

Use of Sensitivity and Uncertainty Analysis to Select Benchmark Experiments for the Validation of Computer Codes and Data

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Abstract—Sensitivity and uncertainty analysis methodologies under development at Oak Ridge National Laboratory were applied to determine whether existing benchmark experiments adequately cover the area of applicability for the criticality code and data validation of PuO₂ and mixed-oxide (MOX) powder systems. The study examined three PuO₂ powder systems and four MOX powder systems that would be useful for establishing mass limits for a MOX fuel fabrication facility. Using traditional methods to choose experiments for criticality analysis validation, 46 benchmark critical experiments were identified as applicable to the PuO₂ powder systems. However, only 14 experiments were thought to be within the area of applicability for dry MOX powder systems.

The applicability of 318 benchmark critical experiments, including the 60 experiments initially identified, was assessed. Each benchmark and powder system was analyzed using the *Tools for Sensitivity and UNcertainty Analysis Methodology Implementation* (TSUNAMI) one-dimensional (TSUNAMI-1D) or TSUNAMI three-dimensional (TSUNAMI-3D) sensitivity analysis sequences, which will be included in the next release of the SCALE code system. This sensitivity data and cross-section uncertainty data were then processed with TSUNAMI-IP to determine the correlation of each application to each experiment in the benchmarking set. Correlation coefficients are used to assess the similarity between systems and determine the applicability of one system for the code and data validation of another.

The applicability of most of the experiments identified using traditional methods was confirmed by the TSUNAMI analysis. In addition, some PuO₂ and MOX powder systems were determined to be within the area of applicability of several other benchmarks that would not have been considered using traditional methods. Therefore, the number of benchmark experiments useful for the validation of these systems exceeds the number previously expected. The TSUNAMI analysis also emphasized some areas where more benchmark data are needed, indicating the need for further evaluation of existing experiments, or possibly the completion of new experiments to fill these gaps. This lack of evaluated data is particularly important for very dry and dense MOX powder systems.

I. INTRODUCTION

The *Tools for Sensitivity and UNcertainty Analysis Methodology Implementation* (TSUNAMI) analysis methods, recently developed at Oak Ridge National Laboratory (ORNL), have been utilized to determine the applicability of critical benchmark experiments to the criticality code and data validation for particular criticality safety applications, or design systems. These meth-

ods, although still under development, have recently been published in several sources.^{1–5} Development of the techniques used in this paper was conducted through joint support from the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission to provide a physics-based approach for the establishment of the area of applicability of critical experiments per the requirements of ANSI/ANS-8.1 (Ref. 6). Use of these methods may allow users to interpolate and extrapolate the traditional area of applicability of a given set of critical experiments to include new application areas that may not have been anticipated during the experiment design.

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Traditional methods for criticality analysis validation include choosing experiments with characteristics that are similar to those of the application being validated. Such characteristics typically include isotopic composition, chemical and physical form, moderation level (H/X), and energy of average lethargy causing fission (EALF). There are seldom sufficient numbers of benchmarks that provide bounds on all major parameters. Thus, it is recognized that extrapolations in parameter space are often necessary and must be made by experienced analysts. The use of EALF as a characteristic for choosing experiments is particularly problematic, as it does not account for the wide range of possible fission neutron spectra that can result in the same calculated EALF. The use of the TSUNAMI methods gives the analyst a more quantitative measure of similarity between critical experiments and applications.

These TSUNAMI methodologies were applied to determine whether existing benchmark experiments adequately cover the areas of applicability for the criticality code and data validation of PuO₂ and mixed-oxide (MOX) powder systems.⁷ Mass limits for powder and fuel pellet handling equipment are needed for the design of a MOX fuel fabrication facility. These limits may be based on criticality code calculations, which, in accordance with ANSI/ANS-8.1, must be validated by comparison with applicable benchmark experiments to establish a value and uncertainty for any computational bias.

The PuO₂ and MOX material may be handled in several forms, including Pu-nitrate and Pu-oxalate aqueous solutions; PuO₂ powders; MOX powders; and MOX pellets, fuel rods, and fuel assemblies. Many applicable critical benchmark experiments are available for the validation of nuclear criticality safety calculations involving plutonium compounds in solution and for MOX fuel and fuel assemblies.⁸ A large number of such experiments are documented in the "International Handbook of Evaluated Criticality Safety Benchmark Experiments," which is published annually by the International Criticality Safety Benchmark Evaluation Project⁹ (ICSBEP). However, very few experiments with PuO₂ or MOX powders are documented in the literature or evaluated by the ICSBEP.

II. SENSITIVITY AND UNCERTAINTY ANALYSIS METHODOLOGY

This section describes the development of TSUNAMI methods to gauge the similarity of systems. A theoretical development of the calculation of the sensitivity coefficients and development of integral parameters to quantitatively assess the similarity of systems are given below.¹⁰

II.A. Sensitivity Theory

Sensitivity coefficients are defined physically such that they represent the percentage effect on some response due to a percentage change in an input parameter. For fissionable material systems, one of the appropriate responses is the system k_{eff} value, relative to input parameters of interest (i.e., the nuclear reaction probabilities, or cross sections). Sensitivity coefficients are typically presented as "profiles," where the change in k_{eff} due to cross sections is given as a function of the energy of the cross section. These sensitivity profiles can be generated for each material in the system and include various nuclear reactions (e.g., scatter, absorption, fission) as well as the neutron energy distribution from fission, χ , and average number of neutrons emitted per fission, \bar{v} .

The techniques used in TSUNAMI to generate sensitivity information are based on the widely used adjoint-based perturbation theory approach.^{11–14} This methodology is very similar to that used in the FORSS code system for fast reactor applications.¹⁵ The sensitivity coefficients produced with these techniques give the sensitivity of the computed k_{eff} to a particular groupwise cross-section data component, the so-called explicit sensitivity coefficients.¹⁶

In operator notation, the eigenvalue-neutron-transport equation can be expressed as

$$A\phi = \frac{1}{k} B\phi , \quad (1)$$

where

ϕ = neutron flux

k = largest eigenvalue, k_{eff}

A = operator that represents all of the transport equation except for the fission term

B = operator that represents the fission term of the transport equation.

The adjoint form of the transport equation can be expressed as

$$A^\dagger \phi^\dagger = \frac{1}{k} B^\dagger \phi^\dagger . \quad (2)$$

In the adjoint equation, the adjoint flux ϕ^\dagger has a special physical significance as the "importance" of the particles within the system.

Using linear perturbation theory, one may show that the relative change in k due to a small perturbation in an energy-dependent macroscopic cross section Σ , of the transport operator at some point in phase space \vec{r} , with the energy variable suppressed, can be expressed as¹⁵

$$\begin{aligned}
S_{k,\Sigma(\vec{r})} &\equiv \frac{\Sigma(\vec{r})}{k} \frac{\partial k}{\partial \Sigma(\vec{r})} \\
&= -\frac{\Sigma(\vec{r})}{k} \frac{\left\langle \phi^\dagger(\vec{\xi}) \left(\frac{\partial A[\Sigma(\vec{\xi})]}{\partial \Sigma(\vec{r})} - \frac{1}{k} \frac{\partial B[\Sigma(\vec{\xi})]}{\partial \Sigma(\vec{r})} \right) \phi(\vec{\xi}) \right\rangle}{\left\langle \phi^\dagger(\vec{\xi}) \frac{1}{k^2} B[\Sigma(\vec{\xi})] \phi(\vec{\xi}) \right\rangle}, \tag{3}
\end{aligned}$$

where $\vec{\xi}$ is the phase space-vector and the brackets indicate integration over space, direction, and energy variables.

In practice, the ∂A and ∂B terms in Eq. (3) are simple functions of the scattering, capture, and fission cross-section data. The evaluation of Eq. (3) then becomes an integration of the forward and adjoint fluxes and the cross sections over the entire phase-space.

Typically, the energy dependence of the cross-section data is represented by averaging the $\Sigma(\vec{r})$ quantities for some reaction x over an energy group g , represented as $\Sigma_{x,g}$. Insertion of these group quantities into Eq. (3) yields the definition of a relative sensitivity coefficient, predicting the relative change in k_{eff} due to a relative perturbation in the cross-section data for reaction x in energy group g :

$$S_{k,\Sigma_{x,g}} = \frac{\Sigma_{x,g}}{k} \frac{\partial k}{\partial \Sigma_{x,g}}. \tag{4}$$

When g is varied to obtain the sensitivity for all groups, which span the energy range of interest, an energy-dependent sensitivity profile is obtained.

The implementation of first-order adjoint-based sensitivity analysis used to derive Eq. (4) is consistent with that used previously in the FORSS code system¹⁵ at ORNL. However, it has been demonstrated that this methodology is incomplete and only accounts for the explicit effect due to the perturbation of the macroscopic cross-section data components in the criticality calculation.¹⁶ The sensitivity coefficients as computed in Eq. (4) require another term to account for the first-order implicit effect of perturbations in the material number densities or nuclear data upon the shielded groupwise macroscopic cross-section data. The implicit portion of the sensitivity coefficient is defined as

$$S_{\Sigma_{x,g},\omega_i} = \frac{\omega_i}{\Sigma_{g,x}} \frac{\partial \Sigma_{x,g}}{\partial \omega_i}, \tag{5}$$

where ω_i is the number density of a particular material or a certain nuclear data component. The sensitivity coefficients defined in Eq. (5) can be propagated to the k_{eff} sensitivity via the chain rule for derivatives. When the implicit sensitivity is added to the explicit sensitivity, the complete sensitivity coefficient, accounting for both the explicit and implicit terms, can be presented as

$$\begin{aligned}
(S_{k,\Sigma_{x,g}})_{complete} &= S_{k,\Sigma_{s,g}} + \sum_i \sum_y \sum_h S_{k,\Sigma_{y,h}} S_{\Sigma_{y,h},\omega_i} S_{\omega_i,\Sigma_{x,g}}, \tag{6}
\end{aligned}$$

where i is the summation index for all parameters that are dependent on the groupwise cross section $\Sigma_{x,g}$, and y and h (data component and energy group indices, respectively) are the summation indices for over all nuclide-reaction pairs and energy groups that are dependent on ω_i .

II.B. Sensitivity- and Uncertainty-Based Integral Parameters

The basis of the TSUNAMI analysis techniques is that systems with neutron multiplication factors that exhibit similar sensitivities to perturbations in the neutron cross-section data on an energy-dependent, nuclide-reaction specific level will have similar biases due to the use of the same computational method and nuclear data used in the criticality safety analysis. The development of a number of different sensitivity- and uncertainty-based integral parameters to assess the degree of similarity between a benchmark experiment and an application has been studied and reported in Refs. 1, 2, 10, and 17.

In this work, two classes of integral parameters were developed: sensitivity based and uncertainty based. The sensitivity-based integral parameters assess system similarity as a function of the sensitivity of k_{eff} to the cross-section data by isotope, reaction, and energy. Uncertainty analyses couple the sensitivity data for each system with the cross-section-covariance data to provide an estimate of the uncertainties in the calculated values of the k_{eff} due to cross-section uncertainties. Correlations in the k_{eff} uncertainties between systems can also be assessed. One integral parameter E_{sum} is based only on sensitivity data and gives a measure of the commonality in the k_{eff} response of an experiment and an application to perturbations in the cross-section data. Another integral parameter c_k couples the sensitivity data with tabulated cross-section-covariance data to give a correlation coefficient that provides a measure of the shared variance, due to cross-section uncertainties, in the computed value of k_{eff} for the application and a given experiment. Previous studies have demonstrated that the use of sensitivity-only-based integral parameters may be inappropriate for systems containing plutonium due to the anticorrelation of certain components of the cross-section data.¹⁸ Therefore, only the correlation coefficient c_k is considered in this paper. For completeness, the derivation of the correlation coefficient, consistent with that given in Ref. 17, follows.

