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Comanche Peak High Density Spent Fuel Rack Criticality Analysis Using Soluble Boron Credit And No Outer Wrapper Plates

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1.0 Introduction

This report presents the results of a criticality analysis of the TXU Electric Comanche Peak spent fuel storage racks with credit for spent fuel pool soluble boron and with no outer wrapper plates of the Boraflex poison panels. The methodology employed here is contained in the topical report, "Westinghouse Spent Fuel Rack Criticality Analysis Methodology"(1).

The spent fuel storage rack design considered herein is an existing array of fuel racks, previously qualified in References 2 and 3 (without Boraflex) for storage of various 17x17 fuel assembly types with maximum enrichments up to 5.0 w/o ^{235}U. Multiple storage configurations are currently allowed. These configurations allow fuel assemblies with maximum enrichments up to 5.0 w/o ^{235}U (with burnup credits) to be stored.

The base enrichment limits reported in Reference 2 for the all cell and the 3-out-of-4 storage configurations were determined assuming the existence of the outer wrapper plates of the Boraflex poison panels. The base enrichment limits reported in Reference 3 for the 2-out-of-4 and the 1-out-of-4 storage configurations were determined assuming no outer wrapper plates of the Boraflex poison panels. The Comanche Peak spent fuel racks for the all cell and the 3-out-of-4 storage configurations previously analyzed in Reference 2 are being reanalyzed in this report to remove the outer wrapper plates of the Boraflex poison panels.

The Comanche Peak spent fuel rack analysis is based on maintaining $K_{eff} < 1.0$ including uncertainties and tolerances on a 95/95 (95 percent probability at 95 percent confidence level) basis without the presence of any soluble boron in the storage pool (No Soluble Boron 95/95 K_{eff} conditions). Soluble boron credit is used to provide safety margin by maintaining 95/95 $K_{eff} \leq 0.95$ including uncertainties, tolerances, and accident conditions in the presence of spent fuel pool soluble boron.

The following storage configurations and enrichment limits are considered in this analysis:

<u>High Density Spent Fuel Rack Enrichment Limits</u>

All Cell Storage	Storage of Westinghouse and Siemens 17x17 fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 1.04 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 800 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1700 ppm.
3-out-of-4 Checkerboard Storage	Storage of Westinghouse and Siemens 17x17 fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 1.51 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 700 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1900 ppm.

1.1 Design Description

The Comanche Peak High Density storage cell is shown in Figure 1 on page 22 with nominal dimensions provided on the figure.

The fuel parameters relevant to this analysis are given in Table 1 on page 14. With the simplifying assumptions employed in this analysis (no grids, sleeves, axial blankets, etc.), the various types of Westinghouse 17x17 STD and OFA (V5, V+, and P+) fuel are beneficial in terms of extending burnup capability and improving fuel reliability, but do not contribute to any meaningful increase in the basic assembly reactivity. This includes small changes in guide tube and instrumentation tube dimensions. Therefore, future fuel assembly upgrades do not require a criticality analysis if the fuel parameters specified in Table 1 remain bounding.

The fuel rod and guide tube claddings are modeled with zircaloy in this analysis. This is conservative with respect to the Westinghouse ZIRLO™ product which is a zirconium alloy containing additional elements including niobium. Niobium has a small absorption cross section which causes more neutron capture in the cladding regions, resulting in a lower reactivity. Therefore, this analysis is conservative with respect to fuel assemblies containing ZIRLO™ cladding in fuel rods, guide tubes, and instrumentation tubes.

1.2 Design Criteria

Criticality of fuel assemblies in a fuel storage rack is prevented by the design of the rack which limits fuel assembly interaction. This is done by fixing the minimum separation between fuel assemblies and inserting neutron poison between them. However, in this analysis the Boraflex poison panels including the outer wrapper plates have been removed from the racks.

In this report, the reactivity of the spent fuel racks is analyzed such that K_{eff} remains less than 1.0 under No Soluble Boron 95/95 K_{eff} conditions as defined in Reference 1. To provide safety margin in the criticality analysis of the spent fuel racks, credit is taken for the soluble boron present in the Comanche Peak spent fuel pool. This parameter provides significant negative reactivity in the criticality analysis of the spent fuel racks and will be used here to offset the reactivity increase after the spent fuel rack Boraflex poison panels were removed. Soluble boron credit provides sufficient relaxation in the enrichment limits of the spent fuel racks.

The design basis for preventing criticality outside the reactor is that, including uncertainties, there is a 95 percent probability at a 95 percent confidence level that the effective neutron multiplication factor, K_{eff}, of the fuel rack array will be less than or equal to 0.95.

2.0 Analytical Methods

The criticality calculation method and cross-section values are verified by comparison with critical experiment data for fuel assemblies similar to those for which the racks are designed. This benchmarking data is sufficiently diverse to establish that the method bias and uncertainty will apply to rack conditions which include strong neutron absorbers, large water gaps, low moderator densities, and spent fuel pool soluble boron.

The design method which insures the criticality safety of fuel assemblies in the fuel storage rack is described in detail in the Westinghouse Spent Fuel Rack Criticality Analysis Methodology topical report(1). This report describes the computer codes, benchmarking, and methodology which are used to calculate the criticality safety limits presented in this report for Comanche Peak.

As determined in the benchmarking in the topical report, the method bias using the described methodology of NITAWL-II, XSDRNPM-S, and KENO-Va is 0.0077 ΔK. There is a 95 percent probability at a 95 percent confidence level that the uncertainty in reactivity due to the method is no greater than 0.0030 ΔK. These values will be used in the final evaluation of the 95/95 basis K_{eff} in this report.

3.0 Criticality Analysis of High Density Storage Racks

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the storage of fuel in the High Density spent fuel storage racks with credit for soluble boron.

Section 3.1 describes the allowed storage configurations for fuel assemblies in the High Density spent fuel storage racks. Section 3.2 describes the No Soluble Boron 95/95 K_{eff} KENO-Va calculations. Section 3.3 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Section 3.4 presents the results of calculations performed to show the minimum burnup requirements for assemblies with initial enrichments above those determined in Section 3.2.

