP 4A, as maintained on the LANL computer systems (Reference 11). The ONEDANT and TWODANT computer programs are integral to the TWODANT-SYS code system (Reference 18). TWODANT-SYS is a deterministic, multigroup, discrete ordinates transport methodology including both the one-dimensional capability, ONEDANT, as well as two-dimensional capabilities. THREEDANT, the three dimensional equivalent to TWODANT, exists in a pre-release version and is used at LANL for special studies. The TWODANT-SYS and THREEDANT code systems are implemented as maintained on the LANL computer systems.

Neutron cross section data used in LANL calculational methods include the following data libraries:

- Hansen & Roach
- MCNPDAT

The LANL practice is to use the Hansen & Roach cross section data library in the KENO V.a, TWODANT-SYS, and THREEDANT calculational methods. Hansen & Roach data files exist as six (6) or sixteen (16) group data with the 16 group data normally used in LANL criticality safety evaluations. The MCNPDAT neutron cross section data library is pointwise data used as direct input to the MCNP 4A computer program. The ENDF/B-V data files within the MCNPDAT library are the primary neutron cross section data used in CSE's at LANL with additional neutron cross section data beyond the MCNPDAT files available for use in special studies.

Bias Development

As described by LANL personnel, calculational methods are used by LANL to predict criticality conditions for complex configurations and supplement handbook evaluations.

The LANL practice is to use predicted values to confirm handbook derived critical limits. As described by LANL personnel, numerous evaluations of benchmark critical experiments have demonstrated a capability to adequately predict experimental values. It is LANL practice to use calculational methods as computational benchmark experiments. Therefore, no calculational bias is defined and calculational uncertainties from MCNP calculations are directly applied to assess the criticality safety of upset conditions.

Bias Application

Based on discussions and reviews of LANL information, calculational bias and uncertainty are not used in LANL criticality safety evaluations. Safety margins are normally set at adequate levels and predicted k_{eff}'s of system upset conditions using the current calculation methods are judged to be acceptable.

Summary

(None required)

Rocky Flats Plant

Review of the methodology for handling calculational bias and uncertainty in criticality safety evaluations at Rocky Flats Plant is based on on-site interviews with a cognizant criticality personnel, review of criticality safety procedures, and on-site review of CSE documents. In addition, telephone conversations with cognizant criticality safety personnel were conducted to review the expert's perception and understanding of the methodology. Documents provided for later review are identified as RF01. In one series of documents reviewed on site, Rocky Flats personnel have recently completed documentation of an extensive series of benchmark critical experiment calculations using current calculational methods.

The following discussion addresses the current Rocky Flats Plant calculational methods and the methodology for handling calculational method bias and uncertainty.

Calculational Methodology

Rocky Flats Plant criticality safety calculational methods used in a production mode are:

- KENO IV (SCALE III)
- KENO V.a (SCALE 4.2)
- MCNP 4A

The KENO IV, KENO V.a, and MCNP 4A methodologies have been implemented in the RSIC distributed format. Each program system is certified and placed under configuration control on the Rocky Flats Plant computer systems per site procedures. Site procedures (RF01) were reviewed to define site implementation of standards and requirements relative to calculational bias and uncertainty.

KENO IV, an earlier version of the KENO Monte Carlo criticality analysis program, is used as a SCALE III version to maintain continuity with prior method validation and criticality safety evaluations. KENO V.a is the current version of the KENO program distributed by RSIC within the SCALE 4.2 package (CCC-545, Reference 10). The MCNP 4A version implemented at Rocky Flats Plant is the current version distributed by RSIC as computer code package CCC-200 (Reference 11). Each program was used in the documents reviewed on-site and applications are consistent with the capabilities of each methodology.

Neutron cross section data files currently used at Rocky Flats Plant are:

- Hansen & Roach (SCALE III)
- Hansen & Roach (SCALE 4.2 CSAS25)
- MCNPDAT ENDF/B-V

The Hansen & Roach data files used at Rocky Flats Plant are data distributed with either the SCALE III or SCALE 4.2 computer code packages. Rocky Flats Plant has historically used SCALE III Hansen & Roach neutron cross section data and has recently evaluated use of the SCALE 4.2 Hansen & Roach neutron cross section data for criticality safety evaluations. The CSAS25 process is used to prepare Hansen & Roach (16 group data) for use in KENO IV/KENO V.a. Recent applications of MCNP 4A have used the MCNPDAT neutron cross section data. MCNPDAT is a pointwise ENDF/B-V data library distributed by RSIC as the DLC-105C data library (Reference 12).

Bias Development

As related by the cognizant criticality safety analyst, the prior Rocky Flats Plant methodology for handling bias and uncertainty was based on a site-imposed safety margin, Δk_m, of 0.05 (or a established allowable limiting neutron multiplication factor of 0.95). The margin of 0.05 was assumed to be an adequate margin to cover bias in the methodology relative to benchmark critical experiments and also cover all identifiable uncertainties related to methodology, modeling, range of applicability, etc.. KENO IV with Hansen & Roach 16 group data was the primary calculational method used in criticality safety evaluations. Recently, an effort to implement the KENO V.a and MCNP 4A methodologies has been completed. Documents reviewed on-site showed an extensive effort to update Rocky Flats Plant calculational method validations. The coordinated effort documents a consistent set of benchmark critical experiment evaluations, using KENO IV, KENO V.a, and MCNP 4A, for a large group of benchmark critical experiments. The documents include KENO/MCNP modeling data and define input preparation methods used to prepare models from archived internal documents. An extensive series of analyses was performed using current methods and computer systems. Consistent formatting of documents includes input files, model information, and key results. Predicted k_{eff}'s and key output results which characterize benchmark experiment, e.g., spatially dependent group neutron flux, fission by group, and neutron leakage, are included in the documents. The documentation format is intended to provide data which can be used by analysts to identify applicable experiments for use in evaluating upset conditions within a criticality safety evaluation. The models of the large number of benchmark criticals were derived from archived Rocky Flats CSE's and the focus of the effort was in documenting the evaluations in a consistent fashion in order to update results obtained with prior methods to current methodologies and nuclear data libraries. MCNP 4A calculations included special tallies to define output results which characterize benchmark critical experiments.

