# 6.0 CRITICALITY EVALUATION

## I. Review Objective

The criticality review ensures that spent fuel remains subcritical under normal, off-normal, and accident conditions involving handling, packaging, transfer, and storage.

## II. Areas of Review

This portion of the dry cask storage system (DCSS) review evaluates the criticality design and analysis related to spent fuel handling, packaging, transfer, and storage procedures for normal, off-normal, and accident conditions. Consequently, this chapter of the DCSS Standard Review Plan (SRP) provides guidance for use in conducting a comprehensive criticality evaluation that *may* encompass any or all of the following areas of review:

1. criticality design criteria and features
2. fuel specification
3. model specification
   a. configuration
   b. material properties
4. criticality analysis
   a. computer programs
   b. multiplication factor
   c. benchmark comparisons
5. supplemental information

## III. Regulatory Requirements

Spent fuel storage systems must be designed to remain subcritical unless at least two unlikely independent events occur. Moreover, the spent fuel cask must be designed to remain subcritical under all credible conditions. Regulations specific to nuclear criticality safety of the cask system are specified in 10 CFR 72.124 and 72.236(c). Other pertinent regulations include 10 CFR 72.24(c)(3), 72.24(d), and 72.236(g). Normal and accident conditions to be considered are also identified in 10 CFR Part 72.

## IV. Acceptance Criteria

In general, the DCSS criticality evaluation seeks to ensure that the given design fulfills the following acceptance criteria:

1. The multiplication factor ($k_{eff}$), including all biases and uncertainties at a 95-percent confidence level, should not exceed 0.95 under all credible normal, off-normal, and accident conditions.

2. At least two unlikely, independent, and concurrent or sequential changes to the conditions essential to criticality safety, under normal, off-normal, and accident conditions, should occur before an accidental criticality is deemed to be possible.

3. When practicable, criticality safety of the design should be established on the basis of favorable geometry, permanent fixed neutron-absorbing materials (poisons), or both. Where solid neutron-absorbing materials are used, the design should provide for a positive means to verify their continued efficacy during the storage period.

4. Criticality safety of the cask system should not rely on use of the following credits:

   a. burnup of the fuel
   b. fuel-related burnable neutron absorbers

c. more than 75 percent for fixed neutron absorbers[a] when subject to standard acceptance tests.

## V. Review Procedures

Review the criticality design features and criteria in SAR Chapters 1 and 2. Also review SAR Chapter 6 for any additional details concerning criticality design features and criteria. Assess the bounding specifications for the spent fuel. Examine the models used by the applicant in the criticality analyses. Verify that the applicant has addressed criticality safety considerations under normal, off-normal, and accident conditions. Verify that the cask system design complies with 10 CFR Part 72. In addition, verify that the criticality calculations determine the highest $k_{eff}$ that might occur under all loading states under normal, off-normal, and accident conditions involving handling, packaging, transfer, or storage. To the extent practicable, use independent methods to perform any $k_{eff}$ calculations to evaluate the applicant's design.

### 1. Criticality Design Criteria and Features

Review the principal criticality design criteria presented in SAR Chapter 2, as well as any related detail provided in SAR Chapter 6. Also review the general cask description presented in SAR Chapter 1 and any related information provided in Chapter 6. Verify that the information in Chapter 6 is consistent with the information in Chapters 1 and 2. Also, verify that all drawings, figures, and tables are sufficiently detailed to support in-depth staff evaluation.

In addition to the general dimensions of the cask components and spacing of fuel assemblies in the basket, the criticality design often relies on neutron poisons. These may be in the form of fixed poisons in the basket structure and/or soluble poisons in the water of the spent fuel pool. The NRC staff accepts the use of borated water as a means of criticality control if the applicant specifies a minimum boron content, and strict controls are established to ensure that the minimum required boron concentration is maintained, which in turn becomes an operating control and limit in SAR Chapter 12. These operating controls should also be discussed in the SER. If borated water is used for criticality control, administrative controls and/or design features should be implemented to ensure that accidental flooding with unborated water cannot occur, or the criticality evaluation should consider accidental flooding with unborated water. If the cask is also intended for transport, borated water cannot be relied upon for criticality control.