3.1 Configuration Descriptions

Two different configurations are analyzed for the High Density spent fuel storage racks. The first configuration contains fresh fuel assemblies of the same enrichment of 1.04 w/o in all of the cells. The second configuration uses a 3-out-of-4 assembly checkerboard with 1 empty cell and 3 fresh assemblies of 1.51 w/o in the other cells. The two configurations are shown in Figure 2 on page 23.

3.2 No Soluble Boron 95/95 K_{eff} Calculations

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity. The equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} KENO-Va model for storage of fuel assemblies in the Comanche Peak High Density spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 STD design, which is the most reactive fuel type under spent fuel rack conditions (see Table 1 on page 14 for fuel parameters).
2. Fuel assemblies contain uranium dioxide at the nominal enrichments over the entire length of each rod.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.

4. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in equivalent or conservative calculations of reactivity for all fuel assemblies, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A value of 1.0 gm/cm^3 is used for the density of water.
9. The array is infinite in the lateral (x and y) extent. The fuel assembly array is finite in the axial (vertical) extent with 12 inch water regions on the top and bottom of the fuel.
10. All allowable storage cells are loaded with fuel assemblies.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 K_{eff} limit. The following biases are included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology is considered.

Water Temperature: A reactivity bias is applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 150°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, perturbation calculations are performed using PHOENIX-P. For the Comanche Peak spent fuel rack High Density storage configurations, UO_2 material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy are also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components are considered in the total uncertainty statistical summation:

^{235}U Enrichment: The enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichments is considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 14) is considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal value (the nominal reference values are listed in Table 1 on page 14) is considered.

Storage Cell I.D.: The ±0.025 inch tolerance about the nominal 8.83 inch reference cell I.D. is considered.

Storage Cell Pitch: A ±0.06 inch tolerance about a nominal 9.0 inch reference cell pitch is considered.

Stainless Steel Thickness: The ±0.004 inch tolerance about the nominal 0.075 inch reference stainless steel thickness for all rack structures is considered.

Assembly Position: The KENO-Va reference reactivity calculation assumes fuel assemblies are symmetrically positioned within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of fuel assemblies are positioned together. This reactivity increase is considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} is considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology is considered.

3.2.1 All Cell No Soluble Boron 95/95 K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the all cell configuration under nominal conditions with no soluble boron in the moderator resulted in a K_{eff} of 0.96756, as shown in Table 2 on page 15.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 2 and results in a 95/95 K_{eff} of 0.99574.

Since K_{eff} is less than 1.0 including uncertainties at a 95/95 probability/confidence level, the High Density spent fuel racks will remain subcritical when all cells are loaded with Westinghouse and Siemens 17x17 fuel assemblies having a nominal enrichment no greater than 1.04 w/o ^{235}U and no soluble boron is present in the spent fuel pool water.

3.2.2 3-out-of-4 Checkerboard No Soluble Boron 95/95 K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the 3-out-of-4 checkerboard configuration under nominal conditions with no soluble boron in the moderator resulted in a K_{eff} of 0.97785, as shown in Table 4 on page 17.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 4 and results in a 95/95 K_{eff} of 0.99811.

Since K_{eff} is less than 1.0 including uncertainties at a 95/95 probability/confidence level, the High Density spent fuel racks will remain subcritical for the 3-out-of-4 checkerboard configuration storage of Westinghouse and Siemens 17x17 fuel assemblies in a 2x2 checkerboard arrangement with 1 empty cell and the remaining 3 cells containing fuel assemblies having a nominal enrichment no greater than 1.51 w/o ^{235}U and no soluble boron is present in the spent fuel pool water.

3.3 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for storage in the High Density spent fuel racks are similar to those in Section 3.2 except for assumption 8 regarding the moderator soluble boron concentration. The moderator boron concentration is increased by the amount required to maintain $K_{eff} \leq 0.95$.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases are included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology is considered.

Water Temperature: A reactivity bias is applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 150°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations are performed. For the Comanche Peak spent fuel rack High Density storage configurations, UO_2 material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy are also considered in the statistical summation of uncertainty components.

The same tolerance and uncertainty components as in the No Soluble Boron case are considered in the total uncertainty statistical summation.

3.3.1 All Cell Soluble Boron Credit K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the all cell configuration under nominal conditions with 200 ppm soluble boron in the moderator resulted in a K_{eff} of 0.90641, as shown in Table 3 on page 16.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 3 and results in a 95/95 K_{eff} of 0.93531.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for all cell storage of Westinghouse and Siemens 17x17 fuel assemblies in the High Density spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 1.04 w/o ^{235}U is acceptable in all cell storage including the presence of 200 ppm soluble boron.

3.3.2 3-out-of-4 Checkerboard Soluble Boron Credit K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the 3-out-of-4 checkerboard configuration under nominal conditions with 200 ppm soluble boron in the moderator resulted in a K_{eff} of 0.91997, as shown in Table 5 on page 18.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 5 and results in a 95/95 K_{eff} of 0.94061.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the 3-out-of-4 checkerboard configuration storage of Westinghouse and Siemens 17x17 fuel assemblies in the High Density spent fuel racks. Storage of fuel assemblies in a 2x2 checkerboard arrangement with 1 empty cell and the remaining 3 cells containing fuel assemblies having a nominal enrichment no greater than 1.51 w/o ^{235}U is acceptable including the presence of 200 ppm soluble boron.

3.4 Burnup and Decay Time Credit Reactivity Equivalencing

Storage of fuel assemblies with enrichments higher than those described in Section 3.2 in the Comanche Peak High Density spent fuel racks is achievable by using the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion and the radioactive decay of the spent fuel actinide isotopes within the fuel assemblies. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment and fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 3 on page 24 and Figure 4 on page 25 show the constant K_{eff} contours generated for the all cell configuration and the 3-out-of-4 configuration, respectively, for fuel storage in the High Density spent fuel racks. These curves represent combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with zero burnup fuel assemblies with maximum allowed enrichments described in Section 3.2 for the two configurations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 ΔK at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculation and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement is 600 ppm for the all cell configuration and 500 ppm for the 3-out-of-4 checkerboard configuration. This is additional boron above the soluble boron required in Section 3.3. This results in a total soluble boron credit of 800 ppm for the all cell configuration and 700 ppm for the 3-out-of-4 checkerboard configuration.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the High Density burnup credit limits. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Reference 1 results in calculations of conservative burnup credit limits.

