

METHODOLOGY FOR EVALUATING CRITICALITY POTENTIAL OF FISSIONABLE MATERIAL EMPLACED IN THE PROPOSED REPOSITORY AT YUCCA MOUNTAIN

Claude W. Mays
CRWMS/Framatome Technologies Group

Joseph J. Sapyta
CRWMS/Framatome Technologies Group

Dan A. Thomas
CRWMS/Framatome Technologies Group

ABSTRACT

A risk-informed methodology is presented for performing postclosure criticality analyses for spent nuclear fuel and high-level waste in the proposed repository at Yucca Mountain, Nevada. The methodology provides a systematic approach for evaluating a combined system of a waste form, waste package, engineered barrier, and repository. Design criteria are presented for assuring that design options are properly implemented for minimizing the potential for, and consequences of criticality following permanent closure of the repository. This methodology is to be used during the licensing process to demonstrate that the risks from a potential criticality are minimized and that public health and safety are protected against postclosure criticality. The neutronic models contained in the methodology are described and the validation process for assuring the adequacy of these models is also illustrated.

INTRODUCTION

The Nuclear Waste Policy Act (NWPA) (1) of 1982 and the Amendments Act (2) of 1987 charged the Department of Energy (DOE) with managing the geologic disposal of high-level radioactive waste (HLW) and spent nuclear fuel (SNF). The NWPA of 1982 established a federal program for permanent disposal of SNF and HLW that would be conducted in a manner to provide reasonable assurance that public health and safety are adequately protected. This act was not site specific. The Amendments Act of 1987 directed DOE to end studies of multiple sites and to focus its studies on the site located at Yucca Mountain. With enactment of the Amendments Act, the emphasis shifted from a comparative assessment of multiple sites to an increased emphasis on the role of the engineered barriers for long-term repository performance. An important concern of long-term repository performance is keeping the fissionable material in a condition so that a self-sustaining nuclear chain reaction (criticality) is highly unlikely. This paper presents a methodology for evaluating criticality potential of HLW and SNF after the repository is sealed and permanently closed (postclosure). A detailed presentation of this methodology, in the form of a topical report (3), was recently submitted to the U.S. Nuclear Regulatory Commission for acceptance. Framatome Technologies, as part of the Civilian Radioactive Waste Management System (CRWMS), has been actively involved in developing methodology for postclosure criticality analysis of waste packages in the proposed repository.

The geologic repository relies on multiple barriers, both natural and engineered, for limiting the potential for criticality during the postclosure phase. The natural barrier system consists of the

rock formations of the repository; the geologic, mechanical, chemical, and hydrological properties of the site; and the climate around the repository. The engineered barrier system consists of the waste packages and the underground facility in which they are emplaced. A waste package is composed of the waste form (radioactive waste and any encapsulating or stabilizing matrix) and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual package. The engineered barrier system and the natural barrier system work in concert to minimize the potential for conditions that would be conducive to a criticality event after the repository has been permanently closed.

The potential for criticality occurring after the repository is permanently closed and sealed is a primary concern. Thus, criticality analyses are performed to project the effectiveness of measures that are implemented before repository closure to minimize criticality potential over thousands of years. The effectiveness of these measures may vary as a function of time after the waste has been emplaced because of the potential degradation of the waste packages as the repository environment changes.

Postclosure criticality analysis differs from conventional analyses for criticality because of the nature and timing of events. For conventional criticality analysis, the events may be attributed to short-term equipment failure and human error. However, the events in the repository leading to a potential criticality are related to long-term processes. These events take place over hundreds, thousands, and tens-of-thousands of years.

The various long-term processes, the combination of events, and any potential criticality are evaluated for the repository with deterministic analyses. The evaluation of any potential consequence resulting from a criticality (e.g., increase in radionuclide inventory) is a deterministic analysis. However, it is not possible to state with certainty what will actually happen – which events will occur – and what actual values the parameters will have. Therefore, the individual deterministic calculations must be applied in a probabilistic context. The various processes and events that may lead to a potential criticality take place over long periods of time and have associated uncertainties that must be considered. Probabilistic analyses are used in establishing the likelihood of a criticality occurring. Hence, the disposal criticality analysis methodology is a blend of deterministic and probabilistic methods.

The consequence of a potential criticality along with the probability of occurrence is used in establishing the risk to the health and safety of the public from the potential release of radioactive material. The acceptability of measures to limit the potential for criticality is decided based on design criteria that are, in part, performance-based. Therefore, decisions concerning design features to minimize criticality potential are based on risk, in conjunction with other information. Hence, the methodology may be referred to as risk-informed.