The current methodology for handling calculational method bias and uncertainty is based on evaluating bias within each CSE for representative benchmark critical results.

Calculational bias currently defined at Rocky Flats relies on engineering judgment to justify values and application of values to evaluations of system upset conditions. The results from the extensive re-analysis of the existing benchmark critical experiments database have been used in judging current calculational bias and the enveloping value selected is assumed to include bias and uncertainty in the bias. A limited number of analyses of the benchmark critical experiment uncertainties have been performed to support the definition of the enveloping bias value.

As related by the cognizant person, the Rocky Flats Plant sponsored effort related to area (range) of applicability has not been examined in detail, however, the subject remains an area of concern.

Bias Application

As discussed previously, the site-imposed k_a was historically defined as $k_{eff} = 0.95$. Current CSE's use a established allowable limiting neutron k_a value which is justified on a case-by-case basis using benchmark critical experiment validation results. A margin in k_a (Δk_m) of $\geq$0.03 is currently procedurally specified based on reevaluations of the extensive benchmark critical experiment database available at Rocky Flats combined with the results from limited evaluations of uncertainties in benchmark critical experiments. The calculational bias selected for use in evaluating upset conditions must always be justified on a case-by-case basis. Justification of the bias must include consideration of uncertainties, i.e., computational, modeling, data, and area (range) of applicability.

The Rocky Flats Plant practice is to not use "positive" calculational method bias in criticality safety evaluations.

Summary

(None required)

Battelle-Pacific Northwest Laboratory

Review of the current handling of calculational bias and uncertainty when calculational methods are used in criticality safety evaluations at Battelle-PNL is based on discussions with cognizant criticality safety analysts and information provided for later review (BP01, BP02). Criticality safety evaluations at the Battelle-PNL site are generally performed for outside customers and only a limited number of CSE's are performed to support in-house activities. Therefore, criticality safety evaluations are performed to requirements imposed by the customer.

Calculational Methodology

The CSE calculational methods currently used in a production mode at Battelle-PNL are the standard versions distributed by the Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory:

- KENO V.a
- MCNP 4A

Both methodologies have been implemented in the standard RSIC distributed format without local modifications. Both program systems is certified and placed under configuration control on computer systems per site procedures. The KENO V.a module is the program module distributed with the SCALE 4.2 package from RSIC (Reference 10). The MCNP 4A version implemented is the current version distributed by RSIC as CCC-200 (Reference 11).

Neutron cross section data files currently in use at Battelle-PNL are the standard distributed data associated with either the SCALE 4.2 system or the MCNP ENDF/B-V data files distributed by RSIC. Neutron cross section data for use in KENO V.a is obtained from the CSAS25 process of SCALE 4.2. Current KENO V.a applications use either the Hansen & Roach 16 group data or the 27 group cross section data from processed ENDF/B-IV data files. Neutron cross section data used in MCNP 4A is the pointwise ENDF/B-V data files distributed by RSIC as the DLC-105C data library (Reference 12).

Bias Development

The development of method bias and uncertainty is specific to each CSE in order to meet customer requirements. A group of benchmark critical experiments is selected and either CSAS25 (BONAMI/NITAWL/KENO V.a) or MCNP 4A analyses used to predict criticality conditions for each of the selected benchmark criticals. A statistical analysis, a zero order regression fit, of the results is performed to calculate the mean k_{eff} (or mean of the differences in the predicted k_{eff} and the experimental k_{eff}) and predict the standard deviation of the predicted values (or differences). The calculated value of the difference is defined as the method bias and the standard deviation of the differences is combined statistically with the standard deviation for the Monte Carlo results of the normal/upset condition evaluated. No correlation of the predicted benchmark critical k_{eff}'s to a physical or neutronic parameter is used at Battelle-PNL. The selected group of benchmark criticals is chosen to be representative of the system under evaluation. As described by cognizant personnel, the group of benchmark critical experiments is selected to cover the area (range) of applicability and by including a sufficient range, a conservative bias is defined. Additional guidance is provided in the reviewed information (BP01) relative to verifying the validity of calculated results for the selected group of benchmark critical experiments. Examples of tests on a representative set of data are discussed (BP01) to illustrate techniques of verifying that the mean value of the differences arises from a nearly normal distributed set of data. Reference 50 includes a discussion and tabular values of critical values used in the testing for normal distributions of small samples of data. As stated in BP01, failure of these tests indicates that the selected group of benchmark criticals may not represent a consistent trend and further review and/or results may be necessary.

Bias Application

The handling of calculational bias and uncertainty is based on an adaptation of the method described in Reference 51.

