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STONE & WEBSTER

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LIST OF ACRONYMS

ANS	American Nuclear Society
ANSI	American National Standards Institute
AOA	area of applicability
CFR	Code of Federal Regulations
DCS	Duke Cogema Stone & Webster
DOE	U.S. Department of Energy
EALF	energy of average lethargy causing fission
FA	fuel assembly
LTB	lower tolerance band
MFFF	Mixed Oxide Fuel Fabrication Facility
MOX	mixed oxide
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
RSICC	Radiation Safety Information Computational Center
USL	upper safety limit
S/U	Sensitivity and uncertainty

EXECUTIVE SUMMARY

This report documents the validation of the nuclear criticality safety codes to be used in the design of the Mixed Oxide (MOX) Fuel Fabrication Facility (MFFF), to be owned by the U.S. Department of Energy (DOE) and operated by the licensee, Duke Cogema Stone & Webster (DCS). This report is applicable to the validation of the SCALE 4.4a code packages [1] using the CSAS26 (KENOVI) sequence and the 238 energy group cross section library 238GROUPNDF5.

Title 10 Code of Federal Regulations (CFR) §70.61(d) requires that all nuclear processes remain subcritical under all normal and credible abnormal conditions. In order to establish that a system or process will be subcritical under all normal and credible abnormal conditions, it is necessary to establish acceptable subcritical limits for the operation and then show that the proposed operation will not exceed those values. In order to comply with this requirement, the *American National Standard for Nuclear Criticality in Operations with Fissionable Material Outside Reactors* [2] and the U.S. Nuclear Regulatory Commission (NRC) *Standard Review Plan for the Review of an Application for a Mixed Oxide (MOX) Fuel Fabrication Facility* [3] require that a validation be performed that (1) demonstrates the adequacy of the margin of subcriticality for safety by assuring that the margin is large compared to the uncertainty in the calculated value of k_{eff} and (2) determines the area(s) of applicability (AOA) and use of the code within the AOA, including justification for extending the AOA by using trends in the bias.

A number of design AOAs are established to cover the range of processes and fissile materials in the MFFF. AOAs covering Pu and MOX applications are as follows: (1) Pu-nitrate aqueous solutions, (2) MOX pellets, fuel rods, and fuel assemblies, (3) PuO_2 powders, (4) MOX powders, and (5) aqueous solutions of Pu compounds (Pu-oxalate solutions). The first two AOAs are validated in the validation report Part I [16]. The present report addresses the third and fourth AOAs: (3) PuO_2 powders (homogeneous systems), and (4) MOX powders (homogeneous systems). The AOA(5) will be addressed in the Part III [17].

The report concludes that the upper safety limit (USL) for the third design AOA (i.e., PuO_2 powder) is 0.9345, and the USL for the fourth design AOA (i.e., MOX powder) is 0.9323. The USL accounts for the computational bias, uncertainties, and a 0.05 administrative margin.

1. INTRODUCTION

1.1 PURPOSE

The purpose of this report is to validate the criticality codes and determine the upper safety limit (USL) to be used for performing nuclear criticality safety calculations and analyses of the Mixed Oxide (MOX) Fuel Fabrication Facility (MFFF), to be owned by the U.S. Department of Energy (DOE) and operated by the licensee, Duke Cogema Stone & Webster (DCS).

1.2 SCOPE

The scope of this report is limited to the validation of the CSAS26 sequence of the SCALE 4.4a code packages [1] with the 238 energy group cross-section library 238GROUPNDF5 on the PC platform for nuclear criticality safety calculations of the MFFF.

1.3 APPLICABILITY

The following areas of applicability (AOAs) are identified to cover a range of processes and fissile materials in the MFFF:

- Pu-nitrate aqueous solutions
- MOX pellets, fuel rods, and fuel assemblies
- PuO_2 powders
- MOX powders
- Aqueous solutions of Pu compounds (e.g., Pu-oxalate solutions).

This report addresses the third and fourth AOAs:

- PuO_2 powder mixture (homogeneous systems),
- MOX powder mixture (homogeneous systems).

1.4 BACKGROUND

1.4.1 Overall MFFF Design

The MFFF is designed to produce MOX fuel assemblies on an industrial scale from a mixture of depleted uranium and plutonium oxides for use in mission light-water reactors. The MFFF will be constructed at a DOE site and will be licensed by the U.S. Nuclear Regulatory Commission (NRC) under Title 10 Code of Federal Regulations (CFR) Part 70. The facility is designed to applicable U.S. codes and standards and operated by DCS, a private consortium under contract to DOE. The goal of the contract is to design, construct, and operate a facility to fabricate MOX fuel based on existing technology from the Cogema MELOX and La Hague plants in France. To maximize the benefit of the existing technology, process and equipment designs from the MELOX and La Hague plants are duplicated, to the maximum extent possible, in the design of the new plant.

The feed material is depleted uranium dioxide and surplus plutonium dioxide (from the Pit Disassembly and Conversion Facility) supplied by DOE. The impurities in the plutonium dioxide feed are extracted by the Aqueous Polishing process. The MOX fuel fabrication process blends this "polished" plutonium dioxide with depleted uranium dioxide to form mixed oxide pellets. These pellets are loaded into the fuel rods, which are integrated into fuel assemblies. The nuclear fuel assemblies are transported for use in specific U.S. commercial reactors as nuclear fuel. The MFFF is designed to process 3.5 metric tons annually, for a total disposition of 33 metric tons of plutonium (as dioxide).

1.4.2 Regulatory Requirements, Guidance, and Industrial Standards

Title 10 CFR §70.61(d) requires that "*under normal and credible abnormal conditions, all nuclear processes are subcritical, including use of an approved margin of subcriticality for safety.*" In order to comply with this requirement, NUREG 1718 [3] and ANSI/ANS-8.1 [2] require a validation report that (1) demonstrates the adequacy of the margin of subcriticality for safety by assuring that the margin is large compared to the uncertainty in the calculated value of keff and (2) determines the AOAs and use of the code within the AOA, including justification for extending the AOA by using trends in the bias.

NUREG 1718 [3] further states that the validation report should contain:

> A description of the AOA that identifies the range of values for which valid results have been obtained for the parameters used in the methodology. As defined in ANSI/ANS 8.1–1983, the AOA is the range of material compositions and geometric arrangements within which the bias of a calculational method is established. Other variables that may affect the neutronic behavior of the calculational method should also be specified in the definition of the AOA. Particular attention should be given to validating the code for calculations involving mixed oxides of differing isotopics and defining the isotopic ranges covered by the available benchmark experiments. In accordance with the provisions in ANSI/ANS 8.1–1983 (applicable section is Section 4.3.2), any extrapolation of the AOA beyond the physical range of the data should be supported by an established mathematical methodology.

2. CALCULATIONAL METHOD

The SCALE 4.4a code package [1] is the computational system used for MFFF criticality analyses. The code package is available from the Radiation Safety Information Computational Center (RSICC). The SCALE 4.4a code package is installed and verified on the SGN PC hardware platform [4].

SCALE 4.4a is a collection of modules designed to perform nuclear criticality, shielding, and thermal calculations. Each SCALE functional module may be run individually, or a sequence of functional modules may be executed using a special module referred to as a control module. For criticality analyses, various criticality safety analysis sequence (CSAS) control modules are available which differ in the specific functional modules executed and in the processing of cross sections used as input. In general, MFFF criticality analyses are performed using the CSAS26 control module and the 238 energy group cross-section library 238GROUPNDF5, based on ENDF/B-V data. These modules perform cross section processing using the BONAMI and NITAWL-II functional modules, and the calculation of k_{eff} is performed using the KENO VI Monte Carlo transport code.

Recent KENO-VI updates, up to and including Update 3 available from the SCALE Download web site, have been applied to SCALE 4.4a used for calculations presented here. Comparison between patched and unpatched SCALE 4.4a versions do not indicate statistically significant differences [15].

3. CRITICALITY CODE VALIDATION METHODOLOGY

In order to establish that a system or process will be subcritical under all normal and credible abnormal conditions, it is necessary to establish acceptable subcritical limits for the operation and then show that the proposed operation will not exceed those values.

Figure 3-1 shows how the validation process fits within the overall MFFF nuclear criticality analysis process. The first step involves the procurement, installation, and verification of the criticality software on a specific computer platform. For the MFFF, the SCALE 4.4a code packages has been procured, installed, and verified on the SGN PC [4] hardware platform. This step is followed by the validation of the criticality software, which is the purpose of this report. The final step involves the criticality safety design analysis calculations, which are performed and presented in separate reports.

The criticality code validation methodology can be divided into four steps:

- Identify general MFFF design applications
- Select applicable benchmark experiments and group them into AOAs
- Model and calculate k_{eff} values of selected critical benchmark experiments
- Perform statistical analysis of results to determine computational bias and upper safety limit (USL).

The first step is to identify the MFFF design applications and key parameters associated with the normal and upset design conditions. Table 3-2 lists some of the key parameters for the MFFF.

The second step involves several substeps. First, based on the key parameters, the AOA and expected range of the key parameter are identified. ANSI/ANS-8.1 [2] defines the AOA as "*the limiting range of material composition, geometric arrangements, neutron energy spectra, and other relevant parameters (such as heterogeneity, leakage interaction, absorption, etc.) within which the bias of a computational method is established.*" AOAs covering Pu and MOX applications are as follows: (1) Pu-nitrate solutions; (2) MOX pellets, fuel rods, and fuel assemblies; (3) PuO_2 powders; (4) MOX powders; and (5) aqueous solutions of Pu compounds. These AOAs are defined and presented in Section 4. After identifying the AOAs, a set of critical benchmark experiments is selected. Benchmark experiments for the AOAs are selected from the references listed in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments [5]*, the *Guide to Verification and Validation of the SCALE-4 Criticality Safety Software [6]*, and the *Neutronics Benchmarks for the Utilization of Mixed-Oxide Fuel [7]*. A description of all relevant experiments used for each AOA considered here is provided in Section 5.

The third step involves modeling the critical experiments and calculating the k_{eff} values of the selected critical benchmark experiments[1].

[1] Note that these models contain simplifications of critical experiments geometry These simplifications lead to additional uncertainties, included in the statistical analysis of the results

The final step involves the statistical analysis of the results in order to calculate the computational bias and USL. Section 6 presents the computational bias and USL results.

3.1 DETERMINATION OF BIAS

ANSI/ANS–8.1–1998 [2] requires a determination of the calculational bias by "*correlating the results of critical and exponential experiments with results obtained for these same systems by the calculational method being validated.*" The correlation must be sufficient to determine if major changes in the bias can occur over the range of variables in the operation being analyzed. The standard permits the use of trends in the bias to justify extension of the area of applicability of the method outside the range of experimental conditions.

Calculational bias is the systematic difference between experimental data and calculated results. The simplest technique is to find the difference between the average value of the calculated results of critical benchmark experiments and 1.0. This technique gives a constant bias over a defined range of applicability.

Another technique is to find the difference between a regression fit of the calculated results of critical benchmark experiments and 1.0, as a function of an independent variable (e.g., enrichment, moderator-to-fuel ratio, etc.). As a rule, the bias is not a constant, but is dependent upon an independent variable, usually the degree of moderation of the neutrons. For example, the bias for an unmoderated system in which fission occurs with fast neutrons would not be expected to be the same as for a moderated system in which fission occurs with thermal neutrons. The AOA for the bias is the limiting range of material composition, geometric arrangement, etc., over which the bias is collectively established.

The recommended approach for establishing subcriticality based on numerical calculations of the neutron multiplication factor is prescribed in Section 5.1 of ANSI/ANS-8.17 [8]. The criteria to establish subcriticality requires that for a design application (system) to be considered as subcritical, the calculated multiplication factor for the system, k_s, must be less than or equal to an established maximum allowed multiplication factor based on benchmark calculations and uncertainty terms that is:

$$k_s \leq k_c - \Delta k_s - \Delta k_c - \Delta k_m \qquad \text{(Eq. 3.1)}$$

where:

k_s	=	the calculated allowable maximum multiplication factor, (k_{eff}) of the design application (system)
k_c	=	the mean k_{eff} value resulting from the calculation of benchmark critical experiments using a specific calculation method and data
Δk_s	=	the uncertainty in the value of k_s
Δk_c	=	the uncertainty in the value of k_c
Δk_m	=	the administrative margin to ensure subcriticality.

Sources of uncertainty that determine Δk_s include:

- statistical and/or convergence uncertainties
- material and fabrication tolerances
- limitations in the geometric and/or material representations used.

Sources of uncertainty that determine Δk_c include:

- uncertainties in critical experiments
- statistical and/or convergence uncertainties in the computation
- extrapolation outside of the range of experimental data
- limitations in the geometric and/or material representations used.

An assurance of subcriticality requires the determination of an acceptable margin based on known biases and uncertainties. The USL is defined as the upper bound for an acceptable calculation.

Critical benchmark experiments used to determine calculational bias (β) should be similar in composition, configuration, and nuclear characteristics to the system under examination. The range of applicability may be extended beyond the range of conditions represented by the benchmark experiments by extrapolating the trends established for the bias. β is related to k_c as follows:

$$\beta = k_c - 1 \qquad \text{(Eq. 3.2)}$$

$$\Delta\beta = \Delta k_c \qquad \text{(Eq. 3.3)}$$

Using this definition of bias, the condition for subcriticality in Eq. 3.1 is rewritten as:

$$k_s + \Delta k_s \leq 1 - \Delta k_m + \beta - \Delta\beta \qquad \text{(Eq. 3.4)}$$

A system is acceptably subcritical if a calculated k_{eff} plus calculational uncertainties lies at or below the USL.

$$k_s + \Delta k_s \leq \text{USL} \qquad \text{(Eq. 3.5)}$$

The USL can be written as:

$$\text{USL} = 1 - \Delta k_m + \beta - \Delta\beta \qquad \text{(Eq. 3.6)}$$

Bias is negative if $k_c < 1$ and positive if $k_c > 1$. For conservatism, a positive bias is set equal to zero for the purpose of defining the USL. $\Delta\beta$ is typically determined at the 95% confidence level.

The USL takes into account bias, uncertainties, and administrative and/or statistical margins such that the calculated configuration will be subcritical with a high degree of confidence.

β is related to system parameters and may not be constant over the range of a parameter of interest. If k_{eff} values for benchmark experiments vary as a function of a system parameter, such as enrichment or degree of moderation, then β can be determined from a best fit as a function of

the parameter upon which it is dependent. Extrapolation outside the range of validation must take into account trends in the bias.

Both $\Delta\beta$ and β can vary with a given parameter, and the USL is typically expressed as a function of the parameter. Normally, the most important system parameter that affects bias is the degree of moderation of the neutrons. This parameter can be expressed in several different ways, such as the energy of average lethargy causing fission (EALF), moderator-to-fuel volume ratio (v^m/v^f), or moderator-to-fuel atomic ratio (H/Pu ratio).

In general, the "bias" can be broken down into components caused by system modeling error, code modeling inaccuracies, cross-sectional inaccuracies, etc. Biases associated with individual inaccuracies are usually combined into a total bias to represent the combined effect from all sources that prevent code and cross-sections from calculating the experimental value of k_{eff} (see Section 0).

One or two calculations are insufficient to determine calculational bias. In practice, it is necessary to determine the "average bias" for a group of experiments. A statistical analysis of the variation of biases around this average value is used to establish an uncertainty associated with the bias value when it is applied to a future calculation of a similar critical system. The lower limit of this band of uncertainty establishes an upper bound for which a future calculation of k_{eff} for a similar critical system can be considered subcritical with a high degree of confidence.

3.2 USL DETERMINATION METHODS

NUREG/CR-6361 [9] describes two parametric statistical methods for the determination of an USL from the bias and uncertainty terms associated with the calculation of criticality. The first method applies a statistical calculation of the bias and its uncertainty, plus an administrative margin, to a linear fit of critical experimental benchmark data. The second method applies a statistical calculation to determine a combined lower confidence band and subcritical margin. Both methods assume that the distribution of data points is normal. The following discussion of each method is taken from NUREG/CR-6361 [9] and is based on equations and techniques described in Dryer, Jordan, and Cain [10], Easter[11], Bowden and Graybill [12], Johnson [13], and Cain [14].

The parametric statistical methods described in NUREG/CR-6361 require the benchmark data to be normally distributed. In cases where the data fails a test for normality, a nonparametric technique is described which is based on rank order statistics. In this analysis, the nonparametric technique described in NUREG/CR-6361 [9] is employed.

3.2.1 USL Method 1: Confidence Band with Administrative Margin

This method applies a statistical calculation of the bias (β) and its uncertainty ($\Delta\beta$) plus an administrative safety margin (Δk_m) to a linear fit of calculated results for a selected set of critical experiments. A confidence band (W) is determined statistically based on the existing data and a specified level of confidence; the greater the standard deviation in the data or the larger the confidence desired, the larger the band width will be. This confidence band, W, accounts for uncertainties in the experiments, the calculational approach, and calculational data (e.g , cross

sections) and is therefore a statistical basis for $\Delta\beta$, the uncertainty in the value of β. W is defined for a confidence level of $(1-\gamma_1)$ using the relationship:

$$W = \max\{w(x)|_{x\,min,\,x\,max}\} \qquad \text{(Eq. 3.7)}$$

where

$$w(x) = t_{1-\gamma_1} s_p \left[1 + \frac{1}{n} + \frac{(x-\bar{x})^2}{\sum_{i=1,n}(x_i-\bar{x})^2} \right]^{\frac{1}{2}} \qquad \text{(Eq. 3.8)}$$

and

n = the number of critical calculations used in establishing $k_c(x)$

$t_{1-\gamma_1}$ = the Student - t distribution for $1-\gamma_1$ and n - 2 degrees of freedom

$\bar{x}$ = the mean value of parameter x in the set of calculations

s_p = the pooled standard deviation for the set of criticality calculations.

The function w(x) is a curvilinear function. For simplicity, it is desirable to obtain a constant width margin. Therefore, for conservatism, the confidence band, W, is defined as the maximum of $(w(x_{min}), w(x_{max}))$, where x_{min} and x_{max} are the minimum and maximum values of the independent parameter x, respectively. Typically, W is determined at a 95% confidence level.

The pooled standard deviation is obtained from the pooled variance $S_p = \sqrt{S_p^2}$, where S_p is given as:

$$S_p^2 = S_{k(x)}^2 + S_w^2 \qquad \text{(Eq. 3.9)}$$

Where $S_{k(x)}^2$ is the variance (or mean square error) of the regression fit, and is given by:

$$s_{k(x)}^2 = \frac{1}{(n-2)} \left[\sum_{i=1,n}(k_i-\bar{k})^2 - \frac{\left\{\sum_{i=1,n}(x_i-\bar{x})(k_i-\bar{k})\right\}^2}{\sum_{i=1,n}(x_i-\bar{x})^2} \right] \qquad \text{(Eq. 3.10)}$$

and S_w^2 is the within-variance of the data:

$$s_w^2 = \frac{1}{n}\sum_{i=1,n}\sigma_i^2 \qquad \text{(Eq. 3.11)}$$

where σ_i is the standard deviation associated with k_i for a Monte Carlo calculation. It is recommended that the individual standard deviations for Monte Carlo calculations be roughly uniform in value for the best results. For deterministic codes that do not have a standard deviation associated with a computed value of k, the standard deviation is zero. However, this term can also be used as a mechanism to include known uncertainties in experimental data.

In USL Method 1, Δk_m is given an arbitrary administrative value. NUREG-1718 [3] states that a "minimum subcritical margin (Δk_m) of 0.05 is generally considered acceptable without additional justification when both the bias and its uncertainty are determined to be negligible." The MFFF criticality analyses use a value of 0.05. Section 0 provides further justification for the 0.05 administrative margin.

Having determined the constant W and substituting for $\Delta\beta$ in equation 3.6, the expression for the USL may be written as:

$$USL_1(x) = 1.0 - \Delta k_m - W + \beta(x). \qquad \text{(Eq. 3.12)}$$

3.2.2 USL Method 2: Single-Sided Uniform Width Closed Interval Approach

In USL Method 2, sometimes referred to as a lower tolerance band (LTB) approach, statistical techniques are applied to determine a combined lower confidence band plus subcritical margin. In USL Method 1, Δk_m and $\Delta\beta$ are determined independently, and in USL Method 2 (LTB method), a combined statistical lower bound is determined.

The purpose of this method is to determine a uniform tolerance band over a specified closed interval for a linear least-squares model. The level of confidence in the limit being calculated is α and is typically in the range of 0.90 to 0.999.

The USL Method 2 is defined as:

$$USL_2(x) = 1.0 - (C_{\alpha/P} \cdot s_p) + \beta(x) \qquad \text{(Eq. 3.13)}$$

where s_p is the pooled variance of k_c described earlier. The term $C_{\alpha/P} \cdot s_p$ provides a band for which there is a probability P with a confidence α that an additional calculation of k_{eff} for a critical system will lie within the band. For example, a $C_{95/99.5}$ multiplier produces a USL for which there is a 95% confidence that 995 out of 1000 future calculations of critical systems will yield a value of keff above the USL.