Decay Time Credit is an extension of the Burnup Credit process which includes the time since an assembly was last discharged as a variable which gains additional margin in reactivity and reduces the minimum burnup requirements. Decay time credit is used here for both the all cell and 3-out-of-4 configurations. Spent fuel decay time credit results from the radioactive decay of isotopes in the spent fuel to daughter isotopes, which results in reduced reactivity. One of the major contributors is the decay of ^{241}Pu to ^{241}Am. In this report, credit is taken only for the decay of actinide isotopes. Decay of the fission products has the effect of further reducing the reactivity of the spent fuel.

For decay time credit, a series of reactivity calculations are performed to generate an ordered set of enrichment, fuel assembly discharge burnup, and decay time parameters which all yield the desired equivalent K_{eff} when stored in the spent fuel storage racks.

In the decay time methodology reported here, the fission product isotopes are frozen at the concentrations existing at the time of discharge of the fuel (except ^{135}Xe which is removed). These calculations are performed at different discharge burnups. The actinide isotopes are allowed to decay based on their natural process. The loss in reactivity due to the radioactive decay of the spent fuel results in reducing the minimum burnup needed to meet the reactivity requirements. Thus for different decay times, a family of curves is generated. In the decay time methodology the following assumptions are used in the PHOENIX-P models:

1. Fuel assemblies are modeled using the same criteria as Section 3.2
2. Fuel is depleted using a conservatively high soluble boron letdown curve and uprated core power to enhance the buildup of plutonium, making the fuel more reactive in the spent fuel storage racks. Sensitivity studies have shown that spectrum effects are also conservative for the decay time calculation.
3. No credit for fission product isotopic decay is used.
4. Actinide only isotopes decay is used.
5. Nominal spent fuel rack configuration/dimensions are used.

With the above assumptions, the calculation of the decay time burnup credit curves are found to be conservative for use in the spent fuel pool criticality analysis.

It is important to recognize that the curves in Figure 3 and Figure 4 are based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered. For convenience, the data from Figure 3 and Figure 4 are also provided in Table 6 on page 19 and Table 7 on page 20, respectively. Use of linear interpolation between the tabulated values is acceptable since the change in reactivity is approximately linear as a function of enrichment between the tabulated points.

4.0 Discussion of Postulated Accidents

Most accident conditions will not result in an increase in K_{eff} of the rack. Examples are:

Fuel assembly drop on top of rack	The rack structure pertinent for criticality is not excessively deformed and the dropped assembly which comes to rest horizontally on top of the rack has sufficient water separating it from the active fuel height of stored assemblies to preclude neutronic interaction.
Fuel assembly drop between rack modules	Design of the spent fuel racks and fuel handling equipment is such that it precludes the insertion of a fuel assembly in other than prescribed locations.
Fuel assembly drop between rack modules and spent fuel pool wall	For High Density storage areas, this accident is bounded by the fuel assembly misload accident discussed below since placing a fuel assembly inside the racks next to other fuel assemblies will result in a higher K_{eff}.

However, two accidents can be postulated for each storage configuration which can increase reactivity beyond the analyzed condition. The first postulated accident would be a change in the spent fuel pool water temperature and the second would be a misload of an assembly into a cell for which the restrictions on location, enrichment, or burnup are not satisfied.

Calculations were performed for the Comanche Peak storage configurations to determine the reactivity change caused by a change in the Comanche Peak spent fuel pool water temperature outside the normal range (50°F to 150°F). For the change in spent fuel pool water temperature accident, a temperature range of 32°F to 212°F is considered. In all cases, additional reactivity margin is available to the 0.95 K_{eff} limit to allow for temperature accidents. The temperature change accident can occur at any time during operation of the spent fuel pool.

For the assembly misload accident, calculations were performed to show the largest reactivity increase caused by a Westinghouse or Siemens 17x17 fuel assembly misplaced into a storage cell for which the restrictions on location, enrichment, or burnup are not satisfied. The assembly misload accident can only occur during fuel handling operations in the spent fuel pool.

For an occurrence of the above postulated accident condition, the double contingency principle of ANSI/ANS 8.1-1983 can be applied. This states that one is not required to assume two unlikely, independent, concurrent events to ensure protection against a criticality accident. Thus, for these postulated accident conditions, the presence of additional soluble boron in the storage pool water (above the concentration required for normal conditions and reactivity equivalencing) can be assumed as a realistic initial condition since not assuming its presence would be a second unlikely event.

The additional amount of soluble boron for accident conditions needed beyond the required boron for uncertainties and burnup is shown in Table 8 on page 21.

5.0 Soluble Boron Credit Summary

Spent fuel pool soluble boron has been used in this criticality analysis to offset storage rack and fuel assembly tolerances, calculational uncertainties, uncertainty associated with burnup credit and the reactivity increase caused by postulated accident conditions. The total soluble boron concentration required to be maintained in the spent fuel pool is a summation of each of these components. Table 8 on page 21 summarizes the storage configurations and corresponding soluble boron credit requirements.

Based on the above discussion, should a spent fuel water temperature change accident or a fuel assembly misload accident occur in the High Density spent fuel racks, K_{eff} will be maintained less than or equal to 0.95 due to the presence of at least 800 ppm (no fuel handling) or 1900 ppm (during fuel handling) of soluble boron in the Comanche Peak spent fuel pool water.

6.0 Storage Configuration Interface Requirements

The Comanche Peak High Density spent fuel pool area has been analyzed for all cell storage, where all cells share the same storage requirements and limits, and checkerboard storage, where neighboring cells have different requirements and limits.

The boundary between different checkerboard zones and the boundary between a checkerboard zone and an all cell storage zone must be controlled to prevent an undesirable increase in reactivity. This is accomplished by examining all possible 2x2 matrices containing rack cells and ensuring that each of these 2x2 matrices conforms to checkerboard restrictions for the given region.

For example, consider a fuel assembly location E in the following matrix of storage cells.

A	B	C
D	E	F
G	H	I

Four 2x2 matrices of storage cells which include storage cell E are created in the above figure. They include (A,B,D,E), (B,C,E,F), (E,F,H,I), and (D,E,G,H). The fuel assemblies in each of these 2x2 matrices of storage cells are required to meet the checkerboard requirements determined for the given region.

