ENCLOSURE 6

GNF2 SPENT FUEL STORAGE RACK CRITICALITY ANALSIS FOR PEACH BOTTOM ATOMIC POWER STATION, UNITS 2 & 3

Non-Proprietary Version

Global Nuclear Fuel

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Non-Proprietary Version

GNF2 Spent Fuel Storage Rack Criticality Analysis for Peach Bottom Atomic Power Station Units 2 & 3

IMPORTANT NOTICE REGARDING

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Revision Status

Revision Number	Section	Description of Change
0, 1		Internal Documents
2		Initial USNRC Submittal

Executive Summary

This report describes the criticality analyses and results for the Peach Bottom Atomic Power Station (PBAPS) spent fuel storage pool for 10x10 GNF2 fuel lattice bundles in the Westinghouse Boraflex (Reference 1) spent fuel storage racks. This analysis was performed with the Monte Carlo neutron transport program MCNP01A (Reference 2). Fuel bundle geometries were assumed with uniform lattice enrichments up to 4.90 wt% ^{235}U using both full and part length fuel rods and including representative placement and numbers of Gadolinia rods with a range of loadings (weights). The spent fuel storage rack-analyzed lattices were evaluated at their respective cold, uncontrolled, peak exposure-dependent reactivity statepoints at both zero and 70 percent void histories. Current design basis was set to specifications concluding a 70% void history. A 4.90 wt % ^{235}U lattice and 2 wt% gadolinium concentrations in 13 specified rods with initial uniformly distributed fissile inventories and burnable absorber, at the peak cold, exposure-dependent eigenvalue statepoint (with associated exposure-dependent isotopics) is the limiting lattice design to satisfy the spent fuel storage rack eigenvalue criteria, in conjunction with the design parameters and calculational assumptions applied. The associated in-core peak eigenvalue (k_∞) of 1.318 is a TGBLA06A production lattice physics computed value, with benchmark uncertainties included, and evaluated in conjunction with the 4.90 wt% ^{235}U lattice average enrichment establishes the spent fuel storage rack design limit for the PBAPS. The analysis conditions and assumptions used are in compliance with the requirements contained in the USNRC Regulatory Guide 1.13, Spent Fuel Storage Facility Design Basis, Rev. 2 (Reference 3), and ANSI/ANS-57.2-1983, Design Requirements for Light Water Reactor Spent Fuel Storage Facilities at Nuclear Power Plants (Reference 4).

The PBAPS spent fuel storage racks were analyzed with GNF2 fuel and shown to have a k_{eff} less than 0.95 for both normal and credible abnormal configurations. The normal configurations included displacement of stored fuel assemblies within the ranges permitted by the rack manufacturing tolerances at a conservative pool water density corresponding to a temperature of 20°C. The abnormal configurations considered the storage of spent fuel without flow channels and with off-center bundle locations. The PBAPS Westinghouse manufactured Boraflex spent fuel storage racks satisfy the reactivity requirements for all storage conditions with GNF2 fuel having an associated in-core peak eigenvalue (k_∞) of no greater than 1.318 inserted. Additionally, a delta (k_{eff}) penalty value for Boraflex degradation was implemented on all simulated in-rack exposures (Reference 18). The conclusions of this analysis are valid only for the assumptions and information provided to GNF by PBAPS for this purpose. Should it be determined that any of the assumptions regarding storage rack design, construction, manufacturing tolerances or material compositions be different than those assumed in this document, this analysis must be re-evaluated to assess any possible impact on the final results that these changes might produce.

This GNF2 analysis bounds all previously manufactured GNF lattice designs for Peach Bottom Units 2 and 3.

1. INTRODUCTION AND SUMMARY

The PBAPS high-density Boraflex fuel storage rack system for spent fuel has been analyzed with GNF2 fuel bundles in order to demonstrate that system's ability to satisfy its design basis licensing requirements while loaded with these fuel products. The analyses were performed using the MCNP01A Monte Carlo neutron transport computer program, which has been qualified for this application (Reference 2). The fuel lattice geometries used are consistent with typical 10x10 fuel designs with a uniform enrichment of 4.90 wt% ^{235}U and varying gadolinium concentrations, consistent with the plant's core geometry (BWR-4). The spent fuel storage rack simulations incorporated lattices with depleted burnable poison and explicit fission product inventories associated with lattice peak cold, exposure-dependent in-core statepoints, and desired void histories for all designs considered. The fuel assemblies considered contained both full and part length fuel rods. Normal and abnormal spent fuel storage rack configurations were evaluated with two-dimensional geometry models. The analysis conditions and assumptions used are in compliance with the requirements contained in the USNRC Regulatory Guide 1.13, Spent Fuel Storage Facility Design Basis, Rev. 2 (Reference 3), and ANSI/ANS-57.2-1983, Design Requirements for Light Water Reactor Spent Fuel Storage Facilities at Nuclear Power Plants (Reference 4).

The PBAPS Boraflex storage racks maintain a subcritical multiplication factor, k_{eff}, for all normal and abnormal material/geometry scenarios for GNF2 fuel bundles and for all GNF/GE fuel bundle products which have been utilized in the Peach Bottom Units 2 and 3. In order to insure that specific bundles are acceptable for storage in the Boraflex spent fuel storage racks, the following three items should be considered:

1. Identify the unique lattices in each assembly (bundle) design.
2. Determine the maximum cold 68F (20C) uncontrolled k_∞ results from standard TGBLA06A lattice physics calculations for each unique lattice in the assembly.
3. Ensure that the k_∞ values obtained from Step 2 for each lattice are less than the rack-specific in-core peak eigenvalue (k_∞) limit of 1.318 at 70 percent void histories. Such fuel can be loaded in any configuration in the storage racks.

Note that lattice physics codes other than TGBLA06A may be used to perform the evaluation, subject to a determination of an appropriate k_∞ limit having been determined for the particular lattice physics code to be used.

2. METHOD OF ANALYSES

The documented fuel storage criticality calculations were performed using the MCNP01A (Reference 2) computer code. MCNP01A is a Monte Carlo program for solving the linear neutron transport equation as a fixed source or an eigenvalue problem in three space dimensions. It implements the Monte Carlo process for neutron, photon or electron transport, or coupled transport involving all these particles, and can compute the eigenvalue for neutron-multiplying systems. For the present application only neutron transport was considered.

2.1 Cross Sections

MCNP01A uses point-wise (i.e., continuous energy) cross section data, and all reactions in a given cross section evaluation (e.g., ENDF/B-V) are considered. For the present work, thermal neutron scattering with hydrogen was described using an $S(\alpha,\beta)$ light water thermal scattering kernel. The cross section tables include all details of the ENDF representations for neutron data. The code requires that all the cross sections be given on a single uniform energy grid suitable for linear interpolation; however, the cross section energy grid varies from isotope to isotope. The libraries include very little data thinning and utilize maximum resonance integral reconstruction error tolerances of 0.001 %.

2.2 Geometry Treatment

MCNP01A implements a robust geometry representation that can correctly model complex components in three dimensions. An arbitrary three-dimensional configuration is treated as geometric cells bounded by first and second-degree surfaces. The cells are described in a Cartesian coordinate system and are defined by the intersections, unions and complements of the regions bounded by the surfaces. Surfaces are defined by supplying coefficients to the analytic surface equations or, for certain types of surfaces, known points on the surfaces. Rather than combining several pre-defined geometrical bodies in a combinatorial geometry scheme, MCNP01A has the flexibility of defining geometrical shapes from all the first and second-degree surfaces of analytical geometry and then combining them with Boolean operators. The code performs extensive checking for geometry errors and provides a plotting feature for examining the geometry and material assignments.

2.3 Validation and Computational Basis

MCNP01A has been compared to critical experiments for different temperatures and moderator-to-fuel ratios and many of these experiments were consistent with BWR geometries and materials. The critical experiments to which MCNP01A has been compared are:

- Cross Section Evaluation Working Group (CSEWG) thermal reactor benchmark problems:, PNL-1 and PNL-2;
- [[ ]]
- Small Core Criticals with and without Poison Curtains;
- Small Core Criticals with and without Burnable Absorbers

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3. ANALYSIS & ACCEPTANCE CRITERIA

3.1 Criticality Analysis

The design of the spent fuel storage racks provides for a subcritical multiplication factor for both normal and abnormal storage conditions. For all conditions, the storage rack eigenvalue must be ≤ 0.95. Normal conditions exist when the fuel storage racks are located in the pool and are covered with a normal depth of water (about 25 ft above the stored fuel) for radiation shielding and with the maximum number of fuel assemblies or bundles in their design storage positions. The spent fuel is covered with water at all times by a minimum depth required to provide sufficient shielding. An abnormal condition may result from accidental dropping of equipment or damage caused by the horizontal movement of fuel handling equipment without first disengaging the fuel from the hoisting equipment. To meet the requirements of General Design Criterion 61 (Reference 9), geometrically-safe configurations of fuel, stored in the spent fuel array, are employed to assure that the eigenvalue will not exceed 0.95 under all normal and abnormal storage conditions. The geometry of the spent fuel storage array must additionally ensure that the eigenvalue will be ≤ 0.95 under optimum moderation conditions.