The nuclear data parameters are represented by the vector $\alpha \equiv (\alpha_n)$, $n = 1, 2, \dots, M$, where M is the number of nuclide-reaction pairs \times the number of energy groups. The corresponding symmetric $M \times M$ matrix containing

the relative variances (diagonal elements) and covariances (off-diagonal elements) in the nuclear data is

$$\mathbf{C}_{\alpha\alpha} \equiv \left[\frac{\text{COV}(\alpha_n, \alpha_p)}{\alpha_n \alpha_p} \right], \\ n = 1, 2, \dots, M; p = 1, 2, \dots, M, \quad (7)$$

where

$$\text{COV}(\alpha_n, \alpha_p) = \langle \delta\alpha_n \delta\alpha_p \rangle, \quad (8)$$

where

$\delta\alpha_n, \delta\alpha_p$ = difference between the values and expectation values of the nuclear data parameters

$\langle \cdot \rangle$ = integration over the ranges of α_n and α_p weighted with a probability density function.

A rigorous definition of the cross-section–covariance data is given in Ref. 19.

The matrix containing sensitivities of the calculated k_{eff} to the α parameters, where each matrix entry is consistent with Eq. (4), is given as

$$\mathbf{S}_k \equiv \left[\frac{\alpha_n}{k_i} \frac{\partial k_i}{\partial \alpha_n} \right], \quad i = 1, 2, \dots, I; n = 1, 2, \dots, M, \quad (9)$$

where I is the number of critical systems being considered. The uncertainty matrix for the system k_{eff} values \mathbf{C}_{kk} is given as

$$\mathbf{C}_{kk} = \mathbf{S}_k \mathbf{C}_{\alpha\alpha} \mathbf{S}_k^\dagger, \quad (10)$$

where \dagger indicates a transpose; \mathbf{S}_k is an $I \times M$ matrix, $\mathbf{C}_{\alpha\alpha}$ is an $M \times M$ matrix, and the resulting \mathbf{C}_{kk} matrix is of dimension $I \times I$. The \mathbf{C}_{kk} matrix consists of relative variance values σ_i^2 for each of the critical systems under consideration (the diagonal elements), as well as the relative covariance between systems σ_{ij}^2 (the off-diagonal elements). These off-diagonal elements represent the shared or common variance between two systems. The off-diagonal elements are typically divided by the square root of the corresponding diagonal elements (i.e., the respective standard deviations) to generate a correlation coefficient matrix. Thus, the correlation coefficient is defined as

$$c_k = \frac{\sigma_{ij}^2}{(\sigma_i \sigma_j)}, \quad (11)$$

such that the single c_k value represents the correlation coefficient between uncertainties in system i and system j .

These correlations are due to the fact that the uncertainties in the calculated k_{eff} values for two different systems are related since they contain the same materials. Cross-section uncertainties propagate to all systems containing these materials. Systems with the same materials

and similar spectra would be correlated, while systems with different materials or spectra would not be correlated. The interpretation of the correlation coefficient is the following: A value of 0.0 represents no correlation between the systems, a value of 1.0 represents full correlation between the systems, and a value of -1.0 represents a full anticorrelation.

II.C. Area of Applicability Using Integral Parameter Techniques

All calculations in this study were conducted with the TSUNAMI tools that will be included in the next release of the SCALE code system.²⁰ For this study, each application and benchmark experiment was analyzed using the sensitivity analysis sequences TSUNAMI one-dimensional (1D) (TSUNAMI-1D) (formerly SEN1) or TSUNAMI three-dimensional (3D) (TSUNAMI-3D) (formerly SEN3) (Ref. 21). The TSUNAMI-1D sequence generates the required forward and adjoint flux solutions from 1-D models with XSDRNP. The TSUNAMI-3D sequence generates flux solutions from 3-D models with KENO V.a. Both TSUNAMI sensitivity sequences use BONAMIST and NITAWLST, enhanced versions of the SCALE codes BONAMI and NITAWL-II, to perform resonance self-shielding calculations in the unresolved and resolved resonance regions, respectively.²¹ In addition to performing the usual functions of the resonance self-shielding calculations, the enhanced codes produce the implicit sensitivity terms described in Eq. (5). All sensitivity coefficients were calculated with the 238-group ENDF/B-V neutron cross-section data library of SCALE.

Cross-section–covariance data were prepared from ENDF/B-V data using the PUFF-II code²² in the 44-group energy structure of SCALE. These sensitivity data and cross-section–uncertainty data were then processed to compute the integral parameters for each application to each experiment in the benchmarking set with TSUNAMI-IP (formerly CANDE) (Ref. 23). For the present study, the criterion for the applicability of an experiment for use in the criticality code validation of applications is indicated by the value of the correlation coefficient c_k of 0.8 or higher. This criterion indicates that 80% of the variance in k_{eff} due to cross-section data uncertainties is common to the two systems. The criterion of 0.8 is somewhat arbitrary and may be reevaluated in future studies.¹⁷

III. DESCRIPTION OF APPLICATION SYSTEMS

Seven applications were chosen for this analysis.⁷ Three of the applications were PuO₂ powder systems, and four were MOX powder systems. The PuO₂ powder systems range in density from 3.5 to 7.0 g/ml and have

moderation levels ranging from 1 to 16.6 wt% water. The MOX powder systems also have a range of densities and moderation levels, and include one system at very high density (10.2 g/ml) and very low moderation (1 wt% water). All seven applications were modeled as critical spheres with reflection by either 30 cm of water or 60 cm of depleted uranium. The parameters associated with each application are given in Table I.

IV. BENCHMARKS CHOSEN USING TRADITIONAL VALIDATION TECHNIQUES

Based on the expert judgment of criticality safety practitioners, a number of benchmark-quality critical experiments were identified as within the area of applicability for the seven applications evaluated in this paper.

For the PuO₂ powder applications, 46 critical benchmark experiments were identified using the traditional technique of selecting experiments with similar H/Pu ratios, compositions, and EALF (Ref. 24). These bench-

marks include 33 experiments with PuO₂/polystyrene compacts and 13 experiments with Pu metal moderated by water. These experiments are documented in the ICSBEP "International Handbook of Evaluated Criticality Safety Benchmark Experiments"⁹ as PU-COMP-MIXED-001, PU-COMP-MIXED-002, PU-MET-FAST-016, PU-MET-FAST-017, and PU-MET-FAST-037.

Traditional techniques identified only 14 experiments as being within the area of applicability for the MOX powder applications. These experiments were performed with low-moderated MOX/polystyrene compacts and are published in Ref. 25 but have not yet been evaluated by the ICSBEP.

V. OTHER BENCHMARKS CHOSEN FOR ANALYSIS

With the anticipation that the TSUNAMI analysis would extend the traditional area of applicability of other benchmark experiments to provide coverage for

TABLE I
Application Specifications

Identifier	Composition (wt%)		Powder Density (g/ml)	H ₂ O Content (wt%)	Reflector	H/U or H/(U+Pu)	EALF (eV)
PU-1	100% PuO ₂	96% ²³⁹ Pu 4% ²⁴⁰ Pu	3.5	5%	30 cm H ₂ O	1.58	1019
PU-2	100% PuO ₂	96% ²³⁹ Pu 4% ²⁴⁰ Pu	3.5	16.6%	30 cm H ₂ O	5.99	94.37
PU-3	100% PuO ₂	96% ²³⁹ Pu 4% ²⁴⁰ Pu	7.0	1%	30 cm H ₂ O	3.04	884.3
MOX-1	22% PuO ₂	96% ²³⁹ Pu 4% ²⁴⁰ Pu	5.5	5%	30 cm H ₂ O	1.58	127.0
	78% UO ₂	0.3% ²³⁵ U 99.7% ²³⁸ U					
MOX-2	22% PuO ₂	96% ²³⁹ Pu 4% ²⁴⁰ Pu	5.5	5%	60 cm depleted uranium	1.58	3751
	78% UO ₂	0.3% ²³⁵ U 99.7% ²³⁸ U					
MOX-3	6.5% PuO ₂	96% ²³⁹ Pu 4% ²⁴⁰ Pu	6.96	5%	30 cm H ₂ O	1.58	27.75
	93.5% UO ₂	0.3% ²³⁵ U 99.7% ²³⁸ U					
MOX-4	6.5% PuO ₂	96% ²³⁹ Pu 4% ²⁴⁰ Pu	10.2	1%	30 cm H ₂ O	0.3031	2355
	93.5% UO ₂	0.3% ²³⁵ U 99.7% ²³⁸ U					

the applications, more relaxed criteria were used in the selection of the full set of critical benchmarks to be included in this study. Thus, 318 experiments, including the 60 initially identified, were compiled into an experimental database for use with this study. A summary description of each set of experiments is given in Table II. The number of benchmark experiments from each set identified as applicable by traditional methods is also given in Table II. The experiments were chosen because of similarity to the applications, either in material type or in fission energy spectrum. The benchmark experiments in this database include plutonium systems, mixed plutonium and uranium systems, and one set of low-enriched uranium systems with low moderation. These low-enriched uranium experiments were chosen to assist in validating ^{238}U capture and fission cross sections in the higher neutron energy region.

VI. RESULTS

Once sensitivity data were generated for all applications and benchmark experiments with TSUNAMI-1D or TSUNAMI-3D, TSUNAMI-IP was used to compute the c_k values relating each application to each benchmark experiment. The results of this analysis are used to determine the applicability of the experiments for the criticality code validation of the applications. Based on the previously stated criteria, any benchmark experiment that demonstrates a c_k value of 0.8 or greater with a given application is deemed applicable for the criticality code validation of that system.

The results presented in this paper are comparable to those previously presented in Ref. 7. However, the current results were computed with the most recent pre-production versions of the TSUNAMI codes and, due to

TABLE II
Summary Description of Benchmark Experiments

Experiment Identifier	Number of Experimental Configurations		Range of H/(Pu+U)	Range of Pu/(Pu+U)	Range of EALF (eV)
	Considered in This Study	Previously Identified			
PU-MET-FAST-001	1		0	1	1.24E+06 ^a
PU-MET-FAST-002	1		0	1	1.26E+06
PU-MET-FAST-003	5		0	1	6.24E+05 to 1.24E+06
PU-MET-FAST-016	6	6	0	1	7.78E+03 to 1.17E+04
PU-MET-FAST-017	5	3	0	1	9.39E+04 to 7.82E+05
PU-MET-FAST-033	1		0	1	4.02E+05
PU-MET-FAST-037	7	5	0	1	1.82E+04 to 1.48E+05
PU-COMP-MIXED-001	5	3	0.04 to 49.6	1	1.54E+00 to 9.57E+05
PU-COMP-MIXED-002	29	29	0.04 to 49.6	1	6.84E-01 to 4.92E+03
PU-COMP-INTER-001	1		0.37	1	3.08E+02
MIX-SOL-THERM-001	13		44.08 to 418.64	0.22 to 0.97	9.25E-02 to 2.84E-01
MIX-SOL-THERM-002	3		481.37 to 1150.66	0.23 to 0.52	4.24E-02 to 4.34E-02
MIX-SOL-THERM-004	9		48.99 to 238.94	0.40 to 8.31	6.75E-02 to 3.54E-01
MIX-SOL-THERM-005	7		49.01 to 241.44	0.40 to 0.41	6.70E-02 to 3.56E-01
MIX-COMP-THERM-001	4		3.33 to 17.53	0.22	2.11E-04 to 1.61E-03
MIX-COMP-THERM-002	6		1.19 to 3.64	0.020	1.38E-01 to 7.73E-01
MIX-COMP-THERM-003	6		1.68 to 10.75	0.066	1.01E-01 to 9.06E-01
MIX-COMP-THERM-004	11		2.42 to 5.55	0.028 to 0.030	8.02E-02 to 1.46E-01
MIX-COMP-THERM-005	7		2.22 to 11.87	0.040	8.30E-05 to 3.82E-04
MIX-COMP-THERM-008	28		1.77 to 7.31	0.02	9.17E-02 to 3.99E-01
MIX-COMP-THERM-009	6		1.41 to 5.89	0.015	9.06E-02 to 5.52E-01
MIX-COMP-THERM-011	6		11.75 to 21.13	0.26	2.50E-01 to 5.66E-01
MIX-COMP-THERM-012	33		39.54 to 101.71	0.076 to 0.15	6.62E-02 to 1.40E-01
PU-8-1 to PU-29-9 (Ref. 25)	14	14	2.77 to 7.33	0.08 to 0.29	6.30E-01 to 4.14E+01
NSE-55, Table 4 (Ref. 26)	22		30.6	0.15	1.43E-01 to 1.58E-01
NSE-55, Table 5 (Ref. 26)	10		2.8	0.30	3.85E+01 to 4.39E+01
BNWL-2129, Table 3 (Ref. 27)	31		30.6	0.15	1.43E-01 to 2.57E-01
BNWL-2129, Table 4 (Ref. 27)	19		7.13 to 9.37	0.27 to 0.28	1.51E+00 to 6.13E+00
MIX-MET-FAST-011	4		0	0.077 to 0.41	2.07E+05 to 3.18E+05
LEU-COMP-THERM-049	18		2.01 to 3.01	0	7.94E-01 to 2.36E+00

^aRead as 1.24×10^6 .