The application of the method bias is by a statistical process, i.e., a one-sided tolerance limit. As described above, the established allowable limiting neutron multiplication factor, k_a, is generally specified by the customer. The evaluation of the normal/upset condition is as follows:

$$k_p - \Delta k_b + \Delta k_m + K_c * (\sigma_b^2 + \sigma_p^2)^{1/2} < k_a$$

where: k_p = predicted k_{eff} for normal/upset condition,

Δk_b = calculational bias defined as the mean difference between predicted k_{eff}'s and experimental k_{eff}'s for benchmark criticals,

Δk_m = margin to ensure subcriticality of system, specified by analyst based on evaluation of system and validation results,

K_c = multiplier for one-sided lower tolerance limit at a 95% confidence level for a 95% proportion of the population and the appropriate degrees of freedom,

σ_b = standard deviation of k_{eff}'s (or differences) of benchmark critical experiments,

σ_p = standard deviation of the Monte Carlo result for the system upset condition, and

k_a = the established allowable limiting neutron multiplication factor.

The multiplier, K_c, is obtained from Table 2.4 of Reference 35 at the degrees of freedom (d.f.) for the calculations which define the standard deviation for either the benchmark criticals, Δk_b, or the Monte Carlo result for the normal/upset condition. In most cases, the multiplier, K_c, is defined by the number of benchmark critical experiments included in the validation process. As described in the Battelle-PNL information (BP01), an alternative approach to define the degrees of freedom is:

$$d.f. = [(\sigma_b^2 + \sigma_p^2)^{½}]^4 / [(\sigma_b^4 /(n+1)) + (\sigma_p^4/(m+1))]$$

where: d.f. = degrees of freedom for the statistically combined standard deviations to be used in selecting K_c from Reference 35,

σ_b = standard deviation of k_{eff}'s (or differences) of benchmark criticals,

σ_p = standard deviation of the Monte Carlo result for system,

n = number of benchmark criticals, and

m = number of generations used in Monte Carlo result.

However, the above alternative approach is not a recommended practice at Battelle-PNL.

The specification of a margin Δk_m at Battelle-PNL is in the range of 0.0 to 0.05 with the a value in the range of 0.01-to-0.02 generally used based on the analyst's judgment of the validity of the benchmark criticals and validation process relative to the systems being evaluated.

The normal practice at Battelle-PNL is to always apply the calculational bias, Δk_b, whether positive or negative. As related by Battelle-PNL personnel, the use positive or negative bias is based on the judgment that the application of the methodology is appropriate and well understood.

Summary

The following items address the current handling of calculational bias and uncertainty at the Battelle-PNL site:

1. The assumption is made that the standard deviation of the normal/upset condition is the only computational method uncertainty used in the evaluation equation. The basis for this assumption is that all Monte Carlo calculations are performed with the same method and that all Monte Carlo results are based on normally distributed results.

2. The prior assumption is only valid if the analyst has assured that the Monte Carlo results are based on a properly converged source distribution and that the convergence pattern to the predicted k_{eff} is as expected and does not show any abnormalities indicating errors in the solution. Tests to verify that the bias is based on normally distributed data are a suggested practice at Battelle-PNL (BP01).

3. Battelle-PNL practice is to skip more than the first three (3) generations of source particles and experience has shown that up to twenty (20) generations are required to obtain source convergence. This approach is valid and consistent with current practices at other sites and with other bias handling methodologies. Use of more skipped generations will reduce the possibility of source convergence affecting the final k_{eff} result.

4. Battelle-PNL handling of bias and uncertainty is appropriate and the use of a zero order regression analysis to evaluate the calculational bias is valid based on the following rationale. Selection of the group of benchmark criticals is assumed to span the area (range) of applicability and use of a zero order regression fit is therefore assumed to capture the uncertainties in; a) the benchmark critical specifications, b) the extrapolation or extension of the area (range) of applicability, c) the limitations in the geometric/material representations of the benchmarks, and d) the calculational bias.

5. Use of a zero order regression has the potential to be conservative or non-conservative if the calculational bias is a function of a physical or neutronic parameter. At the limits of the parameter which defines a range (area) of applicability, the bias could be larger or smaller than the mean value. As discussed with Battelle-PNL personnel, the use of a linear or multiple regression fit would reduce the degrees of freedom and therefore increase the K_c factor used in the evaluation equation and offset the impact of using a zeroth order versus a higher order fit.

In summary, the Battelle-PNL practice of handling calculational bias is consistent with the requirements of the ANSI/ANS 8.1 standard. If the planned revisions to the standard are approved as currently drafted, the practice of using a zero order regression fit may require extension to a higher order. However, the Battelle-PNL practice provides for a consistent handling of bias and uncertainty in CSE's.

Babcock & Wilcox (Nuclear Fuel), Lynchburg, VA

Review of the current handling of calculational bias and uncertainty at the B&W Naval nuclear fuel fabrication site was included to extend the coverage outside defense complex sites. Cognizant criticality personnel were contacted and interviewed via telephone. The information is limited to the conversations and the expert's perceptions and conclusions based on this information. Criticality safety evaluations at the B&W site are related to fuel fabrication activities including the handling of fuel material and fabricated fuel components. Criticality safety evaluations are performed to requirements imposed by the NRC Regulations and the requirements called out in the regulations.