Using the requirement that all 2x2 matrices within the storage racks must conform to both all cell and 2x2 checkerboard requirements, the following interface requirements are applicable to High Density storage cells:

All Cell Storage Next to 3-out-of-4 Storage or 2-out-of-4 Storage	The boundary between all cell storage and 3-out-of-4 storage or 2-out-of-4 storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of carryover in the checkerboard storage zone uses 1.51 w/o fuel assemblies alternating with empty cells. Figure 5 on page 26 illustrates the carryover configuration.
3-out-of-4 Storage Next to 2-out-of-4 Storage	The boundary between 3-out-of-4 storage and 2-out-of-4 storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of carryover in the 2-out-of-4 storage zone uses 2.90(3) w/o fuel assemblies alternating with empty cells. Figure 6 on page 27 illustrates the carryover configuration.
1-out-of-4 Storage Next to All Cell Storage and 3-out-of-4 Storage	The boundary between 1-out-of-4 storage and all cell storage or 3-out-of-4 storage must be separated by a vacant row of cells. Figure 7 on page 28 illustrates the carryover configuration.
2-out-of-4 Storage Next to 1-out-of-4 Storage	The boundary between 2-out-of-4 storage and 1-out-of-4 storage must be separated by a vacant row of cells. Figure 8 on page 29 illustrates the carryover configuration.

7.0 Summary of Criticality Results

For the storage of Westinghouse and Siemens 17x17 fuel assemblies in the Comanche Peak spent fuel storage racks, the acceptance criteria for criticality requires the effective neutron multiplication factor, K_{eff}, to be less than 1.0 under No Soluble Boron 95/95 conditions, and less than or equal to 0.95 including uncertainties, tolerances and accident conditions with the presence of spent fuel pool soluble boron. This report shows that the acceptance criteria for criticality is met for the Comanche Peak spent fuel racks for the storage of Westinghouse and Siemens 17x17 fuel assemblies under both normal and accident conditions with soluble boron credit and the following storage configurations and enrichment limits:

<u>High Density Spent Fuel Rack Enrichment Limits</u>

All Cell Storage	Storage of Westinghouse and Siemens 17x17 fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 1.04 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 800 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1700 ppm.
3-out-of-4 Checkerboard Storage	Storage of Westinghouse and Siemens 17x17 fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 1.51 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 700 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1900 ppm

The analytical methods employed herein conform with ANSI N18.2-1973, "Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants," Section 5.7 Fuel Handling System, except for the use of pure water; ANSI 57.2-1983, "Design Requirements for Light Water Reactor Spent Fuel Storage Facilities at Nuclear Power Plants," Section 6.4.2; ANSI/ANS 8.1-1983, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors," Section 4.3; and the NRC Standard Review Plan, Section 9.1.2, "Spent Fuel Storage". The spent fuel rack criticality analysis takes credit for the soluble boron in the spent fuel pool water as discussed in Reference 1.

Table 1. Fuel Parameters Employed in the Criticality Analysis

Parameter	Westinghouse 17x17 OFA	Westinghouse 17x17 STD	Siemens 17x17 OFA	Siemens 17x17 STD
Number of Fuel Rods per Assembly	264	264	264	264
Fuel Rod Zirc-4 Clad O.D. (inch)	0.360	0.374	0.360	0.376
Clad Thickness (inch)	0.0225	0.0225	0.0250	0.0240
Fuel Pellet O.D.(inch)	0.3088	0.3225	0.3035	0.3215
Fuel Pellet Density (% of Theoretical)	95.5	95.5	95.5	95.5
Fuel Pellet Dishing Factor (%)	1.211	1.2074	1.3579	1.2737
Rod Pitch (inch)	0.496	0.496	0.496	0.496
Number of Zirc Guide Tubes	24	24	24	24
Guide Tube O.D. (inch)	0.474	0.482	0.480	0.480
Guide Tube Thickness (inch)	0.016	0.016	0.016	0.016
Number of Instrument Tubes	1	1	1	1
Instrument Tube O.D. (inch)	0.474	0.482	0.480	0.480
Instrument Tube Thickness (inch)	0.016	0.016	0.016	0.016

Table 2. Comanche Peak High Density All Cell Storage No Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.96756**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 150°F)	0.00033
TOTAL Bias	0.00803
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01868
UO_2 Density Tolerance	0.00313
Fuel Pellet Dishing Variation	0.00185
Cell Inner Diameter	0.00017
Cell Pitch	0.00443
Cell Wall Thickness	0.00213
Asymmetric Assembly Position	0.00320
Calculational Uncertainty (95/95)	0.00073
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.02015

$$\sqrt{\sum_{i=1}^{9}((\text{tolerance}_i \text{ ... or ... } \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances:	**0.99574**

Table 3. Comanche Peak High Density All Cell Storage 200 ppm Soluble Boron 95/95K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.90641**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 150°F)	0.00084
TOTAL Bias	0.00854
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01874
UO_2 Density Tolerance	0.00379
Fuel Pellet Dishing Variation	0.00223
Cell Inner Diameter	0.00013
Cell Pitch	0.00550
Cell Wall Thickness	0.00172
Asymmetric Assembly Position	0.00110
Calculational Uncertainty (95/95)	0.00069
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.02036

$$\sqrt{\sum_{i=1}^{9}((\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances:	**0.93531**

Table 4. Comanche Peak High Density 3-out-of-4 Checkerboard Storage No Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.97785**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50˚F - 150˚F)	0.00002
TOTAL Bias	0.00772
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01070
UO_2 Density Tolerance	0.00290
Fuel Pellet Dishing Variation	0.00172
Cell Inner Diameter	0.00017
Cell Pitch	0.00288
Cell Wall Thickness	0.00193
Asymmetric Assembly Position	0.00309
Calculational Uncertainty (95/95)	0.00092
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01254

$$\sqrt{\sum_{i=1}^{9}((\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances:	**0.99811**