TABLE III

Tabulated c_k Values and Calculated Parameters for Applications and Benchmark Experiments*

Experiment	c_k for PU-1	c_k for PU-2	c_k for PU-3	c_k for MOX-1	c_k for MOX-2	c_k for MOX-3	c_k for MOX-4 454 kg Pu	c_k for MOX-4 163 kg Pu	c_k for MOX-4 40 kg Pu	c_k for MOX-4 8 kg Pu	H/ (Pu+U)	Pu/ (Pu+U)	Weight Percent ^{240}Pu	EALF (eV)	k_{eff}	σ
BNWL2129T3-01	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.44E-01	1.0178	0.0005
BNWL2129T3-02	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.46E-01	1.0188	0.0006
BNWL2129T3-03	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.47E-01	1.0196	0.0006
BNWL2129T3-04	0.48	0.61	0.49	0.63	0.52	0.75	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.49E-01	1.0198	0.0006
BNWL2129T3-05	0.48	0.61	0.49	0.63	0.52	0.75	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.50E-01	1.0216	0.0005
BNWL2129T3-06	0.48	0.61	0.49	0.63	0.53	0.75	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.51E-01	1.0195	0.0006
BNWL2129T3-07	0.48	0.61	0.49	0.63	0.52	0.75	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.52E-01	1.0198	0.0005
BNWL2129T3-08	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.53E-01	1.0177	0.0006
BNWL2129T3-09	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.54E-01	1.0183	0.0006
BNWL2129T3-10	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.54E-01	1.0190	0.0005
BNWL2129T3-11	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.55E-01	1.0193	0.0006
BNWL2129T3-12	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.55E-01	1.0186	0.0007
BNWL2129T3-13A	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.54E-01	1.0183	0.0006
BNWL2129T3-14	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.55E-01	1.0165	0.0006
BNWL2129T3-15	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.55E-01	1.0166	0.0006
BNWL2129T3-16	0.47	0.60	0.49	0.64	0.53	0.76	0.39	0.42	0.52	0.69	30.6	0.146	7.97	1.68E-01	1.0202	0.0005
BNWL2129T3-17	0.47	0.60	0.49	0.64	0.54	0.77	0.40	0.44	0.54	0.70	30.6	0.146	7.97	2.04E-01	1.0182	0.0005
BNWL2129T3-18	0.47	0.60	0.49	0.64	0.55	0.78	0.43	0.47	0.56	0.71	30.6	0.146	7.97	2.46E-01	1.0173	0.0006
BNWL2129T3-19	0.47	0.60	0.49	0.64	0.55	0.78	0.44	0.48	0.57	0.71	30.6	0.146	7.97	2.57E-01	1.0174	0.0006
BNWL2129T3-20	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.54E-01	1.0227	0.0005
BNWL2129T3-21	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.55E-01	1.0216	0.0005
BNWL2129T3-22	0.48	0.61	0.50	0.63	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.56E-01	1.0200	0.0006
BNWL2129T3-23	0.48	0.61	0.50	0.63	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.55E-01	1.0212	0.0005
BNWL2129T3-24	0.48	0.61	0.49	0.63	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.56E-01	1.0449	0.0006
BNWL2129T3-25	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.53E-01	0.9868	0.0006
BNWL2129T3-26	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.53E-01	0.9778	0.0006
BNWL2129T3-27	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.44E-01	1.0183	0.0006
BNWL2129T3-28	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.43E-01	1.0199	0.0006
BNWL2129T3-29	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.43E-01	1.0191	0.0005
BNWL2129T3-30	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.43E-01	1.0193	0.0007
BNWL2129T3-31	0.48	0.60	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.43E-01	1.0216	0.0005
BNWL2129T4-01	0.79	0.90	0.82	0.93	0.86	0.94	0.66	0.69	0.77	0.87	7.13	0.28	10.95	6.13E+00	1.0164	0.0005
BNWL2129T4-02	0.77	0.88	0.80	0.91	0.84	0.93	0.64	0.68	0.76	0.86	7.64	0.28	10.89	4.51E+00	1.0178	0.0005
BNWL2129T4-03	0.73	0.85	0.76	0.88	0.80	0.92	0.61	0.65	0.73	0.85	8.08	0.27	10.83	3.44E+00	1.0177	0.0005
BNWL2129T4-04	0.78	0.89	0.81	0.92	0.85	0.93	0.65	0.68	0.76	0.87	7.51	0.28	10.9	5.08E+00	1.0175	0.0006
BNWL2129T4-05	0.73	0.85	0.76	0.88	0.80	0.92	0.61	0.65	0.73	0.85	8.29	0.27	10.8	3.22E+00	1.0181	0.0006
BNWL2129T4-06	0.69	0.81	0.72	0.85	0.76	0.90	0.58	0.61	0.70	0.83	8.81	0.27	10.74	2.24E+00	1.0181	0.0006
BNWL2129T4-07	0.77	0.88	0.80	0.92	0.84	0.93	0.64	0.68	0.76	0.86	7.57	0.28	10.89	4.91E+00	1.0159	0.0005
BNWL2129T4-08	0.70	0.82	0.73	0.85	0.77	0.90	0.58	0.62	0.71	0.83	8.71	0.27	10.75	2.40E+00	1.0165	0.0006
BNWL2129T4-09	0.77	0.88	0.80	0.92	0.84	0.94	0.65	0.69	0.77	0.87	7.39	0.28	10.92	5.78E+00	1.0176	0.0006

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NUCLEAR SCIENCE AND ENGINEERING	VOL. 145	OCT. 2003	BNWL2129T4-10	0.75	0.87	0.78	0.91	0.84	0.94	0.65	0.69	0.77	0.87	7.72	0.28	10.88	5.24E+00	1.0158	0.0005
			BNWL2129T4-11	0.69	0.81	0.71	0.84	0.77	0.91	0.62	0.65	0.74	0.85	8.52	0.27	10.77	3.48E+00	1.0158	0.0005
			BNWL2129T4-12	0.75	0.86	0.78	0.90	0.82	0.92	0.63	0.66	0.75	0.86	8.09	0.27	10.83	3.84E+00	1.0198	0.0006
			BNWL2129T4-13	0.70	0.82	0.73	0.86	0.77	0.90	0.59	0.63	0.71	0.84	8.79	0.27	10.74	2.47E+00	1.0223	0.0005
			BNWL2129T4-14	0.64	0.76	0.66	0.79	0.70	0.87	0.53	0.56	0.66	0.79	9.37	0.27	10.67	1.51E+00	1.0204	0.0005
			BNWL2129T4-15	0.77	0.89	0.80	0.92	0.84	0.93	0.64	0.68	0.76	0.87	7.51	0.28	10.9	5.08E+00	1.0159	0.0006
			BNWL2129T4-16	0.78	0.89	0.81	0.93	0.85	0.93	0.65	0.69	0.77	0.87	7.37	0.28	10.92	5.24E+00	1.0176	0.0005
			BNWL2129T4-17	0.76	0.88	0.79	0.91	0.83	0.93	0.63	0.67	0.75	0.86	7.68	0.28	10.88	4.28E+00	1.0187	0.0005
			BNWL2129T4-18	0.74	0.86	0.77	0.89	0.81	0.92	0.61	0.65	0.74	0.85	7.91	0.27	10.85	3.58E+00	1.0178	0.0006
			BNWL2129T4-19	0.76	0.88	0.79	0.91	0.83	0.93	0.63	0.67	0.75	0.86	7.79	0.27	10.87	4.05E+00	1.0186	0.0006
			LCT049-01	0.00	0.01	0.01	0.13	0.19	0.27	0.23	0.24	0.24	0.22	2.0124	0	0	2.19E+00	0.9910	0.0005
			LCT049-02	0.00	0.01	0.01	0.14	0.19	0.27	0.22	0.23	0.22	0.22	2.0124	0	0	2.21E+00	0.9913	0.0005
			LCT049-03	0.00	0.01	0.00	0.13	0.19	0.27	0.24	0.25	0.24	0.22	2.0124	0	0	2.34E+00	0.9904	0.0005
			LCT049-04	0.00	0.01	0.01	0.14	0.19	0.27	0.24	0.24	0.24	0.22	2.0124	0	0	2.36E+00	0.9954	0.0005
			LCT049-05	0.00	0.01	0.01	0.14	0.18	0.25	0.20	0.21	0.21	0.20	2.5164	0	0	1.23E+00	0.9899	0.0006
			LCT049-06	0.00	0.01	0.01	0.14	0.18	0.25	0.19	0.20	0.21	0.21	2.5164	0	0	1.25E+00	0.9913	0.0005
			LCT049-07	0.00	0.01	0.01	0.14	0.18	0.25	0.19	0.20	0.21	0.20	2.5164	0	0	1.20E+00	0.9898	0.0005
			LCT049-08	0.00	0.01	0.01	0.14	0.18	0.26	0.20	0.20	0.21	0.21	2.5164	0	0	1.29E+00	0.9902	0.0005
			LCT049-09	0.00	0.01	0.01	0.13	0.17	0.24	0.17	0.18	0.19	0.19	3.0067	0	0	7.94E-01	0.9897	0.0005
			LCT049-10	0.01	0.01	0.01	0.14	0.17	0.24	0.16	0.17	0.19	0.19	3.0067	0	0	8.00E-01	0.9913	0.0005
			LCT049-11	0.01	0.01	0.01	0.14	0.17	0.24	0.17	0.18	0.19	0.19	3.0067	0	0	7.95E-01	0.9900	0.0005
			LCT049-12	0.00	0.01	0.01	0.14	0.17	0.24	0.17	0.18	0.19	0.19	3.0067	0	0	8.39E-01	0.9894	0.0005
			LCT049-13	0.01	0.01	0.01	0.14	0.18	0.26	0.19	0.20	0.21	0.21	3.0067	0	0	1.53E+00	0.9900	0.0006
			LCT049-14	0.00	0.01	0.01	0.14	0.18	0.26	0.20	0.21	0.22	0.21	3.0067	0	0	1.53E+00	0.9911	0.0006
			LCT049-15	0.00	0.01	0.01	0.14	0.18	0.26	0.20	0.21	0.22	0.21	3.0067	0	0	1.54E+00	0.9918	0.0006
			LCT049-16	0.01	0.01	0.01	0.14	0.18	0.25	0.19	0.19	0.20	0.20	3.0067	0	0	1.19E+00	0.9917	0.0006
			LCT049-17	0.00	0.01	0.01	0.13	0.18	0.25	0.20	0.21	0.22	0.21	3.0067	0	0	1.28E+00	0.9911	0.0005
			LCT049-18	0.00	0.01	0.01	0.13	0.18	0.25	0.21	0.21	0.22	0.20	3.0067	0	0	1.09E+00	0.9938	0.0005
			MCT001-01	0.65	0.78	0.68	0.81	0.71	0.87	0.52	0.56	0.65	0.79	3.3346	0.2237	11.5414	1.61E-03	1.0014	0.0006
			MCT001-02	0.56	0.68	0.57	0.70	0.58	0.77	0.42	0.46	0.56	0.73	6.8576	0.2237	11.5414	4.76E-04	1.0014	0.0005
			MCT001-03	0.51	0.62	0.52	0.64	0.52	0.72	0.38	0.42	0.52	0.69	10.8808	0.2237	11.5414	2.91E-04	1.0031	0.0006
			MCT001-04	0.48	0.59	0.48	0.60	0.48	0.68	0.35	0.39	0.49	0.67	17.5335	0.2237	11.5414	2.11E-04	1.0047	0.0005
			MCT002-01	0.46	0.58	0.48	0.68	0.60	0.83	0.46	0.50	0.59	0.74	1.1946	0.0204	7.7593	5.79E-01	0.9935	0.0005
			MCT002-02	0.47	0.59	0.49	0.69	0.62	0.85	0.49	0.53	0.62	0.76	1.1946	0.0204	7.7593	7.73E-01	0.9960	0.0005
			MCT002-03	0.44	0.55	0.45	0.62	0.51	0.74	0.36	0.40	0.51	0.70	2.5249	0.0204	7.7593	1.93E-01	0.9990	0.0005
			MCT002-04	0.46	0.57	0.47	0.65	0.56	0.78	0.43	0.47	0.57	0.73	2.5249	0.0204	7.7593	2.82E-01	1.0053	0.0006
			MCT002-05	0.44	0.54	0.44	0.60	0.48	0.70	0.34	0.38	0.49	0.68	3.641	0.0204	7.7593	1.38E-01	1.0041	0.0005
			MCT002-06	0.45	0.56	0.46	0.62	0.52	0.74	0.40	0.44	0.54	0.71	3.641	0.0204	7.7593	1.83E-01	1.0060	0.0006
			MCT003-01	0.57	0.70	0.59	0.77	0.67	0.87	0.49	0.53	0.63	0.78	1.6814	0.0659	8.5826	9.06E-01	0.9929	0.0006
			MCT003-02	0.55	0.67	0.57	0.73	0.63	0.83	0.45	0.49	0.59	0.76	2.1645	0.0659	8.5826	5.50E-01	0.9933	0.0006
			MCT003-03	0.55	0.68	0.57	0.74	0.64	0.84	0.46	0.50	0.60	0.77	2.1645	0.0659	8.5826	6.56E-01	0.9937	0.0006
			MCT003-04	0.49	0.60	0.50	0.64	0.52	0.73	0.36	0.40	0.51	0.70	4.7057	0.0659	8.5826	1.88E-01	0.9983	0.0007
			MCT003-05	0.48	0.59	0.48	0.63	0.50	0.71	0.35	0.39	0.50	0.69	5.672	0.0659	8.5826	1.56E-01	0.9973	0.0006
			MCT003-06	0.45	0.56	0.45	0.58	0.46	0.66	0.32	0.37	0.47	0.67	10.7543	0.0659	8.5826	1.01E-01	1.0015	0.0007
			MCT004-01	0.43	0.54	0.43	0.60	0.49	0.72	0.35	0.39	0.49	0.67	2.4201	0.03	22.0825	1.46E-01	0.9933	0.0005