OVERVIEW OF METHODOLOGY

Criticality potential is governed by the composition of the waste and its geometry (i.e., waste-form configuration, including the amount of moderator, structural material, and neutron absorbers present). Waste forms are initially emplaced in the repository in a subcritical configuration. Criticality evaluations will be performed to demonstrate that the initially emplaced waste form (i.e., waste-package configuration) will remain subcritical for as long as the waste

package remains intact. The methodology described in this paper can be used to support confirmation that even with waste-package failure and the sequence of events that may follow, the repository will provide adequate protection of the health and safety of the public against postclosure criticality.

Figure 1 provides an overview of the disposal criticality analysis methodology. The flow process of major analysis components and inputs are illustrated, as well as the decision points in the process. The input data include the designs of the waste package/engineered barrier system (WP/EBS) (including the waste-form characteristics), the site characteristics, and the degradation characteristics of the waste-package materials. A master scenario list with associated configuration classes is also provided as input. This list represents a comprehensive set of degradation scenarios that must be considered as part of the criticality analysis for any waste form. These scenarios, which are based on the features, events, and processes associated with Yucca Mountain, are described in Reference 3.

Moving through Figure 1, the process examines the characteristics of the repository site and the types of likely conditions and anticipated interactions that could take place, and then builds scenarios that result in degraded configurations. The possible degraded configurations are grouped into classes. A single scenario or set of related scenarios defines each class. The composition and geometry of the configurations in each class vary as a function of specific parameters. These parameters may include the amounts of fissionable material, neutron-absorber material, corrosion products, and moderator and may also stipulate the time of occurrence. Subsequent criticality evaluations focus on the range of values of these configuration parameters.

Degradation analyses are performed to define appropriate parameter ranges for the configurations in each class, and the original configuration class definitions are reconsidered. For example, an original class of "partial basket degradation" may be split into two sub-classes, one with the corrosion products fully distributed in the water surrounding the fissionable material, and another with the corrosion products settled to the bottom of the waste package but still contained within the package.

The criticality potential of configurations in each class is then evaluated. These evaluations are performed at various parameter values for the range of parameters comprising each configuration class. The criterion for judging the potential for criticality is provided by the critical limit (CL), which is the value of k_{eff} at which the configuration is considered potentially critical. CL values are obtained by analysis of experimental systems with a range of neutronic parameters that are representative of those analyzed for the repository. The process for calculating the CL is described in the following section.

For configuration classes showing potential for criticality, multivariate regressions are developed in which k_{eff} values are expressed as a function of configuration parameter values for each of these classes. The regression expressions cover the range of these parameter values for which the peak k_{eff} may exceed the CL. The standard error of regression is established during the