### 2. Fuel Specification

Review the specifications for the ranges or types of spent fuel that will be stored in the cask as presented in SAR Sections 1 and 2, as well as any related information provided in SAR Sections 6. Verify that the spent fuel specifications given in Section 6 are consistent with, or bounded by, the specifications given in Section 1 and 2.

Of primary interest is the type of fuel assemblies and maximum fuel enrichment, which should be specified and used in the criticality calculations. Some boiling water reactors (BWR) use multiple fuel pin enrichments, in which case, the criticality calculations should use the maximum fuel pin enrichment present. Depending upon the fuel design, an applicant may propose use of assembly averaged, or lattice averaged enrichments. This may be acceptable if the applicant can demonstrate that any averaging techniques are technically defensible and, for the criticality calculation, produce conservative results. Because of the natural uranium blankets present in many BWR designs, use of an assembly-averaged enrichment is not normally considered appropriate or conservative for BWR fuel.

Although the burnup of the fuel affects its reactivity, the NRC staff does not currently allow credit for burnup, either in depleting the quantity of fissile nuclides or in producing fission product poisons for spent fuel storage or transport casks. Specifications for the fuel that will be stored in the cask should be included in Section 12 of both the SAR and SER and should also be explicitly listed in the Certificate of Compliance.

The fresh fuel assumption should be used in the criticality analyses; therefore, inadvertent loading of the cask with unirradiated fuel is not a major concern. Nonetheless, detailed loading procedures may need to

[a] For greater credit allowance, special, comprehensive fabrication tests capable of verifying the presence and uniformity of the neutron absorber are needed.

include steps to prevent misloading if fuel exceeding the design basis for the DCSS is present in the pool at the time of loading.

Because casks are typically designed to store many types and configurations of fuel assemblies, the applicant should demonstrate that criticality requirements are satisfied for the most reactive case. A determination of which fuel is bounding in a criticality analysis depends on many factors and usually requires examination of several types of fuel assemblies and compositions. The design-basis fuel has often been the Westinghouse 17x17 optimized fuel assembly (OFA); however, this will not be the case for all cask designs because of cask-specific effects on reactivity. Therefore, the applicant should demonstrate and reviewers should verify, that the fuel assembly used as the design basis is the most reactive for the specific cask design. Chapter 12 of both the SAR and SER should either clearly indicate the design-basis assemblies or reference the SAR chapter in which they are identified.

Determine if the applicant has included any specifications regarding the fuel condition. To date, casks have not typically been intended to store fuel that is significantly damaged or has a gross cladding defect. Consequently, the criticality analyses have generally specified that any damaged fuel rods should be replaced with dummy rods that can displace an equal amount of water as the original rods. If invoked by the applicant, these requirements, should be included as operating controls and limits and discussed in SAR Chapter 12.

## 3. Model Specification

When manufacturing and fabrication tolerances are specified, verify that the applicant assumed the most conservative value within the range of acceptable values.

### a. Configuration

Verify that the model used in the criticality evaluation is adequately described for normal, off-normal, and accident conditions. Coordinate with the structural reviewer to understand any damage that could result from accident or natural phenomena events.

Examine the sketches or figures of the model used for criticality calculations. Verify that the dimensions and materials of the model are consistent with those in the drawings of the actual cask. Differences between the actual cask configuration and the models should be identified, and the models should be shown to be conservative. Substitution of ordinary water for end sections and support structures of the fuel is a common and conservative practice in criticality analysis; however, substitution of borated water is non-conservative. Tolerances for poison material dimensions and/or concentrations should be defined, and the most reactive conditions should be used in the criticality analysis. In addition, the analysis should identify all important design conditions and then address these conditions for normal, off-normal, and accident conditions.

Verify that the applicant has considered deviations from nominal design configurations. The evaluation of $k_{eff}$ should not be limited to a model in which all of the fuel bundles are neatly centered in each basket compartment with the center line of the basket coincident with the center line of the cask. For example, a cask with steel confinement and lead shielding may have a higher $k_{eff}$ when the basket and fuel assemblies are positioned as close as possible to the lead.