(Continued)

TABLE III (Continued)

Experiment	c_k for PU-1	c_k for PU-2	c_k for PU-3	c_k for MOX-1	c_k for MOX-2	c_k for MOX-3	c_k for MOX-4 454 kg Pu	c_k for MOX-4 163 kg Pu	c_k for MOX-4 40 kg Pu	c_k for MOX-4 8 kg Pu	H/ (Pu+U)	Pu/ (Pu+U)	Weight Percent ^{240}Pu	EALF (eV)	k_{eff}	σ
MCT004-02	0.43	0.54	0.43	0.60	0.49	0.72	0.35	0.39	0.50	0.67	2.4201	0.0299	22.1504	1.45E-01	0.9944	0.0005
MCT004-03	0.43	0.54	0.44	0.60	0.49	0.72	0.35	0.39	0.50	0.67	2.4201	0.028	23.7291	1.45E-01	0.9946	0.0005
MCT004-04	0.42	0.53	0.43	0.58	0.48	0.70	0.34	0.38	0.48	0.66	2.9761	0.03	22.078	1.21E-01	0.9955	0.0006
MCT004-05	0.42	0.53	0.43	0.59	0.48	0.70	0.34	0.38	0.48	0.66	2.9761	0.0299	22.1521	1.20E-01	0.9966	0.0006
MCT004-06	0.43	0.53	0.43	0.59	0.48	0.70	0.34	0.38	0.49	0.67	2.9761	0.0298	22.289	1.19E-01	0.9979	0.0004
MCT004-07	0.42	0.52	0.42	0.56	0.45	0.67	0.32	0.36	0.47	0.65	4.2387	0.03	22.0708	9.34E-02	0.9983	0.0006
MCT004-08	0.42	0.52	0.42	0.56	0.45	0.67	0.32	0.36	0.47	0.65	4.2387	0.0299	22.1533	9.31E-02	0.9993	0.0005
MCT004-09	0.42	0.52	0.42	0.57	0.45	0.67	0.33	0.36	0.47	0.65	4.2387	0.0298	22.2246	9.28E-02	0.9996	0.0005
MCT004-10	0.41	0.51	0.41	0.55	0.44	0.65	0.32	0.36	0.46	0.64	5.5521	0.03	22.0739	8.05E-02	1.0002	0.0005
MCT004-11	0.41	0.51	0.41	0.55	0.44	0.65	0.32	0.36	0.46	0.64	5.5521	0.0299	22.155	8.02E-02	0.9999	0.0005
MCT005-01	0.48	0.60	0.50	0.68	0.58	0.80	0.42	0.46	0.56	0.73	2.2187	0.0399	18.2054	3.82E-04	0.9970	0.0005
MCT005-02	0.47	0.59	0.48	0.65	0.54	0.76	0.38	0.42	0.53	0.71	2.8531	0.0399	18.2054	2.54E-04	0.9954	0.0006
MCT005-03	0.46	0.57	0.46	0.62	0.51	0.72	0.35	0.40	0.50	0.69	3.9116	0.0399	18.2054	1.73E-04	1.0040	0.0005
MCT005-04	0.45	0.56	0.46	0.60	0.49	0.70	0.34	0.38	0.49	0.68	4.8202	0.0399	18.2054	1.39E-04	1.0275	0.0005
MCT005-05	0.44	0.54	0.44	0.57	0.46	0.66	0.33	0.37	0.47	0.66	7.558	0.0399	18.2054	1.03E-04	1.0057	0.0005
MCT005-06	0.43	0.53	0.43	0.55	0.44	0.64	0.32	0.36	0.47	0.65	10.4047	0.0399	18.2054	8.80E-05	1.0058	0.0005
MCT005-07	0.42	0.52	0.42	0.55	0.43	0.63	0.32	0.36	0.46	0.64	11.8748	0.0399	18.2054	8.30E-05	1.0073	0.0005
MCT008-01	0.43	0.55	0.45	0.65	0.57	0.80	0.44	0.48	0.57	0.72	1.7672	0.02	23.5804	3.99E-01	0.9913	0.0006
MCT008-02	0.43	0.54	0.44	0.61	0.51	0.74	0.38	0.42	0.52	0.70	2.7396	0.02	23.5727	1.99E-01	0.9951	0.0005
MCT008-03	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9967	0.0005
MCT008-04	0.42	0.53	0.42	0.58	0.47	0.69	0.34	0.38	0.49	0.67	4.6486	0.02	23.6031	1.19E-01	1.0011	0.0004
MCT008-05	0.42	0.52	0.42	0.56	0.45	0.66	0.33	0.37	0.48	0.66	6.5336	0.02	23.5994	9.67E-02	1.0018	0.0004
MCT008-06	0.41	0.51	0.41	0.55	0.44	0.65	0.33	0.37	0.47	0.65	7.3056	0.02	23.5727	9.17E-02	1.0026	0.0006
MCT008-07	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.41E-01	0.9967	0.0004
MCT008-08	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.41E-01	0.9947	0.0005
MCT008-09	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9969	0.0004
MCT008-10	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9949	0.0004
MCT008-11	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9946	0.0004
MCT008-12	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9937	0.0005
MCT008-13	0.43	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.41E-01	0.9943	0.0006
MCT008-14	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9957	0.0005
MCT008-15	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9949	0.0006
MCT008-16	0.43	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9930	0.0005
MCT008-17	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9944	0.0005
MCT008-18	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9928	0.0005
MCT008-19	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.42E-01	0.9938	0.0004
MCT008-20	0.43	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9936	0.0006
MCT008-21	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9940	0.0005
MCT008-22	0.43	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9940	0.0004
MCT008-23	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9935	0.0005