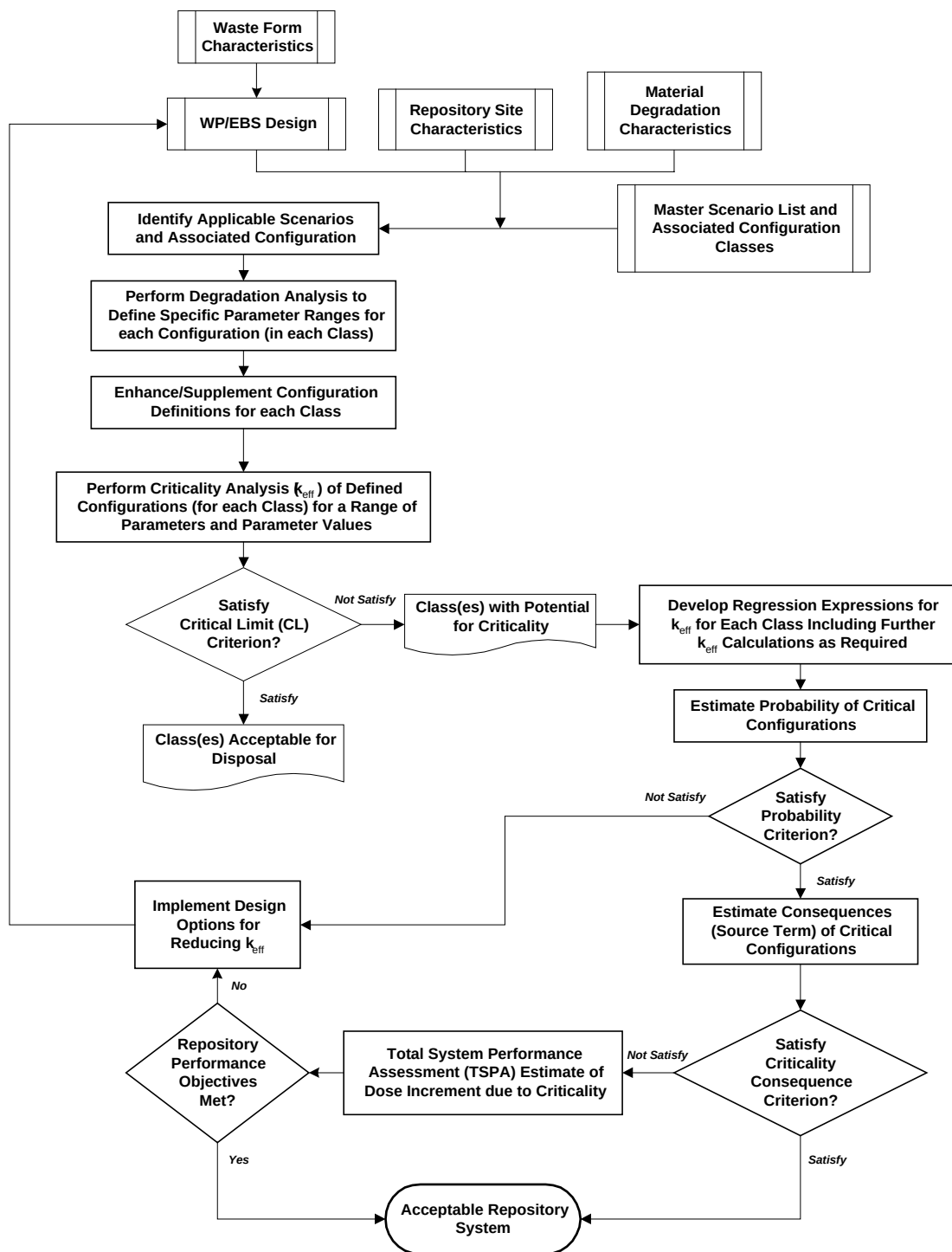


Figure 1. Overview of Disposal Criticality Analysis Methodology

development of the regression expressions and is added to the predicted k_{eff} values for comparison with the CL criterion.

The probability of exceeding the CL criterion is estimated for each class (on a per-package basis) as a function of the characteristics of the waste form. The estimated probability is compared with the per-package probability criterion. As discussed in Reference 3, the probability criterion states that "a criticality frequency of 10^{-4} per year for the entire repository will not be exceeded in any of the first 10,000 years for all combinations of waste packages and waste forms." If this criterion is exceeded, additional design options for reducing k_{eff} are implemented.

Additional design guidelines are followed beyond the probability criterion. A criticality consequence evaluation is performed when the probability criterion is satisfied. This evaluation estimates changes in the radionuclide inventory that may impact the total system performance assessment (TSPA). Changes are measured against a criterion for increases in the radionuclide inventory (the criticality consequence criterion). The criticality consequence criterion as stated in Reference 3 is "the expected radionuclide increase from any criticality event will be less than 10 percent of the radiologically significant radionuclide inventory (curies present at time of criticality) that is available for release and transport to the accessible environment." If this criterion is satisfied, the design criteria are satisfied and the system is acceptable for disposal. Otherwise, the estimated additional source term is provided as input to the TSPA. The TSPA estimates the dose increment due to the criticality and determines if the dose at the accessible environment or other locations is less than the regulatory limit (i.e., performance objectives of the repository are met). If the dose criterion (repository performance objective) is not satisfied, additional design options for reducing k_{eff} are implemented. Otherwise, the design criteria are satisfied, and the system is acceptable for disposal. A discussion of estimating criticality risk is presented in Reference 3.

NEUTRONIC MODELS

Material composition and geometry (i.e., the waste-form configuration) establish the potential for nuclear criticality. For a commercial SNF assembly, the initial material composition (i.e., composition at time of emplacement in a repository) is governed by the operating history of the assembly in a nuclear reactor and the time elapsed since the assembly was removed from the reactor. One component of the methodology addresses the effects of reactor operating history on the initial material composition of commercial SNF. The potential for nuclear criticality will change during the long disposal time period because material composition and geometry will change as a result of isotopic decay and material-degradation processes. The criticality analysis methodology is applicable for evaluating the criticality potential of fissionable material configurations throughout the regulatory life of the repository.

Computer Codes

A combination of neutronic computer codes are used to calculate the material (isotopic) composition of commercial SNF and the effective neutron multiplication factor (k_{eff}) of waste-form geometric configurations. Isotopic concentrations for commercial SNF are obtained from computer codes contained in the SAS2H sequence of SCALE (4). For most other waste forms (except naval SNF), fuel fabrication design values or HLW technical specification limits are used for the isotopic concentrations of fissionable material. Neutron multiplication factors (k_{eff}) are

calculated with the MCNP (5) code. MCNP uses the isotopic compositions of the materials (including those from the degradation analysis described in Reference 3), a system of nuclear data libraries, and a detailed model of the geometry to calculate the k_{eff} of the system.