Calculational Methodology

CSE calculational methods currently used in a production mode are the standard versions distributed by the Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory:

- KENO V.a
- MCNP 4A

Each methodology has been implemented in the standard RSIC distributed format without local modifications. Each program system is certified and placed under configuration control on computer systems per site procedures. The KENO V.a module is the program module distributed with the SCALE 4.2 package from RSIC (CCC-545, Reference 10). The MCNP 4A version implemented is the current version distributed by RSIC (CCC-200, Reference 11). The primary calculational method is KENO V.a with MCNP 4A used as a second and independent methodology for evaluation and confirmation of complex systems or extension and/or extrapolation of the area (range) of applicability of benchmark critical experiment data.

Neutron cross section data files currently in use at the B&W site are the standard distributed data associated with the SCALE 4.2 system. The Hansen & Roach data (16 group), ENDF/B-IV in both 218 groups and 27 groups, and the 123 group GAM/THERMOS data are used in the KENO V.a applications. Neutron cross section data for use in KENO V.a is obtained with the CSAS25 process of SCALE 4.2. MCNP cross section data are the ENDF/B-V data files distributed by the Radiation Shielding Information Center, RSIC, at Oak Ridge National Laboratory as the DLC-105C data library (Reference 12).

Bias Development

Development of the calculational bias and uncertainty is generally specific to each CSE. Global validations of the calculational methods have been developed and are included in CSE's by reference. Benchmark critical experiments specific to each CSE are selected to supplement the global validations. Either the CSAS25 process (BONAMI/NITAWL/KENO V.a) or MCNP 4A analyses are used to predict criticality conditions for selected benchmark criticals and results are used to extend or extrapolate the global validation results to the systems under evaluation.

The global and CSE specific calculational bias is defined from an expert review of a large benchmark critical database and is based on expert's technical judgment. In special cases where benchmark criticals are non-existent, a second and independent method, e.g., MCNP 4A, is used to extend the range (area) of applicability. As related by B&W personnel, in special core component areas where benchmark criticals representative of the system are non-existent, computational benchmarks defined by other reactor design organizations, Bettis Atomic Power Laboratory (BAPL) or Knolls Atomic Power Laboratory (KAPL), are used to assess the calculational bias for B&W applications. The predicted computational k_{eff}'s are considered valid benchmark data due to the extensive independent validations of the BAPL/KAPL methodologies.

Based on expert review and judgment, the global or generic calculational bias used at the B&W site is a $\Delta k_b = 0.02$. In special cases, e.g., special core components, the analyst can justify a Δk_b of <0.02 with case specific validations and evaluations.

Bias Application

The evaluation process for normal/upset conditions of a system at the B&W site is based on a site established allowable limiting neutron multiplication factor, k_a, of 0.95 consistent with NRC regulations and guidance. The evaluation equation is:

$$k_p - \Delta k_b + K_p * \sigma_p < k_a$$

where: k_p = predicted k_{eff} for normal/upset condition,

Δk_b = calculational bias, typically $\Delta k_b = -0.02$,

K_p = multiplier to define confidence interval, normally defined as 95%, $K_c \cong 2.0$,

σ_p = standard deviation of the predicted k_{eff} of the normal/upset condition, and

k_a = established allowable limiting neutron multiplication factor.

Summary

An assessment of the current B&W methodology for handling of calculational method bias and uncertainty is difficult due to the limited amount of information available for review. The use of a global (or generic) calculational bias is justified by B&W on the basis of a large benchmark critical database which is representative of the majority of the systems evaluated. The selection of a enveloping calculational bias of 0.02 assumes that calculational methods provide similar results and that the variability of the benchmark critical results are bounded by the value of $\Delta k_b = 0.02$.

Westinghouse Nuclear Manufacturing Division @ Monroeville, PA

The review of the methodology for handling calculational method bias and uncertainty at the Westinghouse Nuclear Manufacturing Division (W-NMD) is included to represent the current practice used in criticality safety evaluations for LWR fuel storage facilities. Cognizant criticality personnel at W-NMD were contacted to discuss the current methodology. Information is limited to the conversations and facsimile interactions and the expert's perceptions and conclusions. Criticality safety evaluations at the W-NMD organization are primarily those related to fuel storage rack criticality safety analyses. Criticality safety evaluations are performed to requirements imposed by NRC guidance (Reference 52), Regulatory Guides, and ANSI/ANS 57.2-1983 Standard (Reference 53).

Calculational Methodology

Calculational methods currently used in a production mode at W-NMD are:

- KENO V.a
- MCNP 4A
- PHOENIX

The KENO V.a and MCNP 4A Monte Carlo programs are the standard versions distributed by the Radiation Shielding Information Center (RSIC) at Oak Ridge National

Laboratory. The KENO V.a version is the program module distributed within the SCALE 4.2 code package (Reference 10) and is used in a stand-alone mode. The MCNP 4A version implemented is the current version distributed by RSIC (Reference 11).

Each of the methods has been implemented as standard RSIC distributed versions without local modifications. Each program system has been certified and placed under configuration control on computer systems per site procedures.

As related by cognizant personnel, the primary calculational method is KENO V.a with MCNP 4A used as a second and independent methodology for evaluation and confirmation of complex systems or extension and/or extrapolation of the area (range) of applicability.