In addition to a fully flooded cask, the SAR should address configurations in which the cask is partially filled with water (borated, if applicable) and the remainder of the cask is filled with steam consisting of ordinary water at partial density. These configurations are considered to be representative of loading and unloading operations in the spent fuel pool. The SAR should also consider the possibility of preferential or uneven flooding within the cask, if such a scenario is credible for the given cask design (e.g., because of blockage in small flow or drain paths). In particular, watch for situations where there is water in the fuel regions but not in the flux traps, if applicable. Cask designs for which this type of flooding is credible are generally unacceptable. The SAR should also consider flooding in the fuel rod pellet-to-clad gap regions. Above all, the analysis must demonstrate that the cask remains subcritical for all credible conditions of moderation.

Examine whether the applicant has prepared a heterogeneous model of each fuel rod or has homogenized the entire fuel assembly. With current computational capabilities, homogenization is now an uncommon practice and should generally be avoided. If such homogenization is used, however, the applicant should clearly demonstrate that it has been treated conservatively. As a minimum, the applicant should calculate the $k_{eff}$ of one assembly and several critical benchmark experiments (see Section V(4)(c) of this chapter)

using both homogeneous and heterogeneous models. The applicant should then compare the results of these calculations.

### b. Material Properties

Verify that the compositions and densities are provided for all materials used in the calculational model. The applicant should also cite the source of all materials data, particularly the data for fuel and poison materials. Ensure that the applicant addressed the validation of the poison concentration in the acceptance testing discussion in SAR Chapter 9. Many criticality codes will allow the densities to be input directly in units of $g/cm^3$. If input is in units of atoms/barn-cm, pay particular attention to the conversion.

Among other specifications, 10 CFR Part 72 requires that when solid neutron-absorbing materials are used, a positive means to verify their continued efficacy should be provided. Continued efficacy can be demonstrated in the following ways:

- Require acceptance testing of the poisons during fabrication (specified in SAR Chapter 9),
- Show that the neutron flux from the irradiated fuel results in a negligible depletion of poison material over the storage period, and
- Assess the structural integrity and potential for poison material degradation during storage.

If continued efficacy can be demonstrated by design and material properties, a surveillance or monitoring program to "verify" continued efficacy of solid neutron absorbers may not be necessary. The neutron flux used for this analysis should be the maximum that may be produced by feasible loadings of irradiated or unirradiated fuel.

Determine whether the applicant has chosen an acceptable set of cross-sections. Cross-sections may be distributed with the criticality computer codes or developed independently from another source. The applicant should provide or reference the source of cross-section data, as well as the method used to obtain the actual data employed in the criticality analysis. For multigroup calculations, the neutron flux spectrum used to construct the group cross-sections should be similar to that of the cask.

## 4. Criticality Analysis

### a. Computer Programs

Both Monte Carlo and deterministic computer codes may be used for criticality calculations. Monte Carlo codes are generally better suited to three-dimensional geometry and, therefore, are more widely used to evaluate spent fuel cask designs. The two most frequently used Monte Carlo codes are SCALE/KENO[1] and MCNP[2]. KENO is a multigroup code that is part of the SCALE sequence, while MCNP permits the use of continuous cross-sections.

If a multigroup treatment is used, ensure that the applicant has appropriately considered the neutron spectrum of the cask. In addition to selecting a cross-section set collapsed with an appropriate flux spectrum, a more detailed processing of the energy-group cross-sections is also required to properly account for resonance absorption and self-shielding. The use of KENO as part of the SCALE sequence will directly enable such processing. Some cross-section sets include data for fissile and fertile nuclides (based on a potential scattering cross-section, $s_p$) that can be input by the user. If the applicant has used a stand-alone version of KENO, ensure that potential scattering has been properly considered. Furthermore, the "working-format" library, once (commonly) distributed with SCALE/KENO to facilitate calculations of the code-manual's sample problems, is not intended for criticality calculations of actual systems. In 1991, the staff provided information concerning cross-section problems to all ISFSI licensees, applicants, and dry storage vendors[3].