To ensure that the design criteria are met, the following normal and abnormal spent fuel storage conditions were analytically considered:

- Normal geometry configuration in the spent fuel storage array
- Temperature and water density effects
- Abnormal locations of a fuel assembly, including non-channeled bundle storage
- Eccentric fuel assembly positioning
- Dropped fuel assembly
- Fuel rack lateral movement

No limitation was placed on the size of the spent fuel storage array from a criticality standpoint, since all calculations are performed on an infinite basis.

To assure the true reactivity would always be less than the calculated reactivity, the following conservative assumptions are made:

- [[ ]]

- [[ ]]

- [[ ]]

- [[ ]]

- [[ ]]

3.2 Conformance with USNRC Regulatory Guide 1.13 and ANSI/ANS-57.2-1983

The basic regulatory requirements for assuring margin to criticality for spent fuel storage at PBAPS are defined in the USNRC Regulatory Guide 1.13 (Reference 3), with design basis and criticality specifications defined in ANSI/ANS-57.2-1983 (Reference 4).

The margin requirement is $k_{eff} \leq 0.95$ for normal and abnormal operation with tolerances and computational uncertainties taken into account. Such Nuclear Criticality Analyses are subject to the following restrictions (ANSI/ANS-57.2-1983 [6.4.2.2]):

- The most reactive fuel assembly anticipated for insertion into the storage must be assumed;

- For fuel assemblies that incorporate a distribution of discrete fissile inventories within the assembly, the conservatively determined mean fissile inventory shall be assumed;

- Credit for fixed neutron poisons (such as integral burnable absorbers - Gadolinia) may be taken;

- The analysis must consider the location of assemblies in transit to the storage racks or in the fuel inspection stand;

- Neutron poisons incorporated in the storage structure may be credited in increasing the margin to criticality.

- The scope of the Nuclear Criticality Analysis shall consider credible abnormal occurrences, as well as normal conditions (ANSI/ANS-57.2-1983 [6.4.2.1]).

The margin requirement is determined in part by establishing a $\Delta k_{uncertainty}$ contribution to the storage rack eigenvalue, as detailed in Section 3.4 of this report.

3.3 Definitions

The following terms are used in this report:

- Fuel Assembly - is a complete fuel unit consisting of a basic 10x10 fuel rod structure, including large central water rods. Several shorter rods may be included in the assembly. These are called "part length" rods. A fuel assembly includes the fuel channel.

- Gadolinia - The compound Gd_2O_3. The gadolinium content in integral burnable absorber fuel rods is usually expressed in weight percentage of Gadolinia.

- Integral Burnable Absorbers - are neutron poisons used to reduce the reactivity of a highly enriched lattice, that are blended with fissile material (i.e., UO_2) in the fuel pellets. In a typical BWR, the absorber of choice is Gadolinia.

- Lattice - An axial zone of a fuel assembly within which the nuclear characteristics of the individual rods are unchanged.

- Dominant Lattice - An axial zone of a fuel assembly typically located in the bottom half of the bundle above the power shaping zone region.

- Vanished Lattice - An axial zone of a fuel assembly typically located in the upper half of the bundle above the dominant zone region.

- Sub-critical - having a neutron multiplication factor (k_{eff} or k_∞) less than 1.0 after taking into account statistical uncertainties and biases. In criticality safety analyses in which Monte Carlo codes are used, subcriticality is usually demonstrated by showing that the maximum k_{eff} is less than some offset from unity - for example, is less than 0.95. Biases are considered to be negative if critical benchmarks are under-predicted (i.e., result in calculated multiplications less than unity).

3.4 Treatment of Biases and Uncertainties

The eigenvalues reported herein contain an assessment for computer code bias and uncertainty that is consistent with Reference 4 and formalized as follows:

(1) $k_{max} = k_{mc} + \Delta k_{bias} + \Delta k_{uncertainty}$

In this equation, the terms are defined as:

k_{mc} - eigenvalue from Monte Carlo calculation;

Δk_{bias} - critical benchmark bias for Monte Carlo code (MCNP01A versus critical experiments); the bias due to Boraflex degradation, and Δk_{U2} = Δk associated with non-channeled analysis

$\Delta k_{uncertainty}$ –

$$\sqrt{\sum_{i=1}^{8} \Delta k_{Ui}^{2}}$$

Δk_{U1} = Problem specific relative error (1σ)
Δk_{U3} = Δk associated with eccentric assembly location (diagonal off-set)
Δk_{U4} = Δk associated with uncertainty in fuel enrichment
Δk_{U5} = Δk associated with uncertainty of lattice spacing
Δk_{U6} = Δk associated with uncertainty in SS box thickness
Δk_{U7} = Δk associated with bias from Boraflex degradation
Δk_{U8} = Δk associated with decreased pool water temperature (4°C)

The standard deviation of the Monte Carlo eigenvalue simulations (Δk_{U1}) is the 1σ eigenvalue uncertainty directly associated with the individual storage rack lattice-calculated k_{∞}(s). This standard deviation is computed by MCNP01A relative to the mean eigenvalue, tallied for a large number of neutron batches, or cycles, and is part of the normal MCNP01A output associated with an eigenvalue solution. The 1σ value incorporated for this uncertainty analysis is extracted from the nominal GNF2 design basis lattice evaluation output. An ambient pool water temperature of 20°C was assumed.

The non-channeled analysis (Δk_{U2}) simulates the storage of the most reactive lattice in an infinite storage rack array, without flow channels, and with nominal specifications of the associated storage rack material/geometry parameters. This geometry is treated as a bias if it results in a positive reactivity impact.

The eccentric assembly location analysis (Δk_{U3}) simulates the storage of the most reactive lattice, including flow channels, offset to an extreme inner corner (diagonal off-set) of an associated storage rack cell, in an infinite storage rack array, and with nominal specifications of the associated storage rack material/geometry parameters.

The uncertainty in the fuel enrichment analysis (Δk_{U4}) simulates the storage of the most reactive lattice, including flow channels, with nominal specifications of the associated storage rack material/geometry parameters, [[

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The uncertainty in lattice spacing analysis (Δk_{U5}) simulates the storage of the most reactive lattice, including flow channels, with nominal specifications of the associated storage rack material/geometry parameters, with a 1 mm decrease in the nominally specified storage cell center-to-center spacing of 15.9512 cm. This value of 1 mm is consistent with the GE14 analysis for PBAPS. Decreasing the lattice spacing, or pitch, in an over-moderated system will increase the system reactivity, and the simulation was performed to quantify the expected result.

The uncertainty in the stainless steel box thickness analysis (Δk_{U6}) simulates the storage of the most reactive lattice, including flow channels, with nominal specifications of the associated storage rack material/geometry parameters, with a 10% (0.0075") decrease in the associated nominally specified inner steel cell wall thickness of 0.075". The 10% reduction is consistent with the previous analysis for GE14.

To account for the reactivity effects of Boraflex degradation, a reactivity penalty will be applied in the form of a bias (Δk_{U7}). This bias is based on previous analyses (Reference 10) performed for Exelon by another vendor. Confirmatory calculations were performed for the bounding GNF2 lattice to verify that the reactivity bias obtained from Reference 10 could be conservatively applied to GNF2.

The uncertainty in the storage rack water (moderator) temperature and density analysis (Δk_{U8}) simulates the storage of the most reactive lattice, including flow channels, with nominal specifications of the associated storage rack material/geometry parameters, with a 4°C ambient water temperature, and an associated density of 62.426 lbs./ft^3, providing a bounding water-temperature sensitivity evaluation.

4. FUEL DESIGN BASIS

4.1 GNF2 Fuel Lattice Composition

Criticality safety analyses to determine stored fuel reactivity were performed using the GNF2 10x10 fuel design for the PBAPS spent fuel storage racks. The GNF2 fuel lattice configuration is a 10x10 fuel rod array minus eight fuel rods that have been replaced with two large water rods as shown in Figure 1. The limiting evaluated lattice(s) incorporated multiple Gadolinia rods (1.0 wt% to 4.0 wt%) with initial uniform enrichments of up to 4.90 wt% ^{235}U (fully rodded and vanished lattice). The Gadolinia loadings (number of rods and weights) utilized have been determined consistent with expected bundle designs. The particular lattice design which could be demonstrated safe in the storage racks (including all uncertainties) had in-core k_∞ =1.318 at the corresponding 70 percent void history. The associated material isotopic compositions used in the analysis are shown in Table 1. The GNF2 bundle dimensions are indicated in Figure 1 and Table 2. Also given in Table 2 is a comparison to the standard GE14 design for comparison. Conservation of mass was used to smear the UO_2 pellet isotopics over the pellet-to-cladding gap. The total UO_2 inventory is consistent with the design pellet stack density of [[ ]] theoretical density for GNF2 fuel. The GNF2 interactive channel geometry was maintained. An example of a GNF2 lattice is depicted in Figure 2 showing the geometry configuration with the Gadolinia rods readily identifiable by their respective multi-ring definitions (also see Appendix A). Two-dimensional nuclear simulations were performed for a number of GNF2 lattice models, using the GEH lattice physics codes, TGBLA06A (Reference 12). Configurations chosen for subsequent analysis and inclusion in this report yielded associated in-core eigenvalues (k_∞), as a function of void, temperature and exposure, utilizing the associated TGBLA06A resolved lattice statepoints.