Table 5. Comanche Peak High Density 3-out-of-4 Checkerboard Storage 200 ppm Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.91997**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 150°F)	0.00006
TOTAL Bias	0.00776
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01091
UO_2 Density Tolerance	0.00352
Fuel Pellet Dishing Variation	0.00208
Cell Inner Diameter	0.00014
Cell Pitch	0.00352
Cell Wall Thickness	0.00151
Asymmetric Assembly Position	0.00238
Calculational Uncertainty (95/95)	0.00092
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01288

$$\sqrt{\sum_{i=1}^{9}((\text{tolerance}_i \text{ ... or ... } \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances:	**0.94061**

Table 6. Summary of Burnup Requirements for Comanche Peak High Density All Cell Configuration

Enrich. (w/o)	Decay Time (years)																
	0	1	2	3	4	5	6	7	8	9	10	12	14	15	16	18	20
1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.20	10180	9765	9410	9104	8837	8603	8395	8208	8042	7893	7758	7524	7327	7240	7158	7014	6896
1.25	11315	10868	10485	10153	9862	9606	9377	9173	8989	8825	8676	8417	8199	8102	8011	7850	7719
1.40	14574	14040	13578	13174	12818	12501	12217	11961	11731	11523	11335	11006	10727	10603	10487	10279	10108
1.60	18540	17913	17366	16883	16453	16068	15721	15407	15123	14866	14631	14219	13869	13712	13565	13303	13087
1.80	22051	21358	20749	20207	19721	19283	18886	18525	18197	17898	17625	17144	16734	16550	16378	16070	15815
2.00	25229	24490	23838	23253	22724	22244	21807	21408	21045	20712	20408	19870	19410	19203	19009	18662	18374
2.20	28214	27440	26754	26136	25574	25062	24594	24165	23772	23412	23081	22495	21991	21765	21552	21171	20853
2.40	31058	30257	29543	28897	28309	27772	27279	26825	26408	26025	25672	25044	24503	24259	24030	23618	23273
2.60	33794	32968	32230	31561	30951	30392	29877	29402	28964	28561	28188	27524	26950	26691	26447	26007	25636
2.80	36452	35601	34840	34150	33519	32939	32404	31909	31453	31031	30640	29942	29338	29064	28806	28340	27947
3.00	39064	38186	37399	36684	36031	35430	34874	34360	33884	33444	33036	32306	31672	31384	31113	30623	30208
3.20	41654	40743	39927	39185	38506	37880	37301	36766	36270	35811	35385	34621	33957	33656	33372	32858	32423
3.40	44216	43270	42422	41651	40944	40293	39691	39132	38615	38136	37692	36895	36202	35887	35591	35054	34599
3.60	46737	45756	44878	44078	43344	42667	42041	41460	40923	40425	39963	39134	38413	38085	37776	37218	36744
3.80	49203	48191	47287	46462	45703	45003	44355	43755	43199	42683	42205	41345	40596	40256	39936	39356	38864
4.00	51601	50567	49643	48799	48020	47301	46635	46017	45445	44914	44421	43534	42761	42409	42078	41478	40968
4.20	53920	52875	51941	51085	50294	49561	48881	48251	47666	47122	46617	45706	44910	44548	44207	43588	43061
4.40	56161	55117	54181	53321	52523	51783	51095	50455	49861	49307	48792	47861	47046	46674	46323	45686	45142
4.60	58330	57296	56365	55507	54709	53967	53275	52630	52029	51468	50944	49996	49163	48782	48423	47769	47209
4.80	60430	59414	58497	57647	56854	56112	55419	54771	54166	53601	53071	52109	51260	50872	50505	49836	49259
4.95	61963	60966	60062	59222	58435	57697	57006	56358	55751	55182	54649	53679	52820	52426	52053	51373	50784
5.00	62466	61476	60577	59740	58956	58220	57530	56883	56276	55706	55172	54199	53337	52941	52567	51882	51290

Table 7. Summary of Burnup Requirements for Comanche Peak High Density 3-out-of-4 Checkerboard Configuration

Enrich. (w/o)	Decay Time (years)																
	0	1	2	3	4	5	6	7	8	9	10	12	14	15	16	18	20
1.51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.60	1268	1250	1235	1221	1207	1195	1184	1174	1165	1157	1149	1135	1122	1116	1111	1101	1093
1.80	5270	5197	5130	5069	5014	4963	4916	4874	4834	4798	4764	4703	4650	4626	4603	4562	4527
2.00	8853	8726	8610	8505	8409	8321	8240	8166	8097	8033	7974	7868	7776	7734	7694	7623	7562
2.20	11953	11775	11610	11461	11327	11204	11091	10985	10888	10798	10714	10565	10435	10376	10320	10219	10133
2.40	14646	14420	14207	14016	13845	13690	13546	13411	13286	13170	13062	12870	12704	12629	12558	12429	12319
2.60	17043	16773	16513	16281	16077	15891	15718	15555	15404	15263	15132	14900	14700	14609	14523	14367	14235
2.80	19256	18944	18642	18373	18136	17921	17720	17532	17355	17191	17039	16769	16536	16431	16331	16150	15996
3.00	21397	21045	20706	20404	20136	19893	19666	19453	19254	19069	18897	18592	18328	18209	18096	17891	17716
3.20	23554	23165	22795	22463	22167	21897	21645	21410	21191	20986	20797	20460	20168	20035	19910	19682	19488
3.40	25731	25308	24911	24553	24230	23935	23661	23405	23166	22945	22739	22371	22052	21907	21770	21521	21309
3.60	27910	27454	27034	26652	26304	25984	25688	25412	25157	24920	24700	24305	23960	23803	23655	23386	23156
3.80	30071	29585	29143	28739	28367	28025	27708	27415	27143	26890	26656	26234	25865	25697	25538	25250	25003
4.00	32197	31682	31219	30794	30400	30036	29700	29388	29100	28833	28585	28137	27744	27565	27396	27089	26826
4.20	34273	33730	33246	32800	32385	32000	31645	31316	31013	30731	30469	29995	29579	29389	29210	28884	28606
4.40	36300	35732	35226	34759	34324	33920	33547	33202	32882	32586	32310	31811	31372	31172	30983	30639	30345
4.60	38286	37694	37165	36677	36224	35803	35413	35052	34717	34406	34116	33592	33131	32921	32722	32361	32051
4.80	40236	39622	39072	38565	38094	37656	37250	36873	36523	36197	35894	35346	34864	34644	34436	34058	33734
4.95	41678	41049	40483	39962	39479	39030	38613	38225	37864	37528	37215	36649	36152	35925	35710	35320	34984
5.00	42156	41522	40951	40426	39938	39486	39065	38673	38309	37969	37653	37081	36579	36350	36133	35739	35400