The PHOENIX methodology is the current lattice physics methodology used in PWR core design at W-NMD. PHOENIX is a deterministic transport methodology used in performing detailed analyses of PWR fuel assembly lattices and functions as the cross section and nuclear data processing module in the W-NMD core design methodology. PHOENIX has been validated for used in core design. The PHOENIX implementation in criticality safety evaluations is for evaluating trends and sensitivity effects for extensions to normal/upset conditions. In addition, PHOENIX is used in defining uncertainty estimates for material/fabrication tolerances and changes encountered in fuel storage design, re-design, and operation.

Neutron cross section data currently used in the W-NMD criticality safety organization includes a locally modified (and validated) library based on the CSRL-V files originally distributed by RSIC (Reference 54). In addition, the MCNP pointwise ENDF/B-V cross section data distributed by RSIC as the DLC-105C data library (Reference 12) is used with MCNP 4A applications. The CSRL-V based ENDF/B-V data files are in a 227 group structure and are processed into 42 group datasets for use in KENO V.a. The PHOENIX design methodology uses the same 42 energy group structure and KENO V.a applications are maintained consistent with the PHOENIX methodology.

Bias Development

Calculational method bias is developed from analyses of a selected group of benchmark critical experiments which are directly applicable to CSE normal/upset conditions. A global (or generic) validation of the KENO V.a and MCNP 4A methods for the current NMD applications is based on evaluation of thirty-two (32) benchmark critical experiments. The calculational bias and uncertainty, i.e., standard deviation, is derived from the mean differences between predicted and experimental k_{eff}'s.

Bias Application

The evaluation process used at W-NMD is similar to other organizations with the exception that a more rigorous evaluation of system uncertainties is performed. This approach is possible due to the availability of design information detailing material/fabrication tolerances. System configuration uncertainties predicted and applied to criticality safety evaluations of normal/upset conditions include the material/fabrication tolerances for both the fuel assemblies and fuel storage racks. Material/fabrication tolerances evaluated are:

- Storage cell center-to-center spacing
- Storage cell inside diameter
- Storage cell wall thickness
- Poison panel dimensions
- Poison material (${}_5B^{10}$) self-shielding
- Fuel pellet enrichment
- Fuel enrichment
- Fuel pellet theoretical density
- Storage pool temperature

Analyses of the uncertainty associated with the above material/fabrication tolerances are normally performed with the PHOENIX lattice physics methodology. In addition, the MCNP 4A methodology has recently been used to validate PHOENIX design methodology and MCNP 4A is used in fuel storage criticality safety analyses as a second and independent method. MCNP 4A is used for evaluation of complex geometry conditions and when extensions or extrapolation of the area (range) of applicability is necessary.

The evaluation process for applying calculational bias and uncertainty at W-NMD is a statistical treatment based on the one-sided lower tolerance limit. The confidence level specified for the W-NMD evaluations is a 95/95 level, i.e., at least 95% of the predicted k_{eff} values is greater than the lower tolerance limit with a confidence level of 95%. Consistent with the regulatory guidance and ANS/ANSI 57.2, the established allowable limiting neutron multiplication factor, k_a, is defined as k_{eff}=0.95. As stated in the NRC guidance, exceptions to a Δk_m (margin to ensure subcriticality) of 0.05 must be justified, with a minimum acceptable value of $\Delta k_m = 0.02$. In the W-NMD applications, the only exception to the safety criteria of $k_a = 0.95$ is applied to criticality safety evaluations in the dry storage area for new (fresh) fuel. In the dry storage area, the minimum value of Δk_m shall not be less than 0.02 or a k_a of 0.98. Dry storage area criteria of a k_a=0.98 is met with optimum moderation conditions.

The evaluation process applied to the safety assessment of normal/upset conditions in the fuel storage racks is:

$$k_p - \Delta k_b + [(K_p * \sigma_p)^2 + (K_b * \sigma_b)^2 + \sum \sigma_i^2)]^{1/2} < k_a$$

where:
- k_p = predicted k_{eff} for normal/upset condition,
- Δk_b = calculational method bias,
- K_p = multiplier for one-sided tolerance limit at a 95/95 level and number of degrees of freedom based on generations in Monte Carlo prediction of normal/upset condition, normally d.f. = ∞,
  ≡ 1.645 (value from Table 2.4 of Reference 35),
- σ_p = standard deviation of Monte Carlo predicted result,
- K_b = multiplier for one-sided tolerance limit at a 95/95 level with 31 degrees of freedom,
  ≡ 2.197 (value from Table 2.4 of Reference 35),
- σ_b = standard deviation from benchmark criticals validation,
- σ_i = uncertainty estimates (standard deviation) from system material/fabrication tolerance evaluations,
- k_a = established allowable limiting neutron multiplication factor.

W-NMD evaluations of upset conditions in spent fuel storage areas are always based on double contingency with the first upset condition being the loss of soluble boron poison in the fuel storage pool.

The multiplicative factors, K_p and K_b, defined above are based on a one-side lower tolerance interval at a 95% probability (confidence level) that at least a 95% proportion of a normal distribution will be above the lower limit defined by the lower tolerance interval.

The normal practice at W-NMD is to not apply "positive bias", i.e., calculational method bias from a mean value of predicted k_{eff}'s for a group of benchmark criticals greater than unity (1.0).

Summary

The following items address the current handling of calculational bias and uncertainty at W-NMD. The W-NMD approach is similar to other site methodologies described in prior site review sections. Similarities in the handling methods are noted in the following discussions.