NUCLEAR SCIENCE AND ENGINEERING	VOL. 145	OCT. 2003	MCT008-24	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9939	0.0005
			MCT008-25	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9939	0.0005
MCT008-26	0.43	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9930	0.0005			
			MCT008-27	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9939	0.0005
MCT008-28	0.42	0.53	0.43	0.59	0.49	0.71	0.35	0.39	0.50	0.68	3.7669	0.02	23.588	1.43E-01	0.9931	0.0005			
			MCT009-01	0.44	0.55	0.45	0.66	0.59	0.83	0.49	0.53	0.61	0.74	1.4103	0.015	7.8651	5.52E-01	0.9940	0.0005
MCT009-02	0.43	0.55	0.45	0.64	0.55	0.79	0.43	0.47	0.57	0.72	1.8685	0.015	7.8647	3.08E-01	0.9925	0.0005			
			MCT009-03	0.43	0.54	0.43	0.60	0.50	0.73	0.37	0.41	0.52	0.69	3.0167	0.015	7.8643	1.57E-01	0.9954	0.0005
MCT009-04	0.42	0.53	0.43	0.58	0.48	0.70	0.35	0.39	0.50	0.68	4.0995	0.015	7.8643	1.18E-01	0.9974	0.0006			
			MCT009-05	0.42	0.52	0.42	0.57	0.46	0.67	0.34	0.38	0.49	0.66	5.4541	0.015	7.8643	9.61E-02	1.0001	0.0006
MCT009-06	0.42	0.52	0.42	0.56	0.45	0.67	0.34	0.38	0.48	0.66	5.8916	0.015	7.8647	9.06E-02	0.9914	0.0004			
			MCT011-01	0.46	0.55	0.48	0.56	0.46	0.60	0.33	0.37	0.45	0.58	11.7459	0.2573	9.7532	5.66E-01	1.0022	0.0007
MCT011-02	0.46	0.55	0.48	0.56	0.47	0.60	0.34	0.37	0.45	0.59	11.7459	0.2573	9.7532	5.55E-01	1.0036	0.0007			
			MCT011-03	0.46	0.55	0.47	0.55	0.46	0.60	0.33	0.36	0.45	0.58	11.7459	0.2573	9.7532	5.35E-01	1.0025	0.0006
MCT011-04	0.44	0.52	0.45	0.53	0.43	0.58	0.31	0.35	0.43	0.58	21.1287	0.2573	9.7532	2.50E-01	1.0007	0.0006			
			MCT011-05	0.44	0.52	0.45	0.53	0.43	0.57	0.31	0.34	0.43	0.58	21.1287	0.2573	9.7532	2.57E-01	1.0007	0.0006
MCT011-06	0.44	0.53	0.45	0.53	0.43	0.58	0.31	0.35	0.44	0.59	21.1287	0.2573	9.7532	2.64E-01	1.0009	0.0005			
			MCT012-01	0.45	0.57	0.46	0.61	0.51	0.75	0.39	0.42	0.52	0.67	39.5351	0.0758	23.0093	1.39E-01	0.9775	0.0007
MCT012-02	0.45	0.57	0.46	0.61	0.51	0.75	0.39	0.42	0.52	0.67	39.5351	0.0758	23.0093	1.39E-01	0.9796	0.0008			
			MCT012-03	0.45	0.57	0.46	0.61	0.51	0.75	0.39	0.42	0.52	0.67	39.5351	0.0758	23.0093	1.39E-01	0.9757	0.0006
MCT012-04	0.45	0.57	0.46	0.61	0.51	0.75	0.38	0.42	0.51	0.67	39.5351	0.0758	23.0093	1.40E-01	0.9806	0.0006			
			MCT012-05	0.45	0.57	0.46	0.61	0.51	0.75	0.38	0.42	0.51	0.67	39.5351	0.0758	23.0093	1.39E-01	0.9781	0.0005
MCT012-06	0.45	0.57	0.46	0.61	0.51	0.75	0.39	0.42	0.52	0.67	39.5351	0.0758	23.0093	1.40E-01	0.9838	0.0006			
			MCT012-07	0.43	0.54	0.43	0.57	0.45	0.68	0.34	0.38	0.48	0.65	101.7127	0.0788	8.1493	6.66E-02	1.0358	0.0005
MCT012-08	0.43	0.54	0.43	0.57	0.45	0.68	0.34	0.38	0.48	0.65	101.7127	0.0788	8.1493	6.64E-02	1.0323	0.0006			
			MCT012-09	0.43	0.54	0.43	0.57	0.45	0.68	0.34	0.38	0.48	0.65	101.7127	0.0788	8.1493	6.62E-02	1.0284	0.0005
MCT012-10	0.43	0.54	0.43	0.57	0.45	0.68	0.34	0.38	0.48	0.65	101.7127	0.0788	8.1493	6.62E-02	1.0301	0.0006			
			MCT012-11	0.43	0.54	0.43	0.57	0.45	0.68	0.34	0.38	0.48	0.65	101.7127	0.0788	8.1493	6.63E-02	1.0270	0.0006
MCT012-12	0.43	0.54	0.43	0.57	0.45	0.68	0.34	0.38	0.48	0.65	101.7127	0.0788	8.1493	6.63E-02	1.0300	0.0006			
			MCT012-13	0.43	0.54	0.43	0.57	0.45	0.68	0.34	0.38	0.48	0.65	101.7127	0.0788	8.1493	6.66E-02	1.0393	0.0006
MCT012-14	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	60.6277	0.1461	8.0016	1.43E-01	1.0241	0.0006			
			MCT012-15	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	60.6277	0.1461	8.0016	1.43E-01	1.0232	0.0006
MCT012-16	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	60.6277	0.1461	8.0016	1.41E-01	1.0199	0.0006			
			MCT012-17	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	60.6277	0.1461	8.0016	1.41E-01	1.0207	0.0006
MCT012-18	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	60.6277	0.1461	8.0016	1.40E-01	1.0197	0.0006			
			MCT012-19	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	60.6277	0.1461	8.0016	1.39E-01	1.0190	0.0005
MCT012-20	0.48	0.62	0.50	0.64	0.54	0.77	0.39	0.42	0.52	0.68	60.6277	0.1461	8.0016	1.98E-01	1.0168	0.0006			
			MCT012-21	0.48	0.62	0.50	0.64	0.54	0.77	0.39	0.42	0.52	0.68	60.6277	0.1461	8.0016	1.98E-01	1.0173	0.0007
MCT012-22	0.48	0.61	0.49	0.64	0.53	0.76	0.39	0.42	0.51	0.67	60.6277	0.1461	8.0016	2.06E-01	1.0147	0.0006			
			MCT012-23	0.50	0.64	0.52	0.65	0.54	0.76	0.39	0.43	0.52	0.68	95.4106	0.3001	8.1648	1.66E-01	1.0145	0.0008
MCT012-24	0.50	0.63	0.52																

TABLE III (Continued)

Experiment	c_k for PU-1	c_k for PU-2	c_k for PU-3	c_k for MOX-1	c_k for MOX-2	c_k for MOX-3	c_k for MOX-4 454 kg Pu	c_k for MOX-4 163 kg Pu	c_k for MOX-4 40 kg Pu	c_k for MOX-4 8 kg Pu	H/ (Pu+U)	Pu/ (Pu+U)	Weight Percent ^{240}Pu	EALF (eV)	k_{eff}	σ
MCT012-29	0.50	0.63	0.52	0.65	0.54	0.76	0.39	0.43	0.52	0.68	95.4106	0.3001	8.1648	1.58E-01	1.0132	0.0008
MCT012-30	0.50	0.63	0.52	0.65	0.54	0.76	0.39	0.43	0.52	0.68	95.4106	0.3001	8.1648	1.60E-01	1.0130	0.0005
MCT012-31	0.51	0.65	0.53	0.66	0.56	0.78	0.40	0.44	0.53	0.68	95.4106	0.3001	8.1648	2.49E-01	0.9995	0.0007
MCT012-32	0.51	0.65	0.53	0.66	0.56	0.78	0.40	0.44	0.53	0.68	95.4106	0.3001	8.1648	2.49E-01	0.9995	0.0008
MCT012-33	0.51	0.65	0.54	0.66	0.56	0.78	0.40	0.44	0.53	0.68	95.4106	0.3001	8.1648	2.49E-01	0.9954	0.0006
MMF011-01	0.82	0.61	0.76	0.63	0.64	0.44	0.55	0.58	0.62	0.63	0	0.414	6.16	2.79E+05	1.0016	0.0005
MMF011-02	0.71	0.52	0.65	0.54	0.55	0.38	0.48	0.50	0.54	0.55	0	0.274	6.73	3.18E+05	1.0051	0.0005
MMF011-03	0.53	0.40	0.49	0.43	0.45	0.32	0.40	0.41	0.44	0.44	0	0.178	7.88	2.07E+05	1.0088	0.0005
MMF011-04	0.21	0.15	0.19	0.18	0.20	0.15	0.17	0.18	0.19	0.20	0	0.077	11.6	2.57E+05	1.0087	0.0005
MST001-01	0.49	0.62	0.51	0.64	0.53	0.76	0.39	0.42	0.52	0.68	46.4302	0.2186	8.3098	1.61E-01	0.9962	0.0005
MST001-02	0.49	0.62	0.51	0.64	0.53	0.76	0.39	0.43	0.52	0.68	46.2535	0.2196	8.31	1.62E-01	0.9970	0.0006
MST001-03	0.49	0.62	0.50	0.64	0.53	0.75	0.39	0.42	0.52	0.68	46.2873	0.2213	8.3097	1.58E-01	0.9927	0.0007
MST001-04	0.49	0.62	0.51	0.64	0.54	0.76	0.39	0.43	0.52	0.68	45.211	0.2216	8.338	1.71E-01	0.9964	0.0006
MST001-05	0.49	0.63	0.51	0.65	0.54	0.76	0.40	0.43	0.53	0.68	44.1552	0.2214	8.3383	1.76E-01	1.0000	0.0005
MST001-06	0.49	0.62	0.51	0.64	0.53	0.76	0.39	0.42	0.52	0.68	44.0763	0.2216	8.338	1.69E-01	1.0002	0.0006
MST001-07	0.55	0.69	0.58	0.69	0.58	0.78	0.42	0.45	0.54	0.69	110.439	0.9678	7.94	2.84E-01	0.9998	0.0006
MST001-08	0.49	0.63	0.51	0.63	0.51	0.73	0.37	0.40	0.50	0.66	213.2237	0.9666	7.9399	1.49E-01	1.0018	0.0006
MST001-09	0.46	0.59	0.47	0.59	0.47	0.69	0.34	0.38	0.48	0.65	418.636	0.962	7.9402	9.25E-02	1.0023	0.0006
MST001-10	0.47	0.59	0.48	0.61	0.50	0.73	0.37	0.40	0.50	0.67	72.9965	0.2273	8.3378	1.16E-01	1.0031	0.0005
MST001-11	0.46	0.59	0.47	0.60	0.49	0.72	0.36	0.40	0.50	0.66	72.0147	0.2273	8.3379	1.12E-01	1.0070	0.0005
MST001-12	0.46	0.59	0.47	0.61	0.49	0.72	0.36	0.40	0.50	0.66	71.5816	0.2278	8.3381	1.09E-01	1.0086	0.0006
MST001-13	0.45	0.57	0.46	0.59	0.47	0.70	0.35	0.39	0.49	0.66	116.3487	0.2255	8.3378	8.42E-02	1.0003	0.0005
MST002-01	0.41	0.51	0.41	0.52	0.40	0.60	0.30	0.33	0.43	0.61	1129.223	0.5181	8.3119	4.25E-02	1.0076	0.0007
MST002-02	0.41	0.51	0.41	0.52	0.40	0.60	0.30	0.33	0.43	0.61	1150.656	0.5211	8.312	4.24E-02	1.0078	0.0006
MST002-03	0.41	0.51	0.41	0.52	0.41	0.61	0.31	0.34	0.44	0.61	481.3749	0.229	8.3119	4.34E-02	1.0067	0.0006
MST004-01	0.44	0.56	0.45	0.57	0.45	0.67	0.33	0.36	0.46	0.64	238.9425	0.3968	8.3101	7.15E-02	1.0002	0.0007
MST004-02	0.44	0.56	0.45	0.56	0.45	0.67	0.33	0.36	0.46	0.64	237.6855	0.3969	8.3099	6.75E-02	1.0017	0.0006
MST004-03	0.44	0.56	0.45	0.57	0.45	0.67	0.33	0.36	0.47	0.65	238.0412	0.3969	8.31	7.01E-02	1.0025	0.0006
MST004-04	0.50	0.63	0.52	0.64	0.53	0.75	0.38	0.42	0.52	0.68	78.8473	0.4056	8.3098	1.76E-01	1.0029	0.0006
MST004-05	0.50	0.63	0.51	0.64	0.52	0.74	0.38	0.41	0.51	0.68	78.3251	0.4053	8.3098	1.60E-01	0.9972	0.0007
MST004-06	0.50	0.64	0.52	0.65	0.53	0.75	0.38	0.42	0.52	0.68	78.5445	0.4052	8.3101	1.93E-01	0.9969	0.0007
MST004-07	0.55	0.69	0.57	0.70	0.59	0.80	0.42	0.46	0.55	0.71	49.142	0.3964	8.3098	3.54E-01	0.9965	0.0006
MST004-08	0.54	0.68	0.56	0.69	0.58	0.79	0.42	0.45	0.55	0.70	49.1257	0.3969	8.3101	2.68E-01	0.9958	0.0007
MST004-09	0.54	0.68	0.57	0.69	0.58	0.79	0.42	0.46	0.55	0.70	48.9859	0.3972	8.31	3.09E-01	0.9978	0.0006
MST005-01	0.44	0.56	0.45	0.57	0.45	0.67	0.33	0.37	0.47	0.64	241.4437	0.395	8.31	7.14E-02	0.9965	0.0007
MST005-02	0.44	0.55	0.44	0.56	0.45	0.67	0.33	0.36	0.46	0.64	238.4842	0.3981	8.3099	6.70E-02	1.0035	0.0008
MST005-03	0.46	0.63	0.51	0.64	0.53	0.75	0.38	0.42	0.51	0.67	78.8898	0.4066	8.3102	1.55E-01	1.0026	0.0006
MST005-04	0.49	0.63	0.51	0.64	0.53	0.75	0.38	0.42	0.51	0.67	78.8898	0.4066	8.3102	1.53E-01	1.0006	0.0005
MST005-05	0.50	0.64	0.52	0.65	0.54	0.76	0.39	0.42	0.52	0.68	78.5768	0.4062	8.3098	1.95E-01	0.9887	0.0006
MST005-06	0.54	0.69	0.57	0.70	0.59	0.80	0.43	0.47	0.55	0.70	49.0373	0.3966	8.3099	3.56E-01	0.9879	0.0006