For analyses of a cask model with separate regions of water and steam, the use of a multigroup cross-section set raises additional concerns. Verify that the applicant has addressed the differences of the flux spectra in the two regions. If the results of these calculations indicate that $k_{eff}$ is close to 0.95, additional independent calculations using a different code and/or cross-section library may be helpful. Reviewers should also closely examine the applicant's benchmark analysis, in order to verify the applicability of critical experiments considered.

### b. Multiplication Factor

Examine the results and discussion of the $k_{eff}$ calculations for the storage cask. Determine if variations in the results caused by different models and sensitivity analyses can be explained and appear reasonable.

For Monte Carlo calculations, assess if the number of neutron histories and convergence criteria are appropriate. As the number of neutron histories increases, the mean value for $k_{eff}$ should approach some fixed value, and the standard deviation associated with each mean value should decrease. Depending on the code used by the applicant, a number of diagnostic calculations are generally available to demonstrate adequate convergence and statistical variation. For deterministic codes, a convergence limit is often prescribed in the input. The selection of a proper convergence limit and the achievement of this limit should be described and demonstrated.

Because of the importance and complexity of the criticality evaluation, independent calculations should be performed to ensure that the most reactive conditions have been addressed and that the reported $k_{eff}$ is conservative. In deciding the level of effort necessary to perform independent confirmatory calculations, the reviewer should consider the following three factors: (1) the calculational method (computer code) used by the applicant; (2) the degree of conservatism in the applicant's assumptions and analyses; and (3) how large a margin exists between the calculated result and the acceptance criterion of $K_{eff} \leq 0.95$. As with any design and review, a small margin below the acceptance criterion and/or a small degree of conservatism necessitate a more extensive analysis.

As the reviewer, develop a model that is independent of the applicant's. If the reported $k_{eff}$ for the worst case is substantially lower than the acceptance criterion of 0.95, a simple model known to produce very conservative results may be all that is necessary for the independent calculations.

If possible and appropriate, perform the independent calculations with a computer code different from that used by the applicant. Likewise, use of a different cross-section set can provide a more independent confirmation.

Although a $k_{eff}$ of 0.95 or lower meets the acceptance criterion, reviewers should watch for design features or content specifications where small changes could result in large changes in the value of $k_{eff}$. When the value of $k_{eff}$ is highly sensitive to system parameters that could vary, the acceptable $k_{eff}$ limit should be reduced below 0.95. When establishing a $k_{eff}$ limit below 0.95, reviewers should consider the degree of sensitivity to system parameter changes, and the likelihood and extent of potential parameter variations.

### c. Benchmark Comparisons

Computer codes for criticality calculations should be benchmarked against critical experiments. A thorough comparison provides justification for the validity of the computer code, its use for a specific hardware configuration, the neutron cross-sections used in the analysis, and consistency in modeling by the analyst. (Using the benchmark results for calculations performed by another analyst does not address this last issue.) The calculated $k_{eff}$ of the cask should then be adjusted to include the appropriate biases and uncertainties from the benchmark calculations.

Examine the general description of the benchmark comparisons. Verify that the analysis of the experiments used the same computer code, hardware, and cross-section data as those used to calculate the $k_{eff}$ values for the cask.

Reviewers should also closely examine the applicant's benchmark analysis to determine whether the benchmark experiments are relevant to the actual cask design. No critical benchmark experiment will precisely match the fissile material, moderation, neutron poisoning, and configuration in the actual cask. However, the applicant can perform a proper benchmark analysis by selecting experiments that adequately represent cask and fuel features and parameters that are important to reactivity. Key features and parameters that should be considered in selecting appropriate critical experiments include the type of fuel, enrichment, hydrogen to urainum (H/U) ratio (dependent largely on rod diameter and pitch), reflector material, neutron energy spectrum, and poisoning material and placement. The applicant should justify, and reviewers should verify, the suitability of the critical experiments chosen to benchmark the criticality code and calculations. UCID-21830[4] provides information on benchmark experiments that may apply to the cask being analyzed.