1. The assumption is made that the standard deviation of the normal/upset condition is the only computational method uncertainty used in evaluation equation. The basis for this assumption is that all Monte Carlo calculations are performed with the same method and that all Monte Carlo results are based on normally distributed results. (Same as Battelle-PNL practice described above)

2. The prior assumption is only valid if the analyst has assured that the Monte Carlo results are based on a properly converged source distribution and that the convergence pattern to the predicted k_{eff} is as expected and does not show any abnormalities indicating errors in the solution. (See Battelle-PNL Summary)

3. W-NMD handling of bias and uncertainty is appropriate and the use of a statistical treatment to evaluate the calculational bias is valid based on the following rationale. The selection of the group of benchmark criticals is assumed to span the area (range) of applicability. The group of benchmark criticals are

judged to closely represent the normal/upset conditions, use of a zero order regression fit is therefore assumed to capture the uncertainties in; a) the benchmark critical specifications, b) the extrapolation or extension of the area (range) of applicability, c) the limitations in the geometric/material representations of the benchmarks, and d) in the calculational bias.

4. Use of a zero order regression has the potential to be conservative or non-conservative if the calculational bias is a function of a physical or neutronic parameter. At the limits of the parameter which defines a range (area) of applicability, the bias could be larger or smaller than the mean value. As discussed in the Battelle-PNL site review section, the use of a linear or multiple regression fit would reduce the degrees of freedom and therefore increase the K_c factor used in the evaluation equation and offset the impact of using a zero versus a higher order fit.

5. The W-NMD practice of statistically combining the various uncertainties (standard deviations) with the appropriate multiplier is a unique approach. The validity of the method is not assessed within the current scope of work. The technique results in combined uncertainty similar to the Batelle-PNL approach, however, it is this expert's opinion that the upset condition uncertainties and uncertainties from the method validation process on the group of benchmark critical experiments should be applied as additive terms in the evaluation process of the upset condition.

In summary, the Westinghouse NMD methodology of handling calculational bias is consistent with the requirements of the ANSI/ANS 8.1 standard. If the planned revisions to the standard are approved as currently drafted, the practice of using a zero order regression fit may require extension to a higher order. The Westinghouse NMD approach is a good example of the use of deterministic methods to define uncertainties related to known fabrication/material tolerances. As shown above, the evaluated uncertainties are directly combined with other variances to define the root mean square value of evaluated standard deviations.

3.6 Site Review Summary

A summary comparison of the current methodologies for handling calculational bias and uncertainty when calculational methods are used in criticality safety evaluations is shown in Tables 3-1 and 3-2. Table 3-1 shows an intercomparison of the methodology used to define bias and uncertainty. Table 3-2 shows a comparison of the methods used to apply the bias uncertainty to the evaluation process of system upset conditions.

The following observations are based on information obtained during site reviews and reviews of documentation provided by the various site criticality safety organizations. Individual site reviews showed the following:

- A majority of sites have recently revised or issued new site procedures which document compliance to DOE Orders and identify ANSI/ANS Standards as requirements applicable to criticality safety evaluations.

- A majority of sites (11 out of 12) perform validation of calculational methods within each criticality safety evaluation. The validation processes support the application of the chosen calculational methods to evaluation of system upset conditions within each CSE.

- Over half of the sites (7 out of 12) use a statistical treatment to define calculational bias and uncertainty based on evaluations of groups of benchmark critical experiments selected to be representative of system upset conditions.

- Of the sites which use a statistical treatment to evaluate calculational method bias and uncertainty;

    * Four of the sites use a small sampling ("exact sampling ") theory method, i.e., one-sided lower tolerance interval, to apply uncertainty in the evaluation equation.

* Two of the sites use a confidence interval method to apply the uncertainty in the evaluation equation.

* One site uses either a confidence interval method or the lower tolerance interval method depending upon the number of benchmark critical experiments in the group and the quality of the selected benchmark criticals database. Generally a limited number of applicable benchmark critical experiments are available and the lower tolerance interval method is used.

* Only three of these sites use a linear or multiple regression analysis to predict bias and uncertainty in bias as a function of a correlation parameter. Two of the three sites use the same statistical treatment which defines the calculational bias and an "upper safety limit" as a function of a correlation parameter. The "upper safety limit" is statistically derived based on the bias uncertainty from the linear fit to the results combined with the statistical uncertainty of the Monte Carlo calculations of the benchmark critical experiments.

* The remaining four sites define calculational bias and uncertainty for the group of benchmark critical experiments. The mean value and standard deviation of the predicted k_{eff}'s (or difference of predicted and experimental k_{eff}'s) are used to define bias and uncertainty for application in the evaluation process.

* Only one site uses a multiple regression analysis method to identify correlations of bias and uncertainty to physical or neutronic parameters.

- At the sites which do not use statistical treatments, i.e. 5 out of 12 sites;

* Four sites rely on technical judgment to define either an enveloping bias which includes uncertainty or that no bias is warranted. Uncertainty in the bias is judged to be included in the enveloping value of bias or a zero value is assumed based on the magnitude of statistical uncertainties for the individual benchmark critical calculations. Judgments are based on the visual examination of the predicted k_{eff}'s and standard deviations of calculated results for the representative group of benchmark critical experiments.

* At one site, a methodology for handing bias and uncertainty is not currently implemented and calculational methods are primarily used to confirm criticality safety evaluations for complex conditions which are initially defined on the basis of criticality handbook values.

- Reviews of CSE and related documents showed that:

    * Use of trend and/or sensitivity analyses to extend or extrapolate the area (range) of applicability is very limited.