MST005-07	0.54	0.68	0.56	0.69	0.58	0.79	0.42	0.46	0.55	0.70	49.0069	0.3964	8.3099	2.54E-01	0.9968	0.0007
NSE55T4-01	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.43E-01	1.0181	0.0005
NSE55T4-02	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.46E-01	1.0187	0.0006
NSE55T4-03	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.47E-01	1.0187	0.0006
NSE55T4-04	0.48	0.61	0.49	0.63	0.52	0.75	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.49E-01	1.0191	0.0005
NSE55T4-05	0.48	0.61	0.50	0.63	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.50E-01	1.0166	0.0006
NSE55T4-06	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.51E-01	1.0170	0.0006
NSE55T4-07	0.48	0.61	0.50	0.63	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.51E-01	1.0202	0.0005
NSE55T4-08	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.53E-01	1.0183	0.0007
NSE55T4-09	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.43E-01	1.0187	0.0006
NSE55T4-10	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.51	0.68	30.6	0.146	7.97	1.43E-01	1.0187	0.0005
NSE55T4-11	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.43E-01	1.0193	0.0006
NSE55T4-12	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.43E-01	1.0179	0.0006
NSE55T4-13	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.46E-01	1.0202	0.0007
NSE55T4-14	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.51E-01	1.0213	0.0006
NSE55T4-15	0.48	0.61	0.50	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.50E-01	1.0202	0.0006
NSE55T4-16	0.48	0.61	0.49	0.63	0.52	0.75	0.39	0.42	0.52	0.68	30.6	0.146	7.97	1.49E-01	1.0206	0.0006
NSE55T4-17	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.54E-01	1.0184	0.0006
NSE55T4-18	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.55E-01	1.0156	0.0007
NSE55T4-19	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.56E-01	1.0160	0.0005
NSE55T4-20	0.48	0.61	0.50	0.64	0.53	0.76	0.39	0.43	0.52	0.68	30.6	0.146	7.97	1.58E-01	1.0207	0.0006
NSE55T4-21	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.46E-01	1.0529	0.0007
NSE55T4-22	0.48	0.61	0.49	0.63	0.52	0.75	0.38	0.42	0.52	0.68	30.6	0.146	7.97	1.45E-01	1.0468	0.0005
NSE55T5-01	0.85	0.95	0.89	0.98	0.93	0.93	0.71	0.75	0.81	0.88	2.8	0.303	11.5	3.97E+01	1.0056	0.0005
NSE55T5-02	0.85	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.8	0.303	11.5	3.97E+01	1.0028	0.0006
NSE55T5-03	0.85	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.8	0.303	11.5	4.00E+01	1.0030	0.0004
NSE55T5-04	0.85	0.95	0.89	0.98	0.93	0.93	0.72	0.76	0.82	0.88	2.8	0.303	11.5	4.10E+01	1.0034	0.0005
NSE55T5-05	0.86	0.95	0.90	0.98	0.93	0.93	0.72	0.75	0.81	0.88	2.8	0.303	11.5	4.03E+01	1.0025	0.0005
NSE55T5-06	0.86	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.8	0.303	11.5	4.14E+01	1.0036	0.0005
NSE55T5-07	0.86	0.95	0.90	0.98	0.93	0.93	0.73	0.76	0.82	0.88	2.8	0.303	11.5	4.39E+01	1.0044	0.0005
NSE55T5-08	0.86	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.8	0.303	11.5	3.93E+01	1.0020	0.0005
NSE55T5-09	0.85	0.94	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.8	0.303	11.5	3.88E+01	1.0018	0.0004
NSE55T5-10	0.85	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.8	0.303	11.5	3.85E+01	1.0039	0.0005
PCI001-01	0.73	0.82	0.78	0.85	0.84	0.75	0.69	0.71	0.73	0.72	0.37	1	5.3	3.08E+02	0.9987	0.0001
PCM001-01	0.80	0.56	0.73	0.54	0.53	0.35	0.46	0.48	0.52	0.54	0.04	1	18.35	9.57E+05	1.0244	0.0004
PCM001-02 ^a	0.95	0.98	0.98	0.94	0.91	0.79	0.70	0.72	0.76	0.78	5	1	11.46	1.73E+03	1.0201	0.0006
PCM001-03 ^a	0.83	0.97	0.90	0.93	0.87	0.86	0.63	0.66	0.71	0.75	15	1	2.2	3.26E+01	1.0156	0.0008
PCM001-04	0.85	0.97	0.91	0.94	0.88	0.87	0.66	0.68	0.74	0.78	15	1	8.06	3.95E+01	0.9882	0.0006
PCM001-05 ^a	0.66	0.81	0.70	0.80	0.71	0.85	0.52	0.55	0.62	0.73	49.6	1	18.35	1.54E+00	1.0099	0.0007
PCM002-01 ^a	0.93	0.76	0.87	0.73	0.70	0.55	0.58	0.61	0.66	0.70	0.04	1	18.35	4.92E+03	1.0318	0.0006
PCM002-02 ^a	0.93	0.77	0.88	0.74	0.71	0.56	0.58	0.61	0.67	0.71	0.04	1	18.35	4.21E+03	1.0309	0.0005
PCM002-03 ^a	0.93	0.77	0.88	0.75	0.71	0.57	0.59	0.62	0.67	0.71	0.04	1	18.35	3.51E+03	1.0255	0.0005
PCM002-04 ^a	0.94	0.79	0.89	0.77	0.73	0.59	0.60	0.62	0.68	0.73	0.04	1	18.35	2.57E+03	1.0199	0.0005
PCM002-05 ^a	0.94	0.79	0.90	0.77	0.74	0.60	0.60	0.63	0.69	0.73	0.04	1	18.35	1.87E+03	1.0163	0.0006
PCM002-06 ^a	0.93	0.99	0.96	0.96	0.90	0.84	0.68	0.71	0.76	0.81	5	1	11.46	9.25E+01	1.0223	0.0006

(Continued)

(Continued)

TABLE III (Continued)

Experiment	c_k for PU-1	c_k for PU-2	c_k for PU-3	c_k for MOX-1	c_k for MOX-2	c_k for MOX-3	c_k for MOX-4 454 kg Pu	c_k for MOX-4 163 kg Pu	c_k for MOX-4 40 kg Pu	c_k for MOX-4 8 kg Pu	H/ (Pu+U)	Pu/ (Pu+U)	Weight Percent ^{240}Pu	EALF (eV)	k_{eff}	σ
PCM002-07 ^a	0.93	0.99	0.96	0.96	0.90	0.84	0.69	0.71	0.77	0.82	5	1	11.46	8.49E+01	1.0224	0.0005
PCM002-08 ^a	0.93	0.99	0.96	0.96	0.90	0.84	0.69	0.72	0.77	0.82	5	1	11.46	6.80E+01	1.0213	0.0005
PCM002-09 ^a	0.92	0.99	0.96	0.96	0.89	0.84	0.68	0.71	0.76	0.81	5	1	11.46	5.68E+01	1.0213	0.0005
PCM002-10 ^a	0.80	0.95	0.86	0.91	0.83	0.87	0.60	0.63	0.70	0.78	15	1	2.2	4.14E+00	1.0308	0.0006
PCM002-11 ^a	0.80	0.95	0.86	0.91	0.83	0.87	0.60	0.63	0.69	0.77	15	1	2.2	4.55E+00	1.0283	0.0006
PCM002-12 ^a	0.80	0.95	0.86	0.91	0.83	0.86	0.60	0.63	0.69	0.76	15	1	2.2	5.13E+00	1.0282	0.0006
PCM002-13 ^a	0.81	0.95	0.86	0.91	0.83	0.87	0.61	0.63	0.70	0.77	15	1	2.2	5.46E+00	1.0251	0.0006
PCM002-14 ^a	0.81	0.95	0.87	0.91	0.84	0.87	0.61	0.64	0.70	0.78	15	1	2.2	5.60E+00	1.0292	0.0005
PCM002-15 ^a	0.81	0.95	0.86	0.91	0.83	0.87	0.61	0.64	0.70	0.78	15	1	2.2	5.56E+00	1.0269	0.0005
PCM002-16 ^a	0.81	0.95	0.87	0.91	0.84	0.87	0.61	0.64	0.70	0.77	15	1	2.2	5.15E+00	1.0238	0.0006
PCM002-17 ^a	0.82	0.95	0.86	0.92	0.84	0.89	0.63	0.66	0.72	0.81	15	1	2.2	4.93E+00	1.0078	0.0006
PCM002-18 ^a	0.82	0.95	0.87	0.93	0.85	0.89	0.63	0.66	0.73	0.81	15	1	2.2	6.19E+00	1.0100	0.0006
PCM002-19 ^a	0.82	0.95	0.87	0.93	0.85	0.89	0.63	0.66	0.73	0.80	15	1	2.2	6.47E+00	1.0089	0.0006
PCM002-20 ^a	0.82	0.95	0.87	0.93	0.85	0.88	0.63	0.66	0.73	0.80	15	1	2.2	6.65E+00	1.0086	0.0006
PCM002-21 ^a	0.82	0.95	0.87	0.93	0.85	0.89	0.63	0.66	0.73	0.81	15	1	2.2	6.64E+00	1.0088	0.0006
PCM002-22 ^a	0.82	0.95	0.87	0.92	0.85	0.88	0.63	0.66	0.72	0.80	15	1	2.2	6.45E+00	1.0132	0.0005
PCM002-23 ^a	0.64	0.78	0.67	0.78	0.68	0.83	0.49	0.52	0.61	0.74	49.6	1	18.35	6.84E-01	1.0081	0.0005
PCM002-24 ^a	0.64	0.79	0.67	0.78	0.68	0.83	0.49	0.52	0.61	0.73	49.6	1	18.35	6.97E-01	1.0102	0.0006
PCM002-25 ^a	0.64	0.79	0.67	0.78	0.68	0.83	0.49	0.52	0.61	0.73	49.6	1	18.35	7.05E-01	1.0092	0.0006
PCM002-26 ^a	0.64	0.79	0.67	0.78	0.68	0.83	0.49	0.53	0.61	0.74	49.6	1	18.35	7.13E-01	1.0092	0.0005
PCM002-27 ^a	0.64	0.79	0.67	0.78	0.68	0.83	0.49	0.53	0.61	0.73	49.6	1	18.35	7.21E-01	1.0101	0.0006
PCM002-28 ^a	0.64	0.79	0.68	0.78	0.68	0.83	0.49	0.53	0.61	0.74	49.6	1	18.35	7.26E-01	1.0118	0.0005
PCM002-29 ^a	0.64	0.78	0.67	0.78	0.68	0.83	0.49	0.53	0.61	0.74	49.6	1	18.35	7.36E-01	1.0108	0.0006
PMF001-01	0.80	0.56	0.73	0.53	0.53	0.33	0.45	0.47	0.51	0.51	0	1	4.7	1.24E+06	0.9944	0.0006
PMF002-01	0.79	0.55	0.72	0.52	0.52	0.33	0.44	0.47	0.50	0.51	0	1	20.1	1.26E+06	0.9966	0.0005
PMF003-01	0.81	0.56	0.73	0.53	0.53	0.33	0.45	0.47	0.50	0.51	0	1	5.97	1.24E+06	0.9948	0.0007
PMF003-02	0.82	0.57	0.74	0.55	0.54	0.35	0.46	0.48	0.52	0.53	0	1	5.97	6.90E+05	0.9933	0.0006
PMF003-03	0.80	0.56	0.73	0.53	0.53	0.33	0.45	0.47	0.50	0.51	0	1	5.97	1.24E+06	0.9895	0.0006
PMF003-04	0.82	0.58	0.75	0.55	0.55	0.35	0.46	0.48	0.52	0.53	0	1	5.97	6.24E+05	0.9936	0.0006
PMF003-05	0.80	0.56	0.73	0.53	0.53	0.33	0.45	0.47	0.50	0.51	0	1	5.97	1.24E+06	0.9912	0.0006