Table 8. Summary of the Soluble Boron Credit Requirements

Spent Fuel Rack	Storage Configuration	Soluble Boron Required for Tolerances/ Uncertainties (ppm)	Soluble Boron Required for Reactivity Equivalencing (ppm)	Total Soluble Boron Credit Required Without Accidents (ppm)	Soluble Boron Required for Accidents (ppm)	Total Soluble Boron Credit Required With Accidents (ppm)
High Density	All Cell Storage	200	600	800	900	1700
High Density	3-out-of-4 Checkerboard Storage	200	500	700	1200	1900

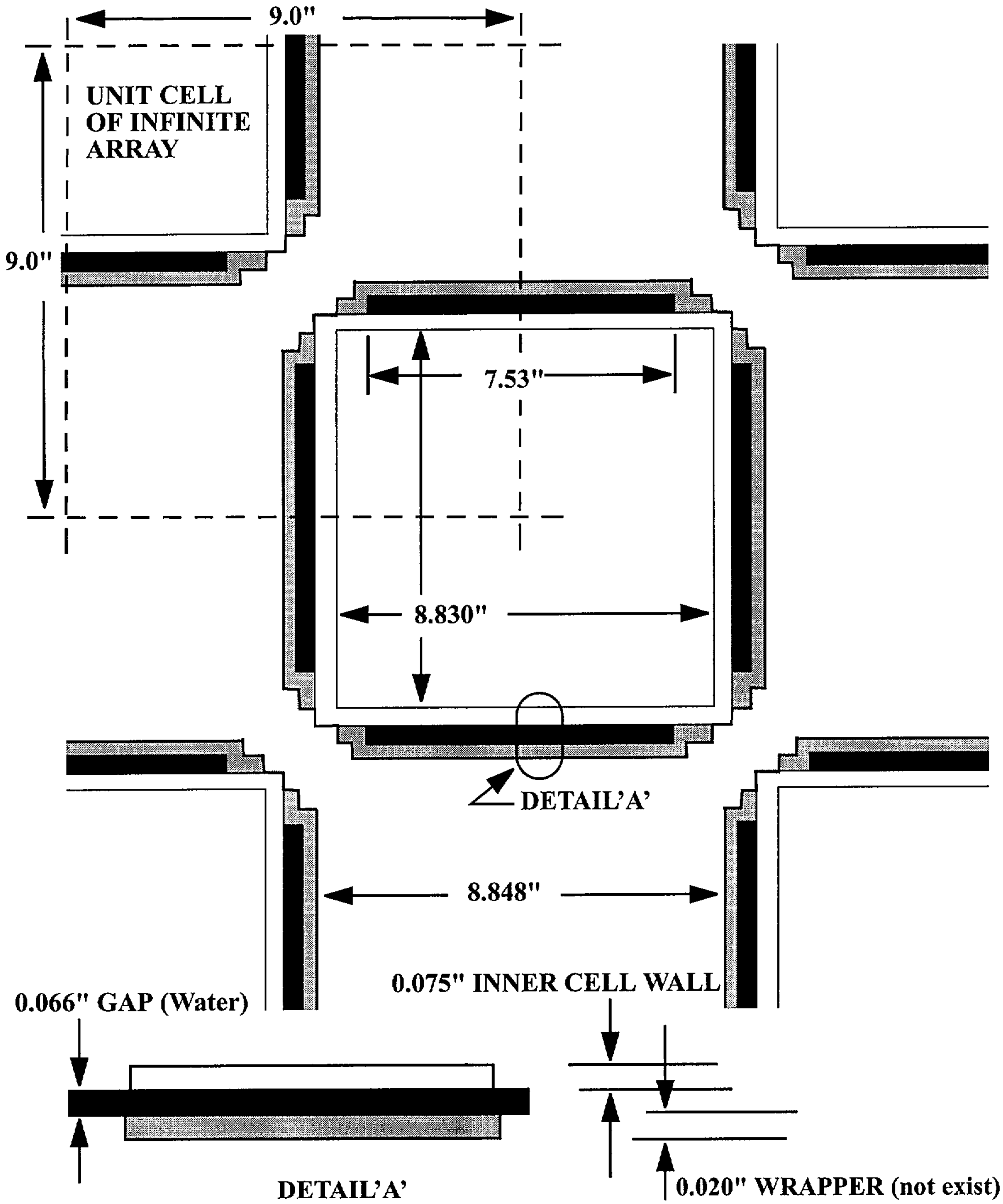


Figure 1. Comanche Peak High Density Spent Fuel Pool Storage Cell Nominal Dimensions

1.04 w/o	1.04 w/o
1.04 w/o	1.04 w/o

High Density All Cell Storage

1.51 w/o	1.51 w/o
Empty Cell	1.51 w/o

High Density 3-out-of-4 Storage

Note: All values are initial nominal enrichments.