    * Statistical treatments of benchmark critical experiment results are assumed to capture the uncertainties related to geometric/material representations of experiments, methodology including neutron cross section data, and experimental measurements.

    * CSE documents in general do not clearly demonstrate or define the area (range) of applicability for the selected group of benchmark critical experiments. Graphical illustrations or tabulations of predicted k_{eff}'s versus experimental k_{eff}'s (or differences) were not generally used.

* Correlation of system upset conditions to the area (range) of applicability specified in by the method validation was not clearly demonstrated in CSE documents.

* In a limited number of documents, a correlation parameter was identified in the method validation and the system upset conditions were not identified by a corresponding value of the chosen correlation parameter.

- In reviews of documents and discussions with cognizant analysts, it was determined that in a limited number of CSE's, method validation was performed after evaluations of the system upset conditions were completed. It is this expert's opinion, that the method validation process should be performed before or in parallel to the CSE evaluations. This approach assures that the area (range) of applicability is representative of the CSE system conditions.

- In general, statistical treatments of bias and uncertainty have been shown to provide considerable insight, improved understanding, and consistency in criticality safety evaluations.

  An example of the value of using a statistical process to evaluate bias and uncertainty was identified in the review of one CSE document. Validation of the calculational method was based on the evaluation of a limited number of benchmark critical experiments. The same Monte Carlo program was implemented on two different workstation platforms and predicted k_{eff}'s were tabulated. Based on a visual review of the results, it was judged by the CSE analyst that no bias was warranted and no uncertainty was defined. A statistical treatment was used to evaluate the two groups of results. The mean and standard deviation of the two groups of results were k_{eff}'s of 0.998 and 1.002, with standard deviations for the groups of 0.0036 and 0.0096, respectively. The range of the predicted standard deviations of the individual benchmark calculations was 0.0036 to 0.0045. The differences in the variability of the two groups of predicted results identified a problem in the analyses. Since the principal difference in the two sets of results are the workstation platform, either the random number sequence, the generation of neutron cross sections, or differences in numerical truncation between the two workstations are suspect. This example illustrates the use of a statistical treatment to identify trends, sensitivities, or differences which have the potential to impact evaluations of critical conditions. Further investigations of the numerical operations for the two workstation implementations of the same method should have be carried out and differences resolved before the method is applied in CSE's.

- In all cases, either with or without the use of a statistical treatment, the definition and application of bias and uncertainty relies strongly on the expertise of the analyst and criticality safety organization. However, a statistical process provides additional information to assist the analyst in the evaluations.

- The different approaches and methodologies of handling of bias and uncertainty are strongly influenced by;

    * The site-established allowable limiting neutron multiplication factor, e.g., $k_a \leq 0.95$. At some sites, the margin provided by this value is considered to encompass all uncertainties except the statistical uncertainty of the Monte Carlo calculation of the upset condition. Other sites use the established value as the maximum value and apply evaluated bias and uncertainty as well as a safety margin in the evaluation of upset conditions.

    * At some sites, the conservatism included in selection of system upset conditions is judged to encompass the magnitude of calculational bias and uncertainty. Therefore, statistical treatments are deemed not necessary to assess criticality safety of the upset conditions.

* The use of sensitivity or trend analyses to evaluate uncertainty or to define "optimum" critical conditions are influenced by the site criticality safety organization focus on "reactor physics" versus "criticality safety" concepts.

* The seniority/expertise level of personnel in site criticality safety organizations.

Table 3-1

Summary Comparison of Handling of Bias/Uncertainty

Site	Bias Type	Statistical Approach	Regression Type	Correlation w/Parameters
Savannah River Site	Specific	Yes	Multiple/ Linear	H/X w/ Trends
Y-12 Plant @ Oak Ridge	Global and Specific	Yes	Linear	AEG w/ Trends
Oak Ridge National Laboratory	Global and Specific	Yes	Linear	AEG w/ Trends
WINCO	Specific	No	No	No
EG&G Idaho	Specific	No	No	No
W-Hanford	Specific	Yes	No	No
W-Hanford (N-Reactor)	Specific	Yes	No	No
Battelle- Pacific Northwest Laboratory	Specific	Yes	No	No
Los Alamos National Laboratory	Not Used	No	No	No
EG&G-Rocky Flats	Specific	No	No	No
W-NMD Monroeville	Global	Yes	No	No
B&W Nuclear Fuel	Global	No	No	No

Table 3-2

Summary Comparison of Site Methods for Applying Bias and Uncertainty to Upset Condition Evaluations

Equation Variable	SRS	Y-12/ORNL	WINCO/ EG&G-Idaho	W-Hanford
K_p, Multiplier Defining Confidence Interval of Predicted k_{eff}	K_p=2 or 3 based on validation	K_p=2	K_p=2	K_p=2
σ_p, Standard Deviation of Predicted k_{eff}	Additive	Additive	Additive	See Below
k_a, Site-Established Allowable Limiting k_{eff}	0.9-0.98 by Area	USL (a) Statistical	0.95/ Customer	0.95-0.98
Δk_b, Calculational Bias	Statistical: Group or Fit	Included in USL	Technical Judgment	Statistical: Group
Δk_m, Safety Margin	Defined in CSE	Included in USL	Included in k_a	Included in k_a
K_b, Multiplier for Uncertainty in Confidence/Tolerance Interval	Confidence/ One-Sided Tolerance (b)	Uniform Width @ 95%/99.9% Level (c)	Not Used	Confidence @ 95% Level
σ_b, Standard Deviation of Bias	Defined for Group or Fit	Defined in USL (d)	Not Defined	Defined for Group
σ_p, σ_b Combination	Additive	Additive	Not Used	Statistical w/ σ_p