4.1.1 Additional GNF2 Fuel Lattice Composition

Recent criticality calculations on the GNF2 10x10 fuel designs incorporated the lattices requirements specified by NETco (Reference 18). The gadolinium rod layout was consistent with Figure 5 at a dominant lattice zone specification. The lattice consisted of uniform enrichments of 4.9 wt% ^{135}Xe and 13 rods containing 2.0 wt% Gadolinium concentration. Two-dimensional lattice physics code, TGBLA06A (Reference 12) established appropriate in-core eigenvalues (k_∞), as a function of void fraction, temperature and exposure.

4.2 Effect of Vanished/Dominant Lattices on In-rack Neutron Multiplication

For this analysis, TGBLA06A exposure-dependent in-core eigenvalues (k_∞) for both dominant and vanished lattices were computed and associated MCNP01A eigenvalues (k_∞) were produced at each lattice's respective peak reactivity exposure point. This calculational suite included the GNF2 design basis lattices in Lead Use Assembly (LUA) bundle [[ ]] (dominant – [[ ]], and vanished – [[ ]]). The TGBLA06A peak, cold in-core eigenvalues (k_∞) were 1.1596 (dominant) and 1.1625 (vanished) at 17 and 15 GWd/st exposure respectively. The associated nominal in-rack eigenvalues (k_∞) for these lattice statepoints were 0.7843 (dominant) and 0.7827 (vanished), respectively (excluding calculational bias). This result indicates that the dominant lattice's slightly lower H/U ratio (relative to the vanished lattice) produces a slightly higher in-rack eigenvalue than the dominant lattice, with a lower in-core eigenvalue.

A fuel product-dependent rack efficiency expression, defined as the ratio of a particular lattice statepoint in-rack eigenvalue (k_∞) divided by the associated lattice nominal in-core eigenvalue (k_∞), allows for a straightforward comparison of both a storage rack's criticality response to different fuel products and to varying lattice designs within a particular fuel product. By this definition, a storage rack's capability to suppress reactivity for a specific lattice design can be readily compared to other fuel products, or lattice designs within the same fuel product line. A lower rack efficiency ratio implies an increased reactivity suppression capability (for a given product/lattice design), relative to an alternate design with a higher rack efficiency ratio. In other words, when comparing two racked statepoints, the lower the efficiency ratio, the more capable (better) the system. By comparing the rack efficiency ratios for the two nominal 10x10 GNF2 lattice designs evaluated, the sensitivity of the in-rack reactivity to lattice design may be gleaned.

A comparison of ratios for the indicated design basis lattices (0.676 (dominant); 0.673 (vanished)) indicates that the there is very little difference in rack efficiency ratios between the dominant and vanished lattices analyzed in this study. This is also seen by examination of Figure A 1 which shows the dominant and vanished lattice reactivity curves essentially on top of each other over a wide range of in-core eigenvalues. As a result, the lattice with the highest in-core eigenvalue (a variant of dominant lattice 6939) will form the GNF2 licensing design basis for this spent fuel storage rack system. Note that previously the most reactive lattice configuration evaluated in the storage rack cell simulations (dominant) yields an in-core peak eigenvalue (k_∞) of 1.359 at zero void and 4.9 wt% U-235 and 1 wt% Gadolinium concentration, without benchmark uncertainties included. Specifically, the (k_∞) values are directly reported from the TGBLA06A cold, uncontrolled summary edits. While single point evaluations could produce misleading results (rack efficiency ratios) for a specific lattice configuration, given the coarse fidelity of the discrete exposure increments employed, multiple lattices at various exposure points have been herein evaluated to characterize the vanished and dominant lattice efficiency ratios.

4.2.1 Additional Effects of Neutron Multiplication Factor on Dominant Lattice

Dominant lattice exposure eigenvalues were calculated by the TGBLA06A lattice physics engine and verified by MCNP01A lattice core simulations. Zero and 70 percent void histories were compared with the new bundle specifications. The simulated TGBLA06A peak, cold in-core zero and 70 percent void eigenvalues (k_∞) were 1.345 (dominant) and 1.318 (dominant) at 8 GWd/st and 10 GWd/st exposures respectively. The associated nominal MCNP01A in-rack eigenvalue (k_∞) for these lattice statepoints at zero and 70 percent voids were 0.916 (dominant) and 0.901 (dominant) correspondingly (excluding calculation bias).

4.3 Infinite Lattice Benchmark Uncertainty

Nominally determined TGBLA06A infinite lattice eigenvalues (k_∞) do not include uncertainties versus benchmark analyses. A [[ ]] has been determined for TGBLA06A cold eigenvalue solutions, relative to MCNP01A benchmark lattice evaluations. The infinite lattice cold eigenvalue uncertainty is an integral component of the maximum storage rack eigenvalue assessment, and accordingly the [[ ]] Δk_∞ is included in the storage rack uncertainty roll-up of k_{max}.

For subsequent benchmarking purposes, several GNF2 lattice designs are evaluated, with each infinite lattice's k_∞ compared with an associated nominal storage rack k_∞, consistent with the in-core k_∞ criteria methodology employed for this analysis and report, and those lattices are fully specified, along with the associated results, in Appendix A of this report.

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Figure 1 GNF2 Fuel Lattice Configuration

Table 1 Material Isotopic Compositions (atoms/bn•cm)

ISOTOPICS ; 4.90wt% ^{235}U	
Moderator at 20° C	
Oxygen	3.3370E-2
Hydrogen	6.6734E-2
Cladding and Channel	
Zirconium	4.32392E-2
304L Stainless Steel*	
Silicon	1.6728E-3
Manganese	1.4906E-2
Iron	5.6437E-2
Nickel	8.4036E-3
Manganese	1.7100E-3
UO_2 at 4.90w% ^{235}U (96.5% TD)	
^{234}U	1.0343E-5
^{235}U	1.1165E-3
^{238}U	2.1386E-2
Oxygen	4.5025E-2

*- Standard material composition taken from Reference 13.

Figure 2 Example of an Infinite D-Lattice Simulation Model

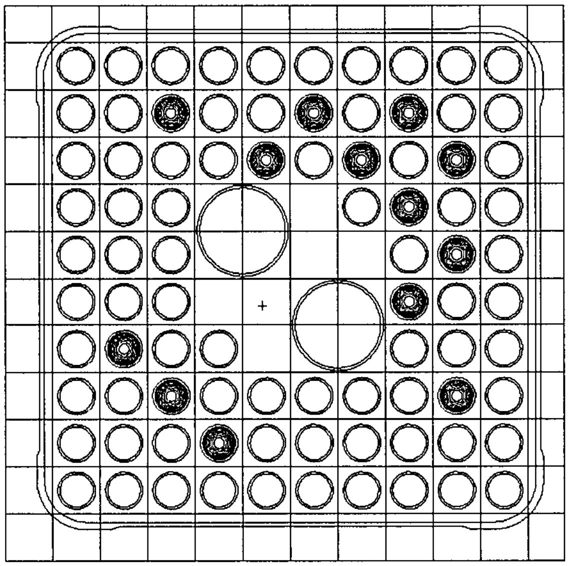


Table 2 Comparison of Geometric and Material Data for GNF2 and GE14 Fuel Lattices

Parameter	**GNF2**	**GE14**
Number of UO_2 Rods	[[	
Total Number of Gd-UO_2 rods		
Number of Water Rods		
Fuel Pin Pitch (cm)		
Fuel Rod OD (cm)		
Fuel Pellet OD (cm)		
Cladding Thickness (cm)		
Cladding Material		
UO_2 Pellet Stack Density (g/cc)		
Fuel Bundle Channel Thickness (cm)		
Channel Material		
Active Fuel Length (cm)		]]

5. SPENT FUEL STORAGE

5.1 Description of Spent Fuel Storage Rack

The PBAPS design basis Boraflex storage rack cell assembly manufactured by Westinghouse (Reference 1) consists of a large 304 stainless steel structure composed of a series of square vertical tubes (cells). These tubes contain 0.081" thick Boraflex panels sandwiched between a 0.075" SS inner cell wall and a 0.020" SS outer wrapper. The Boraflex containing cells are arranged in a checkerboard pattern with the space between a 4-cell group forming a fifth bundle storage location with a center-to-center cell pitch of 6.280 inches. Rack array sizes ranging from 9x14 up to 19x20 are placed adjacent to one another in the spent fuel pools of both PBAPS Units 2 and 3. The rack employs thermal neutron absorption in the B-10 of the Boraflex as the primary mechanism of reactivity control. A schematic of a single storage rack unit-cell is shown in Figure 3. All information pertaining to the geometry and material composition of the racks was taken from the original design basis document (Reference 1) for these racks given by the supplier Westinghouse.