The analysis is over the closed interval from $x = a$ to $x = b$. $C_{\alpha/P}$ is calculated according to the following equations:

$$g = \sqrt{\frac{1}{n} + \frac{(a-\bar{x})^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}} \qquad \text{(Eq. 3.14)}$$

$$h = \sqrt{\frac{1}{n} + \frac{(b-\bar{x})^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}} \qquad \text{(Eq. 3.15)}$$

$$\rho = \frac{1}{gh} \cdot \left\{ \frac{1}{n} + \frac{(a-\bar{x})(b-\bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \right\} \qquad \text{(Eq. 3.16)}$$

$$A = \frac{g}{h} \qquad \text{(Eq. 3.17)}$$

A, ρ, and *(n-2)* are used to determine the value of *D* from Table 3 in Bowden [12], which covers values of $0.5 \leq A \leq 1.5$. The procedure to follow when *A* is in this range is:

$$C^* = D \cdot g. \qquad \text{(Eq. 3.18)}$$

When *A* is outside the above range, *A* is replaced by *1/A* for the determination of *D*, and *C** is given by:

$$C^* = D \cdot h. \qquad \text{(Eq. 3.19)}$$

Next,

$$C_{\alpha/P} = C^* + z_p \cdot \sqrt{\frac{n-2}{\chi^2}}, \qquad \text{(Eq. 3.20)}$$

where

z_p = the Student t statistic depending on *n* and *P*
χ^2 = the chi square distribution, a function of *n-2* and α.

This approach provides a statistically based subcritical margin, Δk_m which can be determined as the difference ($C_{\alpha/P}\, s_p$)-W. In criticality safety applications, such a statistically determined approach generally, but not necessarily, yields a margin of less than 0.05, which serves to illustrate the adequacy of the administrative margin specified in USL Method 1. The recommended purpose of USL Method 2 is to apply it in tandem with USL Method 1 to verify that the administrative margin is conservative relative to a purely statistical basis.

3.2.3 Non-Normal Distributions

In cases where the benchmark results fail the χ^2 test for normality, the nonparametric technique described in NUREG-6698 [18] is applied to the data. This statistical technique is based on a rank order analysis of the data. The USL is established according to

USL = Smallest k_{eff} value – Uncertainty for smallest k_{eff} – Nonparametric margin – Δk_m (Eq. 3.1)

Where the nonparametric margin is an additional margin intended to account for small sample size, and Δk_m is the administrative margin. Recommended values for the nonparametric margin

as a function of the degree of confidence are obtained from Table 2.2 of NUREG-6698, which is reproduced in Table 3-1.

The degree of confidence β that a fraction q of the population is greater than the lowest observed value is established for a given sample size n according to

$$\beta = 1 - q^n \qquad \text{(Eq. 3.2)}$$

For a desired population fraction of 95%, this becomes

$$\beta = 1 - 0.95^n \qquad \text{(Eq. 3.3)}$$

In order to obtain a 95% confidence that 95% of the population is larger than the smallest observed sample, at least 59 critical experiments are required.

Table 3-1 Recommended Non-Parametric Margin Values from NUREG-6698

Degree of Confidence for 95% of the Population	Non-parametric Margin (NPM)
>90%	0.00
>80%	0.01
>70%	0.02
>60%	0.03
>50%	0.04
>40%	0.05
≤40%	Additional data needed. (This corresponds to less than 10 data points.)

3.3 UNCERTAINTIES

Uncertainties, as used in this report, refer to the uncertainty in k_{eff} associated with experimental unknowns or assumptions and to the uncertainty values associated with Monte Carlo analyses.

Experimental uncertainty (σ_e) – Modeling of validation experiments frequently result in assumptions about experimental conditions. In addition, experimental uncertainties (such as measurement tolerances) influence the development of a computer model. Recent efforts by the OECD – NEA [5] have resulted in the quantification of these uncertainties in validation experiments.

Statistical uncertainty (σ_s) – Monte Carlo calculation techniques result in a statistical uncertainty associated with the actual calculation. This type of uncertainty is dependent upon many factors, including number of neutron generations performed, variance reduction techniques employed, and problem geometry. For this document, σ_s refers to the statistical Monte Carlo uncertainty associated with the computer modeled validation experiment.

Total uncertainty –This is the total uncertainty associated with a calculated k_{eff} on a benchmark experiment. The total uncertainty for an individual benchmark is the combined error of the experimental and statistical uncertainties:

$$\sigma_t = \sqrt{\sigma_{e,i}^2 + \sigma_{s,i}^2} \qquad \text{(Eq. 3.21)}$$

where the subscript (i) refers to an individual benchmark calculation.

3.4 NORMALIZING K_{EFF}

In many instances, benchmark experiments used for validation may not be exactly critical. Experimental results may show that the experiment is slightly above or below a $k_{eff} = 1.0$. For these cases, the calculated k_{eff} values should be normalized to the experimental value. This assumes that any inherent bias in the calculation is not affected by the normalization, which is valid for small differences in k_{eff}. To normalize k_{eff}, the following formula applies:

$$k_{eff}\text{ (normalized)} = k_{eff}\text{ (calculated)} / k_{eff}\text{ (experimental)} \qquad \text{(Eq. 3.22)}$$

The normalized k_{eff} values are to be used in the determination of the USL. Since only small adjustments to the calculated k_{eff} value are made as a result of normalization, no adjustment to the total uncertainty, σ_t, is made.

3.5 APPLICATION OF THE USL

The equations for USL Methods 1 and 2 (equations 3.12 and 3.13) represent an upper bound to assure subcriticality for a given configuration when the calculated k_{eff} plus uncertainty for the configuration is less than the USL. USLs may be calculated for a number of independent parameters for a given system. Here, the subcritical limit is taken as the minimum of all USLs computed for the specific parameters of the system. This approach is conservative with respect to the guidance provided in NUREG/CR-6361 [9] in which the USL is determined based on the statistical results for the parameter "*with the strongest correlation to the calculated k_{eff} values.*"

Another advantage of the USL is that it may also be used to establish guidelines for quantitatively determining the applicability of the bias (or validation) to specific applications. For a given parameter, the USL is valid over the range of that parameter in the set of calculations used to determine the USL. However, ANSI/ANS-8.1 [2] allows the range of applicability to be extended beyond this range by extrapolating the trends established for the bias. No precise guidelines are specified for the limits of extrapolation. Thus, engineering judgment should be applied when extrapolating beyond the range of the parameter bounds.

Appendix C in NUREG/CR-6361 [9] documents the USLSTATS computer program that was developed to perform the required statistical analysis and calculate USLs based on USL Methods 1 and 2.

In this validation report, USLSTATS is used to trend the following parameters:

- Moderator to fuel atomic ratio (H/Pu)
- Energy of Average Lethargy Causing Fission (EALF)

- ^{240}Pu and PuO_2 content (percentage by weight)

The H/Pu ratio is a parameter that describes the moderation of the neutrons in the fissile medium. The EALF parameter is a measure of the energy dependent fission efficiency of the fissile medium.

The administrative margin, Δk_m, is fixed in order to have a sufficient confidence that the calculated results are subcritical.

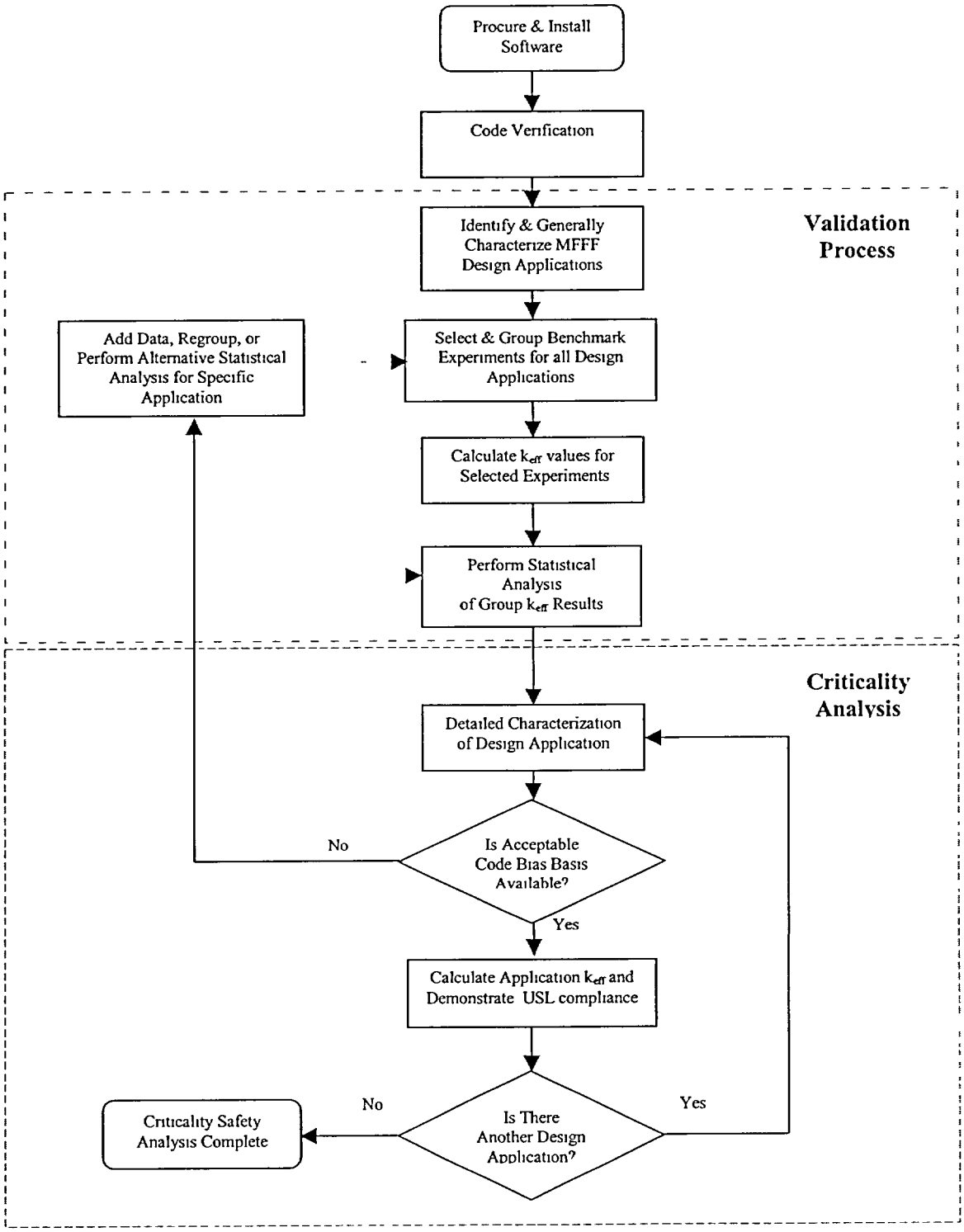

Figure 3-1 Overview of the Criticality Analysis Process of the MFFF

Table 3-2 Characteristics of the MFFF Application Areas*

Parameter	Pu-nitrate solution	MOX pellets, fuel rods, FAs	PuO_2 powder/water mixtures	MOX powder/water mixtures	Aqueous solutions of Pu compounds
Fissile Material Physical/Chemical Form	Pu-nitrate	MOX green and sintered pellets, MOX Rods and FAs	PuO_2 powder	MOX powder	(a) Pu-oxalate (b) PuO_2F_2
Isotopic composition of fissile material **	96% ^{239}Pu 4% ^{240}Pu	96% ^{239}Pu 4% ^{240}Pu depleted U	96% ^{239}Pu 4% ^{240}Pu	96% ^{239}Pu 4% ^{240}Pu depleted U	96% ^{239}Pu 4% ^{240}Pu
$PuO_2/(UO_2+PuO_2)$	100 %	≤ 6.3 %	100 %	6.3% – 22%	100 %
Maximum oxide density [g/cm^3]	–	7 0, 11.0	3.5, 7.0, 11.46	4.1, 5.5	–
Pu concentration [g/liter]	125 – 237	–	–	–	(a) 242 (b) 696
Type of moderation	Homogeneous	Heterogeneous	Homogeneous	Homogeneous	Homogeneous
Optimum moderation ***	H/Pu=100–200	v^m/v^f= 1.9 – 9	H/Pu= 0.3 – 6 and 700 – 1900	H/Pu=1.6 – 291	(a) H/Pu=100 (b) H/Pu=30
Low density moderation [wt.% H_2O]	–	≤ 5 ****	≤ 5	≤ 5	–
Anticipated absorber/reflector materials	Water Cd/water Concrete Borated concrete	Water Concrete Borated concrete	Water Borated concrete	Water	Water Cd/water Concrete
Typical geometry	Annular cylinders Cylinders Slabs	Cylinders Arrays Cuboids	Various configurations	Various configurations	Annular cylinders Cylinders Slabs

* Characteristics presented typically refer to optimal or bounding values or ranges associated with respective AOAs
** Bounding design isotopic composition from Aqueous Polishing System basis of design
*** Per calculation
**** Green Pellets (i e., unsintered pellets) < 5; sintered pellets < 1

3.6 IDENTIFICATION OF BENCHMARK EXPERIMENTS

Benchmark experiments applicable to the validation of SCALE 4.4a for the areas of applicability covered in this report are identified using the sensitivity and uncertainty analysis technique developed by Oak Ridge National Laboratory [25]. This technique provides a quantitative means of identifying applicable experiments which exhibit a high degree of correlation with the design application with respect to both computed sensitivities and known uncertainties in the underlying cross-section data.

The S/U analytical tools include the SEN1 and SEN3 sensitivity analysis sequences, which will be available with the next release of the Standardized Computer Analyses for Licensing Evaluation (SCALE) code system. These analysis sequences compute the relative change in the system neutron multiplication factor, k_{eff}, which would be observed for perturbations in the group-wise neutron cross-section data for each reaction of each nuclide in the system. The CANDE code uses sensitivity data determined separately for the design system applications and the individual experiments, along with the cross-section-covariance data, to calculate integral parameters which give a measure of the similarity between a particular design system and an experimental benchmark. A high-valued integral parameter for an experiment application pair indicates that the experiment demonstrates similar properties to the application. Thus, the experiment is applicable for the criticality code validation of the design system. A theoretical basis for the S/U techniques applied in this report is given in Sect. 2 of [25].

The experiments identified in the ORNL report [25] are included here for use in the validation of SCALE 4.4a for AOA(3) and AOA(4).

3.6.1 Sensitivity and Uncertainty Analysis

A detailed description of the theory supporting the S/U technique is provided in [25] and in the references cited therein. For the purposes of this report, the end result of the S/U technique applied to a candidate benchmark experiment with respect to a particular design application is a parameter c_k which represents the correlation coefficient between uncertainties in the two systems.

These correlations arise due to the fact that the uncertainties in the k_{eff} values for two different systems are related, since they contain the same materials. Cross-section uncertainties will propagate to all systems containing these materials. Systems with the same materials and similar spectra would be correlated, while systems with different materials or differing spectra would not be correlated. The interpretation of the correlation coefficient is the following: a value of 0 represents no correlation between the systems, a value of 1 represents full correlation between the systems, and a value of -1 represents a full anti-correlation.

In [21], the criterion for the acceptance of a benchmark for the validation of a design system was established such that experiments exhibiting a c_k value of 0.8 or higher could be used for the validation of the design system. This criterion was chosen based on two methods of evaluation. The first was objectively viewing the sensitivity profiles to determine which systems appear to exhibit similar properties. The systems that exhibited the most similarities were those with a ck value of 0.8 or higher. The second method for establishing the criterion was the divergence of the computational bias predicted by the Generalized Linear Least Squares Methodology (GLLSM)

procedure. Through this procedure, the GLLSM code was used to predict the computational bias of a system based on differing sets of experimental benchmarks. First, a large number of critical systems, with a wide range of c_k values, were included in the evaluation, and a bias was computed. Next, systems with ck values of 0.9 or greater were removed from the experimental set, thus the experiment set included only those experiments with ck values of 0.89 or lower. No change in the computational bias calculated by GLLSM was observed. A third GLLSM evaluation was performed using only experiments exhibiting a c_k value of 0.79 or lower. In this case, the computational bias computed by GLLSM varied from the previous two calculations by approximately 0.5%. A similarly skewed bias was found when only including systems with a c_k of 0.69 or lower. Thus, it is concluded in [21], there is a clear break in the behavior of systems at a c_k value of 0.8, and this should be used as the criterion for applicability.

3.6.2 Benchmark Experiments Identified for AOA(3)

In order to identify experiments applicable to AOA(3), three typical PuO_2 powder systems are first identified and the S/U methodology is applied to determine the sensitivity of k_{eff} for these design applications to cross section data. The three design applications characterizing AOA(3) are described in Table 3-3.

Table 3-3 Characteristics of Design Systems for AOA(3)

Application	H/Pu	EALF (eV)	keff
AOA 3-1	1.58	1019	0.9984
AOA 3-2	5.99	94.37	1.001
AOA 3-3	3.04	884.3	1.006

Table 3-4 Experimental configurations with c_k coefficients ≥0.8 for AOA 3-1

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
PMF016-05	0 87	0 00	0 00	5 99%	100 0%	7 96E+03	0 9986	0 0006	11	503	5000
PMF016-01	0 87	0 00	0 00	5 99%	100 0%	1 17E+04	1 0128	0 0006	20	503	5000
PMF037-16	0 86	0 00	0 00	5 98%	100 0%	2 84E+04	1 0007	0 0005	8	503	5000
PMF037-15	0 86	0 00	0 00	5 98%	100 0%	1 83E+04	0 9992	0 0006	26	503	5000
PMF003-02	0 86	0 00	0 00	5 97%	100 0%	6 94E+05	0 9930	0 0006	3	503	5000
PMF003-01	0 86	0 00	0 00	5 97%	100 0%	1.24E+06	0 9946	0 0006	5	503	5000
PMF037-07	0 86	0 00	0 00	5 98%	100 0%	3.32E+04	0 9978	0 0006	21	503	5000
PMF003-03	0 86	0 00	0 00	5 97%	100 0%	1.24E+06	0 9876	0 0006	4	503	5000
PMF001-01	0 86	0 00	0 00	4 52%	100 0%	1.24E+06	0 9957	0 0006	11	503	5000
PMF016-03	0 86	0 00	0 00	5 99%	100 0%	8 23E+03	0 9994	0 0006	3	503	5000
PMF037-12	0 86	0 00	0 00	5 98%	100 0%	2.36E+04	0 9996	0 0006	11	503	5000
PMF003-04	0 86	0 00	0 00	5 97%	100 0%	6 28E+05	0 9922	0 0006	30	503	5000
PMF016-04	0 86	0 00	0 00	5 99%	100 0%	8 08E+03	0 9983	0 0006	16	503	5000
PMF017-01	0 86	0 00	0 00	5 97%	100 0%	7 83E+05	0 9896	0 0006	63	503	5000
PMF037-01	0 86	0 00	0 00	5 98%	100 0%	1 46E+05	0 9977	0 0006	15	503	5000
PMF003-05	0 86	0 00	0 00	5 97%	100 0%	1 25E+06	0 9914	0 0006	24	503	5000
PMF037-10	0 86	0 00	0 00	5 98%	100 0%	2 58E+04	0 9985	0 0006	6	503	5000
PMF016-02	0 86	0 00	0 00	5 99%	100 0%	8 56E+03	1 0008	0 0006	13	503	5000
PMF017-02	0 86	0 00	0 00	5 97%	100 0%	4 07E+05	0 9912	0 0007	6	503	5000
PMF017-03	0 85	0 00	0 00	5 97%	100 0%	2 31E+05	0 9951	0 0006	4	503	5000
PMF017-04	0 85	0 00	0 00	5 97%	100 0%	4 57E+05	0 9903	0 0007	5	503	5000
PMF037-05	0 85	0 00	0 00	5 98%	100 0%	5 12E+04	0 9969	0 0006	5	503	5000
PMF002-01	0 85	0 00	0 00	20 16%	100 0%	1.26E+06	0 9973	0 0006	19	503	5000
PMF016-06	0 84	0 00	0 00	5 99%	100 0%	7 80E+03	1 0003	0 0006	20	503	5000
PMF017-05	0 84	0 00	0 00	5 97%	100 0%	9.38E+04	1 0004	0 0006	26	503	5000
PCM002-02	0 83	0 04	0 04	18 35%	100 0%	4.24E+03	1 0306	0 0006	19	503	5000
PMF033-01	0 83	0 00	0 00	5 85%	52 5%	4 00E+05	1 0072	0 0005	30	503	5000
PCM002-01	0 82	0 04	0 04	18 35%	100 0%	4 92E+03	1 0329	0 0006	8	503	5000
PCM002-03	0 81	0 04	0 04	18 35%	100 0%	3 49E+03	1 0275	0 0005	3	503	5000
PCM002-04	0 81	0 04	0 04	18 35%	100 0%	2 58E+03	1 0204	0 0006	7	503	5000