Isotopic Model for Commercial SNF

The method for predicting commercial SNF composition at any postclosure time starts with calculating the isotopic concentrations of fissionable and neutron-absorbing isotopes to be used for criticality evaluations. These calculations are based on conservative model input parameters, fuel-assembly burnup data (which are verified with measurements), disposal time period, and fuel-assembly design data.

Burnup is the amount of exposure of a nuclear fuel assembly (in a power-production mode) to a high neutron flux in a reactor and is usually expressed in units of gigawatt days per metric ton of uranium (GWd/mtU) initially loaded into the assembly. Taking credit for the reduced reactivity potential of a fuel assembly associated with burnup is referred to as burnup credit. The amount of reduced reactivity potential of a fuel assembly will vary with the fuel burnup, "cooling time" since it was removed from the reactor, and the initial enrichment of fissile material in the fuel.

Local conditions in the reactor core during burnup that affect the neutron spectrum will also affect the isotopic composition of the fuel at the time of discharge from the reactor. These conditions must be quantified if burnup credit is to be appropriately applied. Such conditions include variations in reactor power density (and associated moderator density and fuel temperature variations) and the addition of neutron-absorbing materials (e.g., soluble boron, control rods, control blades, and burnable poison rods). Investigations of some of these conditions are discussed in Reference 6. The disposal criticality analysis methodology examines local variations in these conditions in reactor cores for commercial SNF.

The reactivity effects resulting from isotopic decay during the time period since the fuel was discharged from the reactor will also be modeled. In modeling isotopic decay, the effects of uncertainties in the half-life and branching fractions used in predicting postclosure isotopic concentrations will be evaluated by a statistical method (using Monte Carlo). This approach is used to model the entire system of isotopic decay with all of the parent-daughter relationships. The effects of the uncertainties are quantified in this analysis in terms of the resulting isotopic distribution and its effect on reactivity.

When the methodology is applied to the WP/EBS design, conservative values will be used for modeling reactor conditions for burnup calculations. Likewise the modeling of isotopic decay for the postclosure time period will also produce conservative isotopic concentration values. Proposed requirements for modeling burnup of commercial SNF for waste package design that will ensure adequate conservatism in the isotopic model for burnup credit will be discussed later.

The criticality analysis methodology uses a subset of the isotopes present in commercial SNF. The process for choosing this subset considers the nuclear, physical, and chemical properties of the commercial SNF isotopes. The nuclear properties are cross sections and half-lives of the isotopes; the physical properties are concentration (amount present in the SNF) and state (solid, liquid, or gas); and the chemical properties are the volatility and solubility of the isotopes.

Isotopic decay and build-up, as well as relative importance of isotopes for criticality (combination of cross sections and concentrations) are also considered in this selection process. None of the isotopes with significant positive reactivity effects (fissionable isotopes) are removed from consideration, only non-fissile absorbers. Thus, the selection process is conservative.

This process results in selecting 14 actinides and 15 fission products (referred to as "Principal Isotopes") as the SNF isotopes to be used for burnup credit. Table I lists these isotopes.

Table I. Principal Isotopes for Commercial SNF Burnup Credit

⁹⁵ Mo	¹⁴⁵ Nd	¹⁵¹ Eu	²³⁶ U	²⁴¹ Pu
⁹⁹ Tc	¹⁴⁷ Sm	¹⁵³ Eu	²³⁸ U	²⁴² Pu
¹⁰¹ Ru	¹⁴⁹ Sm	¹⁵⁵ Gd	²³⁷ Np	²⁴¹ Am
¹⁰³ Rh	¹⁵⁰ Sm	²³³ U	²³⁸ Pu	^{242m} Am
¹⁰⁹ Ag	¹⁵¹ Sm	²³⁴ U	²³⁹ Pu	²⁴³ Am
¹⁴³ Nd	¹⁵² Sm	²³⁵ U	²⁴⁰ Pu	

Criticality Model

The criticality model is used to calculate the k_{eff} of a wide range of fissionable-material configurations in the repository. A critical limit criterion is used for judging the predicted k_{eff} values. The CL is the value of k_{eff} at which the configuration is considered potentially critical, with allowances made for the bias and uncertainty in the calculation model, as well as other potential margin. CL values are established during the criticality model validation process.