Figure 2. Comanche Peak High Density Spent Fuel Storage Configurations

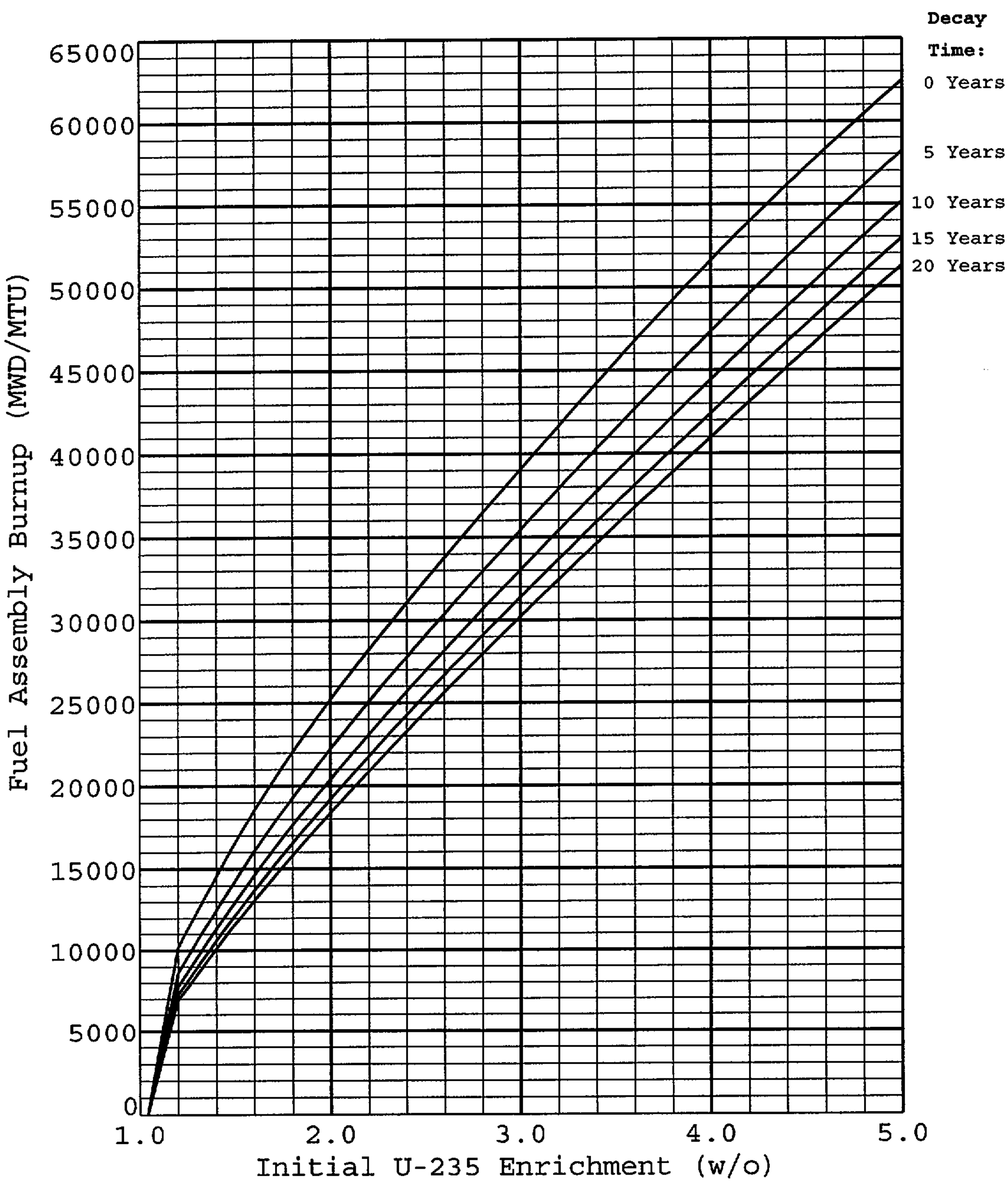


Figure 3. Comanche Peak High Density All Cell Configuration Burnup Credit Requirements

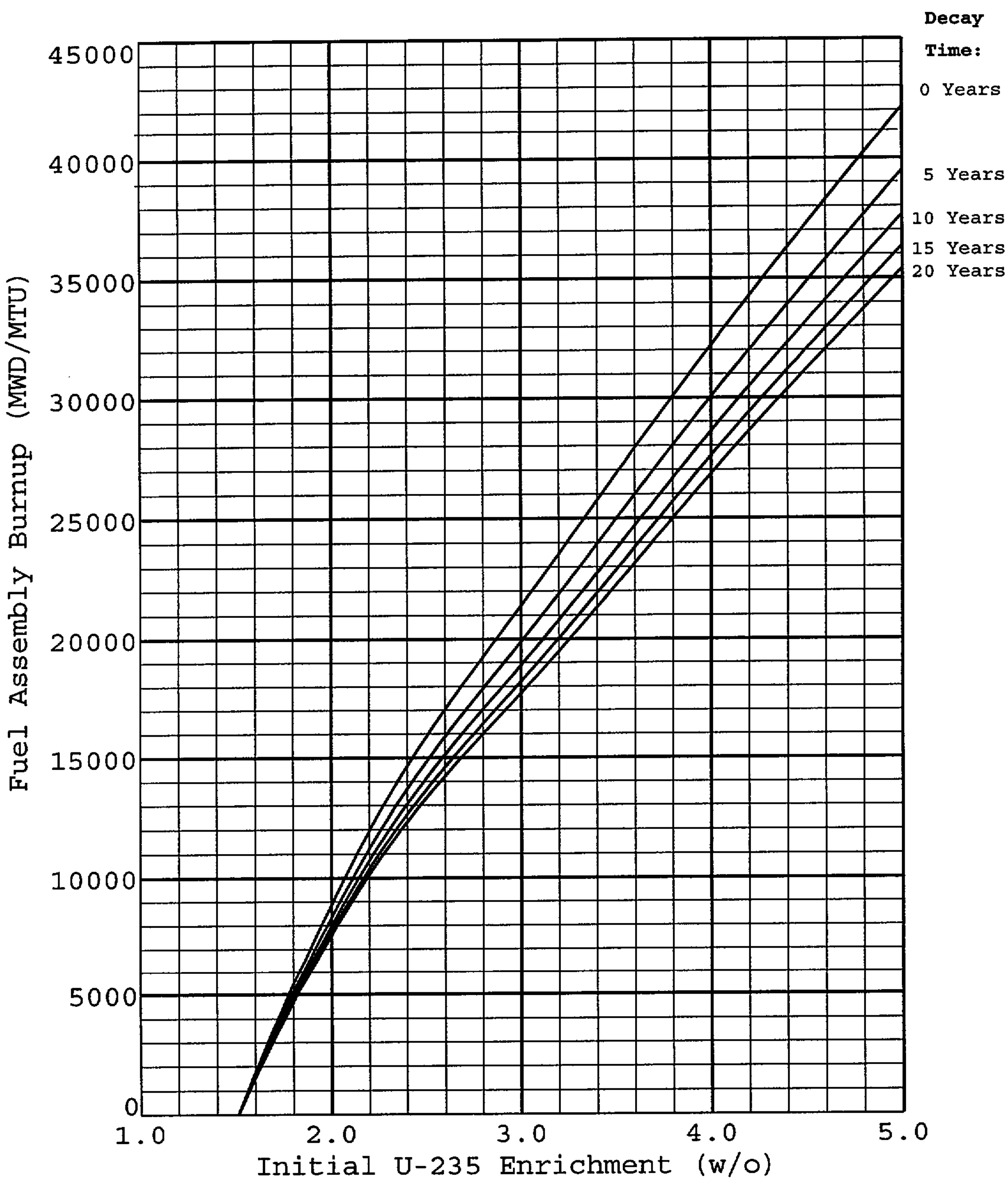


Figure 4. Comanche Peak High Density 3-out-of-4 Checkerboard Configuration Burnup Credit Requirements