Table 3-5 Experimental configurations with c_k coefficients ≥0.8 for AOA 3-2

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
PCM002-06	0 99	5 05	5 05	11 46%	100 0%	9.26E+01	1 0230	0 0005	15	503	5000
PCM002-07	0 99	5 05	5 05	11 46%	100 0%	8 43E+01	1 0219	0 0006	9	503	5000
PCM002-08	0 99	5 05	5 05	11 46%	100 0%	6.79E+01	1 0210	0 0006	3	503	5000
PCM002-09	0 98	5 05	5 05	11 46%	100 0%	5.73E+01	1 0223	0 0006	63	503	5000
PCM001-02	0 98	5 05	5 05	11 46%	100 0%	1.74E+03	1.0203	0 0007	29	503	5000
PCM001-04	0 97	14 95	14 95	8 06%	100 0%	3.95E+01	0 9881	0 0006	10	503	5000
PCM001-03	0 97	15 10	15 10	2.20%	100 0%	3.26E+01	1.0164	0 0006	10	503	5000
PCM002-21	0 95	14 95	14 95	8 06%	100 0%	6.66E+00	1 0092	0 0005	5	503	5000
PCM002-22	0 95	14 95	14 95	8 06%	100 0%	6 41E+00	1 0145	0 0006	6	503	5000
PCM002-20	0 95	14 95	14 95	8 06%	100 0%	6 68E+00	1 0090	0 0005	4	503	5000
PCM002-19	0 95	14 95	14 95	8 06%	100 0%	6 46E+00	1 0091	0 0005	8	503	5000
PCM002-18	0 95	14 95	14 95	8 06%	100 0%	6 17E+00	1 0101	0 0005	5	503	5000
NSE55T5-07	0 95	9 55	2 79	11 53%	29.3%	4.35E+01	1 0045	0 0005	8	503	5000
PCM002-14	0 95	15 10	15 10	2 20%	100 0%	5 59E+00	1 0297	0 0006	8	503	5000
PU-29-1	0 95	9 47	2 77	11 52%	29.3%	4 16E+01	0 9934	0 0003	52	1503	5000
NSE55T5-01	0 95	9 55	2 79	11 53%	29.3%	4 02E+01	1 0044	0 0005	3	503	5000
PU-29-4	0 95	9 47	2 77	11 52%	29 3%	3 80E+01	0 9928	0 0005	4	503	5000
NSE55T5-10	0 95	9 55	2 79	11 53%	29 3%	3 86E+01	1 0038	0 0005	29	503	5000
PU-29-3	0 95	9 47	2 77	11.52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
PU-29-2	0 95	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000
PU-29-7	0 94	9 47	2 77	11 52%	29 3%	3 52E+01	0 9938	0 0005	3	503	5000
PCM002-15	0 94	15 10	15 10	2 20%	100 0%	5 56E+00	1 0279	0 0006	7	503	5000
NSE55T5-08	0 94	9 55	2 79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
PCM002-16	0 94	15 10	15 10	2 20%	100 0%	5 14E+00	1 0250	0 0006	57	503	5000
PU-29-5	0 94	9 47	2 77	11 52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
NSE55T5-05	0 94	9 55	2 79	11.53%	29 3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-02	0 94	9 55	2 79	11.53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
PU-29-8	0 94	9 47	2 77	11.52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
PU-29-6	0 94	9 47	2 77	11.52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-9	0 94	9 47	2 77	11.52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
PCM002-17	0 94	14 95	14 95	8 06%	100 0%	4 90E+00	1 0080	0 0006	41	503	5000
NSE55T5-03	0 94	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
NSE55T5-04	0 94	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-06	0 94	9 55	2 79	11 53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
PCM002-12	0 94	15 10	15 10	2.20%	100 0%	5 15E+00	1 0284	0 0006	10	503	5000
PCM002-11	0 94	15 10	15 10	2.20%	100 0%	4 55E+00	1 0286	0 0005	3	503	5000
PCM002-10	0 94	15 10	15 10	2.20%	100 0%	4 14E+00	1 0325	0 0006	22	503	5000
NSE55T5-09	0 94	9 55	2 79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
BNWL2129T4-01	0 90	209 96	30 56	8 00%	14 6%	6 14E+00	1 0166	0 0005	12	503	5000
BNWL2129T4-02	0 89	209 96	30 56	8 00%	14 6%	4 50E+00	1 0181	0 0005	13	503	5000
BNWL2129T4-04	0 89	209 96	30 56	8 00%	14 6%	5 00E+00	1 0180	0 0005	4	503	5000
BNWL2129T4-16	0 89	209 96	30 56	8 00%	14 6%	5 21E+00	1 0168	0 0005	12	503	5000
BNWL2129T4-15	0 89	209 96	30 56	8 00%	14 6%	5 00E+00	1 0155	0 0005	17	503	5000
BNWL2129T4-07	0 89	209 96	30 56	8 00%	14 6%	4 90E+00	1 0165	0 0005	4	503	5000
BNWL2129T4-09	0 89	209 96	30 56	8 00%	14 6%	5.76E+00	1 0178	0 0005	21	503	5000
BNWL2129T4-17	0 88	209 96	30 56	8 00%	14 6%	4.24E+00	1 0188	0 0005	19	503	5000
PCM002-13	0 88	15 10	15 10	2.20%	100 0%	5.44E+00	1 0261	0 0006	5	503	5000
BNWL2129T4-19	0 87	209 96	30 56	8 00%	14 6%	4 03E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-12	0 87	209 96	30 56	8 00%	14 6%	3 71E+00	1 0210	0 0006	4	503	5000
BNWL2129T4-10	0 86	209 96	30 56	8 00%	14 6%	5.23E+00	1 0165	0 0005	12	503	5000
BNWL2129T4-03	0 86	209 96	30 56	8 00%	14 6%	3.38E+00	1 0190	0 0006	8	503	5000
BNWL2129T4-18	0 86	209 96	30 56	8 00%	14 6%	3 56E+00	1 0180	0 0006	12	503	5000
BNWL2129T4-05	0 85	209 96	30 56	8 00%	14 6%	3.21E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-08	0 83	209 96	30 56	8 00%	14 6%	2.38E+00	1 0177	0 0006	5	503	5000
BNWL2129T4-11	0 82	209 96	30 56	8 00%	14 6%	3 50E+00	1 0171	0 0005	6	503	5000
BNWL2129T4-13	0 82	209 96	30 56	8 00%	14 6%	2 52E+00	1 0220	0 0006	4	503	5000
PCM001-05	0 82	49 63	49 63	18 50%	100 0%	1 54E+00	1 0105	0 0006	13	503	5000
PCM002-05	0 82	0 04	0 04	18 35%	100 0%	1 87E+03	1 0167	0 0005	23	503	5000
PCI001-01	0 82	0 37	0 37	5 36%	100 0%	3 08E+02	0 9988	0 0001	15	503	5000
BNWL2129T4-06	0 81	209 96	30 56	8 00%	14 6%	2.21E+00	1 0193	0 0005	9	503	5000

Table 3-6 Experimental configurations with c_k coefficients ≥0.8 for AOA 3-3

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
PCM001-02	0 96	5 05	5 05	11 46%	100 0%	1 74E+03	1 0203	0 0007	29	503	5000
PCM002-06	0 95	5 05	5 05	11 46%	100 0%	9 26E+01	1 0230	0 0005	15	503	5000
PCM002-09	0 95	5 05	5 05	11 46%	100 0%	5 73E+01	1.0223	0 0006	63	503	5000
PCM002-08	0 95	5 05	5 05	11 46%	100 0%	6 79E+01	1 0210	0 0006	3	503	5000
PCM002-07	0 93	5 05	5 05	11 46%	100 0%	8 43E+01	1 0219	0 0006	9	503	5000
PCM002-05	0 93	0 04	0 04	18 35%	100 0%	1 87E+03	1 0167	0 0005	23	503	5000
PCM002-03	0 92	0 04	0 04	18 35%	100 0%	3 49E+03	1 0275	0 0005	3	503	5000
PCM002-04	0 91	0 04	0 04	18 35%	100 0%	2 58E+03	1 0204	0 0006	7	503	5000
PCM002-01	0 91	0 04	0 04	18 35%	100 0%	4 92E+03	1 0329	0 0006	8	503	5000
PCM002-02	0 90	0 04	0 04	18 35%	100 0%	4 24E+03	1 0306	0 0006	19	503	5000
PMF016-06	0 89	0 00	0 00	5 99%	100 0%	7 80E+03	1 0003	0 0006	20	503	5000
PCM001-04	0 88	14 95	14 95	8 06%	100 0%	3 95E+01	0 9881	0 0006	10	503	5000
PMF016-01	0 88	0 00	0 00	5 99%	100 0%	1 17E+04	1 0128	0 0006	20	503	5000
PMF016-02	0 88	0 00	0 00	5 99%	100 0%	8 56E+03	1 0008	0 0006	13	503	5000
PMF016-04	0 88	0 00	0 00	5 99%	100 0%	8 08E+03	0 9983	0 0006	16	503	5000
PU-29-1	0 88	9 47	2 77	11 52%	29 3%	4 16E+01	0 9934	0 0003	52	1503	5000
PU-29-2	0 88	9 47	2 77	11 52%	29.3%	4 07E+01	0 9931	0 0005	6	503	5000
PU-29-3	0 87	9 47	2 77	11 52%	29 3%	4.10E+01	1 0029	0 0005	50	503	5000
NSE55T5-01	0 87	9 55	2 79	11.53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
PU-29-4	0 87	9 47	2 77	11.52%	29.3%	3.80E+01	0 9928	0 0005	4	503	5000
PU-29-5	0 87	9 47	2 77	11 52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
NSE55T5-05	0 87	9 55	2 79	11 53%	29 3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-07	0 87	9 55	2 79	11 53%	29 3%	4 35E+01	1 0045	0 0005	8	503	5000
NSE55T5-08	0 87	9 55	2 79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
PCM001-03	0 87	15 10	15 10	2.20%	100 0%	3 26E+01	1 0164	0 0006	10	503	5000
PMF037-15	0 87	0 00	0 00	5 98%	100 0%	1 83E+04	0 9992	0 0006	26	503	5000
NSE55T5-02	0 87	9 55	2 79	11 53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-10	0 87	9 55	2 79	11 53%	29 3%	3 86E+01	1 0038	0 0005	29	503	5000
PU-29-8	0 87	9 47	2 77	11 52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
PU-29-7	0 87	9 47	2 77	11 52%	29 3%	3 52E+01	0 9938	0 0005	3	503	5000
NSE55T5-06	0 87	9 55	2 79	11 53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
PU-29-6	0 87	9 47	2 77	11 52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
NSE55T5-04	0 87	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-03	0 87	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
PU-29-9	0 87	9 47	2 77	11 52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
PMF016-05	0 87	0 00	0 00	5 99%	100 0%	7 96E+03	0 9986	0 0006	11	503	5000
NSE55T5-09	0 87	9 55	2 79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
PMF037-07	0 87	0 00	0 00	5 98%	100 0%	3.32E+04	0 9978	0 0006	21	503	5000
PMF037-12	0 87	0 00	0 00	5 98%	100 0%	2.36E+04	0 9996	0 0006	11	503	5000
PMF016-03	0 87	0 00	0 00	5 99%	100 0%	8 23E+03	0 9994	0 0006	3	503	5000
PMF037-05	0 87	0 00	0 00	5 98%	100 0%	5 12E+04	0 9969	0 0006	5	503	5000
PMF017-05	0 86	0 00	0 00	5 97%	100 0%	9.38E+04	1 0004	0 0006	26	503	5000
PMF037-16	0 86	0 00	0 00	5 98%	100 0%	2 84E+04	1 0007	0 0005	8	503	5000
PMF037-10	0 86	0 00	0 00	5.98%	100 0%	2 58E+04	0 9985	0 0006	6	503	5000
PCM002-21	0 85	14 95	14 95	8 06%	100 0%	6 66E+00	1 0092	0 0005	5	503	5000
PCM002-20	0 85	14 95	14 95	8 06%	100 0%	6 68E+00	1 0090	0 0005	4	503	5000
PCM002-22	0 85	14 95	14 95	8 06%	100 0%	6 41E+00	1 0145	0 0006	6	503	5000
PCM002-18	0 85	14 95	14 95	8 06%	100 0%	6 17E+00	1 0101	0 0005	5	503	5000
PCM002-19	0 85	14 95	14 95	8 06%	100 0%	6 46E+00	1 0091	0 0005	8	503	5000
PCM002-17	0 84	14 95	14 95	8 06%	100 0%	4 90E+00	1 0080	0 0006	41	503	5000
PMF037-01	0 84	0 00	0 00	5 98%	100 0%	1 46E+05	0 9977	0 0006	15	503	5000
PCM002-14	0 84	15 10	15 10	2 20%	100 0%	5 59E+00	1 0297	0 0006	8	503	5000
PCM002-15	0 84	15 10	15 10	2 20%	100 0%	5 56E+00	1 0279	0 0006	7	503	5000
PCM002-16	0 84	15 10	15 10	2 20%	100 0%	5 14E+00	1 0250	0 0006	57	503	5000
PCM002-12	0 83	15 10	15 10	2 20%	100 0%	5 15E+00	1 0284	0 0006	10	503	5000
PMF017-03	0 83	0 00	0 00	5 97%	100 0%	2 31E+05	0 9951	0 0006	4	503	5000
PCM002-11	0 83	15 10	15 10	2 20%	100 0%	4 55E+00	1 0286	0 0005	3	503	5000
PCM002-10	0 83	15 10	15 10	2 20%	100 0%	4 14E+00	1 0325	0 0006	22	503	5000
PMF017-04	0 82	0 00	0 00	5 97%	100 0%	4.57E+05	0 9903	0 0007	5	503	5000
PMF017-02	0 82	0 00	0 00	5 97%	100 0%	4 07E+05	0 9912	0 0007	6	503	5000
BNWL2129T4-01	0 81	209 96	30 56	8 00%	14 6%	6 14E+00	1 0166	0 0005	12	503	5000

3.6.3 Benchmark Experiments Identified for AOA(4)

Typical design applications for AOA(4) MOX powders are characterized in Table 3-7. Design application 4-4 is based on nearly dry MOX powder systems for which the critical mass is significantly larger than any anticipated application in the MFFF. Hence, in addition to the

design application corresponding to a critical mass of plutonium (4-4-Critical), three additional masses of powder are analyzed with the S/U technique, corresponding to 163, 40, and 8 kg of Pu, which more closely correspond to the masses of material which will be analyzed in the MFFF.

The resulting experiments identified as applicable to AOA(4) by the S/U analysis are shown in Table 3-8 through Table 3-14. Note that for the AOA 4-4-Critical and AOA4-4-P163 cases, the c_k acceptance criteria is reduced to 0.7. The inclusion of these additional experiments is conservative because the USL for this AOA is determined using the nonparametric technique described in Section 3.2.3 which is based on the overall observed minimum k_{eff} value in the benchmark set. Also, no unique experiments are introduced for these design applications. That is, all experiments listed in Table 3-11 (4-4-Critical) and Table 3-12 (4-4-P163) appear in some other result set for which a c_k value greater than 0.8 is computed.

Furthermore, the 4-4-Critical and 4-4-P163 design applications correspond to plutonium masses of 454 and 163 kg Pu, respectively. These masses are far in excess of anticipated analyzed conditions in the MFFF, even under worst case credible accident conditions. Hence, these design applications might well have been omitted altogether without affecting the USL analysis for this AOA. However, they have been retained for consistency with the results presented in [25].

Table 3-7 Characteristics of Design Systems for AOA(4)

Application	H/Pu	EALF (eV)	K_{eff}
AOA 4-1	1.58	127	1.0020
AOA 4-2	1.58	3751	0.9989
AOA 4-3	1.58	27.8	1.0000
AOA 4-4-Critical	0.30	2355	0.9993
AOA 4-4-P163	0.30	1214	0.9350
AOA 4-4-P40	0.30	368	0.8120
AOA 4-4-P8	0.30	86.4	0.6430

Table 3-8 Experimental configurations with c_k coefficients ≥0.8 for AOA 4-1

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
PU-29-2	0 98	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000
PU-29-1	0 98	9 47	2 77	11 52%	29 3%	4 16E+01	0 9934	0 0003	52	1503	5000
NSE55T5-07	0 98	9 55	2 79	11 53%	29 3%	4.35E+01	1 0045	0 0005	8	503	5000
PU-29-3	0 98	9 47	2 77	11 52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
PU-29-4	0 98	9 47	2.77	11.52%	29 3%	3 80E+01	0 9928	0 0005	4	503	5000
NSE55T5-10	0 98	9 55	2 79	11.53%	29 3%	3 86E+01	1 0038	0 0005	29	503	5000
PU-29-5	0 98	9 47	2 77	11.52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
NSE55T5-06	0 98	9 55	2 79	11.53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
NSE55T5-01	0 98	9 55	2 79	11 53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
NSE55T5-05	0 98	9 55	2 79	11 53%	29.3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-02	0 98	9 55	2 79	11 53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-08	0 98	9 55	2 79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
PU-29-7	0 98	9 47	2 77	11 52%	29 3%	3 52E+01	0 9938	0 0005	3	503	5000
NSE55T5-04	0 98	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
PU-29-8	0 98	9 47	2 77	11 52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
NSE55T5-03	0 98	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
PU-29-6	0 98	9 47	2.77	11.52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-9	0 98	9 47	2.77	11.52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
NSE55T5-09	0 98	9 55	2.79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
PCM002-06	0 95	5 05	5 05	11 46%	100 0%	9.26E+01	1 0230	0 0005	15	503	5000
PCM002-07	0 95	5 05	5 05	11 46%	100 0%	8 43E+01	1 0219	0 0006	9	503	5000
PCM002-09	0 95	5 05	5 05	11 46%	100 0%	5 73E+01	1 0223	0 0006	63	503	5000
PCM002-08	0 94	5 05	5 05	11 46%	100 0%	6 79E+01	1 0210	0 0006	3	503	5000
BNWL2129T4-01	0 94	209 96	30 56	8 00%	14 6%	6 14E+00	1 0166	0 0005	12	503	5000
PCM001-04	0 94	14 95	14 95	8 06%	100 0%	3 95E+01	0 9881	0 0006	10	503	5000
PCM001-02	0 93	5 05	5 05	11 46%	100 0%	1 74E+03	1 0203	0 0007	29	503	5000
BNWL2129T4-02	0 93	209.96	30 56	8 00%	14 6%	4 50E+00	1 0181	0 0005	13	503	5000
BNWL2129T4-09	0 93	209.96	30 56	8 00%	14 6%	5 76E+00	1 0178	0 0005	21	503	5000
BNWL2129T4-04	0 93	209 96	30.56	8 00%	14 6%	5 00E+00	1 0180	0 0005	4	503	5000
PCM001-03	0 92	15 10	15 10	2 20%	100 0%	3 26E+01	1 0164	0 0006	10	503	5000
BNWL2129T4-16	0 92	209 96	30 56	8 00%	14 6%	5 21E+00	1 0168	0 0005	12	503	5000
BNWL2129T4-07	0 92	209 96	30 56	8 00%	14 6%	4 90E+00	1 0165	0 0005	4	503	5000
BNWL2129T4-15	0 92	209 96	30 56	8 00%	14 6%	5 00E+00	1 0155	0 0005	17	503	5000
PCM002-21	0 92	14 95	14 95	8 06%	100 0%	6 66E+00	1 0092	0 0005	5	503	5000
BNWL2129T4-17	0 92	209 96	30 56	8 00%	14 6%	4 24E+00	1 0188	0 0005	19	503	5000
PCM002-22	0 92	14 95	14 95	8 06%	100 0%	6 41E+00	1 0145	0 0006	6	503	5000
PCM002-20	0 92	14 95	14 95	8 06%	100 0%	6 68E+00	1 0090	0 0005	4	503	5000
PCM002-18	0 92	14 95	14 95	8 06%	100 0%	6 17E+00	1 0101	0 0005	5	503	5000
PCM002-19	0 91	14 95	14 95	8 06%	100 0%	6 46E+00	1 0091	0 0005	8	503	5000
PCM002-17	0 91	14 95	14 95	8 06%	100 0%	4 90E+00	1 0080	0 0006	41	503	5000
BNWL2129T4-19	0 91	209 96	30 56	8 00%	14 6%	4 03E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-12	0 91	209 96	30.56	8 00%	14 6%	3 71E+00	1 0210	0 0006	4	503	5000
PCM002-15	0 91	15 10	15 10	2 20%	100 0%	5 56E+00	1 0279	0 0006	7	503	5000
PCM002-14	0 90	15 10	15 10	2 20%	100 0%	5 59E+00	1 0297	0 0006	8	503	5000
BNWL2129T4-10	0 90	209 96	30 56	8 00%	14 6%	5.23E+00	1 0165	0 0005	12	503	5000
PCM002-16	0 90	15 10	15 10	2.20%	100 0%	5 14E+00	1 0250	0 0006	57	503	5000
PCM002-12	0 90	15 10	15 10	2 20%	100 0%	5 15E+00	1 0284	0 0006	10	503	5000
PCM002-10	0 90	15 10	15 10	2.20%	100 0%	4 14E+00	1 0325	0 0006	22	503	5000
PCM002-11	0 90	15 10	15 10	2 20%	100 0%	4 55E+00	1 0286	0 0005	3	503	5000
BNWL2129T4-03	0 89	209 96	30 56	8 00%	14 6%	3.38E+00	1 0190	0 0006	8	503	5000
BNWL2129T4-18	0 89	209 96	30 56	8 00%	14 6%	3 56E+00	1 0180	0 0006	12	503	5000
BNWL2129T4-05	0 88	209 96	30 56	8 00%	14 6%	3 21E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-11	0 86	209 96	30 56	8 00%	14 6%	3 50E+00	1 0171	0 0005	6	503	5000
BNWL2129T4-08	0 86	209 96	30 56	8 00%	14 6%	2 38E+00	1 0177	0 0006	5	503	5000
BNWL2129T4-13	0 85	209 96	30 56	8 00%	14 6%	2 52E+00	1 0220	0 0006	4	503	5000
PCI001-01	0 85	0 37	0 37	5 36%	100 0%	3 08E+02	0 9988	0 0001	15	503	5000
PCM002-13	0 85	15 10	15 10	2 20%	100 0%	5 44E+00	1 0261	0 0006	5	503	5000
BNWL2129T4-06	0 84	209 96	30 56	8 00%	14 6%	2.21E+00	1 0193	0 0005	9	503	5000
MCT001-01	0 81	0 00	0 00	11 54%	22 4%	9 69E-01	1 0023	0 0005	5	503	5000