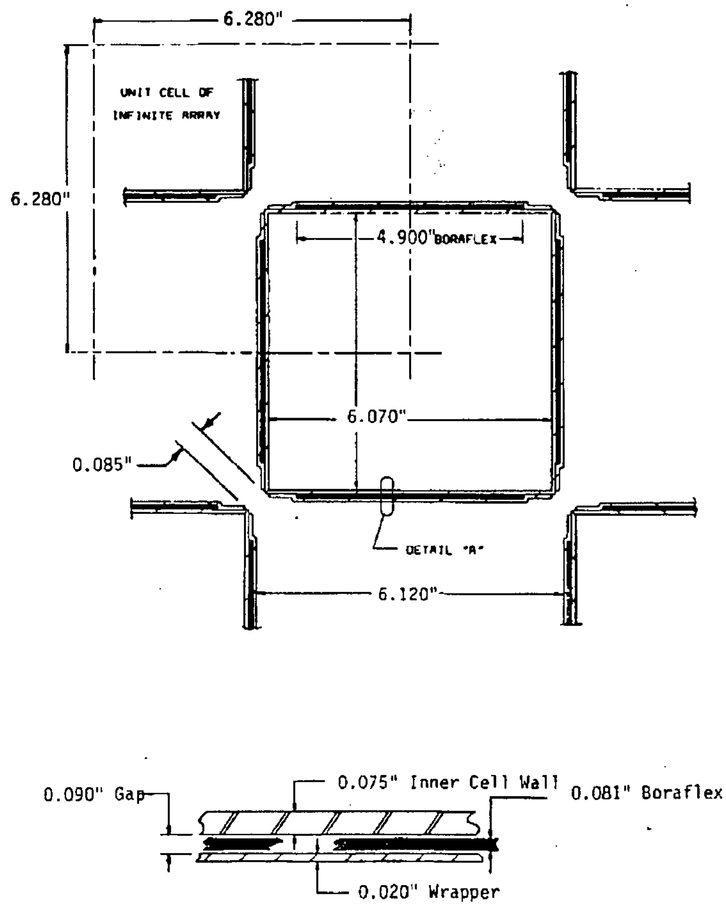


Figure 3. PBAPS Boraflex Spent Fuel Storage Rack Cell

5.2 Normal Configuration

The normal storage environment includes bundles with flow channels, within 304L stainless steel sleeves, in a normally pitched spacing arrangement, with a conservative ambient water temperature of 20°C. In the associated analysis simulations, the fuel material inventories include pin-by-pin isotopic representations of the infinite lattice loading at the peak cold, exposure-dependent reactivity statepoint. For the two dimensional lattices evaluated, with pins initially loaded with uniform enrichments of ^{235}U and fixed initial loadings of Gadolinia rods, the peak cold, exposure-dependent reactivity statepoints are considered (burned under hot, zero-void, full power conditions). Consideration of an arrangement of in-rack spent fuel assemblies containing burnable absorbers and fission products (versus no poisons) is necessary to demonstrate subcriticality compliance for highly enriched fuel assemblies in HDFS systems, with regard to USNRC Regulatory Guide 1.13 (Reference 3) and ANSI/ANS-57.2-1983 (Reference 4).

5.2.1 Analytical Model

Due to the design of the racks, a 2-D, axially infinite checkerboard lattice was created. The first lattice cell contained the center storage rack cell position (seen in Figure 3) composed of the inner stainless steel liner and part of the Boralfex panel region. The second (adjacent) storage cell position contained the remaining Boraflex region and the outer stainless steel structure. The design of the checkerboard rack necessitated this type of modeling since the periodic line of symmetry for the square lattice (6.280" pitch) occurred in between the two adjacent cells. A 23x23 checkerboard array of alternating cells was created and periodic reflecting boundary conditions were imposed on the four peripheral X and Y boundary planes to accurately simulate an infinite checkerboard storage pattern. Axially reflective (spectral) boundary conditions are imposed in the Z plane, conservatively simulating an axially infinite pool geometry.

Previous studies have based spent fuel storage rack analytical calculations on beginning-of-life material configuration models without incorporating burnable absorbers. It was recognized early in the process of performing this study, that for an infinite array of highly enriched GNF2 bundles in the PBAPS Boraflex spent fuel storage racks, the pertinent reactivity criteria could not be satisfied without incorporating burnable absorbers in some of the fuel pins.

As a result, a number of conservative material configuration scenarios, incorporating burnable absorbers, have been herein defined for this spent fuel storage rack analytical study. The conservative interpretation stems from the selection of peak, exposed reactivity statepoints, ignoring significant poisons in the form of "lumped" fission products, and ignoring any ^{135}Xe inventory which is assumed to have decayed away.

Pin-by-pin isotopic specifications were generated by burning the GEH lattice physics production code (TGBLA06A), with hot operating fuel and moderator temperatures, at the zero-void moderator condition, to peak reactivity anomaly statepoints. For conservatism, the lattice physics generated "lumped" fission product was neglected in the Monte Carlo simulations (non beginning-of-life configurations), adding an additional degree of conservatism to the spent fuel storage rack calculations.

The vast majority of the initially loaded Gadolinia has burned out by these exposure points, so the remaining Gadolinia inventory is small. The ^{135}Xe inventory is assumed to have decayed away completely, and is ignored for all exposed spent fuel storage rack analyses.

To determine the loading arrangement of pins for the subject evaluation, lattice configurations (number and location of Gd rods) were chosen consistent with anticipated GNF2 bundle design for PBAPS GNF2 New Fuel Introduction, with regard to evaluating lattice peak cold, exposure-dependent eigenvalues against the anticipated storage rack reactivity capacity. The identified configurations were benchmarked with MCNP01A calculations to determine the accuracy of the lattice physics predicted eigenvalues and to determine the acceptability of the lattice physics based methodology of establishing the respective peak reactivity points, without uncertainties. The Monte Carlo analyses confirmed the TGBLA06A's predicted statepoint design eigenvalues to within the documented 95%/95% tolerance uncertainty range of [[ ]], validating the design basis methodology and statepoint selection criteria for the pertinent material configurations. Additionally, the Monte Carlo results fall within the uncertainty ranges developed for the GNF2 fuel product line cold eigenvalue basis 95%/95% confidence level.

5.2.2 Results

The normal configuration fully-loaded rack Monte Carlo simulation results indicate that the limiting lattice configuration (in-core k_∞ =1.321), in the nominally specified (material/geometry) spent fuel storage rack with 20°C, 70 percent void water, yields an in-rack eigenvalue below the (k_{max}) < 0.95 limit, with computational uncertainties taken into account, for an initial uniform lattice enrichment of 4.90 wt% ^{235}U with a 2 wt% gadolinium concentration.

The spent fuel storage rack limiting lattice, with a lattice enrichment of 4.90 wt% ^{235}U and 2 wt% gadolinium concentrations with the current GNF2 bundle design (see Figure 5). This yields a nominal MCNP01A peak in-core eigenvalue (k_∞) of 1.321 with an associated nominal peak in-rack eigenvalue ($k_{in\text{-}rack}$) of 0.9018 (± 0.00036), without bias for 20°C ambient pool water temperature. (Note that the fuel pin isotopics used in the Monte Carlo in-rack lattice simulations are identical to those produced by the TGBLA06A lattice burn calculations. There was no re-distribution of fissile (or non-fissile) inventory; the as-burned spatial isotopic pin inventories were exactly preserved at the respective exposure point(s)).