PMF016-01 ^a	0.90	0.71	0.84	0.68	0.65	0.50	0.54	0.57	0.62	0.66	0	1	5.97	1.17E+04	1.0121	0.0006
PMF016-02 ^a	0.90	0.71	0.84	0.68	0.65	0.50	0.54	0.57	0.62	0.66	0	1	5.97	8.61E+03	1.0011	0.0006
PMF016-03 ^a	0.90	0.70	0.83	0.68	0.65	0.49	0.54	0.56	0.62	0.66	0	1	5.97	8.34E+03	0.9982	0.0006
PMF016-04 ^a	0.90	0.70	0.84	0.68	0.65	0.50	0.54	0.57	0.62	0.66	0	1	5.97	8.01E+03	0.9978	0.0008
PMF016-05 ^a	0.90	0.71	0.84	0.68	0.65	0.50	0.54	0.57	0.62	0.66	0	1	5.97	7.93E+03	0.9963	0.0006
PMF016-06 ^a	0.90	0.71	0.84	0.68	0.65	0.50	0.54	0.57	0.62	0.66	0	1	5.97	7.78E+03	0.9997	0.0006
PMF017-01	0.83	0.59	0.75	0.56	0.56	0.36	0.47	0.50	0.53	0.54	0	1	5.97	7.82E+05	0.9893	0.0005
PMF017-02 ^a	0.85	0.62	0.78	0.59	0.59	0.39	0.50	0.52	0.56	0.56	0	1	5.97	4.05E+05	0.9922	0.0004
PMF017-03 ^a	0.86	0.64	0.79	0.61	0.60	0.41	0.51	0.53	0.57	0.58	0	1	5.97	2.30E+05	0.9954	0.0004
PMF017-04	0.85	0.62	0.78	0.60	0.59	0.40	0.50	0.52	0.56	0.57	0	1	5.97	4.58E+05	0.9904	0.0004
PMF017-05 ^a	0.89	0.68	0.82	0.65	0.64	0.46	0.53	0.56	0.60	0.62	0	1	5.97	9.39E+04	1.0004	0.0003
PMF033-01	0.82	0.60	0.75	0.61	0.62	0.42	0.54	0.57	0.61	0.61	0	1	5.83	4.02E+05	1.0069	0.0005
PMF037-01 ^a	0.87	0.65	0.80	0.62	0.61	0.43	0.51	0.54	0.58	0.59	0	1	5.97	1.48E+05	0.9980	0.0006
PMF037-05 ^a	0.89	0.68	0.82	0.65	0.63	0.46	0.53	0.56	0.60	0.62	0	1	5.97	5.12E+04	0.9976	0.0003
PMF037-07 ^a	0.89	0.69	0.83	0.67	0.64	0.47	0.54	0.56	0.61	0.64	0	1	5.97	3.30E+04	0.9967	0.0006
PMF037-10 ^a	0.89	0.69	0.83	0.66	0.64	0.47	0.53	0.56	0.61	0.64	0	1	5.97	2.61E+04	0.9990	0.0005
PMF037-12 ^a	0.90	0.69	0.83	0.67	0.64	0.48	0.54	0.56	0.61	0.64	0	1	5.97	2.35E+04	0.9998	0.0003
PMF037-15	0.90	0.70	0.83	0.67	0.65	0.49	0.54	0.57	0.62	0.65	0	1	5.97	1.82E+04	0.9990	0.0006
PMF037-16	0.89	0.68	0.82	0.66	0.64	0.47	0.53	0.56	0.60	0.63	0	1	5.97	2.84E+04	1.0003	0.0004
PU-15-1 ^b	0.77	0.88	0.81	0.95	0.90	0.97	0.72	0.75	0.82	0.89	2.86	0.15	11.5	1.51E+01	0.9808	0.0003
PU-29-1 ^b	0.86	0.95	0.90	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.77	0.29	11.5	4.14E+01	0.9941	0.0003
PU-29-2 ^b	0.86	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.77	0.29	11.5	4.03E+01	0.9932	0.0005
PU-29-3 ^b	0.86	0.95	0.89	0.98	0.93	0.93	0.73	0.76	0.82	0.88	2.77	0.29	11.5	4.07E+01	1.0028	0.0005
PU-29-4 ^b	0.86	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.82	0.88	2.77	0.29	11.5	3.78E+01	0.9928	0.0005
PU-29-5 ^b	0.86	0.94	0.89	0.98	0.93	0.93	0.72	0.76	0.82	0.89	2.77	0.29	11.5	3.77E+01	0.9940	0.0005
PU-29-6 ^b	0.85	0.95	0.89	0.98	0.93	0.94	0.72	0.75	0.82	0.88	2.77	0.29	11.5	3.67E+01	0.9926	0.0005
PU-29-7 ^b	0.85	0.95	0.89	0.98	0.93	0.93	0.72	0.75	0.81	0.88	2.77	0.29	11.5	3.48E+01	0.9943	0.0005
PU-29-8 ^b	0.85	0.95	0.89	0.98	0.93	0.94	0.72	0.76	0.82	0.88	2.77	0.29	11.5	3.44E+01	0.9943	0.0005
PU-29-9 ^b	0.85	0.94	0.89	0.98	0.93	0.94	0.72	0.75	0.82	0.88	2.77	0.29	11.5	3.46E+01	0.9989	0.0004
PU-8-1 ^b	0.55	0.68	0.57	0.74	0.65	0.86	0.49	0.52	0.61	0.75	7.33	0.08	11.5	6.45E-01	1.0045	0.0005
PU-8-2 ^b	0.55	0.68	0.57	0.74	0.65	0.86	0.49	0.53	0.61	0.75	7.33	0.08	11.5	6.41E-01	1.0040	0.0005
PU-8-3 ^b	0.55	0.68	0.57	0.74	0.65	0.86	0.49	0.53	0.62	0.75	7.33	0.08	11.5	6.38E-01	1.0035	0.0006
PU-8-4 ^b	0.55	0.68	0.57	0.74	0.65	0.86	0.49	0.53	0.62	0.75	7.33	0.08	11.5	6.30E-01	1.0044	0.0006

*Values in bold exceed applicability criteria of $c_k = 0.8$.

^aPreviously identified as applicable to PuO₂ applications.

^bPreviously identified as applicable to MOX applications.

recent code enhancements, differ to some degree from the results previously reported. A complete listing of the c_k values for each benchmark experiment in relation to each application is presented in Table III. Also included in Table III are the H/(Pu+U) and Pu/(Pu+U) atomic ratios, ^{240}Pu content, EALF, and computed k_{eff} value for each of the 318 benchmark experiments examined in this study.

Of the 318 benchmark experiments evaluated in this study, 92 were determined to satisfy the criteria of $c_k \geq 0.8$ used to define applicability to at least one of the PuO_2 powder applications. Of the 46 experiments identified as applicable to PuO_2 powder systems using traditional selection techniques, 39 were confirmed as applicable by TSUNAMI analysis. For application PU-1, 71 systems exhibit a c_k value of 0.8 or greater. Of these 71 systems, 39 are plutonium fueled and 20 contain MOX fuel. The majority of the systems are of metal composition with a fast energy spectrum. For application PU-2, 60 systems exhibit a c_k value of 0.8 or greater. Of these 60 systems, 22 are plutonium-only systems, and 38 are MOX systems. For application PU-3, 66 systems exhibit a c_k value of 0.8 or greater. Of these 66 systems, 39 are plutonium fueled, and 27 contain MOX fuel. Note that numerous MOX benchmarks exceed the applicability criterion for these plutonium applications. The applicable MOX benchmarks typically had high Pu/(U+Pu) ratios and low H/(U+Pu) ratios.

For the MOX powder applications, 83 of the 318 experiments were identified as applicable to at least one of the applications. All 14 experiments identified previously through traditional selection techniques were confirmed by the TSUNAMI analysis to be applicable. For application MOX-1, 61 experimental benchmarks exceed the 0.8 criterion for c_k . Of these, 51 exceed a c_k value of 0.9, with 19 even exceeding 0.98, exhibiting a very strong correlation to the application. Of the 61 experiments with a c_k of 0.8 or greater, 39 benchmarks were MOX and 22 were plutonium fueled.

For application MOX-2, 55 benchmarks exceed the 0.8 criterion for c_k . Of these, 24 values exceed 0.9. Of the 55 experiments with c_k values exceeding 0.8, 34 are MOX, and the remaining 21 are plutonium fueled. The matching systems exhibited EALF values of ~ 40 eV, where the EALF of this application is nearly 4000 eV. Thus, the TSUNAMI methods have identified applicable experiments that might not have been selected through traditional means.

The selection by the TSUNAMI methods of certain experiments as applicable to application MOX-2 can be explained through examination of the sensitivity data, on which the correlation coefficients are based. Experiment 1 from NSE-55 table 4 (Ref. 26) [NSE55T4-01] and experiment 4 from NSE-55 table 5 (Ref. 26) [NSE55T5-04] exhibit EALF values of 0.143 and 41.0 eV, respectively. As shown in Table I, application MOX-2 has an EALF value of 3751 eV. Based on this informa-

tion alone, these experiments would not be selected for the validation of MOX-2. However, the TSUNAMI methods provide a more rigorous analysis. The energy-dependent-sensitivity profiles for ^{239}Pu fission for application MOX-2 and benchmark experiments NSE55T4-01 and NSE55T5-04 are shown in Fig. 1. The sensitivity of MOX-2 is most significant in the fast energy region with some significant values in the thermal region. The peak values in the resonance region are also large, but their contribution to the integral of the sensitivity profile is limited by their small group widths. With the TSUNAMI methodology, the sensitivity profiles of the benchmark experiment for all significant nuclide reactions must nearly match, or exceed, those of the application at all energies to demonstrate applicability. The sensitivity of NSE55T4-01 is strongly peaked in the thermal energy region, with almost no sensitivity in the fast region. Thus, NSE55T4-01 is a poor match for MOX-2, and when all nuclides are examined, a low c_k value of 0.52 results. Experiment NSE55T5-04 exhibits more sensitivity in the thermal region than does MOX-2 but also exhibits significant sensitivity in the fast region, and a high c_k value of 0.93 is produced. Therefore, although the EALF value shows that MOX-2 and NSE55T5-04 have different average parameters, the TSUNAMI methodology shows that the most significant areas of the application are, in fact, covered by the benchmark experiment. Furthermore, the TSUNAMI methodology confirms that experiment NSE55T4-01 is not applicable to the validation of MOX-2.