Table 3-9 Experimental configurations with c_k coefficients ≥0.8 for AOA 4-2

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
NSE55T5-07	0 94	9 55	2 79	11 53%	29 3%	4 35E+01	1 0045	0 0005	8	503	5000
NSE55T5-04	0 94	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-06	0 94	9 55	2 79	11 53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
NSE55T5-05	0 94	9 55	2 79	11 53%	29 3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-01	0 93	9 55	2 79	11 53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
PU-29-3	0 93	9 47	2 77	11 52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
NSE55T5-03	0 93	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
PU-29-1	0 93	9 47	2 77	11 52%	29 3%	4 16E+01	0 9934	0 0003	52	1503	5000
PU-29-2	0 93	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000
NSE55T5-10	0 93	9 55	2 79	11 53%	29 3%	3 86E+01	1 0038	0 0005	29	503	5000
NSE55T5-02	0 93	9 55	2 79	11 53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-08	0 93	9 55	2 79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
PU-29-4	0 93	9 47	2 77	11 52%	29.3%	3 80E+01	0 9928	0 0005	4	503	5000
PU-29-5	0 93	9 47	2 77	11 52%	29.3%	3 78E+01	0 9935	0 0005	17	503	5000
PU-29-8	0 93	9 47	2 77	11 52%	29.3%	3 45E+01	0 9926	0 0005	7	503	5000
NSE55T5-09	0 93	9 55	2 79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
PU-29-7	0 93	9 47	2 77	11 52%	29 3%	3 52E+01	0 9938	0 0005	3	503	5000
PU-29-6	0 93	9 47	2 77	11 52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-9	0 93	9 47	2 77	11 52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
PCM001-02	0 90	5 05	5 05	11 46%	100 0%	1 74E+03	1 0203	0 0007	29	503	5000
PCM002-07	0 90	5 05	5 05	11 46%	100 0%	8 43E+01	1 0219	0 0006	9	503	5000
PCM002-06	0 89	5 05	5 05	11 46%	100 0%	9 26E+01	1 0230	0 0005	15	503	5000
PCM002-09	0 88	5 05	5 05	11 46%	100 0%	5 73E+01	1 0223	0 0006	63	503	5000
PCM002-08	0 88	5 05	5 05	11 46%	100 0%	6 79E+01	1 0210	0 0006	3	503	5000
PCM001-04	0 88	14 95	14 95	8 06%	100 0%	3 95E+01	0 9881	0 0006	10	503	5000
BNWL2129T4-01	0 87	209 96	30 56	8 00%	14 6%	6 14E+00	1 0166	0 0005	12	503	5000
PCM001-03	0 86	15 10	15 10	2.20%	100 0%	3 26E+01	1 0164	0 0006	10	503	5000
BNWL2129T4-02	0 86	209 96	30 56	8 00%	14 6%	4 50E+00	1 0181	0 0005	13	503	5000
BNWL2129T4-09	0 85	209 96	30 56	8 00%	14 6%	5 76E+00	1 0178	0 0005	21	503	5000
BNWL2129T4-04	0 85	209 96	30 56	8 00%	14 6%	5 00E+00	1 0180	0 0005	4	503	5000
BNWL2129T4-07	0 85	209 96	30 56	8 00%	14 6%	4 90E+00	1 0165	0 0005	4	503	5000
BNWL2129T4-16	0 85	209 96	30 56	8 00%	14 6%	5.21E+00	1 0168	0 0005	12	503	5000
BNWL2129T4-15	0 85	209 96	30 56	8 00%	14 6%	5 00E+00	1 0155	0 0005	17	503	5000
BNWL2129T4-17	0 85	209 96	30 56	8 00%	14 6%	4 24E+00	1 0188	0 0005	19	503	5000
PCM002-21	0 85	14 95	14 95	8 06%	100 0%	6 66E+00	1 0092	0 0005	5	503	5000
PCM002-22	0 84	14 95	14 95	8 06%	100 0%	6 41E+00	1 0145	0 0006	6	503	5000
PCM002-20	0 84	14 95	14 95	8 06%	100 0%	6 68E+00	1 0090	0 0005	4	503	5000
PCI001-01	0 84	0 37	0 37	5 36%	100 0%	3 08E+02	0 9988	0 0001	15	503	5000
PCM002-18	0 84	14 95	14 95	8 06%	100 0%	6 17E+00	1 0101	0 0005	5	503	5000
PCM002-19	0 84	14 95	14 95	8 06%	100 0%	6 46E+00	1 0091	0 0005	8	503	5000
BNWL2129T4-10	0 84	209 96	30 56	8 00%	14 6%	5 23E+00	1 0165	0 0005	12	503	5000
PCM002-17	0 83	14 95	14 95	8 06%	100 0%	4 90E+00	1 0080	0 0006	41	503	5000
BNWL2129T4-19	0 83	209 96	30 56	8 00%	14 6%	4 03E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-12	0 83	209.96	30 56	8 00%	14 6%	3 71E+00	1 0210	0 0006	4	503	5000
PCM002-14	0 83	15 10	15 10	2 20%	100 0%	5 59E+00	1 0297	0 0006	8	503	5000
PCM002-15	0 83	15 10	15 10	2 20%	100 0%	5 56E+00	1 0279	0 0006	7	503	5000
PCM002-16	0 82	15 10	15 10	2 20%	100 0%	5 14E+00	1 0250	0 0006	57	503	5000
PCM002-12	0 82	15 10	15 10	2.20%	100 0%	5 15E+00	1 0284	0 0006	10	503	5000
BNWL2129T4-03	0 82	209 96	30 56	8 00%	14 6%	3 38E+00	1 0190	0 0006	8	503	5000
PCM002-10	0 82	15 10	15 10	2.20%	100 0%	4 14E+00	1 0325	0 0006	22	503	5000
PCM002-11	0 82	15 10	15 10	2.20%	100 0%	4 55E+00	1 0286	0 0005	3	503	5000
BNWL2129T4-18	0 81	209 96	30 56	8 00%	14 6%	3 56E+00	1 0180	0 0006	12	503	5000
BNWL2129T4-05	0 80	209 96	30 56	8 00%	14 6%	3 21E+00	1 0186	0 0005	4	503	5000

Table 3-10 Experimental configurations with c_k coefficients ≥0.8 for AOA 4-3

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
BNWL2129T4-10	0 85	209 96	30 56	8 00%	14 6%	5 23E+00	1 0165	0 0005	12	503	5000
BNWL2129T4-09	0 85	209 96	30 56	8 00%	14 6%	5 76E+00	1 0178	0 0005	21	503	5000
NSE55T5-07	0 84	9 55	2 79	11 53%	29 3%	4.35E+01	1 0045	0 0005	8	503	5000
BNWL2129T4-01	0 84	209 96	30 56	8 00%	14 6%	6 14E+00	1 0166	0 0005	12	503	5000
NSE55T5-10	0 84	9 55	2 79	11 53%	29 3%	3 86E+01	1 0038	0 0005	29	503	5000
PU-29-7	0 84	9 47	2 77	11 52%	29.3%	3 52E+01	0 9938	0 0005	3	503	5000
NSE55T5-01	0 84	9 55	2 79	11 53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
NSE55T5-02	0 84	9 55	2 79	11 53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-04	0 84	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-05	0 84	9 55	2 79	11 53%	29 3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-03	0 84	9 55	2.79	11.53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
PU-29-3	0 84	9 47	2.77	11.52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
PU-29-4	0 84	9 47	2 77	11.52%	29 3%	3 80E+01	0 9928	0 0005	4	503	5000
BNWL2129T4-02	0 84	209 96	30 56	8 00%	14 6%	4 50E+00	1 0181	0 0005	13	503	5000
PU-29-8	0 84	9 47	2 77	11 52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
PU-29-9	0 84	9 47	2 77	11 52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
PU-29-1	0 84	9 47	2 77	11 52%	29 3%	4 16E+01	0 9934	0 0003	52	1503	5000
BNWL2129T4-11	0 84	209 96	30 56	8 00%	14 6%	3 50E+00	1 0171	0 0005	6	503	5000
BNWL2129T4-16	0 84	209 96	30 56	8 00%	14 6%	5 21E+00	1 0168	0 0005	12	503	5000
NSE55T5-06	0 84	9 55	2 79	11 53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
PU-29-5	0 84	9 47	2 77	11 52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
PU-29-6	0 84	9 47	2 77	11 52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-2	0 84	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000
BNWL2129T4-04	0 84	209 96	30.56	8 00%	14 6%	5 00E+00	1 0180	0 0005	4	503	5000
BNWL2129T4-15	0 84	209 96	30 56	8 00%	14 6%	5 00E+00	1 0155	0 0005	17	503	5000
NSE55T5-08	0 84	9 55	2.79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
BNWL2129T4-07	0 84	209 96	30 56	8 00%	14 6%	4 90E+00	1 0165	0 0005	4	503	5000
BNWL2129T4-17	0 84	209 96	30 56	8 00%	14 6%	4 24E+00	1 0188	0 0005	19	503	5000
NSE55T5-09	0 84	9 55	2.79	11.53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
BNWL2129T4-19	0 83	209 96	30 56	8 00%	14 6%	4 03E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-12	0 83	209 96	30 56	8 00%	14 6%	3 71E+00	1 0210	0 0006	4	503	5000
BNWL2129T4-03	0 83	209 96	30 56	8 00%	14 6%	3 38E+00	1 0190	0 0006	8	503	5000
BNWL2129T4-18	0 83	209 96	30 56	8 00%	14 6%	3 56E+00	1 0180	0 0006	12	503	5000
BNWL2129T4-05	0 82	209 96	30 56	8 00%	14 6%	3 21E+00	1 0186	0 0005	4	503	5000
MCT002-02	0 82	0 00	0 00	7 76%	2 0%	7.72E-01	0 9967	0 0005	23	503	5000
MCT009-01	0 82	0 00	0 00	7 87%	1.5%	5 53E-01	0 9944	0 0005	4	503	5000
BNWL2129T4-08	0 82	209 96	30 56	8 00%	14 6%	2 38E+00	1 0177	0 0006	5	503	5000
PU-8-3	0 82	90 86	7 33	11 59%	8 1%	6 37E-01	1 0061	0 0005	10	503	5000
PU-8-4	0 82	90 86	7.33	11 59%	8 1%	6 32E-01	1 0051	0 0005	6	503	5000
PU-8-2	0 82	90 86	7.33	11 59%	8 1%	6 42E-01	1 0040	0 0005	12	503	5000
PU-8-1	0 82	90 86	7 33	11 59%	8 1%	6 43E-01	1 0046	0 0006	8	503	5000
BNWL2129T4-13	0 81	209 96	30 56	8 00%	14 6%	2 52E+00	1 0220	0 0006	4	503	5000
BNWL2129T4-06	0 81	209 96	30 56	8 00%	14 6%	2 21E+00	1 0193	0 0005	9	503	5000
MCT002-01	0 80	0 00	0 00	7 76%	2 0%	5 80E-01	0 9939	0 0005	13	503	5000

Table 3-11 Experimental configurations with c_k coefficients ≥0.7 for AOA 4-4 (critical)

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
NSE55T5-04	0 74	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-03	0 74	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
NSE55T5-05	0 74	9 55	2 79	11 53%	29 3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-07	0 74	9 55	2 79	11 53%	29 3%	4 35E+01	1 0045	0 0005	8	503	5000
NSE55T5-01	0 74	9 55	2 79	11 53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
NSE55T5-08	0 74	9 55	2 79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
NSE55T5-06	0 74	9 55	2 79	11.53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
NSE55T5-02	0 73	9 55	2 79	11.53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-09	0 73	9 55	2 79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
PU-29-3	0 73	9 47	2 77	11 52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
PU-29-8	0 73	9 47	2 77	11 52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
PU-29-9	0 73	9 47	2 77	11 52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
NSE55T5-10	0 73	9 55	2 79	11 53%	29.3%	3 86E+01	1 0038	0 0005	29	503	5000
PU-29-6	0 73	9 47	2 77	11 52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-4	0 73	9 47	2 77	11 52%	29 3%	3 80E+01	0 9928	0 0005	4	503	5000
PU-29-5	0 73	9 47	2 77	11 52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
PU-29-7	0 73	9 47	2 77	11 52%	29 3%	3 52E+01	0 9938	0 0005	3	503	5000
PU-29-1	0 73	9 47	2 77	11 52%	29 3%	4 16E+01	0 9934	0 0003	52	1503	5000
PU-29-2	0 73	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000

Table 3-12 Experimental configurations with c_k coefficients ≥0.7 for AOA 4-4-P163

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
NSE55T5-04	0 77	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-03	0 77	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
NSE55T5-05	0 77	9 55	2 79	11 53%	29.3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-07	0 77	9 55	2 79	11 53%	29 3%	4.35E+01	1 0045	0 0005	8	503	5000
NSE55T5-01	0 77	9 55	2 79	11 53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
NSE55T5-08	0 77	9 55	2 79	11 53%	29 3%	3.94E+01	1 0015	0 0005	17	503	5000
NSE55T5-06	0 77	9 55	2 79	11 53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
NSE55T5-02	0 77	9 55	2 79	11 53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-09	0 76	9 55	2 79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
PU-29-3	0 76	9 47	2 77	11 52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
PU-29-8	0 76	9 47	2 77	11.52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
PU-29-9	0 76	9 47	2 77	11 52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
NSE55T5-10	0 76	9 55	2 79	11.53%	29 3%	3 86E+01	1 0038	0 0005	29	503	5000
PU-29-6	0 76	9 47	2 77	11 52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-5	0 76	9 47	2 77	11.52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
PU-29-4	0 76	9 47	2 77	11.52%	29 3%	3 80E+01	0 9928	0 0005	4	503	5000
PU-29-1	0 76	9 47	2 77	11.52%	29 3%	4 16E+01	0 9934	0 0003	52	1503	5000
PU-29-7	0 76	9 47	2 77	11.52%	29 3%	3 52E+01	0 9938	0 0005	3	503	5000
PU-29-2	0 76	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000
PCM002-09	0 71	5 05	5 05	11 46%	100 0%	5 73E+01	1 0223	0 0006	63	503	5000
PCM001-02	0 71	5 05	5 05	11 46%	100 0%	1 74E+03	1 0203	0 0007	29	503	5000
PCM002-06	0 71	5 05	5 05	11 46%	100 0%	9 26E+01	1 0230	0 0005	15	503	5000
BNWL2129T4-01	0 70	209 96	30 56	8 00%	14 6%	6 14E+00	1 0166	0 0005	12	503	5000
PCM002-07	0 70	5 05	5 05	11 46%	100 0%	8 43E+01	1 0219	0 0006	9	503	5000
PCM002-08	0 70	5 05	5 05	11 46%	100 0%	6 79E+01	1 0210	0 0006	3	503	5000
BNWL2129T4-02	0 70	209 96	30 56	8 00%	14 6%	4 50E+00	1 0181	0 0005	13	503	5000
PCI001-01	0 70	0 37	0 37	5 36%	100 0%	3 08E+02	0 9988	0 0001	15	503	5000

Table 3-13 Experimental configurations with c_k coefficients ≥0.8 for AOA 4-4-P40

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
NSE55T5-04	0 83	9 55	2 79	11 53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-03	0 83	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
NSE55T5-05	0 83	9 55	2 79	11 53%	29 3%	4 07E+01	1 0021	0 0005	17	503	5000
NSE55T5-01	0 83	9 55	2 79	11 53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
NSE55T5-08	0 83	9 55	2 79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
NSE55T5-02	0 83	9 55	2 79	11 53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-09	0 83	9 55	2 79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
NSE55T5-06	0 83	9 55	2 79	11 53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
PU-29-8	0 83	9 47	2 77	11 52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
NSE55T5-07	0 83	9 55	2 79	11 53%	29 3%	4.35E+01	1 0045	0 0005	8	503	5000
PU-29-3	0 83	9 47	2 77	11 52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
PU-29-9	0 83	9 47	2 77	11 52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
PU-29-6	0 83	9 47	2 77	11 52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-5	0 83	9 47	2 77	11 52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
PU-29-4	0 83	9 47	2 77	11 52%	29.3%	3 80E+01	0 9928	0 0005	4	503	5000
PU-29-7	0 83	9 47	2 77	11 52%	29.3%	3 52E+01	0 9938	0 0005	3	503	5000
PU-29-1	0 82	9 47	2 77	11 52%	29.3%	4 16E+01	0 9934	0 0003	52	1503	5000
NSE55T5-10	0 82	9 55	2 79	11 53%	29.3%	3 86E+01	1 0038	0 0005	29	503	5000
PU-29-2	0 82	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000