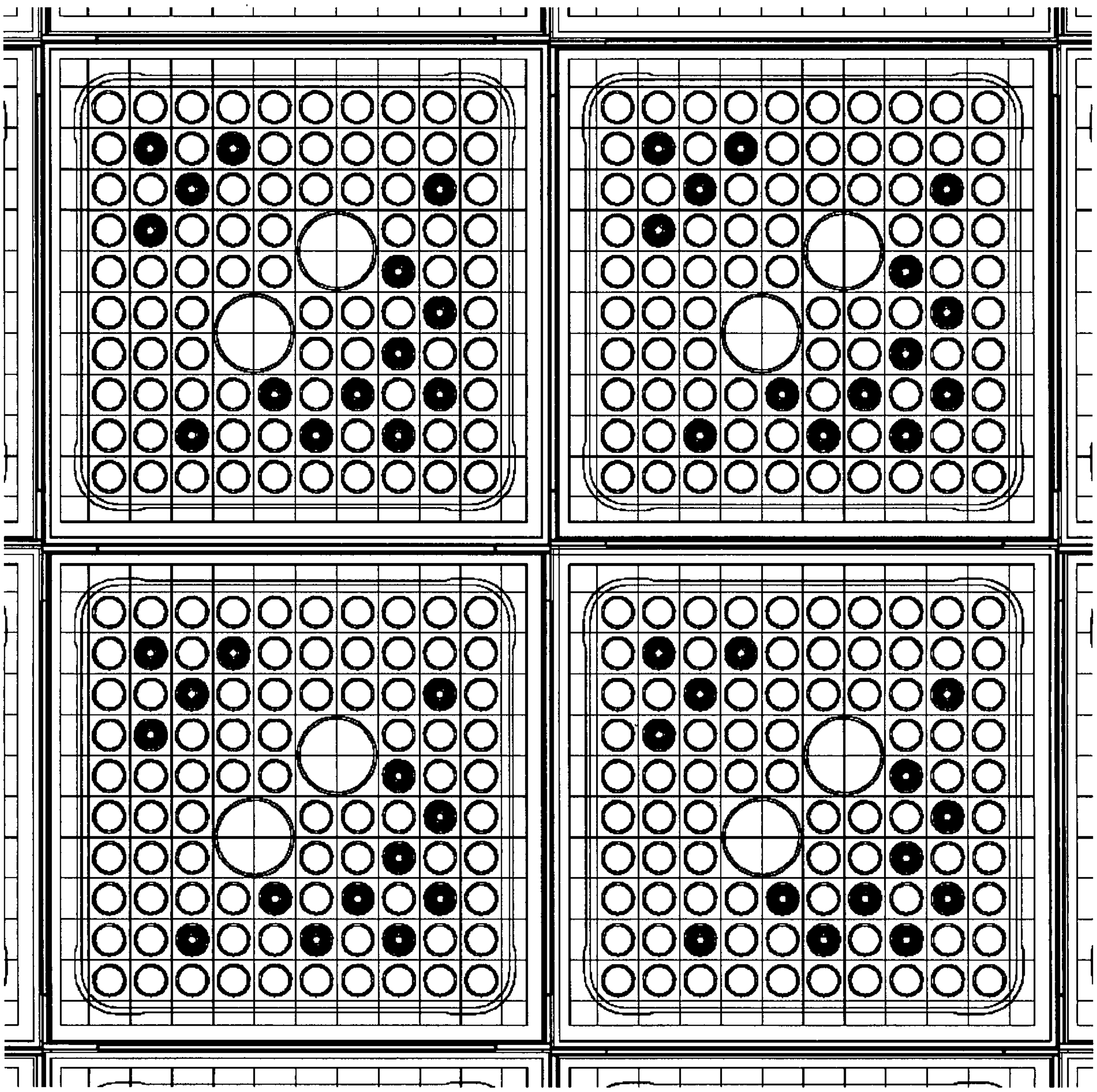


Figure 4 Spent Fuel Storage Rack Cell

Table 3 Assumed Spent Fuel Storage Rack Dimensions

Rack Cell Dimensions	
Storage Cell Pitch	15.9512 cm
Storage Cell Liner Dimension	15.4178 cm
Intermediate Storage Location Inner Dimension	15.5448 cm
304L Stainless Steel Inner Cell Wall	0.1905 cm
304L Stainless Steel Outer Wrapper	0.0508 cm
Gap Between Inner Cell Wall and Wrapper	0.2286 cm
Boraflex Panel Thickness	0.20574 cm
Water Gaps on Either Side Of Boraflex Panel	0.01143 cm

Table 4 In-core versus Nominal In-rack Eigenvalues for Evaluated Benchmark Lattices (20°C)

Lattice ID+	Lattice Type	In-core TBGLA06	In-core MCNP01A	In-rack MCNP01A
6939c	Dominant	[[		
6941c	Vanished			
6939b	Dominant			
6941b	Vanished			
6943a	Vanished			
6939a	Dominant			
6941a	Vanished			
6943	Vanished			
6942	Vanished			
6939	Dominant			
6941	Vanished			
6940	Dominant			
*543212	MXDom-0%vh			
*543212	MXDom-70%vh			]]

+**Note:** GNF2 lattices with varying enrichments, Gd loadings (number, placement, weight) and peak reactivity exposure points are shown. Lattices IDs are given as 4-digit integers. For lattices specified as XXXXa, XXXXb, XXXXc, etc., these are variations of the most reactive dominant (6939) or vanished (6943) lattice obtained by changing the Gd wt% content in the rods.

***Note:** GNF2 lattices with 4.90 wt% ^{235}U enrichments and 2.00 wt% gadolinium concentrations (see Figure 5). Peak zero and 70 percent void history reactivity exposure points are shown.

5.3 Accident/Abnormal Configuration

The spent fuel storage rack abnormal configurations involve the following postulated scenarios, or occurrences, and are evaluated with MCNP01A in the nominal storage rack cell model, where needed:

- Temperature increase/decrease of pool water
- Lateral movement of a rack module
- Misplacement of a fuel assembly
- An assembly dropped on top of the rack
- Eccentric fuel assembly positioning
- Other (non-channeled assemblies if appropriate)

5.3.1 Analytical Model

The nominally specified material/geometry parameters for the storage rack cell were utilized, in conjunction with the limiting dominant GNF2 lattice to form the basis for the abnormal scenarios. Individual parameters were perturbed accordingly, to appropriately simulate the physical changes associated with a given abnormal scenario.

5.3.2 Results

5.3.2.1 Temperature Increase of Pool Water

All calculations in this analysis were performed for material densities and cross-sections corresponding to 20°C. In order to account for pool water temperature decrease effects, a cold water simulation at 4°C (the maximum theoretical water density temperature of 62.426 lbs/ft^3) was performed. This increase in water density resulted in a reactivity increase of +0.0017 Δk in overall rack reactivity relative to the nominal design basis temperature model at 20°C.

5.3.2.2 Lateral Movement of a Rack Module

For a finite spent fuel storage rack assembly, any enhanced separation between individual rack modules, or cells, results in a decrease of the actual system eigenvalue. The infinite array, close-packed storage cell configuration, forming the basis for all the calculations performed for this evaluation, establishes effective limiting eigenvalues. Considering that the actual PBAPS storage racks have some small separation between them, and that the Monte Carlo simulations used herein model individual storage cells in infinite arrays, the resulting solutions implicitly provide conservative estimates of the actual spaced storage rack modules in the pool.

5.3.2.3 Misplacement of a Fuel Assembly; Dropped Assembly

The spent fuel storage rack criticality calculations assumed an infinite array of storage cells, loaded with the most reactive lattice analyzed, and did not incorporate any radial or axial leakage. As a result, a model simulating a misplaced assembly adjacent to any plane, and in any orientation, would only begin to approach the limiting reactivity value evaluated for the nominal two-dimensional configuration. Specifically, because of the distance between the top of the upper tie plate bale handle and the actual top of active fuel (a distance of >12"), any assembly that drops on the top of the racks is physically isolated from the remainder of the fuel, and thus the dropping of an assembly does not change the multiplication factor for the entire storage system as a whole.

5.3.2.4 Eccentric Fuel Assembly Positioning

A fuel assembly is normally centered within an individual storage cell, with appropriate bottom fittings and spacers to prevent lateral fuel assembly motion. An eccentric position scenario was analyzed whereby a group of four bundles were each positioned in the extreme storage cell corner (diagonal off-set) of their respective positions in the center of the 23x23 periodic reflected array of bundles stored in their nominally centered positions. This case produced a positive reactivity delta of +0.0012 Δk, relative to the normal storage cell configuration result. This configuration is depicted in Figure 5.

5.3.2.5 Non-channeled Assemblies

A fuel assembly is typically stored in the spent fuel storage rack within a zirconium flow channel. Since the storage racks are over-moderated to start with, eliminating the channel and replacing it with water produces a negative reactivity delta of –0.0030 Δk in the spent fuel storage rack eigenvalue (k_{max}), relative to the normal storage cell configuration result. This perturbation is considered a bias.