The neutronic model for predicting the potential for criticality uses the MCNP 4B computer code to calculate k_{eff} of systems with fissionable material. Nuclear cross-section data are obtained by MCNP from several source evaluations (data libraries). The neutron cross-sections in the libraries are provided at energies ranging from very low energies through 20 MeV in sufficient detail that the original evaluation can be accurately reproduced by linear-linear interpolation. MCNP also allows explicit geometrical modeling of material configurations.

Neutronic Model Validation

Three types of experimental data are used in validating the neutronic models. These are laboratory critical experiments (LCEs), commercial reactor criticals (CRCs), and radiochemical assays. The CRCs are used in this paper to illustrate the method for estimating CL values.

LCEs are used to benchmark the criticality model (as part of the validation) for a range of fissionable materials, enrichments of fissile isotopes, moderator materials, and absorber materials. A total of 338 LCEs were analyzed for the topical report (3). These experiments were divided into four sets: 1) Homogeneous Thermal systems, 2) Homogeneous Fast systems, 3) Thermal Arrays, and 4) Thermal Lattices (arrays of fuel rods). The results of the LCE experiments are summarized in Table II.

For the LCE experiments in Table II, intermediate-enriched uranium is defined as having U-233 or U-235 concentrations greater than 10 but less than 80 weight percent (wt.%). Low- and high-enriched uranium are outside this range. The measured k_{eff} value was unity for all of these experiments; hence they were true critical experiments.

The CRCs provide excellent criticality benchmarks for SNF in a reactor. They do not provide benchmarks for the concentration of individual isotopes, but the integral contribution to criticality of the isotopic concentrations is provided by these experiments. Thus, CRC evaluations address both isotopic model validation and criticality model validation with a single class of experiments but do not provide complete validation of both models. Evaluations of both LCEs and radiochemical assays will be required to supplement the CRC evaluations and complete the neutronic model validation for repository applications.

This paper includes data for 45 CRC statepoints (measured critical conditions at zero-power) that were analyzed. The analyses were for two Babcock & Wilcox- and two Westinghouse-designed pressurized water reactors (PWRs). The CRC database is used to benchmark both the isotopic and the criticality models for intact initial configurations of commercial SNF. This database is believed to accurately represent the composition and geometry of much of the commercial SNF to be loaded into the waste packages. The CRC database covers annual, 18-month, and 2-year fuel cycles; initial U-235 enrichments ranging from 1.93 to 4.17 wt.%; soluble boron concentrations ranging from less than 400 ppmB to over 2300 ppmB; radial zone loaded fuel; and a variety of burnable-poison designs. The CRC database also covers statepoints for beginning-of-life with all fresh fuel, beginning-of-cycle with a mixture of fresh and burned fuel, and middle-of-cycle to end-of-cycle with all burned fuel. The k_{eff} values for the 45 CRC statepoint calculations are summarized in Table II, where the average, maximum, minimum, and standard deviation of the k_{eff} values are presented. Data from the 45 statepoint calculations are also used to illustrate the method for estimating CL values.

For the CRC evaluations, the material composition of the SNF for each criticality statepoint is obtained from SAS2H. For the data presented in this paper, the change in material composition with burnup is modeled with 16 to 18 axial zones for each fuel assembly based on fuel-assembly design and core-operations data. Local thermal-hydraulic feedback effects during core operations are modeled based on core follow calculations. The number of axial zones for the SAS2H model is chosen to agree with the core follow calculations. Thus, detailed core history data are provided as input to SAS2H.

Radiochemical assay data will be used in conjunction with CRC data to validate the isotopic model. The CRC data address the integral contribution of isotopic concentrations to criticality. Radiochemical assay data provide measured concentrations for individual isotopes. The assay samples are typically from individual fuel pellets from discharged fuel assemblies. As discussed below, the measured isotopic data will be used in an evaluation process to ensure appropriate conservatism are incorporated in the isotopic model for design applications.

Table II. Summary Results of LCE and CRC k_{eff} Calculations

		k-effective			
Type of System	Number	Average	Max.	Min.	Standard Deviation
Homogeneous Thermal Systems	209				
Mixed Pu and Natural U	34	1.00431	1.01511	0.99318	0.00527
Plutonium	73	1.01172	1.02390	1.00169	0.00525
High Enriched U-235	81	1.00504	1.02880	0.98345	0.00817
Low Enriched U-235	15	1.00078	1.00425	0.99469	0.00267
High Enriched U-233	6	0.99977	1.00153	0.99826	0.00124
Homogeneous Fast Systems	10				
High Enriched U-233	10	0.99818	1.00705	0.99297	0.00447
Thermal Arrays	51				
High Enriched U-235	22	1.00744	1.01399	0.99730	0.00395
Intermediate Enriched U-235	29	0.99923	1.00780	0.99300	0.00374
Thermal Lattices	68				
Low Enriched Mixed Oxide	13	1.00277	1.00835	0.98750	0.00593
Low Enriched Uranium Oxide	55	0.99896	1.00827	0.98895	0.00432
Commercial Reactor Criticals	45	0.99220	1.00141	0.98541	0.00323

For design applications, two aspects of the isotopic model for commercial SNF must be addressed. First, values for the initial isotopic concentrations must be conservative with respect to their contribution towards criticality. Second, changes to the initial isotopic concentration values as a function of time for postclosure must also be conservative with respect to their contribution towards criticality. Proposed requirements that address these two aspects are presented below.