Table 3-14 Experimental configurations with c_k coefficients ≥0.8 for AOA 4-4-P8

Experiment	ck	H/Pu	H/(Pu + U)	Wt % ^{240}Pu	Wt % Pu	EALF (eV)	keff	σ	NSK	GEN	NPG
PU-29-6	0 89	9 47	2 77	11 52%	29 3%	3 67E+01	0 9924	0 0005	12	503	5000
PU-29-8	0 89	9 47	2 77	11 52%	29 3%	3 45E+01	0 9926	0 0005	7	503	5000
PU-29-9	0 89	9 47	2 77	11 52%	29 3%	3 46E+01	0 9968	0 0005	9	503	5000
NSE55T5-09	0 89	9 55	2 79	11 53%	29 3%	3 92E+01	1 0029	0 0005	12	503	5000
PU-29-5	0 89	9 47	2 77	11 52%	29 3%	3 78E+01	0 9935	0 0005	17	503	5000
PU-29-7	0 89	9 47	2 77	11 52%	29 3%	3.52E+01	0 9938	0 0005	3	503	5000
NSE55T5-04	0 89	9 55	2.79	11.53%	29 3%	4 08E+01	1 0037	0 0005	9	503	5000
NSE55T5-03	0 89	9 55	2 79	11 53%	29 3%	4 02E+01	1 0043	0 0006	12	503	5000
NSE55T5-02	0 89	9 55	2.79	11.53%	29 3%	3 97E+01	1 0023	0 0005	20	503	5000
NSE55T5-05	0 89	9 55	2 79	11.53%	29 3%	4 07E+01	1 0021	0 0005	17	503	5000
PU-29-4	0 89	9 47	2 77	11.52%	29 3%	3 80E+01	0 9928	0 0005	4	503	5000
PU-29-3	0 89	9 47	2 77	11.52%	29 3%	4 10E+01	1 0029	0 0005	50	503	5000
PU-29-1	0 89	9 47	2 77	11.52%	29 3%	4 16E+01	0 9934	0 0003	52	1503	5000
NSE55T5-08	0 89	9 55	2 79	11 53%	29 3%	3 94E+01	1 0015	0 0005	17	503	5000
PU-29-2	0 89	9 47	2 77	11 52%	29 3%	4 07E+01	0 9931	0 0005	6	503	5000
NSE55T5-01	0 89	9 55	2 79	11 53%	29 3%	4 02E+01	1 0044	0 0005	3	503	5000
NSE55T5-06	0 88	9 55	2 79	11.53%	29 3%	4 17E+01	1 0024	0 0005	10	503	5000
NSE55T5-10	0 88	9 55	2 79	11 53%	29 3%	3 86E+01	1 0038	0 0005	29	503	5000
NSE55T5-07	0 88	9 55	2 79	11 53%	29.3%	4.35E+01	1 0045	0 0005	8	503	5000
BNWL2129T4-10	0 88	209 96	30 56	8 00%	14 6%	5 23E+00	1 0165	0 0005	12	503	5000
BNWL2129T4-09	0 88	209 96	30 56	8 00%	14 6%	5 76E+00	1 0178	0 0005	21	503	5000
BNWL2129T4-01	0 88	209 96	30 56	8 00%	14 6%	6 14E+00	1 0166	0 0005	12	503	5000
BNWL2129T4-07	0 87	209 96	30 56	8 00%	14 6%	4 90E+00	1 0165	0 0005	4	503	5000
BNWL2129T4-15	0 87	209 96	30 56	8 00%	14 6%	5 00E+00	1 0155	0 0005	17	503	5000
BNWL2129T4-02	0 87	209 96	30 56	8 00%	14 6%	4 50E+00	1 0181	0 0005	13	503	5000
BNWL2129T4-04	0 87	209.96	30 56	8 00%	14 6%	5 00E+00	1 0180	0 0005	4	503	5000
BNWL2129T4-16	0 87	209 96	30 56	8 00%	14 6%	5.21E+00	1 0168	0 0005	12	503	5000
BNWL2129T4-17	0 87	209 96	30 56	8 00%	14 6%	4 24E+00	1 0188	0 0005	19	503	5000
BNWL2129T4-12	0 86	209 96	30 56	8 00%	14 6%	3 71E+00	1 0210	0 0006	4	503	5000
BNWL2129T4-11	0 86	209 96	30 56	8 00%	14 6%	3 50E+00	1 0171	0 0005	6	503	5000
BNWL2129T4-19	0 86	209 96	30 56	8 00%	14 6%	4 03E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-03	0 86	209 96	30 56	8 00%	14 6%	3 38E+00	1 0190	0 0006	8	503	5000
BNWL2129T4-18	0 86	209 96	30 56	8 00%	14 6%	3 56E+00	1 0180	0 0006	12	503	5000
BNWL2129T4-05	0 85	209 96	30 56	8 00%	14 6%	3.21E+00	1 0186	0 0005	4	503	5000
BNWL2129T4-08	0 85	209 96	30 56	8 00%	14 6%	2.38E+00	1 0177	0 0006	5	503	5000
BNWL2129T4-13	0 84	209 96	30 56	8 00%	14 6%	2 52E+00	1 0220	0 0006	4	503	5000
PCM002-09	0 84	5 05	5 05	11 46%	100 0%	5 73E+01	1 0223	0 0006	63	503	5000
BNWL2129T4-06	0 83	209 96	30 56	8 00%	14 6%	2 21E+00	1 0193	0 0005	9	503	5000
PCM002-06	0 82	5 05	5 05	11 46%	100 0%	9 26E+01	1 0230	0 0005	15	503	5000
PCM002-08	0 82	5 05	5 05	11 46%	100 0%	6 79E+01	1 0210	0 0006	3	503	5000
PCM002-13	0 80	15 10	15 10	2.20%	100 0%	5 44E+00	1 0261	0 0006	5	503	5000
PCM002-20	0 80	14 95	14 95	8 06%	100 0%	6 68E+00	1 0090	0 0005	4	503	5000
PCM002-18	0 80	14 95	14 95	8 06%	100 0%	6 17E+00	1 0101	0 0005	5	503	5000
PCM002-17	0 80	14 95	14 95	8 06%	100 0%	4 90E+00	1 0080	0 0006	41	503	5000
PCM002-22	0 80	14 95	14 95	8 06%	100 0%	6 41E+00	1 0145	0 0006	6	503	5000

4. MFFF DESIGN APPLICATION CLASSIFICATION

This section describes the characteristics of the established AOAs based on the various fuel configurations encountered in the MFFF. AOAs covering Pu and MOX applications are as follows (see Table 3-2):

- Pu-nitrate aqueous solution
- MOX pellets, fuel rods, and fuel assemblies (FA)
- PuO_2 powders
- MOX powders
- Aqueous solutions of Pu compounds (e.g., Pu-oxalate solution).

4.1 DESIGN APPLICATION (3) – PuO_2 POWDER

Table 4-1 summarizes the anticipated criticality calculations to be performed for the design of the MFFF in which PuO_2 will be processed. The table provides the relevant parameters (i.e., chemical form, isotopic vector, moderator to fuel atomic ratio (H/Pu), and EALF) for each criticality design application.

For some applications, geometry control is used and the calculations are performed at optimum moderation taking into account full water reflection. In these cases a thermal neutron spectrum will be found. In other applications (e.g., jar store and the can receiving and emptying unit) where mass and moderation control are used and the fissile materials are reflected by borated concrete materials, or the concrete reflector is far from the fuel, the neutron spectrum will be intermediate to fast.

4.2 DESIGN APPLICATION (4) – MOX POWDER

Table 4-2 summarizes the anticipated criticality calculations to be performed for the design of the MOX powder process. In addition, the table provides the relevant parameters (i.e., chemical form, moderator to fuel atomic ratio (H/Pu), and EALF) for each criticality design application.

Table 4-1 Anticipated Criticality Calculation Derived Characteristics for Design Applications Involving PuO_2 Powder

Fuel Configuration	Reflector Conditions	Chemical Form	Pu-Isotopic Composition	Max $\rho(PuO_2)$ [g/cm^3]	H/Pu	EALF [eV]
AP: Decanning						
PuO_2 dosing hopper	Water	PuO_2 powder	4% ^{240}Pu	7 0	1.67	12500 to 13500
AP: Dissolution						
Electrolyzer	Water/concrete	PuO_2 powder	4% ^{240}Pu	7.0	1 67	200 to 25000
Filter glove box	Water/concrete	PuO_2 powder	4% ^{240}Pu	7.0	1.67	696
Tanks in cell	Cd/water/concrete	PuO_2 powder	4% ^{240}Pu	7.0	1.67	10000 to 50000
AP: Oxalic Precipitation Conversion						
Furnace GB	Water/concrete	PuO_2 powder	4% ^{240}Pu	3 5	5.97	67
AP: Homogenization						
Separating hopper	Water	PuO_2 powder	4% ^{240}Pu	3.5	5.97	100 to 200
PuO_2 powder sampling GB	Water	PuO_2 powder	4% ^{240}Pu	3.5	5.97	50 to 500[2]
Sampling GB	Water	PuO_2 powder	4% ^{240}Pu	3.5	5.97	50 to 500[2]
Sample storage GB	Water/concrete	PuO_2 powder	4% ^{240}Pu	3.5	5.97	50 to 500[2]
Cylindrical condenser	Water/concrete	PuO_2 powder	4% ^{240}Pu	3 5	5.97	50 to 500[2)]
MP: Powder Area						
PuO_2 3013 can store	Concrete reflected array	PuO_2 powder	4% ^{240}Pu	7.0, 11.46	1.67	65000
PuO_2 can buffer store	Borated concrete reflected array	PuO_2 powder	4% ^{240}Pu	3.5	5.97	46 5
Primary dosing unit	Water/concrete	PuO_2 powder	4% ^{240}Pu	3.5	1.58	1572
PuO_2 decanning unit	Water/concrete	PuO_2 powder	4% ^{240}Pu	3.5	0 3	12 to 1340
Jar store unit	Concrete reflected array	PuO_2 Powder[1]	4% ^{240}Pu	3 5	1.58	0.5 to 371
Laboratory	Water	PuO_2 Powder	4% ^{240}Pu	11.46	900	0.05[2]
Waste store	Water/concrete	PuO_2 Powder	4% ^{240}Pu	11.46	1300	0 05
Waste units	Water	PuO_2 Powder	4% ^{240}Pu	11.46	700-1900	0.05[2]
Range of Design Application	**Various**	**PuO_2 powder**	**4% ^{240}Pu**	**3.5 – 11.46**	**0.3 to 1900**	**0.05 to 65000**

[1] The jar store unit contains only MOX powder, cf Table 4-2. Nevertheless PuO_2 powder can appear as a part of non-homogenized MOX components in abnormal situations.
[2] Expected range of EALF-values

Table 4-2 Anticipated Criticality Calculation Derived Characteristics for Design Applications Involving MOX Powder

Fuel Configuration	Reflector Condition	Chemical Form	PuO_2/ (UO_2+PuO_2)	Pu-isotopic Composition	Max ρ(MOX) [g/cm^3]	H/Pu	EALF [eV]
MP: Powder area							
Primary dosing unit	Water	MOX powder	6 3 – 22%	4% ^{240}Pu	4.1	7.2	25.3
Ball milling units	Water	MOX powder	6.3 – 22%	4% ^{240}Pu	5.5	1.6 – 7.8	20 – 54
Jar store unit	Water/ concrete	MOX powder	6 3 – 22%	4% ^{240}Pu	5.5	1.6	0.8 – 31
Final dosing unit	Water	MOX powder	6 3 – 22%	4% ^{240}Pu	5 5	7.2 – 25.2	5.8 – 57.6
Final mix homogenization and press station unit	Water	MOX powder	6.3 – 22%	4% ^{240}Pu	5.5	4.2 – 291	2.8 – 8.24
Scrap processing unit	Water	MOX powder	6 3%	4% ^{240}Pu	5 5	14.8 – 15.2	20 – 94
Auxiliary powder unit	Water	MOX powder	6.3 – 22%	4% ^{240}Pu	5.5	4.2 – 15.2	20 – 317
Expected Range of Application	**Various**	**MOX powder**	**6.3–22 %**	**4% ^{240}Pu**	**4.1 – 5.5**	**1.6 – 291**	**0.8 – 317**

5. BENCHMARK EXPERIMENTS

Descriptions of the critical experiments comprising the candidate experiment database to which the S/U technique is applied are presented below. The discussion is adapted from Section 5 of [25].

Resulting comparisons of the selected benchmark experiments and the design applications with respect to key design parameters are shown in Table 5-1 and Table 5-2 for AOA(3) and AOA(4), respectively.

5.1 PLUTONIUM SYSTEMS

Sixty-one plutonium benchmarks are included in the database. These include metal systems and oxide systems.

5.1.1 Plutonium Metal Systems

Twenty-six plutonium metal experiments are included in this set of benchmarks. Two bare metal spheres are included: one with a low ^{240}Pu content (4.5 at. %), designated ^{239}Pu Jezebel (PU-MET-FAST-001), and another with a higher ^{240}Pu content (20.1 at. %) designated as ^{240}Pu Jezebel (PU-MET-FAST-002). A set of three experiments using arrays of unmoderated plutonium metal buttons, and either bare or with one side reflected by polyethylene, were included (PU-MET-FAST-003). A group of thirteen experiments using plutonium metal in cans, and placed in 3 × 3 × 3 or 2 × 2 × N arrays with water moderation and reflection are taken from PU-MET-FAST-016 and PU-MET-FAST-037. Five experiments using moderated arrays of plutonium metal cylinders are included from PU-MET-FAST-017. The final plutonium metal experiment is from PU-MET-FAST-033, and is part of the ZPPR-21 series of experiments, which also include MIX-MET-FAST-011 and HEU-MET-FAST-061. The ZPPR-21 series began with a fissile core containing only plutonium, and gradually substituted highly-enriched uranium metal for some of the plutonium metal until the final configuration contained only uranium.

5.1.2 Plutonium Oxide Systems

A set of thirty-four experiments involve plutonium oxide that has been mixed with various quantities of polystyrene, and then compacted into cubes. These cubes are stacked in arrays to form critical configurations with or without Plexiglas reflection. Five unreflected experiments are taken from PU-COMP-MIXED-001, and twenty-nine experiments from PU-COMP-MIXED-002. The H/Pu ratios in these compacts range from 0.04 to 49.6, giving a range of fission neutron spectra from fast to thermal.

One benchmark using plutonium oxide, graphite, and boron was included from PU-COMP-INTER-001. This benchmark describes a system with a k_{inf} of one, and is interpolated from measured reactivity worths for a number of fuel samples with varied boron content. With an energy of average lethargy causing fission (EALF) of approximately 300 eV, this benchmark was chosen to represent the dry plutonium oxide powders in applications AOA(3)–1 through AOA(3)–3.

5.2 MIXED PLUTONIUM AND URANIUM SYSTEMS

Two hundred and thirty-seven mixed plutonium and uranium systems are included in this set of benchmarks. These experiments involve solution systems, fuel pin lattices, solid mixed-oxide systems moderated by polystyrene, and mixed metal systems.

5.2.1 Mixed Plutonium and Uranium Solution Systems

Thirteen experiments with mixed plutonium and uranium solution in annular cylinder geometry are taken from MIX-SOL-THERM-001. The ratio of Pu/(U+Pu) is 0.22 or 0.97, and the concentration of the solution in the annular region is varied from 61 to 489 g (U+Pu)/liter. All experiments use a water reflector.

Three experiments with similar solution in large cylindrical geometry are from MIX-SOL-THERM-002. The objective of these experiments was to obtain data on the minimum fissile concentration for criticality in an effectively infinite cylindrical geometry. The reaction vessel has an inside diameter of 68.68 cm. The concentrations of the solution are 23 and 53 g (U+Pu)/liter with a ratio of Pu/(Pu + U) of 0.52 and 0.23, respectively. All three experiments are water reflected.

Nine experiments from this same series that use small cylindrical geometry are also included from MIX-SOL-THERM-004. The reaction tank has an inside diameter of 35.39 cm and inside height of 106.60 cm. The concentrations of the solution are 105, 293, and 435 g (U+Pu)/liter with a ratio of Pu/(U+Pu) of 0.4 for all nine experiments. Three measurements have a water reflector, three have a concrete reflector, and three have no reflector.

Seven experiments with mixed plutonium and uranium solution in slab geometry are taken from MIX-SOL-THERM-005. The solution concentration ranged from 105 to 435 g (U+Pu)/liter with a ratio of Pu/(U+Pu) of 0.4. Four experiments were water-reflected, and four were bare.

5.2.2 Mixed Plutonium and Uranium Fuel Pin Lattices

Four experiments using natural UO_2–20 wt. % PuO_2 (11.5 wt. % ^{240}Pu) fuel pins in a square lattice were analyzed (MIX-COMP-THERM-001). These experiments used water reflection, and incorporated polypropylene grid plates to minimize the effect of the grids on the reactivity of the core. The pitch was varied from 0.95 to 1.9 cm.

Six experiments with natural UO_2-2 wt. % PuO_2 (8% ^{240}Pu) fuel include square-pitched lattices, with 0.70-inch, 0.87-inch, or 0.99-inch pitch, in borated or pure water moderator (MIX-COMP-THERM-002). These experiments are also referred to as PNL 30-35 in NUREG/CR-0210 in the CSEWG Thermal Reactor Benchmarks (BNL-19302).

Six more experiments with natural UO_2-6.6 wt. % PuO_2 fuel include square-pitched, partial-moderator-height lattices with five lattice pitches of 0.52 inch, 0.56 inch, 0.735 inch, 0.792 inch, and 1.04 inch (MIX-COMP-THERM-003). The purpose of these experiments was to verify the nuclear design of the Saxton partial plutonium core, which consisted of MOX assemblies in the central region with peripheral enriched UO2 assemblies. The experiments with 0.56-inch-

pitched lattices were performed with borated or pure water moderator, but the other pitched-lattice experiments were performed only with pure water moderator.

Eleven experiments conducted at the Tokai Research Establishment of JAERI in Japan used natural UO_2 – 3.01 wt. % PuO_2 rods in square arrays of varying pitch (MIX-COMP-THERM-004). The plutonium in the fuel pins contained 24 wt. % ^{240}Pu.

Forty-one experiments from the Plutonium Utilization Program at Pacific Northwest Laboratories are included (MIX-COMP-THERM-005, MIX-COMP-THERM-008, and MIX-COMP-THERM-009). These experiments were performed using MOX fuel with PuO_2 enrichments varying from 1.5 to 4 wt. % PuO_2, and the ^{240}Pu isotopic composition of the plutonium was varied from 8% to 24%. The fuel pins are arranged in hexagonal lattices with varying pitches with the rods uniformly arrayed in such a manner that the core is a right circular cylinder.

Six benchmark experiments using MOX fuel designed for the RAPSODIE fast breeder reactor in Cadarache, France are included from MIX-COMP-THERM-011. The uranium was enriched to 60 wt. % ^{235}U, and the plutonium content of the MOX fuel was 25.8 wt. %, with 9.72 wt. % of the plutonium being ^{240}Pu. The pitch was triangular, and measured either 1.9 cm or 2.5 cm.

5.2.3 Mixed Plutonium and Uranium Solid Systems

Several experiments using various combinations of plutonium oxide, depleted uranium oxide and polystyrene, which had been pressed into compacts and stacked into arrays, are included in this database. They are included in MIX-COMP-THERM-012 and three other published references that have not yet been included in the IHECSBE. The configurations are similar to those in PU-COMP-THERM-001 and -002, but with MOX instead of plutonium oxide. There are both reflected and unreflected arrays, and some of the stacked arrays contain neutron poison plates.

There are thirty-three experiments included from MIX-COMP-THERM-012. These configurations contain mixtures of plutonium and DU oxides containing between 7.6 and 30 wt. % plutonium, with H/X ratios from 19.5 to 51.8. Six experiments with 7.6 wt. % plutonium used plutonium that contains 23 wt. % ^{240}Pu. The other experiments use plutonium with 8 wt. % ^{240}Pu. Twenty-seven experiments are Plexiglas-reflected, while six are bare.

Fourteen other experiments were done with a similar range of plutonium oxide concentrations, but with much lower moderation levels [23]. These experiments also utilize compacts with between 7.6 and 30 wt. % plutonium, and H/X ratios ranging from 3 to 7. The plutonium contained 11.5 wt % ^{240}Pu. Only the Plexiglas-reflected configurations from this reference are included. In the attached tables, these experiments are labeled PU-8-1 through PU-8-4, PU-15-1, and PU-29-1 through PU-29-9. However, the result for case PU-15-1 is not included as a candidate benchmark experiment since it is based on only a single experiment with this fuel configuration, and the indicated experimental uncertainty in the result suggests that the resulting benchmark is unreliable.

Thirty-two experiments were performed with MOX-polystyrene compacts in arrays that contained either one or two copper, copper/cadmium, or aluminum plates of varying thickness within the stack [22]. All of these experiments were fully reflected with Plexiglas. Two types of fuel were used in these experiments. The first contained MOX with a plutonium content of 14.6 wt. %, of which 7.97 wt. % was ^{240}Pu, and with an H/X of 30.6. The second type of fuel contained MOX with a plutonium content of 30.3 wt. %, of which 11.5 wt. % was ^{240}Pu, and with an H/X of 2.8. Twenty-two experiments contained the fuel with an H/X of 30.6, and ten experiments used the fuel with an H/X of 2.8. These experiments are labeled NSE55Tx-xx in subsequent sections of this report.

Fifty experiments were performed using these same two fuel compositions, but with other types of neutron poison plates contained with the array stacks. All of these experiments were also fully reflected with Plexiglas [24]. The poison plate materials included Type 304 stainless steel, steel with 1.1 wt. % boron, steel with 1.6 wt. % boron, boral, lead, depleted uranium, cadmium, and aluminum. Thirty-one independent experiments were performed with the fuel with an H/X of 30.6. In the case of the fuel with an H/X of 2.8, the nineteen configurations used some of the fuel with an H/X of 30.6 as a driver. An 8 × 8 × 2 array of the lower moderated fuel was used above and below the neutron poison plate, and on top of this was placed at least two layers of the higher moderated fuel. The thickness of driver fuel was varied to achieve criticality with the various neutron poison plate materials and thicknesses. The reference states that the neutron flux in the region containing the poison plate was characteristic of the lower-moderated fuel, and that less than 30% of the fissions occurred in the higher-moderated fuel. However, when using these experiments as critical benchmarks, the importance of the more moderated fuel is significant, and the overall flux is more thermal than the experiments using only the lower-moderated fuel. These experiments are labeled BNWL2129Tx-xx in subsequent sections of this report.