Reviewers need to assess whether the applicant analyzed a sufficient number of appropriate benchmark experiments, and how the results of these benchmark calculations have been converted to a bias for the cask calculations. Simply averaging the biases from a number of benchmark calculations is typically not sufficient, particularly if one benchmark yields results that are significantly different from the others. In addition, benchmark comparisons should be checked for bias trends with respect to parameter variations (such as pitch-to-rod-diameter ratio, assembly separation, reflector material, neutron absorber material, etc.). Ref. 4 provides some guidance, but other methods have also been considered appropriate.

For Monte Carlo codes, the statistical uncertainties of both benchmark and cask calculations also need to be addressed. The uncertainties should be applied to at least the 95-percent confidence level. As a general rule, if the acceptability of the result depends on these rather small differences, reviewers should question the overall degree of conservatism of the calculations. Considering the current availability of computer resources, a sufficient number of neutron histories can readily be used so that the treatment of these uncertainties should not significantly affect the results.

Verify that only biases that increase $k_{eff}$ have been applied. For example, if the benchmark calculation for a critical experiment results in a neutron multiplication that is greater than unity, it should not be used in a manner that would reduce the $k_{eff}$ calculated for the cask. Only corrections that increase $k_{eff}$ should be applied to preserve conservatism.

Reviewers may have already performed a number of benchmark calculations applicable to storage casks and may have a reasonable estimation of the bias to be applied to the independent calculation of the cask. If such is not the case, or if the acceptability depends on small bias differences, reviewers again need to determine whether sufficient conservatism has been applied to the calculations.

### 5. Supplemental Information

Ensure that all supportive information or documentation is provided. This would include, but not be limited to, justification of assumptions or analytical procedures, test results, photographs, computer program descriptions, input/output, and applicable pages from referenced documents. In addition, the SER should include a list of fuel designs with the acceptable parametric limits, and the maximum enrichments for which the criticality analysis is satisfactory. Reviewers should request any additional information needed to complete the review.

## VI. Evaluation Findings

Review the 10 CFR Part 72 acceptance criteria and provide a summary statement for each. These statements should be similar to the following model:

> Structures, systems, and components important to criticality safety are described in sufficient detail in Chapters _____ of the SAR to enable an evaluation of their effectiveness.
>
> The _____ cask and its spent fuel transfer systems are designed to be subcritical under all credible conditions.
>
> The criticality design is based on favorable geometry, fixed neutron poisons, and soluble poisons of the spent fuel pool [as applicable]. An appraisal of the fixed neutron poisons has shown that they will remain effective for the 20-year storage period, and there is no credible way to lose it, therefore there is no need to provide a positive means to verify their continued efficacy as required by 10 CFR 72.124(b).
>
> The analysis and evaluation of the criticality design and performance have demonstrated that the cask will enable the storage of spent fuel for a minimum of 20 years with an adequate margin of safety.
>
> The staff concludes that the criticality design features for the [cask designation] are in compliance with 10 CFR Part 72, as exempted [if applicable], and that the applicable design and acceptance criteria have been satisfied. The evaluation of the criticality design provides reasonable assurance that the [cask designation] will allow safe storage of spent fuel. This finding is reached on the basis of a review that considered the regulation itself, appropriate regulatory guides, applicable codes and standards, and accepted engineering practices.

## VII. References

1. U.S. Nuclear Regulatory Commission, "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," NUREG/CR-0200, Vol. 1–4, Rev. 4, April 1995.

2. Los Alamos National Laboratory, "MCNP 4A, Monte Carlo N-Particle Transport Code System," December 1993.

3. U.S. Nuclear Regulatory Commission, "Potential Nonconservative Errors in the Working Format Hansen-Roach Cross-Section Set Provided with the KENO and SCALE Codes," Information Notice No. 91-26, April 15, 1991.

4. W.R. Lloyd, Lawrence Livermore National Laboratory, "Determination and Application of Bias Values in the Criticality Evaluation of Storage Cask Designs," UCID-21830, January 1990. (This report contains a substantial bibliography of numerous benchmark experiments and validation testing.)