The first two requirements will ensure that the initial isotopic concentrations (i.e., at time of discharge from the reactor) are conservative with respect to criticality. The third requirement will ensure that changes to the initial isotopic concentration values as a function of time will also be conservative with respect to criticality. These requirements are stated (3) as follows:

- A. "Reactor operating histories and conditions must be selected together with axial burnup profiles such that the isotopic concentrations used to represent commercial SNF assemblies in waste package design shall produce values for k_{eff} that are conservative in comparison to any other expected combination of reactor history, conditions, or profiles."
- B. "These bounding reactor parameters will be used to predict isotopic concentrations that, when compared to best estimate isotopic predictions of the measured radiochemical assay

data or the measured radiochemical data itself, must produce values for k_{eff} that are conservative.”

- C. “The values for the isotopic concentrations representing commercial SNF must produce conservative values for k_{eff} for all postclosure time periods for which criticality analyses are performed.”

The first requirement addresses axial burnup effects. The quantities and distributions of the isotopics are governed by the local neutron spectrum. The local neutron spectrum is dependent upon the operating history of the reactor. The CRC statepoint analyses summarized in this paper used isotopic concentrations from burnup calculations that were based on core-operations data. Local neutron spectra effects are modeled for the burnup calculations by including local power density, moderator density, and fuel temperatures, as well as soluble boron concentrations for the burnup period of interest. However, for waste package design, the detailed modeling of reactor operating histories and conditions is not practical. Bounding values will be chosen for the parameters that represent reactor operating histories and conditions. These bounding parameter values, along with bounding burnup profiles for individual fuel assemblies from the CRC statepoint analyses will be used to verify that the isotopic model for waste package design is conservative with respect to criticality. As part of the isotopic model validation process, the sufficiency of the fuel assembly database used in satisfying the first requirement will be demonstrated.

The second requirement addresses the problem with using integral experiments (CRCs) exclusively for validating the isotopic model, and imposes the use of radiochemical assay data from commercial SNF as an additional requirement. Radiochemical assay data are generally measured for a small sample from a fuel rod. Two criticality calculations will be performed that are identical except for the isotopic concentration input. The first will use measured assay data as input. The second will use the isotopic model to generate isotopic concentrations for input. Both calculations will be performed for the same condition (enrichment, burnup, and decay time). The criticality calculations will assume an infinite array of the small sample of fuel rod where the assay data were obtained. Both calculations will consider those isotopes that were measured, plus moderator and cladding material. Following this procedure, the isotopic model must be shown to be conservative with respect to k_{eff} based on analysis of the entire range of radiochemical assay data.

The third requirement addresses changes to the initial isotopic concentration values, as a function of time, for postclosure. As previously described, uncertainties in the half-life and branching fractions used in determining postclosure isotopic concentrations are propagated with a statistical method (using Monte Carlo). Using this approach, uncertainties in k_{eff} resulting from uncertainties in the half-life and branching fractions are established as a function of enrichment, burnup, and decay time. Satisfying the third requirement will necessitate repeatedly applying the method for treating uncertainties in isotopic decay to a range of sets of initial isotopic concentrations to determine the largest values for uncertainty in k_{eff} .

These requirements are provided to ensure that the assumptions used in modeling fuel depletion (and decay during the disposal time period) are conservative with respect to criticality. Therefore, the proposed requirements define the isotopic model validation process.

Determination of Critical Limits

An essential element of validating a method for calculating criticality multiplication factors, k_{eff} , is estimating biases and associated uncertainties and incorporating these into critical limits (CL). A CL is a value of k_{eff} at which a configuration is considered potentially critical, with allowances made for statistical tolerance limits and other potential margin. A CL is associated with a specific type of waste form as represented by a particular set of benchmark criticality experiments.