5.2.4 Mixed Plutonium and Uranium Metal System

A set of four mixed plutonium and uranium metal systems was analyzed as a means of including homogeneous uranium/plutonium systems with a fast energy spectrum. These experiments are documented in MIX-MET-FAST-011, and are part of the ZPPR-21 series of experiments that also include PU-MET-FAST-033 and HEU-MET-FAST-061. As described previously, the ZPPR-21 series began with a fissile core containing only plutonium, and gradually substituted highly enriched uranium metal for some of the plutonium metal until the final configuration contained only uranium. (The last configuration is described in HEU-MET-FAST-061, and was not included in this database since it did not pertain to any of the applications of interest.) The four experiments in MIX-MET-FAST-011 contain between 41.4 and 7.7 wt. % plutonium metal, which included between 6.16 and 11.6 wt. % ^{240}Pu. The bulk of the neutron spectrum is in the 100-keV to 4-MeV energy range and the peak is at about 600 keV. Thus, the spectrum is in the fast range, although not as hard as the spectrum in many other fast metal assemblies.

5.3 LOW-ENRICHED URANIUM OXIDE SYSTEMS

In order to include experiments with low-enriched uranium oxide at low moderation levels, eighteen experiments from LEU-COMP-THERM-049 were placed in the database. These models primarily assist in validating ^{238}U capture and fission cross-sections in the higher neutron

energy region. The experiments were performed under the MARACAS program at the Valduc facility in France. The uranium dioxide was enriched to 5 wt. % ^{235}U, and was moderated to an H/X of between 2 and 3. Uranium dioxide powder was moistened and contained in metal boxes, which were placed in various sized arrays on a split table, and the overall configuration was reflected with polyethylene. The overall neutron spectrum is thermal but has a significant intermediate energy component.

Table 5-1 AOA(3) Comparison of Key Parameters

Parameter	Design application (cf. Table 4-1)	Benchmarks
Geometric shape	Parallelepipeds Arrays of cylinders Spheres	Parallelepipeds Arrays of cylinders Spheres
Absorber/reflector	Water, Cd, Borated concrete	Plexiglas, air, water
Chemical form	PuO_2 powder	PuO_2 in polystyrene (C_8H_8) Pu-metal in air/water
Isotopic composition	4 wt. % ^{240}Pu	2.2 wt % to 20.2 wt. % ^{240}Pu
H/Pu	0.3 to 1900	0 to 210
EALF [eV]	0.05 to 65000	1 to 10^6

Table 5-2 AOA(4) Comparison of Key Parameters

Parameter	**Design application (cf. Table 4-2)**	**Benchmark**
Geometrical shape	Various configurations	Parallelepipeds Arrays of pins
Absorber/reflector	Water, concrete	Plexiglas
Chemical form	MOX powder	MOX and PuO_2 powder in polystyrene Water moderated MOX fuel pins
Pu/(U+Pu) composition	6.3 to 22 wt. %	1.5 to 100 wt %
Isotopic composition	4 wt. % ^{240}Pu	2.2 to 11.6 wt. % ^{240}Pu
H/(U+Pu)	0.1 to 64	0[1] to 31
H/Pu	1.6 to 291	0[1] to 210
EALF [eV]	0 8 to 317	0 6 to 1740

[1]Moderated arrays of fuel pins

6. ANALYSIS OF VALIDATION RESULTS

6.1 DESIGN APPLICATION (3) – PuO_2 POWDER

The benchmark experiments identified using the S/U technique are modeled with CSAS26/KENO VI using the 238 group library 238GROUPNDF5. The calculated k_{eff} values for selected benchmark experiments are presented in Table 3-4 through Table 3-6.

Figure 6-1 shows the distribution of calculated k_{eff} values for the experiments as calculated with SCALE 4.4a (KENO-VI Update 3) on the PC platform. The k_{eff} values are first analyzed statistically using the USLSTATS computer code[2]. However, the data fails the test for normality employed in that analysis. Hence, the nonparametric technique described in Section 3.2.3 is employed.

With a total of 90 unique experiments for this AOA, the degree of confidence, β, obtained from Equation 3.3 is 99.0%. Hence, the required nonparametric margin obtained from Table 3-1 is 0.0. The minimum computed benchmark k_{eff} is 0.9876 ± 0.0006 obtained for case PMF003-03 [5]. The experimental uncertainty determined for this case in the Handbook evaluation [5] is 0.0030. The resulting combined uncertainty associated with this benchmark calculation is

$$\sqrt{0.0030^2 + 0.0006^2} = 0.0031$$

The resulting USL for AOA(3) is then determined from Equation 3.1 as

USL = Smallest k_{eff} value – Uncertainty for smallest k_{eff} – Nonparametric margin – Δk_m

$$\text{USL AOA(3)} = 0.9876 - 0.0031 - 0.0 - 0.05 = 0.9345$$

This USL is applicable for design applications falling within the range of key parameters shown in Table 5-1. For design applications outside the AOA, ANSI/ANS 8.1-1998 [2] permits extension of the AOA based on observed trends in the bias as a function of the extended parameter. In order to establish these trends, computed k_{eff} results are plotted as a function of trending parameter in Figure 6-2 through Figure 6-4. To facilitate trending analysis, the plotted data is fitted linearly, and the resulting regression formula is shown in each figure. Data for EALF is fitted logarithmically due to the extended range of the parameter.

The USL for AOA(3) is 0.9345. This value includes a 0.05 administrative margin and consideration for calculational bias and allowance for uncertainties. Justification for an administrative margin of 0.05 is provided in Section 7.1.

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[2] Many of the benchmark experiments in the International Handbook of Evaluated Criticality Safety Benchmark Experiments (Nuclear Energy Agency 1999) are considered to be critical (i.e., k_{eff} =1.000), while other experiments are not considered critical (i.e., $k_{eff} \neq 1.000$) Therefore, all calculated k_{eff} values are normalized to the handbook values.

6.2 DESIGN APPLICATION (4) – MOX POWDER

The benchmark experiments identified using the S/U technique for AOA(4) are modeled with CSAS26/KENO VI using the 238 group library 238GROUPNDF5. The calculated k_{eff} values for selected benchmark experiments are presented in Table 3-8 through Table 3-14.

Figure 6-5 shows the distribution of calculated k_{eff} values for the experiments as calculated with SCALE 4.4a (KENO-VI Update 3) on the PC platform. The k_{eff} values are first analyzed statistically using the USLSTATS computer code. Although the data passes the test for normality employed in that analysis, visual inspection of the double-peaked histogram shown in Figure 6-5 suggests that an assumption of normality for this data is inappropriate. Hence, the nonparametric technique described in Section 3.2.3 is employed.

With a total of 66 unique experiments for this AOA, the degree of confidence, β, obtained from Equation 3.3 is 96.6%. Hence, the required nonparametric margin obtained from Table 3-1 is 0.0. The minimum computed benchmark k_{eff} is 0.9881 ± 0.0006 obtained for case PCM001-004 [5]. The experimental uncertainty determined for this case in the Handbook evaluation [5] is 0.0058. The resulting combined uncertainty associated with this benchmark calculation is

$$\sqrt{0.0058^2 + 0.0006^2} = 0.0058$$

The resulting USL for AOA(4) is then determined from Equation 3.1 as

USL = Smallest k_{eff} value – Uncertainty for smallest k_{eff} – Nonparametric margin – Δk_m

$$\text{USL AOA(4)} = 0.9881 - 0.0058 - 0.0 - 0.05 = 0.9323$$

This USL is applicable for design applications falling within the range of key parameters shown in Table 5-1. For design applications outside the AOA, ANSI/ANS 8.1-1998 [2] permits extension of the AOA based on observed trends in the bias as a function of the extended parameter. In order to establish these trends, computed k_{eff} results are plotted as a function of trending parameter in Figure 6-6 through Figure 6-10. To facilitate trending analysis, the plotted data is fitted linearly, and the resulting regression formula is shown in each figure. Data for EALF is fitted logarithmically due to the extended range of the parameter.

The USL for AOA(4) is 0.9323. This value includes a 0.05 administrative margin and consideration for calculational bias and allowance for uncertainties. Justification for an administrative margin of 0.05 is provided in Section 7.1.

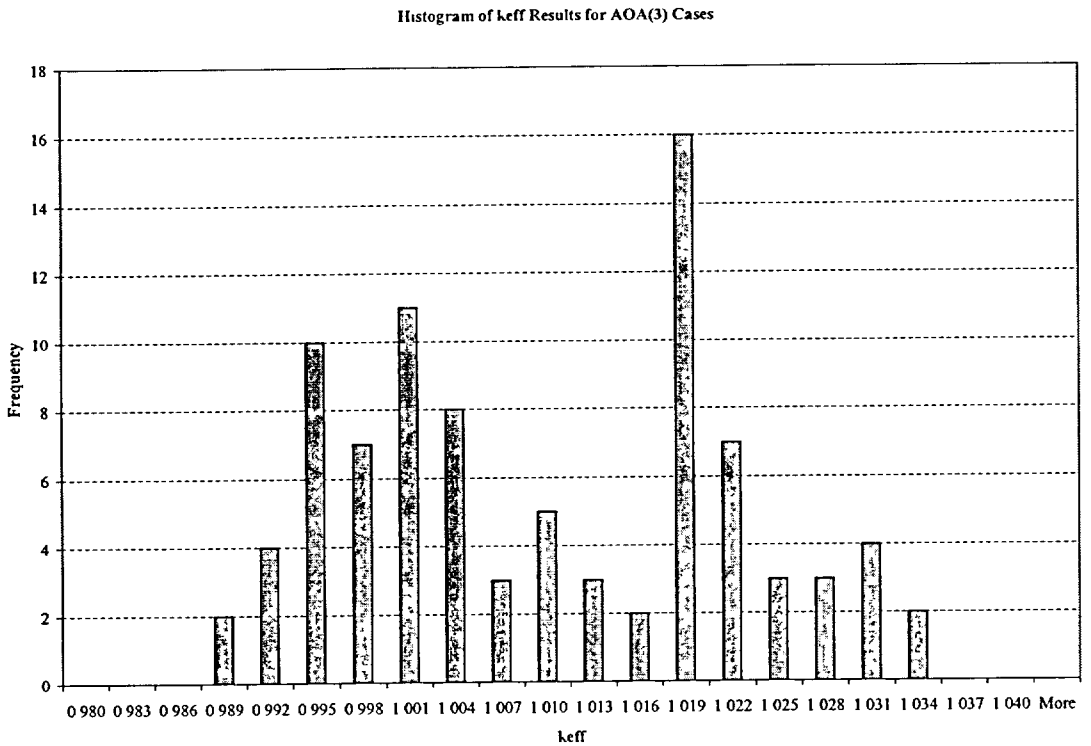

Figure 6-1 Histogram of k_{eff} occurrences for AOA(3)

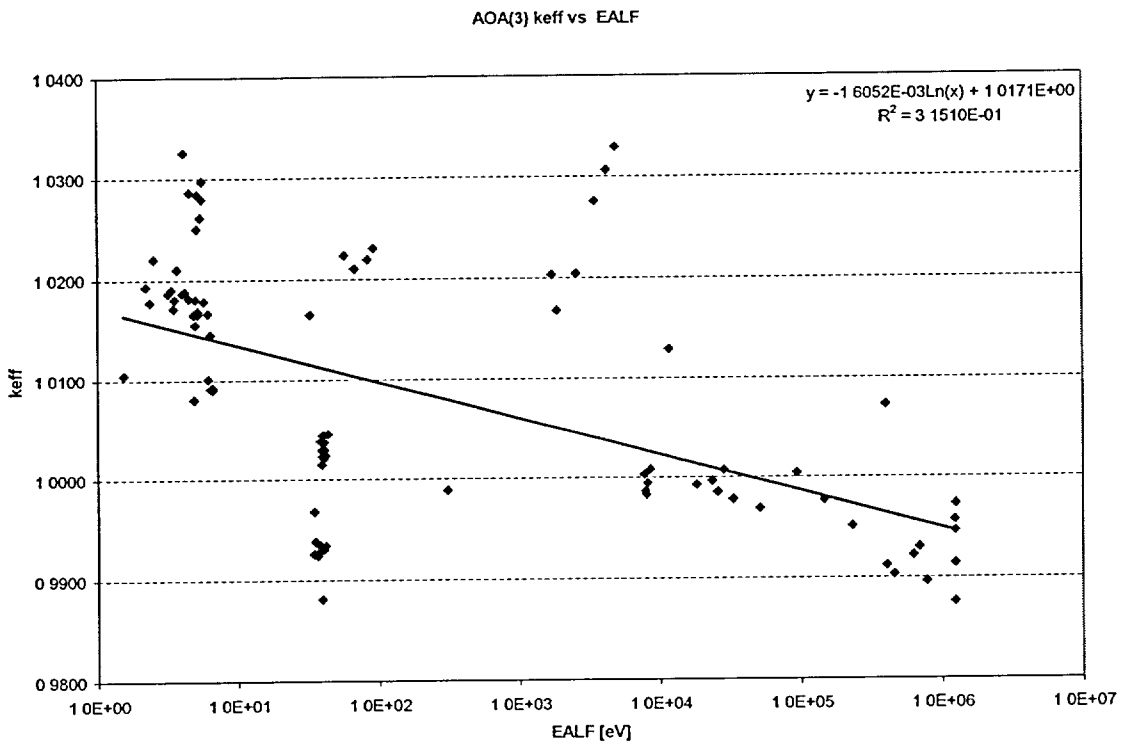

Figure 6-2 AOA(3) k_{eff} as a function of EALF

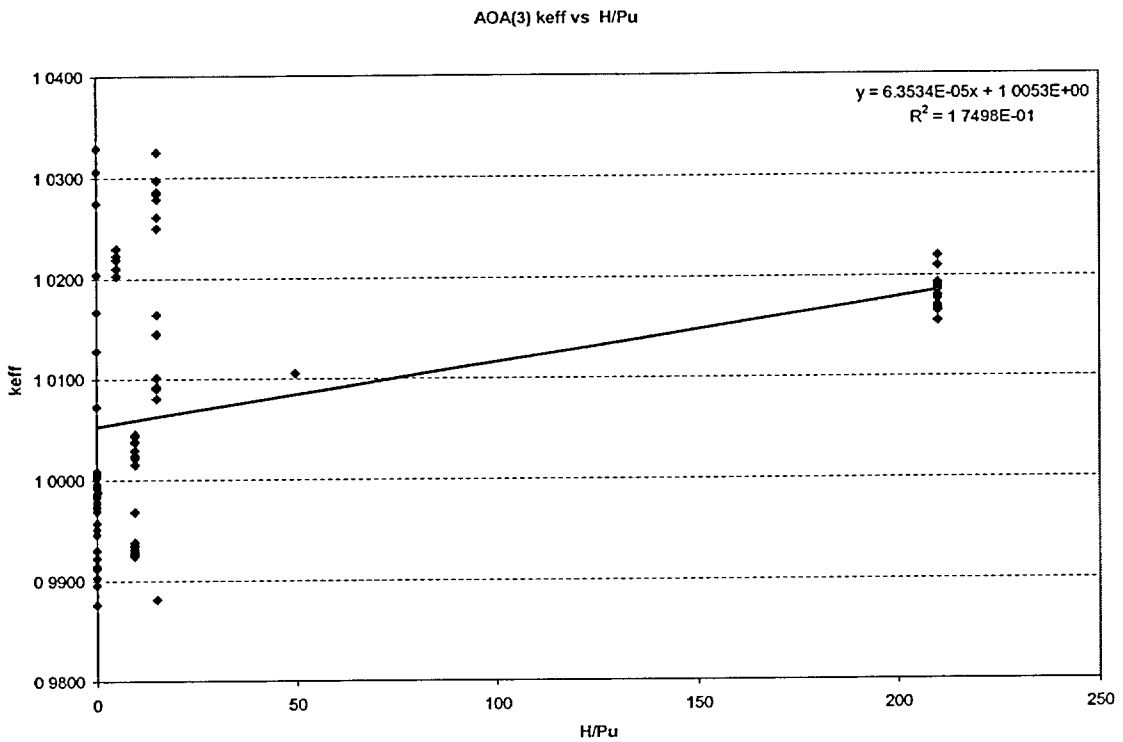

Figure 6-3 AOA(3) k_{eff} as a function of H/Pu

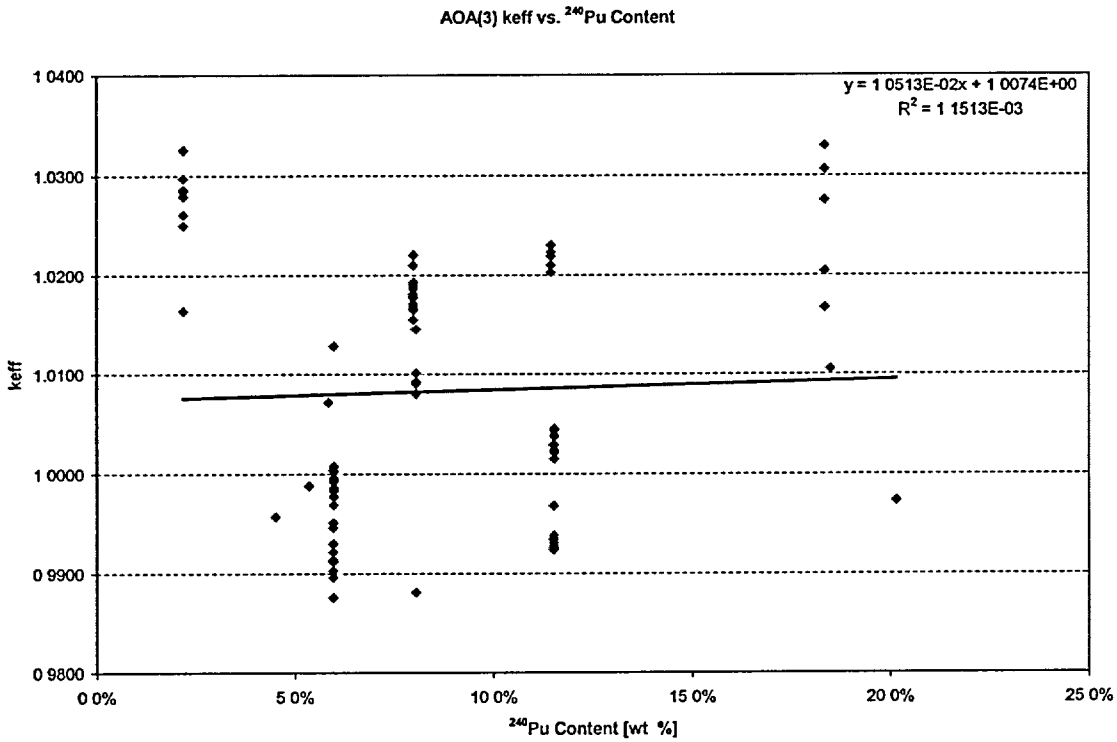

Figure 6-4 AOA(3) k_{eff} as a function of ^{240}Pu content

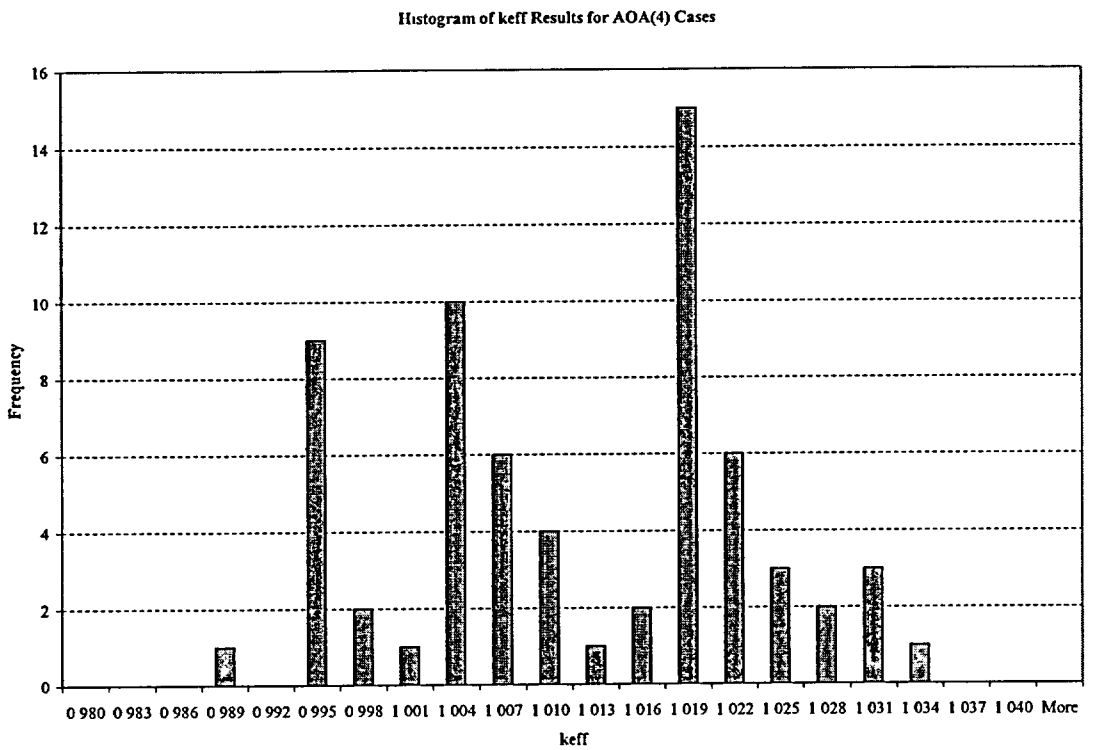

Figure 6-5 Histogram of k_{eff} occurrences for AOA(4)