For application MOX-3, 81 benchmarks exhibit c_k values in excess of 0.8, with 38 of these values exceeding 0.9. Of the 81 experiments with c_k values exceeding 0.8, 54 are MOX, and the remaining 27 are plutonium fueled.

For application MOX-4, which is MOX powder with a density of 10.2 g/cm^3 and only 1 wt% water, no benchmarks exceed the c_k criterion of 0.8. However, the values for 21 systems exceed 0.7. Twenty of these 21 benchmarks are low-moderated MOX systems from either Ref. 25 or 26. This result indicates that application MOX-4 is marginally outside the area of applicability of the 318 experiments in the benchmark set, which points to the need for further evaluation of existing experiments, or possibly the completion of new experiments.

Because of its low moderation, this application has a very large critical spherical mass containing 454 kg of plutonium (7900 kg total mass). An effort was made to determine if more benchmark experiments would meet the applicability criterion if the application were evaluated at a smaller subcritical size and mass. The correlations between the reduced mass subcritical configurations and the benchmark experiments were improved with decreasing mass. With the mass of Pu reduced to 163 kg, still no benchmarks exceed the 0.8 criterion for c_k . However, for a 40-kg Pu case, 20 benchmarks exceed the 0.8 criterion for c_k . All of these benchmarks consist of MOX fuel. For an 8-kg Pu case, 48 benchmarks exceed the 0.8

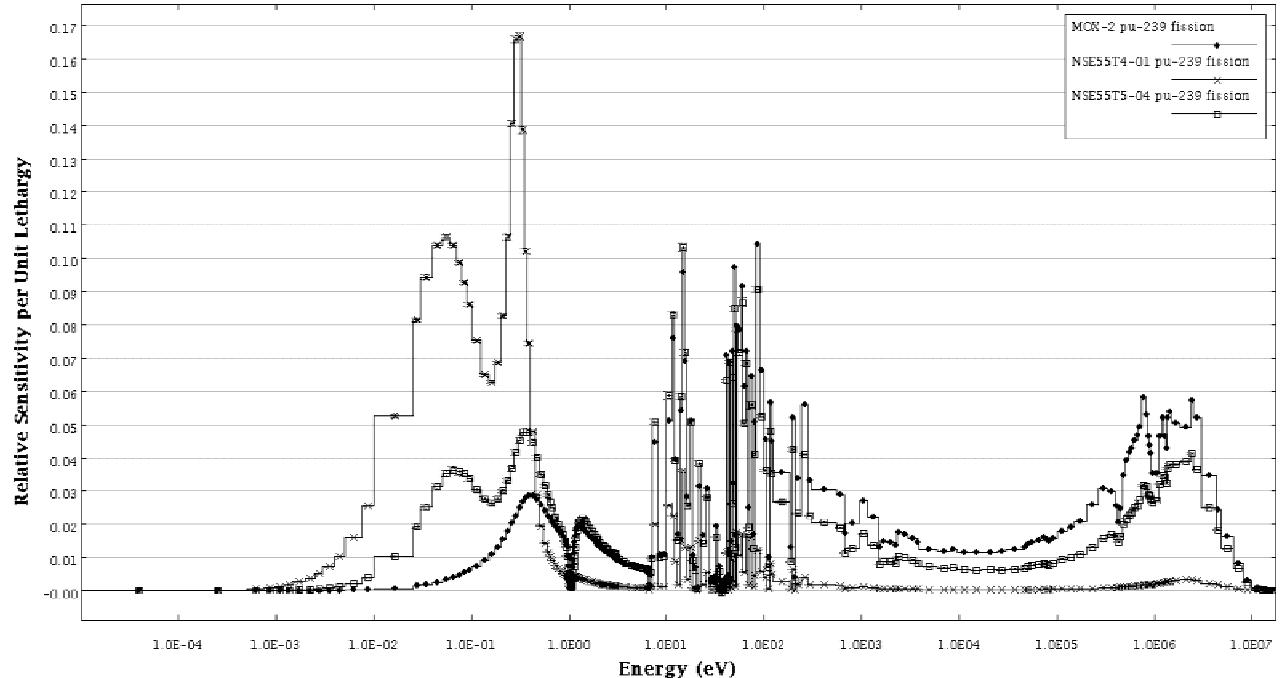


Fig. 1. Energy-dependent-sensitivity profiles for ^{239}Pu fission for MOX-2, experiment 4 from NSE-55 table 5 and experiment 1 from NSE-55 table 4.

criterion for c_k . Of these experiments, 38 are MOX, and the remaining 10 are plutonium fueled.

Upon further investigation of the critical configuration of application MOX-4, it was determined that this system exhibits unique energy-dependent sensitivities in the fast energy range for several important reactions including ^{239}Pu fission and ^{238}U capture. It is these particular reactions that are likely responsible for the lower correlation between the critical experiments and the application. For the reduced mass configurations, the energy-dependent sensitivities in these reactions are similar to those of the benchmark experiments, resulting in improved correlation.

VII. CONCLUSIONS

In this paper, the use of the TSUNAMI methods, currently under development for inclusion in SCALE, has been demonstrated for the selection of benchmark experiments applicable to criticality code validation. This study has identified a number of critical benchmark experiments that exceed the previously established criterion for applicability to the criticality code validation for PuO_2 powders and MOX powders. This criterion is that the correlation coefficient c_k meets or exceeds a value of 0.8.

In some cases, it was determined that both PuO_2 and MOX benchmark experiments are within the area of applicability for either type of application, confirming the

value of including both types of systems in the validation of either. It is not necessary to confine the validation of MOX systems to only MOX experiments. For example, several plutonium-fueled benchmarks exhibit high correlation coefficients with a subset of the MOX applications studied. This can increase the number of experiments available for validation, providing a larger statistical population and more reliable results.

The TSUNAMI analysis also emphasized some areas where more benchmark data are needed, indicating the need for further evaluation of existing experiments, or possibly the completion of new experiments to fill these gaps. This lack of evaluated data is particularly important for very dry and dense MOX powder systems.

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REFERENCES

1. B. L. BROADHEAD and B. T. REARDEN, "Foundations for Sensitivity-Based Criticality Validation Techniques," *Trans. Am. Nucl. Soc.*, **83**, 93 (2000).
2. B. L. BROADHEAD, "Uncertainty Analysis Methods for S/U Criticality Validation Techniques," *Trans. Am. Nucl. Soc.*, **83**, 95 (2000).

3. B. L. BROADHEAD, R. L. CHILDS, and C. M. HOPPER, "Illustrative Examples of Least Squares Methods for Criticality Safety," *Trans. Am. Nucl. Soc.*, **83**, 100 (2000).
4. B. T. REARDEN, C. M. HOPPER, K. R. ELAM, B. L. BROADHEAD, and P. B. FOX, "Prototypic Applications of Sensitivity and Uncertainty Analysis for Experiment Needs," *Trans. Am. Nucl. Soc.*, **83**, 103 (2000).
5. M. E. DUNN and B. T. REARDEN, "Application of Sensitivity and Uncertainty Analysis Methods to a Validation Study for Weapons-Grade Mixed-Oxide Fuel," *Proc. Embedded Topl. Mtg. Practical Implementation of Nuclear Criticality Safety*, Reno, Nevada, November 11–15, 2001, American Nuclear Society (2001) (CD-ROM).
6. "American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors," ANSI/ANS-8.1, American Nuclear Society (1983).
7. 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 (June 2002).
8. S. O. BADER et al., "MOX Fuel Fabrication Facility Nuclear Criticality Validation Approach," *Proc. Embedded Topl. Mtg. Practical Implementation of Nuclear Criticality Safety*, Reno, Nevada, November 11–15, 2001, American Nuclear Society (2001) (CD-ROM).
9. "International Handbook of Evaluated Criticality Safety Benchmark Experiments," NEA/NSC/DOC(95)03, Organisation for Economic Co-operation and Development/Nuclear Energy Agency (1999).
10. B. L. BROADHEAD, B. T. REARDEN, C. M. HOPPER, J. J. WAGSCHAL, and C. V. PARKS, "Sensitivity- and Uncertainty-Based Criticality Safety Validation Techniques," *Nucl. Sci. Eng.* (to be published).
11. E. M. OBLOW, "Sensitivity Theory from a Differential Viewpoint," *Nucl. Sci. Eng.*, **59**, 187 (1976).
12. W. M. STACEY, Jr., "Variational Estimates and Generalized Perturbation Theory for the Ratios of Linear and Bilinear Functionals," *J. Math. Phys.*, **13**, 1119 (1972); see also W. M. STACEY, Jr., "Variational Estimates of Reactivity Worths and Reaction Rate Ratios in Critical Nuclear Reactors," *Nucl. Sci. Eng.*, **48**, 444 (1972).
13. L. N. USACHEV, "Perturbation Theory for the Breeding Ratio and for Other Number Ratios Pertaining to Various Reactor Processes," *J. Nucl. Energy A/B*, **18**, 571 (1964).
14. A. GANDINI, "A Generalized Perturbation Method for Bilinear Functionals of the Real and Adjoint Neutron Fluxes," *J. Nucl. Energy*, **21**, 755 (1967).
15. C. R. WEISBIN et al., "Application of FORSS Sensitivity and Uncertainty Methodology to Fast Reactor Benchmark Analysis," ORNL/TM-5563, Oak Ridge National Laboratory (1976).
16. M. L. WILLIAMS, B. L. BROADHEAD, and C. V. PARKS, "Eigenvalue Sensitivity Theory for Resonance-Shielded Cross Sections," *Nucl. Sci. Eng.*, **138**, 177 (2001).
17. 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), Oak Ridge National Laboratory (Nov. 1999).
18. B. L. BROADHEAD, C. M. HOPPER, K. R. ELAM, B. T. REARDEN, and R. L. CHILDS, "Criticality Safety Applications of S/U Validation Methods," *Trans. Am. Nucl. Soc.*, **83**, 107 (2000).
19. M. E. DUNN, "PUFF-III: A Code for Processing ENDF Uncertainty Data Into Multigroup Covariance Matrices," ORNL/TM-1999/235 (NUREG/CR-6650), Oak Ridge National Laboratory (June 2000).
20. "SCALE: A Modular Code System for Performing Standardized Computer Analysis for Licensing and Evaluations," NUREG/CR-0200, Rev. 6 (ORNL/NUREG/CSD-2R6), Vols. I, II, and III, Oak Ridge National Laboratory (May 2000); see also CCC-545, Radiation Safety Information Computational Center, Oak Ridge National Laboratory.
21. B. T. REARDEN, "Perturbation Theory Eigenvalue Sensitivity Analysis with Monte Carlo Techniques," *Nucl. Sci. Eng.* (to be published).
22. J. D. SMITH III, "Processing ENDF/B-V Uncertainty into Multigroup Covariance Matrices," ORNL/TM-7221, Oak Ridge National Laboratory (1980).
23. B. T. REARDEN and R. L. CHILDS, "Prototypical Sensitivity and Uncertainty Analysis Codes for Criticality Safety with the SCALE Code System," *Trans. Am. Nucl. Soc.*, **83**, 98 (2000).
24. J. J. LICHTENWALTER, S. M. BOWMAN, M. D. DEHART, and C. M. HOPPER, "Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages," NUREG/CR-6361 (ORNL/TM-13211), Oak Ridge National Laboratory (Mar. 1997).
25. S. R. BIERNAN 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**, 370 (1976).
26. S. R. BIERNAN, and E. D. CLAYTON, "Critical Experiments to Measure the Neutron Poisoning Effects of Copper and Copper-Cadmium Plates," *Nucl. Sci. Eng.*, **55**, 58 (1974).
27. S. R. BIERNAN, 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 (Oct. 1976).