A regression or “trending” method uses linear regression techniques with an associated lower-uniform tolerance-band to establish an estimate of a CL. This trend is established using appropriate benchmark criticality experiments for the waste material of interest. Trending in this context is simple linear regression of k_{eff} on the predictor variable that exhibits the strongest correlation coefficient with k_{eff} , with a statistically significant slope. Here the predictor variable may be a parameter such as burnup, or a parameter that indicates the distribution of neutrons within the system, such as the average energy of a neutron that causes either fission or absorption.

A critical limit is estimated such that a calculated k_{eff} below this limit is subcritical, and a system is considered acceptably subcritical if a calculated k_{eff} plus calculational uncertainties lies at, or below, this limit. In equation notation,

$$k_S + \Delta k_S \leq \text{CL} \quad \text{Eq. 1}$$

where,

k_S = the calculated multiplication factor of a system to be considered subcritical,

Δk_S = the uncertainty in the value of k_S .

CL is defined as,

$$\text{CL} = k_C(x) - \Delta k_C(x) - \Delta k_m \quad \text{Eq. 2}$$

where,

x = a neutronic parameter used for trending.

$k_C(x)$ = the value obtained from a regression of the calculated k_{eff} of benchmark critical experiments or the mean value of the data set if there is no trend.

$\Delta k_C(x) =$ the uncertainty of k_C based on the statistical scatter of the k_{eff} values of the benchmark critical experiments, accounting for the confidence limit, the proportion of the population covered, and the size of the data set.

$\Delta k_m =$ additional quantified margin that would reduce the CL.

Based on a given set of critical experiments, CL is estimated as a function of a trending parameter for the experiments. Because both $\Delta k_C(x)$ and $k_C(x)$ can vary with this parameter, the CL is typically expressed as a function of this parameter within an appropriate range of applicability derived from the parameter bounds.

The preferred method for estimating a CL uses a tolerance band approach referred to as a single-sided, uniform-width, closed interval approach in Reference 7, and referred to here as a Lower Uniform Tolerance Band approach. This approach applies statistical techniques to estimate a lower tolerance band. Further, this approach deals with estimates of criticality for a population of waste material, which is the approach used here for a repository. This is the preferred method for estimating a CL provided significant trends could be identified.

Part of the range of applicability (ROA) of a benchmark data set is based on the range of parameter variation in the benchmark experiments that are used for estimating the CL. The other part is based on the range of fundamental parameters of the benchmark experiments. Reference 7 defines three classes of fundamental characteristics from which a fundamental parameter may be defined. The three characteristics are (1) materials of construction (including fissionable materials), (2) the geometry of construction, and (3) the inherent neutron energy spectrum affecting the fissionable material(s).

Once fundamental parameters and a set of critical experiments have been established, calculated values of k_{eff} are trended against a number of these parameters to determine the parameter that provides the best fit to the data from the benchmark critical experiments. This parameter may be used for extending the range of applicability to the waste form, which may be necessary for almost all waste forms and their waste packages.

The repository will contain various types of waste forms, the majority of which will be commercial SNF. The various types of commercial SNF (i.e., PWR and BWR fuel) will have separate and different waste packages. Each of the waste packages and its waste form will be analyzed separately for criticality potential. As such, each combination will be characterized with a set of benchmark critical experiments that span the characteristics of the waste package and the waste form. The waste form and waste packages, in turn, must be evaluated for criticality potential while in an intact or degraded condition. Each of these conditions will require a different set of benchmark critical experiments since the neutronic parameters will also change. For example, the geometric structure of degraded commercial SNF will be different from the intact condition; therefore, this difference must be accommodated in the benchmark data set. The set of laboratory critical experiments classified as thermal lattices will be a part of the data set used to characterize degraded commercial SNF.

For commercial PWR SNF in the intact form, CRC data are being used as benchmark data to estimate critical limits for a limited range. Evaluation of additional CRC benchmark data will be performed.

For commercial PWR SNF, using 45 of the CRC statepoints, the set of k_{eff} values was fit against core average burnup. Evaluation of several statistics showed that burnup has the strongest correlation with the k_{eff} values of the CRC benchmark data set. Therefore, the trended parameter (burnup) and its range define the ROA for commercial SNF in the intact form.

Figure 2 compares the calculated data (k_{eff}) for a set of 45 CRC statepoints, the regression of k_{eff} , and the critical limit for the commercial SNF. Note that the slope of the regression is negative; therefore, as burnup increases, the regression model estimates of k_{eff} decrease. The CL for the commercial SNF was calculated at a confidence level of 95% with 99.5% of the population of the benchmark data set covered (95% / 99.5%).