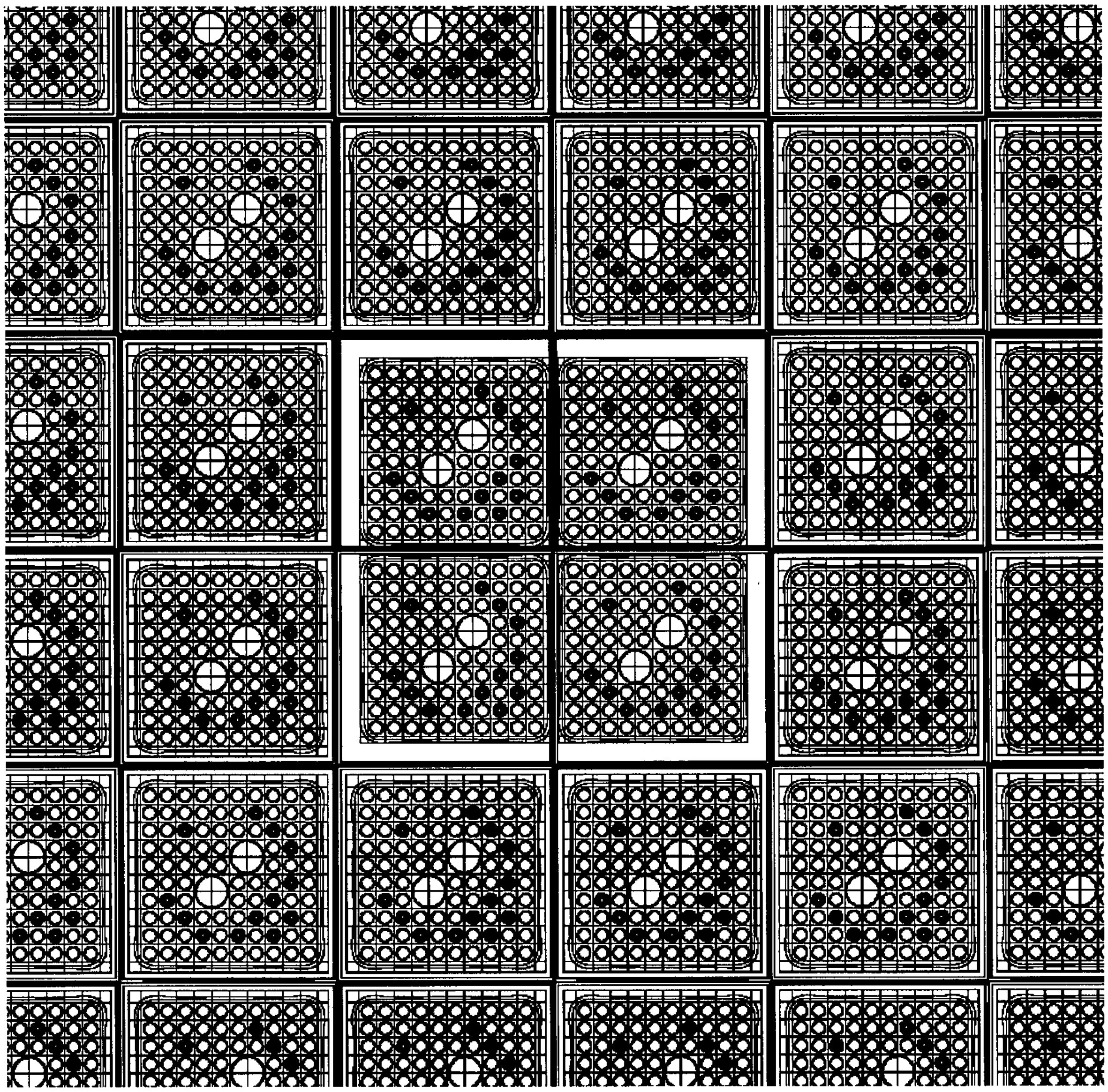
5.4 Uncertainty Analyses

The spent fuel storage rack criticality margin requirement is determined in part by establishing a $\Delta k_{uncertainty}$ contribution to the storage rack eigenvalue, as detailed in Section 3.4 of this report. One of the contributions to the eigenvalue (k_{max}) uncertainty component stem from manufacturing tolerances associated with the fuel pellet enrichment. The Monte Carlo calculation relative errors contribute to the uncertainty, with a principal contribution stemming from the Monte Carlo/lattice-physics-code solutions. The Monte Carlo uncertainty analysis eigenvalue deltas consider the limiting lattice in the nominal storage rack cell geometry.

5.4.1 Analytical Model

The nominally specified material/geometry parameters for the storage rack cell were utilized, in conjunction with the limiting vanished GNF2 lattice to form the basis for the uncertainty analyses cases. Individual parameters were perturbed accordingly, to appropriately simulate the physical changes associated with a given manufacturing uncertainty or abnormal condition.

Figure 5 Spent Fuel Storage Rack, Eccentric Loading



5.4.2 Results

5.4.2.1 Fuel enrichment

The uncertainty in the fuel enrichment analysis simulates the storage of the most reactive lattice, including flow channels, with nominal specifications of the associated storage rack material/geometry parameters, [[ ]]. This increase in enrichment results in an incremental reactivity uncertainty of +0.0014 Δk.

5.4.2.2 Stainless Steel Liner Thickness

The uncertainty in the stainless steel box thickness analysis simulates the storage of the most reactive lattice, including flow channels, with nominal specifications of the associated storage rack material/geometry parameters, with a 10% (0.0075") decrease associated with a nominally specified box thickness of 0.075 inches. This stainless steel thickness reduction resulted in essentially no statistically meaningful change in the system reactivity and is consistent with the results for GE14 fuel.

5.4.2.3 Lattice Spacing

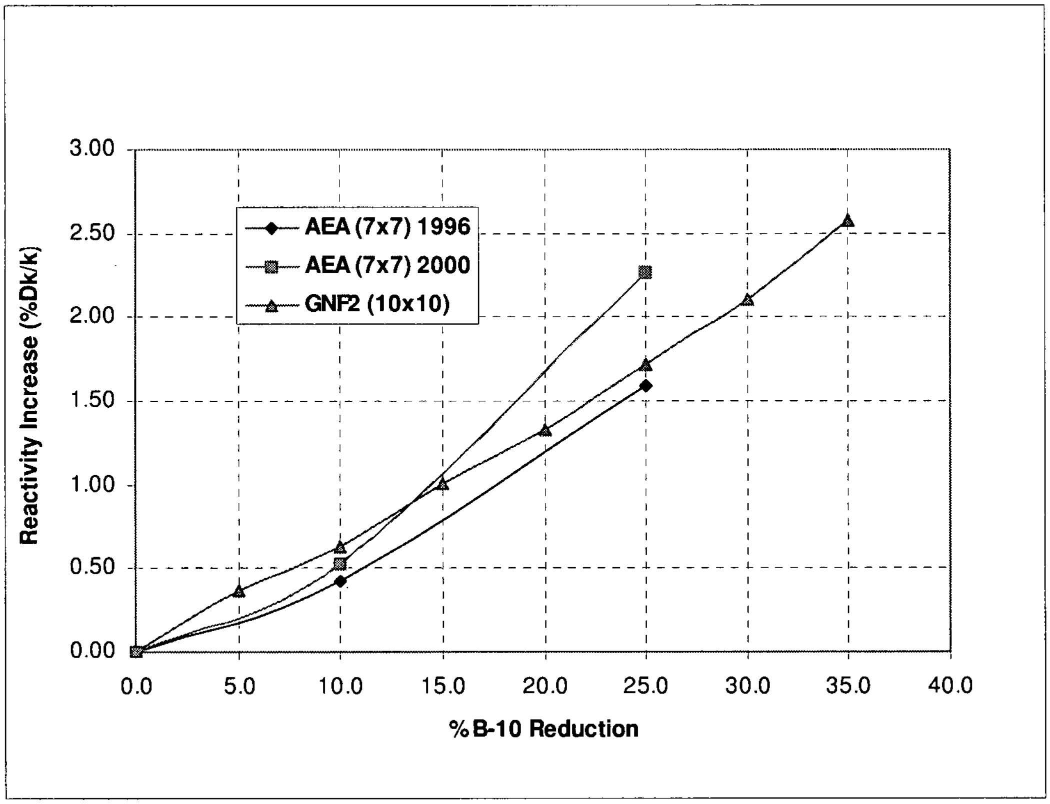
The uncertainty in the lattice spacing analysis simulates the storage of the most reactive lattice, including flow channels, with nominal specifications of the associated storage rack material/geometry parameters, with a 1 mm (0.1 cm) decrease in the nominally specified storage rack cell dimension of 15.9512 cm. Decreasing the cell pitch causes an associated increase of +0.0082 Δk in the modeled rack reactivity. The associated decrease in the storage rack cell pitch results in a strong positive eigenvalue contribution, and a 1 mm change was chosen to be consistent with the GE14 analysis performed for the racks.

5.5 Boraflex Degradation

AEA Technology performed a detailed Boraflex degradation analysis for the PBAPS racks in July of 2000 (Reference 10) which was an update to an earlier analysis performed in 1996 (Reference 17). The Reference 10 analysis assumed a generic 7x7 BWR spent fuel lattice and evaluated the reactivity effects of both uniform B-10 density reduction as well as the reactivity effects of gaps in the Boraflex panels of various sizes. Based on this work, a reactivity bias penalty of +0.0131 Δk was recommended by Exelon for an assumed 10% B-10 uniform atom density reduction in all panels and 10 cm randomly distributed axial gaps in all panels. For this updated analysis, Exelon assessed a reactivity bias penalty of +0.0258 Δk for an assumed 35% B-10 uniform Boraflex panel-thinning penalty (Reference 18).

In order to confirm the applicability of the +0.0131 Δk and the +0.0258 Δk reactivity penalty to the 10x10 GNF2 lattices used in this report, the reactivity effects of 10% to 35% uniform B-10 atom density reduction in all Boraflex panels was evaluated and compared to the published results in Table 1 of Reference 10 and Table 4 of Reference 17. Figure 6 show a comparison of these results.