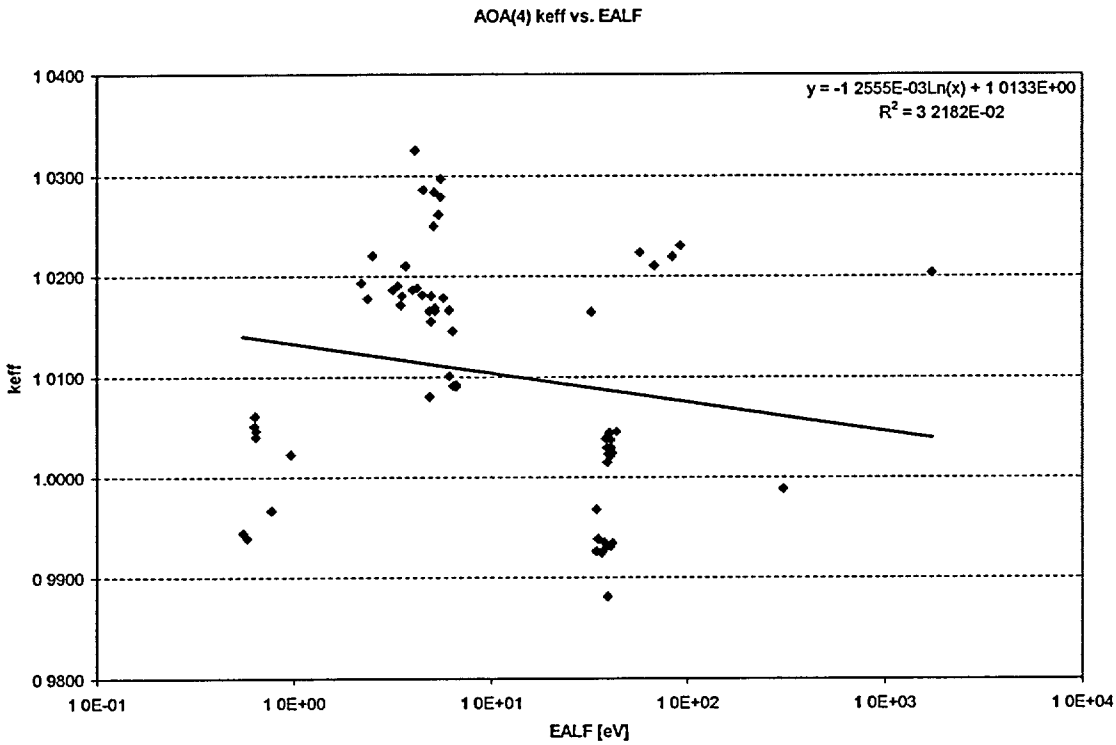

Figure 6-6 AOA(4) k_{eff} as a function of EALF

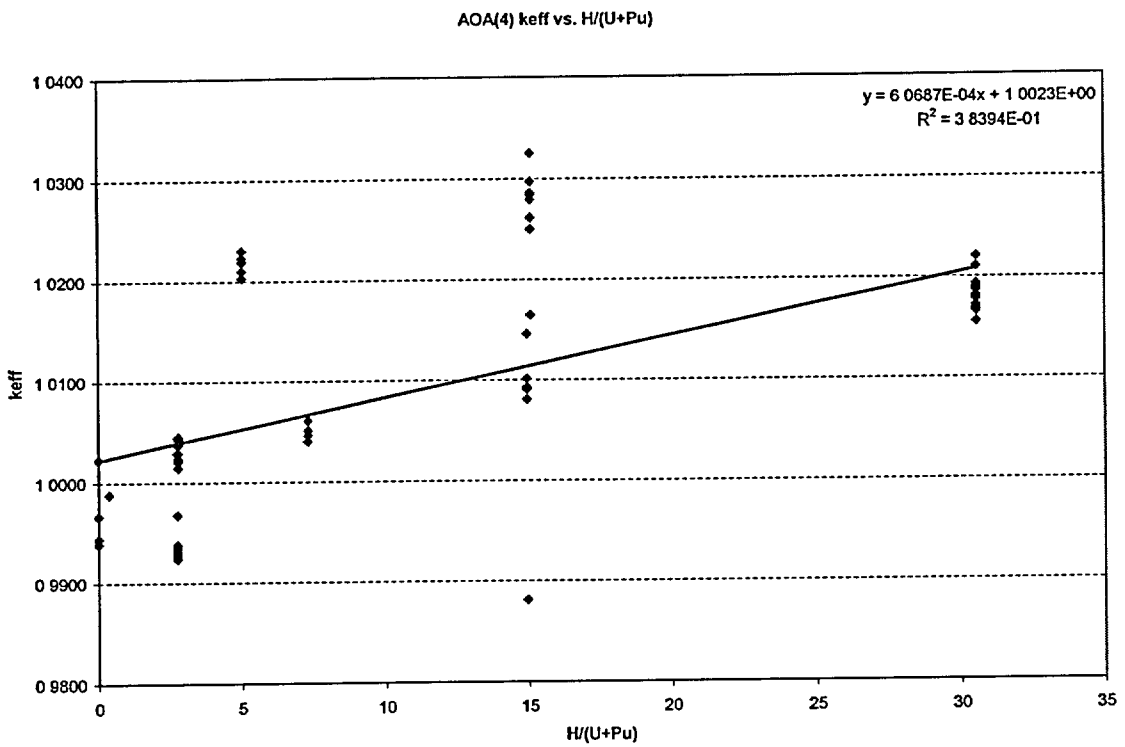

Figure 6-7 AOA(4) k_{eff} as a function of H/(U+Pu)

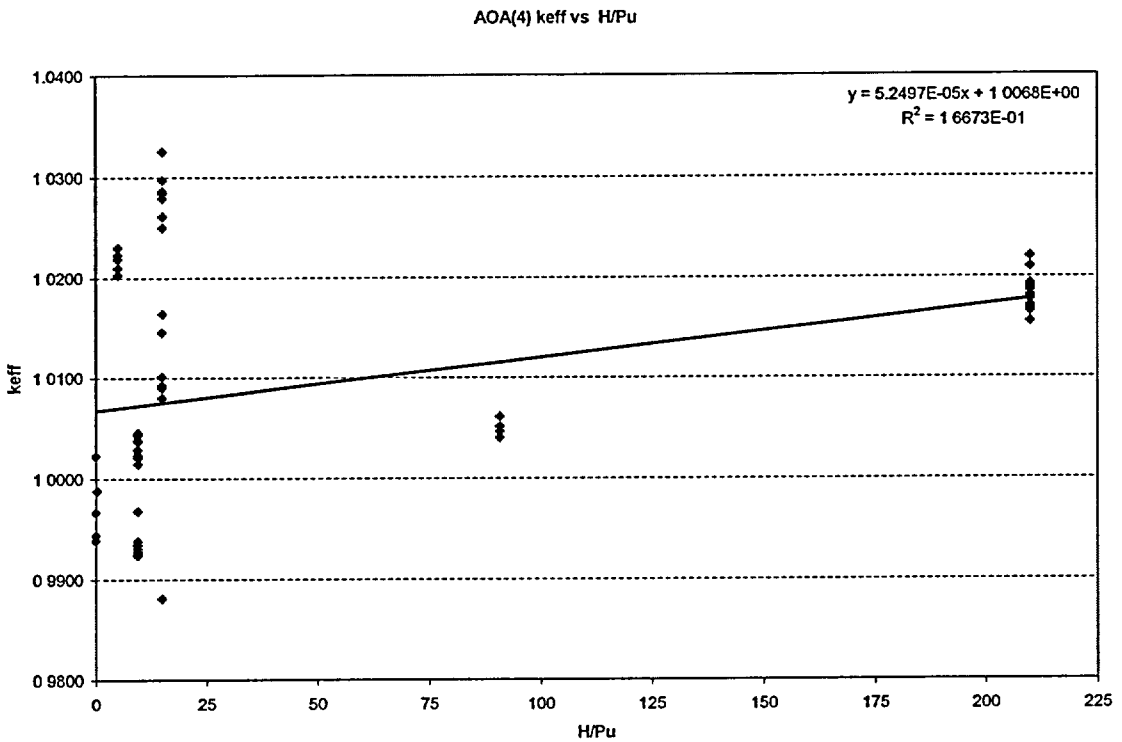

Figure 6-8 AOA(4) k_{eff} as a function of H/Pu

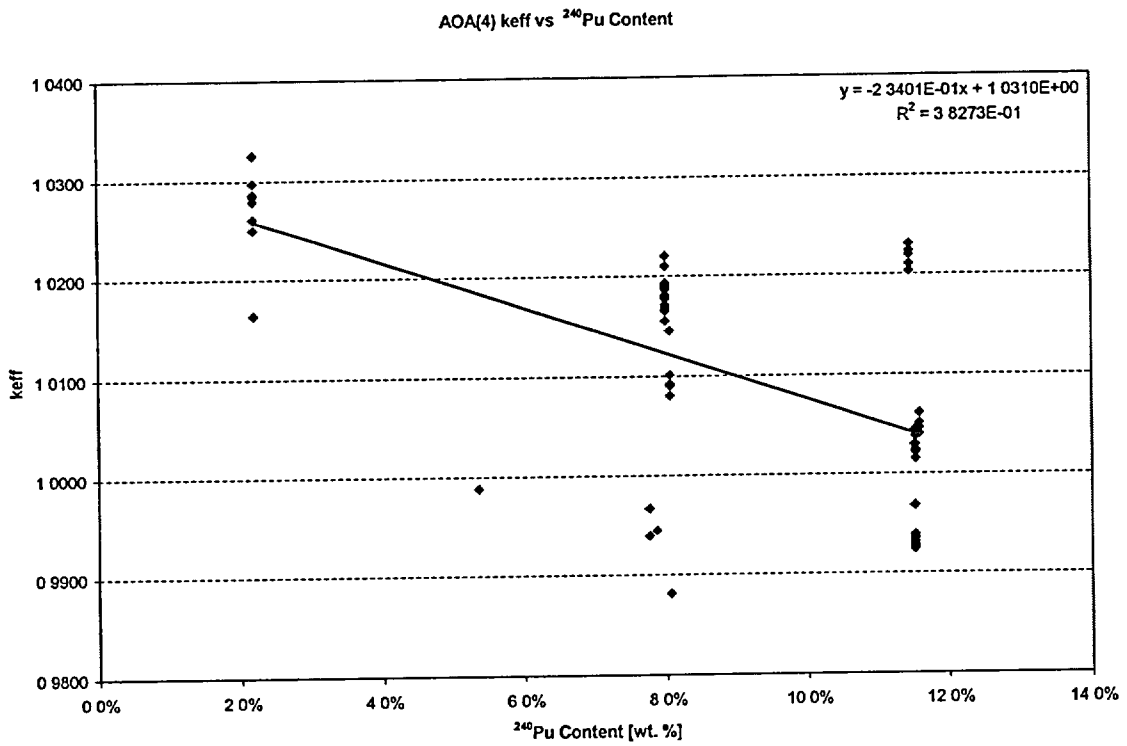

Figure 6-9 AOA(4) k_{eff} as a function of ^{240}Pu content

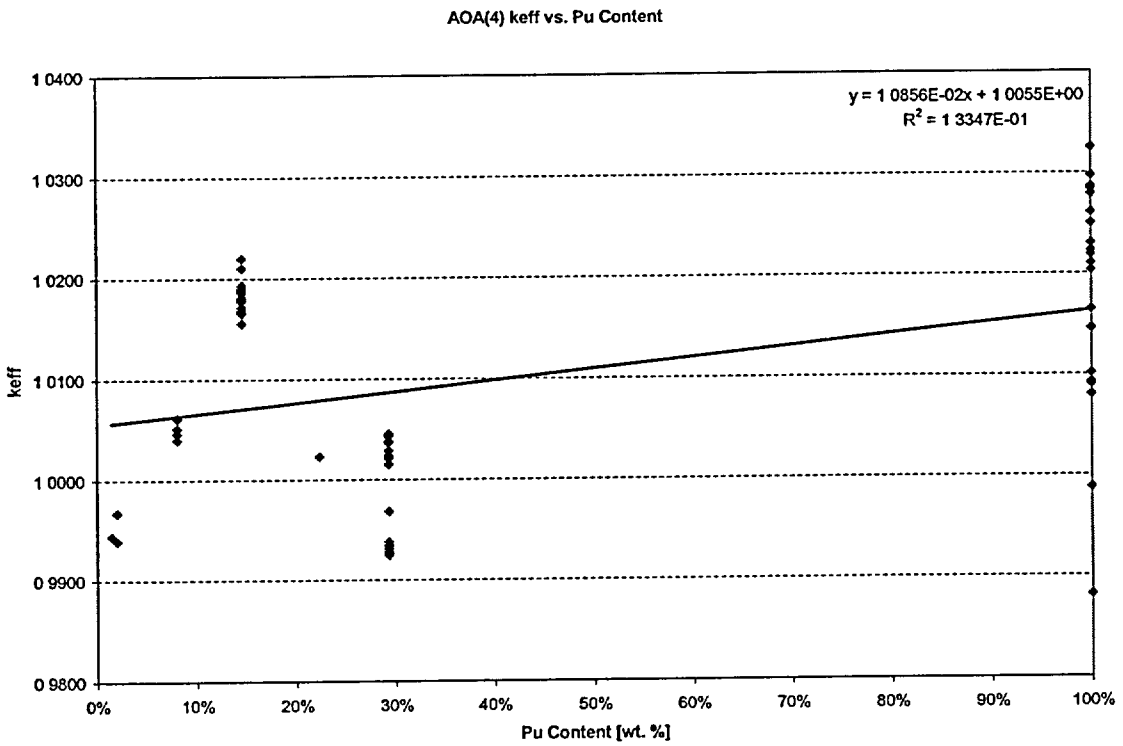

Figure 6-10 AOA(4) k_{eff} as a function of Pu content

7. CONCLUSIONS

The SCALE 4.4a code package using the CSAS26 (KENOVI) sequence and the 238 energy group cross section library 238GROUPDF5 has been validated to perform criticality calculations for the MFFF on the PC platform. It has been validated for two of the design applications: AOA(3) PuO_2 powder and AOA(4) MOX powder.

The USL for the two design application areas is as follows:

- Design application (3) PuO_2 powder USL AOA(3) = 0.9345
- Design application (4) MOX powder USL AOA(4) = 0.9323

The USL accounts for the computational bias, uncertainties, and an administrative margin. The administrative margin is established at 0.05 such that $k_{eff} + 2\sigma - bias \leq 0.95$ for all normal and credible abnormal conditions. Section 7.1 contains a detailed justification of the administrative margin.

Where extrapolation outside the range of applicability for AOA(3) or AOA(4) is necessary, ANSI/ANS-8.1 [2] allows extrapolating the trends established for the bias and USL. Results presented here provide the required trending regressions for determining adjusted USL values. If extrapolation is necessary, it will be discussed on a case-by-case basis in the respective calculation.

7.1 JUSTIFICATION FOR ADMINISTRATIVE MARGIN

The administrative margin applied in the determination of the USL is intended as an added level of conservatism. The code validation effort accounts for all code bias and the effects of both code and experimental benchmark uncertainties. The administrative margin is applied *in addition* to the code bias and bias uncertainty in determining the USL.

The USL values determined here are based on an administrative margin of 0.05. Based on actual process conditions, including 1) the degree to which application parameters fall within the validated Area of Applicability (AOA) of the calculational method and 2) the results of sensitivity analyses demonstrating the sensitivity of k_{eff} values to variations in controlled parameters, the USL may be adjusted. Each NCSE and criticality calculation will include a discussion of the appropriateness of the USL applied for each specific design application.

Typically, the NCSEs and criticality calculations will present k_{eff} results for various scenarios, including normal operation and credible abnormal situations. The results of these analyses permit a quantitative assessment of the degree of subcriticality of the system measured in terms of variation of one or more controlled parameters. Hence, the NCSEs/criticality calculations for specific design applications will verify the conformance with the AOA used in the validation reports.

In general, based on the discussion below, the administrative margin used in criticality analyses is 0.05. This assessment is based on a comparison against administrative margin practices at both NRC and DOE facilities, and past NRC guidance and practice, and is further substantiated by a statistical analysis of the benchmark validation results.

7.1.1 Fuel Cycle and Industry Practice

A review of NRC materials licensees and analogous DOE facilities (including plutonium facilities) indicates that administrative margins for accident analysis conditions range from 0.02 to 0.05 as shown in Table 7-1. These values apply to applications within the validated AOAs; adjustments to the administrative margin are typically made for application outside the validated region.

These values are consistent with precedent information provided by the NRC Staff [20], which indicates administrative margins with a similar range to those indicated in Table 7-1.

An administrative margin of 0.05 is greater than or equal to the most conservative margins identified in Table 7-1 and other NRC precedent [20] for analysis of credible abnormal conditions. .

This margin is consistent with guidance provided in NUREG-1718 [3], which supports an administrative margin of 0.05 for the MFFF. It is also consistent with past NRC-accepted practice in reactor operations (10 CFR 50) [19], and transportation (10 CFR 71) and on-site storage (10 CFR 72) of spent nuclear fuel. Examination of various precedents indicates 0.05 is a conservative administrative margin for activities falling within the validated AOA. For criticality analyses applied outside the validated AOA, specific guidance is provided in ANSI/ANS–8.1–1998 which indicates that the administrative margin may be adjusted based on established trends in the bias, if necessary.

7.1.2 Summary of Administrative Margin Practice

This effort involves the validation of the code to applications within one or more specific areas of applicability. There is no intent to account for or to address the uncertainties and unknowns involved in the actual design applications. This approach is consistent with NUREG/CR-6698 which states "*the subcritical margin is not intended to account for process upset conditions or for uncertainties associated with a process.*" These issues are properly addressed in the nuclear criticality safety evaluations (NCSEs). These evaluations will demonstrate that the design application falls within the required AOA, that design uncertainties and unknowns are properly and conservatively addressed, that sensitivity to controlled parameters is adequately addressed, and that the criticality models themselves are suitably conservative representations of the actual physical phenomena. In cases where calculated k_{eff} values are shown to be sensitive to controlled parameters, the NCSE will demonstrate the adequacy of the control.

In conclusion, an administrative margin of 0.05, selected on the basis of NRC guidance and conservative comparison with applicable precedent is justified, and is sufficiently conservative to provide for an adequate margin of subcriticality.

Table 7-1 Fuel Cycle and Industry Practice

Facility	Process/Application	Material	Administrative Margin
Framatome Cogema Fuels	Fuel assembly manufacture	Low enriched U	0.05
Westinghouse Columbia Site	Fuel assembly manufacture	Low enriched U	0.02
Nuclear Fuel Services	Fuel processing (solutions, powder, pellets, etc.)	Various U enrichments	0.03 LEU 0.05 HEU
Paducah Uranium Enrichment Plant	Uranium enrichment	Low enriched U	0.02
Rocky Flats	Weapons material processing	Plutonium	0.03
BWXT	Fuel assembly manufacture	Low to High Enriched U	0.03 LEU 0.05 HEU
Savannah River Site	a) MTR fuel assemblies b) Pipe overpack material storage c) Mark 42 tube dissolution d) Ion exchange columns with fissile solutions e) DDF-1 package	a) High enriched U b) ^{239}Pu c) ^{239}Pu d) ^{239}Pu solution e) Pu metal and oxide	a) 0.02 b) 0.02 c) 0.05 d) 0.04 e) 0.05
Y-12	Weapons material processing	High enriched U	0.02 – 0.05[1]
Idaho National Engineering and Environmental Lab	Solutions/spent fuel/powders/pieces	Low to High Enriched U, including ^{233}U;some Pu	0.02 – 0.05 0.05 typical
Hanford Site	Waste tanks Packaging and transportation	Various	0.05

[1] Pending final approval of validation document.

8. REFERENCES

[1] SCALE 4.4 : A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation, NUREG/CR-0200 (ORNL/NUREG/CSD-2/R6), Volumes I, II and III. Available from Radiation Shielding Information Center as CCC-545.

[2] ANSI/ANS (American National Standards Institute/American Nuclear Society), 1998. American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, ANSI/ANS–8.1–1998, La Grange Park, IL.