Interface

1.04	1.04	1.04	1.04	1.04	1.04
1.04	1.04	1.04	1.04	1.04	1.04
1.04	1.04	1.04	1.04	1.04	1.04
Empty	1.51	Empty	1.04	1.04	1.04
1.51	1.51	1.51	1.04	1.04	1.04
Empty	1.51	Empty	1.04	1.04	1.04

High Density Boundary Between All Cell Storage and 3-out-of-4 Storage

Interface

1.04	1.04	1.04	1.04	1.04	1.04
1.04	1.04	1.04	1.04	1.04	1.04
1.04	1.04	1.04	1.04	1.04	1.04
Empty	1.51	Empty	1.04	1.04	1.04
2.90	Empty	1.51	1.04	1.04	1.04
Empty	2.90	Empty	1.04	1.04	1.04

High Density Boundary Between All Cell Storage and 2-out-of-4 Storage

Figure 5. High Density Interface Requirements
(All Cell Storage to 3-out-4 and 2-out-4 Storages)

Interface

1.51	Empty	1.51	Empty	1.51	Empty
1.51	1.51	1.51	1.51	1.51	1.51
1.51	Empty	1.51	Empty	1.51	Empty
Empty	2.90	Empty	1.51	1.51	1.51
2.90	Empty	2.90	Empty	1.51	Empty
Empty	2.90	Empty	1.51	1.51	1.51

High Density Boundary Between 2-out-of-4 Storage and 3-out-of-4 Storage

Interface

Empty	1.51	Empty	1.51	1.51	1.51
1.51	1.51	1.51	1.51	Empty	1.51
Empty	1.51	Empty	1.51	1.51	1.51
2.90	Empty	2.90	Empty	1.51	Empty
Empty	2.90	Empty	1.51	1.51	1.51
2.90	Empty	2.90	Empty	1.51	Empty

High Density Boundary Between 2-out-of-4 Storage and 3-out-of-4 Storage

Figure 6. High Density Interface Requirements
(2-out-of-4 storage to 3-out-of-4 Storage)

Interface

1.04	1.04	1.04	1.04	1.04	1.04	1.04
1.04	1.04	1.04	1.04	1.04	1.04	1.04
1.04	1.04	1.04	1.04	1.04	1.04	1.04
Empty	Empty	Empty	Empty	1.04	1.04	1.04
5.00	Empty	5.00	Empty	1.04	1.04	1.04
Empty	Empty	Empty	Empty	1.04	1.04	1.04
5.00	Empty	5.00	Empty	1.04	1.04	1.04

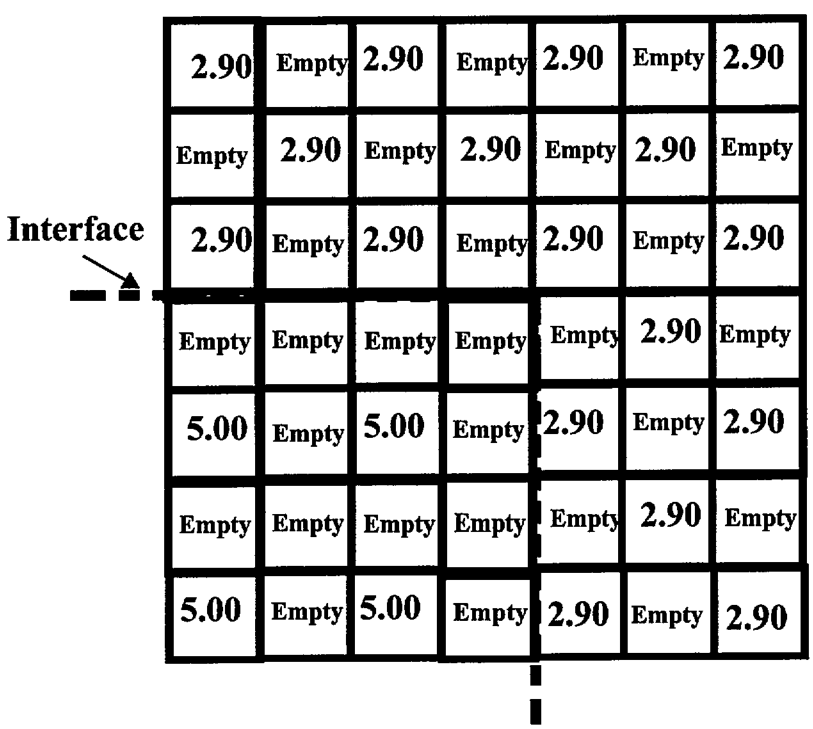
High Density Boundary Between All Cell Storage and 1-out-of-4 Storage

Interface

1.51	Empty	1.51	Empty	1.51	1.51	1.51
1.51	1.51	1.51	1.51	1.51	Empty	1.51
1.51	Empty	1.51	Empty	1.51	1.51	1.51
Empty	Empty	Empty	Empty	Empty	1.51	Empty
5.00	Empty	5.00	Empty	1.51	1.51	1.51
Empty	Empty	Empty	Empty	Empty	1.51	Empty
5.00	Empty	5.00	Empty	1.51	1.51	1.51

High Density Boundary Between 3-out-of-4 Storage and 1-out-of-4 Storage

Figure 7. High Density Interface Requirements (1-out-4 Storage to All Cell and 3-out-4 Storages)



High Density Boundary Between 2-out-of-4 Storage and 1-out-of-4 Storage

Figure 8. High Density Interface Requirements
(2-out-4 Storage to 1-out-of-4 Storage)

Bibliography

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ENCLOSURE 3 to TXX-00144

CPSES Spent Fuel Pool Boron Dilution Analysis