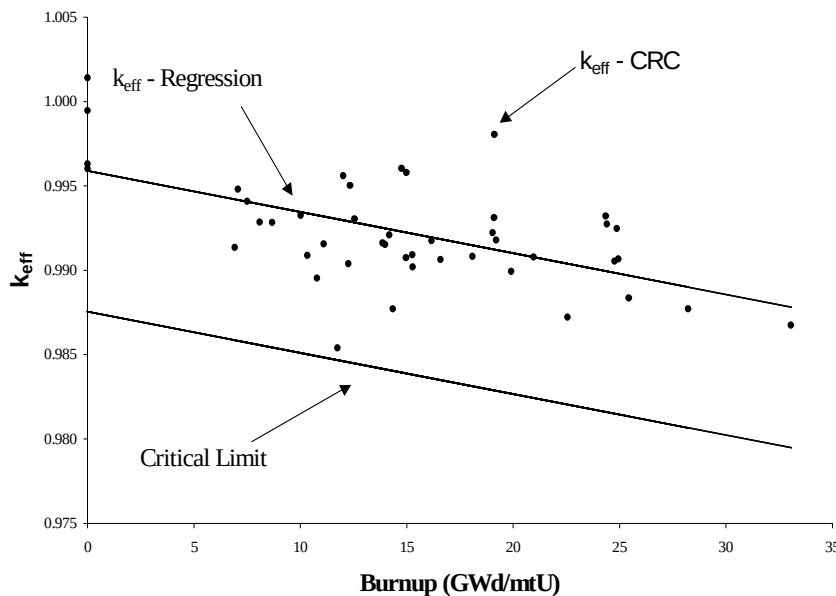


Figure 2. Comparison of k_{eff} , the Regression of k_{eff} , and the Critical Limit for Commercial SNF

The range of applicability of core average burnup is from 0.0 to 33.1 GWd/mtU for commercial SNF in a reactor environment as is shown in Figure 2. The critical limit for this range is approximately from 0.988 to 0.979. This would establish burnup as the trending parameter for extending the range of applicability to include average burnup values outside the stated range. This extension could be made by adding more experimental data or by increasing the margin (Δk_m), which would lower the CL for waste packages outside the stated range.

For commercial PWR SNF in the degraded condition, the lattice geometry will change (i.e., the distance between fuel rods will change as the skeletal structure of the assemblies corrode). In this case, the repository conditions and the benchmark conditions will not be identical. Therefore, an additional neutronic parameter will be chosen for the degraded condition.

Other parameters will change for a waste package in a repository versus the benchmark parameters. The importance of these parameters relative to their effect on criticality will have to be analyzed to establish their importance as a fundamental parameter with a defined range of applicability.

SUMMARY AND CONCLUSIONS

A methodology is presented for performing postclosure criticality analyses for the proposed repository at Yucca Mountain, NV. The primary differences in this methodology and conventional criticality analysis methodology arise from the nature and timing of events that may lead to a criticality. The events in the repository that may lead to a criticality are related to long-term processes. These events take place over hundreds, thousands, and tens of thousands of years. The methodology presented is a blend of deterministic and probabilistic methods. The consequence of a potential criticality along with the probability of occurrence is used in establishing the risk to the health and safety of the public from the potential release of radioactive material. Decisions concerning design features to minimize criticality potential are based on risk, in conjunction with other information. It is concluded that this risk-informed methodology is an appropriate methodology to use for postclosure criticality analyses in the repository.

An overview was provided of the methodology for examining various degradation scenarios for waste packages and establishing configurations of fissionable and other materials to be examined for criticality potential. The composition and geometry of the configurations vary as a function of specific configuration parameters. Subsequent criticality evaluations focus on the range of values of these configuration parameters. The criterion for judging the potential for criticality is provided by the critical limit (CL), which is the value of k_{eff} at which the configuration is considered potentially critical.

Two types of neutronic models were introduced in this paper. The first model is for calculating isotopic concentrations of commercial SNF that are applicable for burnup credit. The isotopes that are applicable for burnup credit were presented as Principal Isotopes. Three requirements imposed on the isotopic model for waste package design were introduced. It is concluded that the imposed requirements for modeling burnup of commercial SNF for design applications are sufficient, if met, to ensure adequate conservatism in the isotopic model for burnup credit.

The second model is for calculating k_{eff} of potential configurations of fissionable and other materials in the repository. This model is used for establishing the criticality potential of these configurations, which is measured against a critical limit criterion. The critical limit criterion is established during model validation. Model validation was illustrated, using data from 45 commercial reactor critical experiments. Critical limit values that are applicable to commercial reactor fuel for the intact condition were derived from these experiments. The trending parameter, burnup, and the range over which it was evaluated (0.0 to 33.1 GWd/mtU) define the range of applicability of these critical limit values for commercial SNF in the intact condition.

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