Figure 6 NETco. Reactivity Comparison and Boraflex Degradation Penalty



As can be seen from the results on Figure 6, the reactivity increase (given in %Δk/k) for all three lattices shows fairly good agreement considering the differences in the initial ^{235}U enrichments, Gadolinium loadings, number/placement of Gadolinium bearing rods, lattice geometries (i.e., 7x7 versus 10x10), computer codes (MONK versus MCNP) and nuclear cross-sections used to perform the analyses.

Based on this comparison, it will be assumed that the reactivity increase from randomly distributed 10 cm axial gaps in all Boraflex panels for the 10x10 GNF2 lattice would be similar to that of the 7x7 lattice analyzed by AEA in Reference 10 (+0.0059 Δk). Therefore, the +0.0258 Δk reactivity penalty for a 10% B-10 density reduction and 10 cm randomly distributed gaps in all panels provides a conservative representation of the Boraflex degradation and will be applied directly to the results for GNF2 (as a bias) with no further qualification. This is summarized in Table 5.

Table 5 PBAPS Criticality Safety Analyses Summary

Nominal eigenvalue plus biases

Reference rack eigenvalue+	0.9018
****Monte Carlo calculational bias (see Sec. 2.3)	0.0020
*Non-channel loading bias (See Sec. 5.3.2.5)	(-0.0030)
Boraflex degradation bias	0.02581
$k_{(nom+bias)}$	*0.9296*

Uncertainties

Item	Δk_U	Lattice Reactivity	Report Section
MCNP01A relative error(95% confidence)	Δk_{U1}	[[	**3.4**
MCNP01A/ENDF-V (95/95 uncertainty)	---		
***MCNP01A/TGBLA06A cold k_∞	---	]]	**2.3/4.3**
Eccentric loading (diagonal off-set)	Δk_{U3}	0.0012	**5.3.2.4**
Fuel enrichment tolerance	Δk_{U4}	[[ ]]	**5.4.2.1**
Lattice Spacing (minimum)	Δk_{U5}	0.0082	**5.4.2.3**
*SS box thickness tolerance	Δk_{U6}	(-0.0001)	**5.4.2.2**
**Cold water (20°C →4°C)	Δk_{U8}	0.0017	**5.3.2.1**
Total	---	**0.0094**	---

Maximum reactivity (k_{max}) **0.9390**
[$k_{(nom+bias)}$ + uncertainties]

+NOTE: This value differs slightly from the result in Table 4 since the reference case simulation was run using a larger number of neutron histories to reduce the statistical uncertainty.

***NOTE:** Negative effects are not included in the roll-up or bias and are indicated parenthetically above.

****NOTE:** All calculations were performed assuming 20°C pool water except for the Δk_{U8} case.

*****NOTE:** Although there is not a k-uncertainty (k_U) term associated with this bias, the 0.0034 is included in the statistical roll-up specified above.

******NOTE:** Treated as a bias. Not included in bias or statistical roll-up

6. SUMMARY

The Westinghouse Boraflex spent fuel storage racks at the PBAPS were analyzed with a bounding GNF2 10x10 lattice fuel design with a peak, cold, in-core k_∞ of 1.318 at the 70 percent void history design basis. The analyses were performed with the MCNP01A Monte Carlo neutron transport program. All storage rack conditions were analyzed assuming the GNF2 fuel lattice geometry with uniform enrichment distributions, explicit burnable absorbers and fission products for the spent fuel racks. The spent fuel storage racks were analyzed with a limiting lattice of 4.90 wt% ^{235}U with 2 wt% gadolinium concentrations in 13 rods on the current GNF2 bundle design, corresponding to a MCNP01A in-core k_∞ of 1.321 and a spent fuel MNCP01A in-rack k_{max} of 0.901. All analyses resulted in a storage rack k_{max} < 0.95 for normal and abnormal configurations, including all biases and uncertainties. Note that an in-core peak eigenvalue (k_∞) of 1.318 is a production lattice physics (TGBLA06A) computed value. Evaluated in conjunction with the 4.90 wt% ^{235}U lattice average enrichment limit and the GNF2 Design Basis descriptions, this result establishes the GNF2 spent fuel storage rack design limit for the PBAPS Boraflex spent fuel storage racks.

Additional data showed a decreasing trend in peak in-core and in-rack neutron multiplication values with increasing gadolinium pellet concentrations in zero and 70 percent void history cases. Previously simulated in-core eigenvalues produced a maximum in-core (k_∞) of 1.359 with uniform fuel lattice enrichments of 4.90 wt % ^{235}U and 1.00 wt% gadolinium concentrations in 13 specified rods. Further lattice simulations resulted in a maximum in-core eigenvalue (k_∞) of 1.345 and 1.318 at zero and 70 percent voids respectively with uniform fuel lattice enrichments of 4.90 wt% ^{235}U and 2.00 wt% gadolinium concentrations in 13 specified rods.

Moreover, in-rack criticality calculations were also effected with the increase in gadolinium concentration of the new GNF2 fuel bundle specifications. Previous MCNP simulations showed a peak in-rack eigenvalue ($k_{in\text{-}rack}$) of 0.919 with uniform enrichments of 4.90 wt% ^{235}U and 1.00 wt% gadolinium concentrations. Increasing neutron absorber concentration, MCNP in-rack calculations estimated a peak in-rack eigenvalue ($k_{in\text{-}rack}$) of 0.916 and 0.901 at zero and 70 percent void histories respectively. Lattice specifications remained consistent with simulated uniform fuel enrichments of 4.90 wt% ^{235}U and 2.00 wt% gadolinium concentrations in 13 rods. A higher peak in-rack eigenvalue ($k_{in\text{-}rack}$) is expected for the zero percent void history as a result of greater in-core moderation that depletes the gadolinium at a greater rate relative to the 70% in-channel void condition.

A review of the peak cold in-core reactivity of GNF bundles previously used over the life of Peach Bottom Units 2 and 3 indicates that this GNF2 lattice provides a bounding rack reactivity. The peak cold in-core reactivity for previous lattice designs is contained the Table 6. All previous lattice designs meet the 1.318 in-core limit.

Table 6 Peak Cold Uncontrolled Lattice Reactivity

Plant: Peach Bottom 2	Lattice Type	Lattice Number	In-core K-infinity
[[	8x8	694	[[
	9x9	1904	
]]	10x10	7257	]]
Plant: Peach Bottom 3			
[[	8x8	1180	[[
	9x9	2030	
]]	10x10	5055	]]

7. REFERENCES

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2. J.F.Briesmeister, "MCNP – A General Monte Carlo N-Particle Transport Code, Version 4A," LA-12625-M Manual, Los Alamos National Laboratory, (1993).
3. USNRC Regulatory Guide 1.13, "Spent Fuel Storage Facility Design Basis," Rev. 2, March 2007.
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5. Reference deleted.
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12. TGBLA Version 06 Letter from S.A. Richards (NRC) to G.A. Watford (GE), "Amendment 26 to GE Licensing Topical Report NEDE-24011-P-A, GESTAR II Implementing Improved GE Steady-State Methods," (TAC NO. MA6481), November 10, 1999.
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14. Reference deleted.
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16. Reference deleted.
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18. NETco. Reactivity comparison and Boraflex degradation penalty values. Net-246-02.

19. NEDC-32868P, "GE14 Compliance with Amendment 22 of NEDE-24011-P-A (GESTAR II)," Rev. 2, September 2007.
20. NEDE-30130-P-A, "Steady-State Nuclear Methods," April 1985.
21. NEDE-24011-P-A-16, "General Electric Standard Application for Reactor Fuel (GESTAR II)," October 2007.