[3] NRC (U.S. Nuclear Regulatory Commission), 2000. Standard Review Plan for the Review of an Application for a Mixed Oxide (MOX) Fuel Fabrication Facility, NUREG-1718, U.S. Nuclear Regulatory Commission, Washington, DC.

[4] Verification of the SCALE 4.4a Code Package on SGN Pentium PCs, SGN Document NT 12046 00 028 A.

[5] Nuclear Energy Agency, 1999. International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, Nuclear Energy Agency, Organization for Economic Co-operation and Development.

[6] Emmett, M.B., and W.C. Jordan, 1996, Guide to Verification and Validation of the SCALE-4 Criticality Safety Software, NUREG/CR-6483 (ORNL/TM-12834), Lockheed Martin Energy Research Corp., Oak Ridge National Laboratory, Oak Ridge, TN.

[7] Neutronics Benchmarks for the Utilization of Mixed-Oxide Fuel: Joint U.S./Russian Progress Report for Fiscal Year 1997, Prepared by the Staffs of the Oak Ridge National Laboratory and the Amarillo National Research Center for Plutonium, Coordinated in the U.S. by R.T. Primm III, ORNL/TM-13603/V2, March 1999.

[8] ANSI/ANS (American National Standards Institute/American Nuclear Society), 1984. Criticality Safety Criteria for Handling Storage, and Transportation of LWR Fuel Outside Reactors, ANSI/ANS-8.17, La Grange Park, IL.

[9] Lichtenwalter, J.J., S.M. Bowman, M.D. DeHart, and C.M. Hopper, 1997. Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages, NUREG/CR-6361 (ORNL/TM-13211), Lockheed Martin Energy Research Corp., Oak Ridge National Laboratory, Oak Ridge, TN.

[10] Dyer, H.R., W.C. Jordan, and V.R. Cain, 1991. A Technique for Code Validation for Criticality Safety Calculations, Trans. Am. Nucl. Soc. 63, 238 (June 1991).

[11] Easter, M.E., 1985. Validation of KENO V.a and Two Cross-Section Libraries for Criticality Calculations of Low-Enriched Uranium Systems, ORNL/CSD/TM-223, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., July 1985.

[12] Bowden D.C. and F.A. Graybill, 1966. Confidence Bands of Uniform and Proportional Width for Linear Models, Am. Stat. Assoc. J. 61, 182 (March 1966).

[13] Johnson, N.L.,1968. Ed., Query, Technometrics 10, 207-209 (February 1968).

[14] Cain, V.R., 1995. A Computer Code to Perform Analyses of Criticality Validation Results, Y/DD-574, Martin Marietta Energy Systems, Inc., Oak Ridge Y-12 Plant, September 1995.

[15] Comparison of original and patched versions of Scale4.4a, Document in preparation.

[16] DCS01 ZJJ CG CAL H 04023 A, Validation of SCALE4.4 and SCALE4.4a for Application to the MOX Fuel Fabrication Facility using the 238 group ENDF/B-V Cross Section Library, Part I: AOA(1) Pu-nitrate solution, AOA(2): MOX Fuel rod lattices

[17] Validation of SCALE4.4 and SCALE 4.4a for Application to the MOX Fuel Fabrication Facility Using the 238 Group ENDF/B-V Cross Section Library Part III: AOA(5) Aqueous solution of Pu compounds, Document in preparation.

[18] J.C. Dean, R.W. Tayloe, Jr., "Guide for Validation of Nuclear Criticality Safety Calculational Methodology," NUREG/CR-6698, Science Applications International Corporation, Oak Ridge, TN, January 2001.

[19] NRC Memorandum, L. Kopp to T. Collins, "Guidance on the regulatory requirements for criticality analysis of fuel storage at light-water reactor power plants," August, 1998.

[20] NRC Letter, A. Persinko to P.S. Hastings, "Nuclear Criticality Safety Staff Qualifications and Administrative Margins for Fuel Fabrication Facilities," 09 November 2001.

[21] B. L. Broadhead, C. M. Hopper, R. L. Childs, and C. V. Parks, Sensitivity and Uncertainty Analyses Applied to Criticality Safety Validation, NUREG/CR-6655, Vols. 1 and 2 (ORNL/TM-13692/V1 and V2), U.S. Nuclear Regulatory Commission, Oak Ridge National Laboratory, November 1999.

[22] S. R. Bierman, and E. D. Clayton, "Critical Experiments to Measure the Neutron Poisoning Effect of Copper and Copper-Cadmium Plates," *Nucl. Sci. Eng.*, 55, pp. 58–66 (1974).

[23] S. R. Bierman and E. D. Clayton, "Critical Experiments with Low-Moderated Homogeneous Mixtures of Plutonium and Uranium Oxides Containing 8, 15, and 30 wt % Plutonium," *Nucl. Sci. Eng.*, 61, pp. 370–376 (1976).

[24] S. R. Bierman, B. M. Durst, and E. D. Clayton, *Critical Experiments Measuring the Reactivity Worths of Materials Commonly Encountered as Fixed Neutron Poisons*, BNWL-2129, Battelle Pacific Northwest Laboratories, October 1976.

[25] B. T. Rearden and K. R. Elam, *Investigations and Recommendations on the Use of Existing Experiments in Criticality Safety Analysis of Nuclear Fuel Cycle Facilities for Weapons-Grade Plutonium*, ORNL/TM-2001/262, Oak Ridge National Laboratory, 2002.

ATTACHMENT NUMBER 1

INPUT AND OUTPUT FILES

The files listed in Figure A7–1 are included on the attached compact disc media.

Figure A7–1 Listing of Files on Attached Media

```
 Volume in drive D is Local Disk
 Volume Serial Number is B177-FD81

 Directory of D:\MFFF

01/02/2003  09:51p      <DIR>          .
01/02/2003  09:51p      <DIR>          ..
01/02/2003  09:51p      <DIR>          Validation
               0 File(s)              0 bytes

 Directory of D:\MFFF\Validation

01/02/2003  09:51p      <DIR>          .
01/02/2003  09:51p      <DIR>          ..
01/02/2003  09:51p      <DIR>          Part2
               0 File(s)              0 bytes

 Directory of D:\MFFF\Validation\Part2

01/02/2003  09:51p      <DIR>          .
01/02/2003  09:51p      <DIR>          ..
01/02/2003  09:51p      <DIR>          Cases
               0 File(s)              0 bytes

 Directory of D:\MFFF\Validation\Part2\Cases

01/02/2003  09:51p      <DIR>          .
01/02/2003  09:51p      <DIR>          ..
01/02/2003  09:51p      <DIR>          PC
               0 File(s)              0 bytes

 Directory of D:\MFFF\Validation\Part2\Cases\PC

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01/02/2003  09:51p      <DIR>          .
01/02/2003  09:53p      <DIR>          ornl_HTC
               0 File(s)              0 bytes

 Directory of D:\MFFF\Validation\Part2\Cases\PC\ornl_HTC

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01/02/2003  10:14p      <DIR>          bnwl-2129
06/19/2002  04:18p                 579 ChangeLog
01/02/2003  10:14p      <DIR>          mct-001
01/02/2003  10:14p      <DIR>          mct-002
01/02/2003  10:14p      <DIR>          mct-009
01/02/2003  10:14p      <DIR>          nse-55
01/02/2003  10:14p      <DIR>          nse-61
01/02/2003  10:14p      <DIR>          pci-001
01/02/2003  10:14p      <DIR>          pcm-001
01/02/2003  10:14p      <DIR>          pcm-002
01/02/2003  10:14p      <DIR>          pmf-001
01/02/2003  10:14p      <DIR>          pmf-002
01/02/2003  10:15p      <DIR>          pmf-003
01/02/2003  10:15p      <DIR>          pmf-016
01/02/2003  10:15p      <DIR>          pmf-017
01/02/2003  10:15p      <DIR>          pmf-033
01/02/2003  10:15p      <DIR>          pmf-037
               1 File(s)            579 bytes

 Directory of D.\MFFF\Validation\Part2\Cases\PC\ornl_HTC\bnwl-2129

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05/10/2002  03:23p              13,167 bnwl2129t4-01.inp
06/19/2002  03:20p             692,379 bnwl2129t4-01.out
05/10/2002  03:23p              14,807 bnwl2129t4-02.inp
06/19/2002  04:26p             711,993 bnwl2129t4-02.out
05/10/2002  03:24p              14,807 bnwl2129t4-03.inp
06/19/2002  05:31p             712,187 bnwl2129t4-03 out
05/10/2002  03:25p              14,889 bnwl2129t4-04.inp
06/19/2002  06:34p             713,731 bnwl2129t4-04.out
05/10/2002  03:25p              14,889 bnwl2129t4-05 inp
06/19/2002  07:35p             714,723 bnwl2129t4-05 out
05/10/2002  03:41p              14,889 bnwl2129t4-06.inp
06/20/2002  11:37a             715,011 bnwl2129t4-06.out
05/10/2002  03:26p              14,889 bnwl2129t4-07.inp
06/20/2002  12:40p             714,705 bnwl2129t4-07.out
05/10/2002  03:26p              14,889 bnwl2129t4-08.inp
06/20/2002  01:43p             715,396 bnwl2129t4-08.out
05/10/2002  03:27p              15,709 bnwl2129t4-09.inp
06/20/2002  02:47p             764,758 bnwl2129t4-09.out
05/10/2002  03:28p              15,709 bnwl2129t4-10.inp
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06/20/2002  04:53p            766,026 bnwl2129t4-11.out
05/10/2002  03:31p             16,611 bnwl2129t4-12.inp
06/20/2002  08:42p            763,147 bnwl2129t4-12.out
05/10/2002  03:32p             17,267 bnwl2129t4-13.inp
06/20/2002  09:43p            765,081 bnwl2129t4-13.out
05/10/2002  03:33p             14,151 bnwl2129t4-15.inp
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05/10/2002  03:34p             14,233 bnwl2129t4-16 inp
06/20/2002  11:47p            697,777 bnwl2129t4-16.out
05/10/2002  03:35p             14,233 bnwl2129t4-17.inp
06/21/2002  12:50a            698,393 bnwl2129t4-17.out
05/10/2002  03:36p             14,233 bnwl2129t4-18.inp
06/21/2002  01:53a            698,413 bnwl2129t4-18.out
05/10/2002  03:36p             15,217 bnwl2129t4-19 inp
06/21/2002  02:56a            722,402 bnwl2129t4-19.out
              36 File(s)   13,299,493 bytes

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05/14/2002  06:23a             55,397 mct001-01.inp
06/19/2002  07:28p            933,867 mct001-01.out
               2 File(s)      989,264 bytes

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01/02/2003  10:14p      <DIR>          ..
05/14/2002  06:23a             16,611 mct002-01.inp
06/19/2002  08:14p            605,829 mct002-01.out
05/14/2002  06:23a             16,611 mct002-02.inp
06/19/2002  08:46p            614,529 mct002-02 out
               4 File(s)    1,253,580 bytes

 Directory of D:\MFFF\Validation\Part2\Cases\PC\ornl_HTC\mct-009

01/02/2003  10:14p      <DIR>          .
01/02/2003  10:14p      <DIR>          ..
05/21/2002  12:20p            143,908 mct009-01.inp
06/19/2002  10:26p          1,344,732 mct009-01.out
               2 File(s)    1,488,640 bytes

 Directory of D:\MFFF\Validation\Part2\Cases\PC\ornl_HTC\nse-55

01/02/2003  10:14p      <DIR>          .
01/02/2003  10:14p      <DIR>          ..
05/14/2002  06:24a              8,575 nse55t5-01.inp
06/19/2002  11:43p            596,596 nse55t5-01.out
05/14/2002  06:24a             11,281 nse55t5-02.inp
06/20/2002  12:59a            626,092 nse55t5-02.out
05/14/2002  06:24a             11,281 nse55t5-03.inp
06/20/2002  02:15a            626,382 nse55t5-03.out
05/14/2002  06:24a             11,281 nse55t5-04.inp
06/20/2002  03:30a            627,482 nse55t5-04.out
05/14/2002  06:24a             11,609 nse55t5-05.inp
06/20/2002  04:46a            668,740 nse55t5-05.out
05/14/2002  06:24a             11,609 nse55t5-06.inp
06/20/2002  06:01a            669,105 nse55t5-06.out
05/14/2002  06:24a             11,609 nse55t5-07.inp
06/20/2002  07:15a            669,453 nse55t5-07.out
05/14/2002  06:24a             11,445 nse55t5-08.inp
06/20/2002  08:32a            635,555 nse55t5-08.out
05/14/2002  06:24a             11,445 nse55t5-09.inp
06/20/2002  09:49a            635,881 nse55t5-09.out
05/14/2002  06:24a             11,445 nse55t5-10.inp
06/20/2002  11:05a            636,276 nse55t5-10 out
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01/02/2003  10:14p      <DIR>          ..
05/14/2002  06:24a              9,723 pu-29-1.inp
06/20/2002  07:31p            932,891 pu-29-1.out
05/14/2002  06:25a              9,723 pu-29-2.inp
06/20/2002  09:07p            591,248 pu-29-2.out
05/14/2002  06:25a              9,723 pu-29-3.inp
06/20/2002  10:41p            591,847 pu-29-3.out
05/14/2002  06:25a              9,723 pu-29-4.inp
06/21/2002  12:17a            590,913 pu-29-4.out
05/14/2002  06:25a              9,723 pu-29-5.inp
06/21/2002  01:53a            590,908 pu-29-5 out
05/14/2002  06:25a              9,723 pu-29-6.inp
06/21/2002  03:30a            590,799 pu-29-6.out
05/14/2002  06:25a              9,723 pu-29-7.inp
06/21/2002  05:09a            591,435 pu-29-7.out
05/14/2002  06:25a              9,723 pu-29-8.inp
06/21/2002  06:47a            591,791 pu-29-8.out
05/14/2002  06:25a              9,723 pu-29-9.inp
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06/21/2002  08:23a            591,900 pu-29-9.out
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05/14/2002  06:25a              9,231 pu-8-2.inp
06/22/2002  03:02a            592,513 pu-8-2.out
05/14/2002  06:25a              9,149 pu-8-3.inp
06/22/2002  04:01a            591,550 pu-8-3.out
05/14/2002  06:25a              9,231 pu-8-4.inp
06/22/2002  05:00a            592,576 pu-8-4 out
               26 File(s)   8,156,552 bytes

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06/21/2002  01:35p            383,519 pci001-01.out
                2 File(s)     385,698 bytes

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06/21/2002  10:20a            433,357 pcm001-02.out
05/14/2002  06:26a              4,311 pcm001-03.inp
06/21/2002  11:10a            418,321 pcm001-03 out
05/14/2002  06:26a              4,393 pcm001-04.inp
06/21/2002  11:56a            427,072 pcm001-04.out
05/18/2002  10:35p              4,885 pcm001-05.inp
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05/18/2002  10:34p              4,475 pcm002-02 inp
06/21/2002  01:10p            419,088 pcm002-02.out
05/18/2002  10:34p              4,475 pcm002-03.inp
06/21/2002  03:24p            418,924 pcm002-03.out
05/18/2002  10:34p              4,475 pcm002-04.inp
06/21/2002  05:38p            419,078 pcm002-04.out
05/18/2002  10:34p              4,475 pcm002-05.inp
06/21/2002  07:51p            419,158 pcm002-05.out
05/14/2002  06:26a              4,475 pcm002-06.inp
06/21/2002  09:38p            422,659 pcm002-06.out
05/14/2002  06:26a              4,475 pcm002-07.inp
06/21/2002  11:25p            422,430 pcm002-07.out
05/14/2002  06:26a              4,475 pcm002-08.inp
06/22/2002  01:12a            422,241 pcm002-08 out
05/14/2002  06:26a              4,475 pcm002-09 inp
06/22/2002  02:58a            423,119 pcm002-09 out
05/14/2002  06:26a              4,393 pcm002-10.inp
06/22/2002  04:39a            407,188 pcm002-10.out
05/14/2002  06:26a              4,393 pcm002-11.inp
06/22/2002  06:20a            407,089 pcm002-11.out
05/14/2002  06:26a              4,393 pcm002-12.inp
06/22/2002  08:02a            407,398 pcm002-12.out
05/14/2002  06:26a              4,393 pcm002-13.inp
06/22/2002  09:44a            407,527 pcm002-13.out
05/14/2002  06:26a              4,393 pcm002-14.inp
06/22/2002  11:25a            407,039 pcm002-14.out
05/14/2002  06:26a              4,393 pcm002-15.inp
06/22/2002  01:07p            407,086 pcm002-15.out
05/14/2002  06:26a              4,393 pcm002-16.inp
06/22/2002  02:49p            406,954 pcm002-16.out
05/14/2002  06:27a              4,393 pcm002-17.inp
06/22/2002  04:26p            416,481 pcm002-17 out
05/14/2002  06:27a              4,393 pcm002-18.inp
06/22/2002  06:02p            415,738 pcm002-18 out
05/14/2002  06:27a              4,393 pcm002-19.inp
06/22/2002  07:38p            416,514 pcm002-19.out
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06/22/2002  09:14p            416,017 pcm002-20.out
05/14/2002  06:27a              4,393 pcm002-21.inp
06/22/2002  10:50p            416,105 pcm002-21.out
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06/23/2002  12:27a            366,262 pmf001-01.out
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05/18/2002  10:32p              24,483 pmf003-02.inp
06/23/2002  12:55a             579,298 pmf003-02 out
05/18/2002  10:32p              20,875 pmf003-03.inp
06/23/2002  01:03a              65,749 pmf003-03 out.gz
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06/12/2002  03:15p              20,307 pmf003-05.inp
06/23/2002  01:27a             565,924 pmf003-05.out
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05/18/2002  10:31p              17,513 pmf016-01.inp
06/23/2002  01:59a             647,089 pmf016-01.out
05/18/2002  10:31p              15,955 pmf016-02.inp
06/23/2002  03:26a             642,198 pmf016-02.out
05/18/2002  10:31p              15,955 pmf016-03.inp
06/23/2002  04:55a             642,447 pmf016-03.out
05/18/2002  10:31p              15,955 pmf016-04.inp
06/23/2002  06:26a             642,543 pmf016-04.out
05/18/2002  10:31p              15,955 pmf016-05.inp
06/23/2002  07:59a             642,506 pmf016-05.out
05/18/2002  10:31p              15,955 pmf016-06.inp
06/23/2002  09:31a             642,619 pmf016-06.out
              12 File(s)     3,956,690 bytes

 Directory of D:\MFFF\Validation\Part2\Cases\PC\ornl_HTC\pmf-017

01/02/2003  10:15p      <DIR>          .
01/02/2003  10:15p      <DIR>          ..
05/18/2002  10:30p              46,131 pmf017-01.inp
06/22/2002  02:20p             840,918 pmf017-01.out
05/18/2002  10:30p              46,131 pmf017-02.inp
06/22/2002  03:35p             840,749 pmf017-02.out
05/18/2002  10:30p              46,131 pmf017-03.inp
06/22/2002  04:49p             841,121 pmf017-03.out
06/14/2002  09:45a              10,412 pmf017-04.inp
06/22/2002  05:08p             809,757 pmf017-04.out
05/18/2002  10:30p              42,933 pmf017-05.inp
06/22/2002  06:20p             818,667 pmf017-05.out
              10 File(s)     4,342,950 bytes

 Directory of D:\MFFF\Validation\Part2\Cases\PC\ornl_HTC\pmf-033

01/02/2003  10:15p      <DIR>          .
01/02/2003  10:15p      <DIR>          ..
06/12/2002  03:28p              17,923 pmf033-01.inp
06/22/2002  11:03a             996,700 pmf033-01.out
               2 File(s)     1,014,623 bytes

 Directory of D \MFFF\Validation\Part2\Cases\PC\ornl_HTC\pmf-037

01/02/2003  10:15p      <DIR>          .
01/02/2003  10:15p      <DIR>          ..
05/18/2002  10:24p              26,451 pmf037-01.inp
06/21/2002  06:02p             637,666 pmf037-01.out
05/18/2002  10:24p              66,385 pmf037-05.inp
06/21/2002  06:45p             752,654 pmf037-05.out
05/18/2002  10:24p              62,449 pmf037-07.inp
06/21/2002  07:31p             741,330 pmf037-07.out
05/18/2002  10:24p              33,831 pmf037-10.inp
06/21/2002  08:23p             659,222 pmf037-10.out
05/18/2002  10:24p              34,159 pmf037-12.inp
06/21/2002  09:31p             661,053 pmf037-12.out
06/12/2002  12:24p              16,538 pmf037-15.inp
06/21/2002  10:31p             753,301 pmf037-15.out
06/12/2002  12:26p              17,850 pmf037-16.inp
06/21/2002  11:35p             758,717 pmf037-16.out
              14 File(s)     5,221,606 bytes

     Total Files Listed.
             197 File(s)    60,814,004 bytes
              65 Dir(s)  3,221,131,264 bytes free
```