Notes:
a) USL is the "upper safety limit"
b) Choice of interval type based on quality of validation database and number of benchmark critical experiments. Either a 95% confidence interval or a one-sided lower tolerance interval at a 95% confidence level and a 95% proportion of the population.
c) USL is conservatively based on a single-sided uniform width lower tolerance interval based at a 95% confidence level and a 99.9% proportion of the population.
d) A "pooled" standard deviation (root mean square value) is calculated based on the standard deviations for the linear fit and the individual benchmark critical experiment calculations.

Table 3-2 (Continued)

Summary Comparison of Site Methods for Applying
Bias and Uncertainty to Upset Condition Evaluations

Equation Variable	Battelle-PNL	Rocky Flats	B&W Nuclear Fuel	W-NMD
K_p, Multiplier Defining Confidence Interval of Predicted k_{eff}	K_p=2	K_p=2	K_p=2	K_p=2
σ_p, Standard Deviation of Predicted k_{eff}	See Below	Additive	Additive	See Below
k_a, Site-Established Allowable Limiting k_{eff}	Customer Defined	1.0	0.95	0.95
Δk_b, Calculational Bias	Statistical: Group	Judgment: $\Delta k_b \geq 0.03$	Judged, Δk_b=0.02	Statistical: Group
Δk_m, Safety Margin	Defined in CSE	Included in k_a	Included in k_a	Included in k_a
K_b, Multiplier for Confidence/Tolerance Interval	One-Sided Tolerance @ 95%/95% Level	Not Used	Not Used	One-Sided Tolerance @ 95%/95% Level (e)
σ_b, Standard Deviation of Bias	Defined for Group	Not Defined	Not Defined	Defined for Group
σ_b Application	Statistical w/ σ_p	Not Used	Not Used	Statistical w/ σ_p, σ_d (e)

Notes: e) A weighted root mean square value is calculated with multipliers defined for each uncertainty. Also includes additional uncertainties related to designs.

4.0 Recommended Methodology

Recommendations on the methodology for handling bias and uncertainty are based on assessments of the current methodologies identified in the site reviews and future directions identified in reviews of DOE sponsored and ANSI/ANS standards activities. The recommended methodology should include a computational method based on a composite of the statistical treatments identified in the site review process. As discussed in prior sections, a statistical method is recommended in order to provide for a consistency in the application of calculational methods and the use of predicted results in criticality safety evaluations. In conjunction with improvements in the CSE documentation and evaluation of benchmark critical experiments, implementation of a consistent method would ease and simplify the review and audit process of criticality safety activities. The additional information provided by the statistical process should be used to supplement the expertise level resident in criticality safety organizations.

It is recommended that the various statistical treatments be combined into a single computer program with the capability for interactively selecting the levels of detail of the statistical treatment. Recommended selections prompted during an interactive evaluation process should be provided on the computing platform of choice. Tabular and graphical illustrations of the calculational method bias and uncertainty should be displayed and hard-copy output provided for documentation or use during upset conditions evaluations.

Based on this expert's perception of the criticality safety evaluation process, the following overall process, which encompasses the statistical method, is recommended. In addition, efforts should continue in the development of methods to define a consistent set of physical/neutronic parameters for used in establishing the area (range) of applicability based on calculational method input and output results. Efforts should be undertaken to incorporate and/or improve processing of input and/or output results in the standard criticality safety methodologies.

Recommended Process

The following steps for the methodology for handling bias and uncertainty are identified:

a) Prepare an estimate of the area (range) of applicability and primary correlation parameter from prior analyses or experience.

b) Select group of benchmark critical experiments representative of estimated area (range) of applicability.

c) Define methodology and solution options, e.g., if Monte Carlo method is used: define target uncertainty, generations, particles/generation, etc.

d) Perform calculations of selected benchmark critical experiments and evaluate predicted results.

e) Perform statistical analysis of the group of benchmark critical experiment results at a level consistent with quality of database. Segregate group of results into subgroups, if necessary, to examine correlation with other physical or neutronic parameters, e.g., reflection (bare, reflected, media), isotopics, concentration, moderation, etc.

f) Select statistical treatment and prepare graphs and tables of established allowable limiting neutron multiplication factor corrected by evaluated bias and uncertainty as a function of the chosen correlation parameter. Graphs should clearly demonstrate the area (range) of applicability.

g) Perform system upset condition calculations and determine the physical and neutronic parameter of choice for each condition analysis:

   i) Evaluate calculational bias and uncertainty applicable to system conditions.

   ii) If necessary, extend range (area) of applicability for bias by evaluating additional benchmark critical experiments and repeating steps d), e), f) and g). If representative benchmark critical data is not available, use independent methodologies to define trends and sensitivities for extending or extrapolating area (range) of applicability.

h) Define established allowable limiting neutron multiplication factor, k_a or adjusted k_a', based on calculational bias and standard deviation at the appropriate correlation parameter value.

i) Prepare graphical illustrations (or tabulations) of results versus the chosen correlation parameter to demonstrate applicability of bias and uncertainty to upset conditions.

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