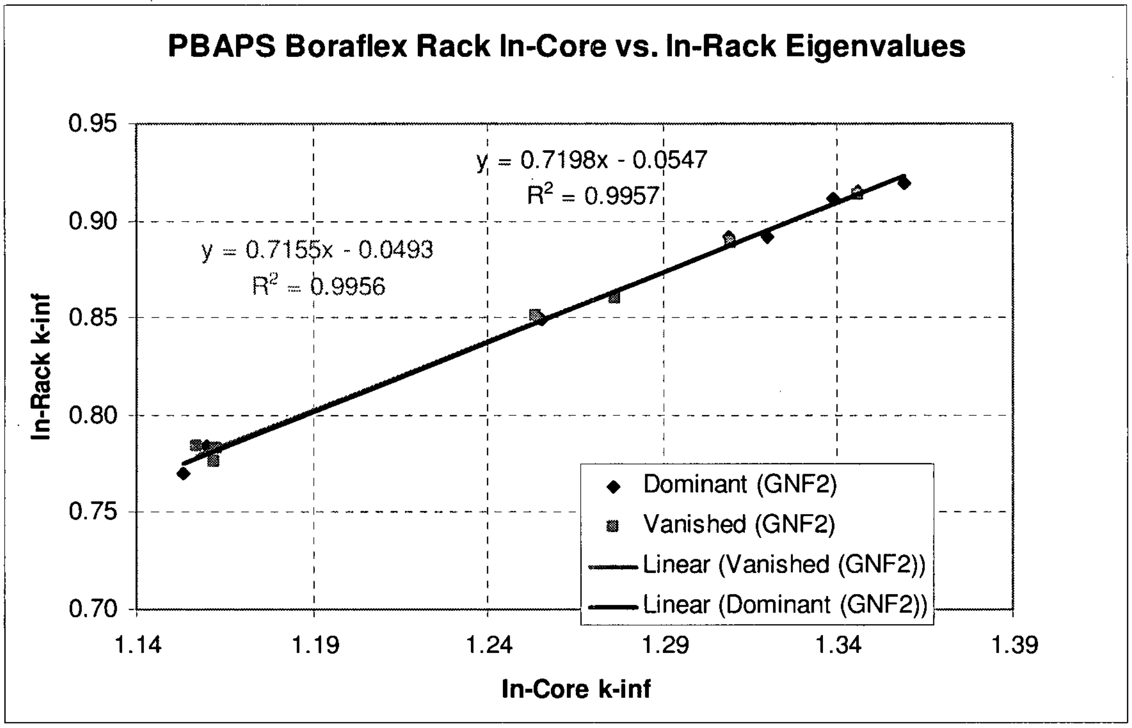
Appendix A INFINITE LATTICE BENCHMARKS

The following case figures and descriptions were among those used in evaluating the PBAPS Boraflex spent fuel storage facilities with GNF2 fuel. The referenced lattices were burned with TGBLA06A based on the standard hot uncontrolled depletions, with appropriate in-core cold, xenon-free restart cases performed to identify the cold, exposure-dependent peak eigenvalues. The cold, exposure-dependent eigenvalues were found to be at their peak when the zero void history depletions were used. Subsequently, the burned lattices were evaluated in the nominal PBAPS Boraflex spent fuel storage rack configuration at the respective peak-eigenvalue statepoints. Consistent with the methodology herein employed, the infinite lattice k_∞ are compared with the nominal storage rack k_{eff}. The results are plotted in Figure A 1 and included in Table A 1.

Revaluated lattices executed the cold, exposure dependent peak eigenvalues at 70% void histories. This would ensure proper representations of core and fuel like behavior.

Lattice Peak 543212 GNF2-[[ ]] is the design basis GNF2 lattice design (T6) to satisfy the spent fuel storage rack eigenvalue criteria, in conjunction with the design parameters and calculational assumptions applied. The accompanying graph (Figure A 1) demonstrates the constant slope relationship between in-core and in-rack eigenvalues within a product line/lattice design family. The slight offset between the plotted vanished and dominant reactivity lines indicates a difference in rack efficiency ratios between these lattice designs, within the same product line.

Figure A 1. PBAPS Boraflex Rack In-Core vs. In-Rack Eigenvalues



NOTE: The Figure above is the simulated TGBLA peak, cold in-core zero percent void history eigenvalues for in-rack (k_∞) eigenvalues as a function of in-core criticality. Lattice specifications remained consistent with specified uniform fuel enrichments of 4.90 wt% ^{235}U. Both bundles contained either 2.00 wt% or 1.00 wt% gadolinium concentrations in 13 rods. New dominant trendline shows a linear slope of y = 0.7198x - 0.0547 similarly to old linear trendline behavior of y = 0.7155x - 0.0493.

Table A 1 – GNF2 Results

Lattice ID	TGBLA06A k_∞	MCNP01A k_{nom}
[[	[[	
]]		]]

NOTE: In the table above, the TGBLA06A k_∞ values are the individual lattice eigenvalues computed in the in-core, reflecting boundary condition geometry. The MCNP01A k_{nom} values are the associated Monte Carlo storage rack eigenvalues at 20°C, computed with the in-rack reflecting boundary condition geometry, without biases and uncertainties included.

Appendix B IN-CORE K_∞ CRITERIA METHODOLOGY

The basic criterion associated with the storage of irradiated (spent) and new fuel is that the effective multiplication factor of fuel stored under normal conditions will be ≤ 0.90 for regular (low) density storage racks and ≤ 0.95 for high-density storage racks. Abnormal conditions are limited to k_{eff} ≤ 0.95 for both low and high density fuel storage racks. These storage rack criteria will be satisfied if the uncontrolled lattice k_∞ calculated in the normal reactor core configuration meets certain storage rack specific k_∞ criterion limits.

Normal and abnormal spent fuel storage rack configurations shall be evaluated with two dimensional geometry models. The analysis conditions and assumptions must in compliance with the requirements contained in the USNRC Regulatory Guide 1.13, Spent Fuel Storage Facility Design Basis, Rev. 2, (Reference 3) and ANSI/ANS-57.2-1983, Design Requirements for Light Water Reactor Spent Fuel Storage Facilities at Nuclear Power Plants (Reference 4).

The in-core k_∞ criterion method relies on a well-characterized relationship between infinite lattice k_∞ (in-core) for a given fuel design (i.e., GNF2) and a specific spent fuel storage rack k_∞ (in-rack) containing that fuel. The use of an infinite lattice k_∞ criterion for demonstrating compliance to fuel storage criticality criteria has been used for all GEH-supplied spent fuel storage racks, and is currently used for re-rack designs at a number of plants where earlier criteria have become limiting for modern fuel designs.

NEDC-32868P, Rev. 2, September, 2007, "GE14 Compliance with Amendment 22 of NEDE-24011-P-A (GESTAR II)" (Reference 19) presents generic information relative to the GNF2 fuel design and analyses of GE BWRs for which GNF provides fuel. The report consists of a description of the fuel licensing acceptance criteria as specified by Amendment 22 of GESTAR (General Electric Standard Application for Reactor Fuel) and the basis for generic compliance of GE fuel designs with those criteria.

Section 2.3.7, Fuel Storage, of NEDC-32868P, referencing Subsection 1.1.3.G of Amendment 22 states, "The effective multiplication factor for fuel designs stored under normal and abnormal conditions shall be shown to meet fuel storage limits by demonstrating that the peak uncontrolled lattice k-infinity calculated in a normal reactor core configuration meets the limits provided in Section 3 (of GESTAR-II) for GE-designed racks." This approved methodology has been applied to storage racks of similar design to those GE-designed racks.

The analysis performed to calculate the lattice k_∞ to confirm compliance with the above criterion uses the lattice physics portion of the methods described in Subsection 2.1.1 of "Steady-State Nuclear Methods," NEDE-30130-P-A (Reference 20). These NRC-approved lattice physics models are encoded into the TGBLA Engineering Computer Program (ECP). One of the outputs of TGBLA solution is the lattice k_∞ of a specific nuclear design for a given set of input state parameters (void fraction, control state, fuel temperature). A description of the requirements and the analytical process to calculate the fuel storage reactivity requirements is contained in Section 3.5 of NEDE-24011-P-A-16 (Reference 21).

Compliance of GNF2 fuel with specified k_∞ limits will be confirmed for each GNF2 lattice as part of the bundle design process. Documentation that this has been met will be contained in the fuel design information report which defines the maximum lattice k_∞ for each bundle nuclear design.

PROCESS FOR VALIDATING SPECIFIC GNF2 ASSEMBLY DESIGNS ARE ACCEPTABLE FOR STORAGE IN THE PBAPS BORAFLEX SPENT FUEL STORAGE RACKS

1. Identify the unique lattices in each assembly design.

2. Determine the maximum cold 68°F uncontrolled k_∞ results from standard TGBLA06 lattice physics calculations for each unique lattice in the assembly.

3. Ensure that the k_∞ values obtained from Step 2 for each lattice are less than the k_∞ limit of 1.318.

   Note: k_∞ limit of 1.318 is based on TGBLA generated GNF2 lattices with 4.90 wt% ^{235}U enrichments and 2 wt% gadolinium concentrations.

Note that lattice physics codes other than TGBLA06 may be used to perform the evaluation, subject to a determination of an appropriate k_∞ limit having been determined for the particular lattice physics code to be used.

Appendix C CRITICALITY ANALYSIS FOR FUEL INSPECTION

The criticality analyses that support the fuel inspection and reconstitution activities are based on calculations using Monte Carlo transport theory methodology.

The results of these analyses are as follows:

[[

]]

The intact fuel rod analysis was based on 5% enriched uranium. A triangular fuel rod array with optimum fuel rod pitch was conservatively assumed. The water density was varied to determine the optimum moderator conditions for each fuel rod diameter. No credit was taken for natural uranium end-segments, gadolinia burnable poisons, fuel rod depletion, nor any fission product inventory.

The maximum pellet free mass calculation was also based on 5% ^{235}U. An optimum spherical heterogeneous mass of pellets and moderator is assumed. Similar to the fuel rod calculations, no credit was taken for natural uranium end-segments, gadolinia burnable poisons, fuel rod depletion, nor any fission product inventory.

The GNFA fuel examination procedure conservatively limits the number of sound rods outside of a bundle loaded in the fuel preparation machine, at any time, to 31. In addition, these procedures limit the number of failed rods outside the bundle to three. In this way, it is assured that the maximum amount of material in an uncontrolled geometry is always maintained subcritical.