

ATTACHMENT 3

Holtec International Report No. HI-2146153, Revision 2, "Licensing Report for the Criticality
Analysis of the Dresden Unit 2 and 3 SFP for ATRIUM 10XM Fuel Design"
(Non-Proprietary Version)



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***Licensing Report for the Criticality Analysis
of the Dresden Unit 2 and 3 SFP for ATRIUM
10XM Fuel Design - Non Proprietary Version***

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1. INTRODUCTION

This report documents the criticality safety evaluation for the storage of BWR fuel in the Unit 2 and Unit 3 spent fuel pools (SFPs) at the Dresden Station operated by Exelon. The Unit 2 and Unit 3 SFP racks are identical and are designed to accommodate BWR fuel. Currently, the SFP racks credit BORAL for reactivity control. This analysis will include a new fuel design, ATRIUM 10XM. This analysis will show that the effective neutron multiplication factor (k_{eff}) in the SFP racks fully loaded with fuel of the highest reactivity, at a temperature corresponding to the highest reactivity, is less than 0.95 with a 95% probability at a 95% confidence level. Reactivity effects of abnormal and accident conditions are also evaluated to assure that under all credible abnormal and accident conditions, the reactivity will not exceed the regulatory limit.

Criticality control in the SFP, as credited in this analysis, relies on the following:

- Fixed neutron absorbers
 - BORAL fixed to the SFP rack cell walls
- Integrated neutron absorbers
 - Gadolinium (Gd) in the fuel (peak reactivity isotopic composition).

Criticality control in the SFP, as credited in this analysis, does not rely on the following:

- Crediting burnup

2. METHODOLOGY

2.1 General Approach

The analysis is performed consistent with regulatory requirements and guidance. The calculations are performed using either the worst case bounding approach or the statistical analysis approach with respect to the various calculation parameters. The approach considered for each parameter is discussed below.

2.2 Computer Codes and Cross Section Libraries

2.2.1 MCNP5-1.51

MCNP5-1.51 is a three-dimensional Monte Carlo code developed at the Los Alamos National Laboratory [1]. MCNP5-1.51 calculations use continuous energy cross-section data based on ENDF/B-VII. MCNP is selected because it has history of successful use in fuel storage criticality analyses and has most of the necessary features (except for fuel depletion analysis) for the analysis to be performed for Dresden Station SFP.

The convergence of a Monte Carlo criticality problem is sensitive to the following parameters: (1) number of histories per cycle, (2) the number of cycles skipped before averaging, (3) the total number of cycles and (4) the initial source distribution. All MCNP5 calculations are performed with a minimum of 12,000 histories per cycle, a minimum of 300 skipped cycles before averaging, and a minimum of 300 cycles that are accumulated. The initial source is specified as uniform over the fueled regions (assemblies). Convergence is determined by confirming that the source distribution converged using the Shannon entropy [1] and the k_{calc} was confirmed to converge by checking the output file.

2.2.1.1 MCNP5-1.51 Validation

Benchmarking of MCNP5-1.51 for criticality calculations is documented in [2]. The benchmarking is based on the guidance in [3], and includes calculations for a total of [REDACTED] critical experiments with fresh UO_2 fuel, fresh MOX fuel, and fuel with simulated actinide composition of spent fuel (HTC experiments [2]). The results of the benchmarking calculations show few significant trends, and indicate a truncated bias of [REDACTED]¹ with an uncertainty of \pm [REDACTED] (95% probability at a 95% confidence level) for the full set of all [REDACTED] experiments. The statistical treatment used to determine those values considered the variance of the population about the mean and used appropriate confidence factors and trend analyses. Note that the area of applicability for the MCNP5-1.51 benchmark is presented in Table 2.1(a) and confirms the applicability of benchmarking in [2] to this Dresden analysis.

Trend analyses are also performed in [2], and significant trends are determined for various subsets and parameters. In order to determine the maximum bias that is applicable to the

¹ A positive bias which results in decrease in reactivity is truncated to zero [3].

calculations in this report, the trend equations from [2] are evaluated for the specific parameters of the current analyses. The subset of all critical experiments with pure water is considered in Table D.3-13 of [2] and the tabulated bias and bias uncertainty values for several energy of average lethargy causing fission (EALF) and U-235 enrichment values are provided in Table 2.1(c).

The evaluation of MCNP5-1.51 bias and bias uncertainty applicable to the current calculations is summarized in Table 2.1(b) for all experiments and experiments with pure water. As included in Table 2.1(b), the EALF and U-235 enrichment parameters show significant trends for experiments with pure water. The bias and bias uncertainty for each of these independent parameters are calculated using the linear correlation formulas provided in Table 2.1(b) and equations 2-1 through 2-6 of [2].

Table 2.1(c) provides tabulated bias and bias uncertainty values for several EALF and U-235 enrichment values. The calculated EALF of the rack with pure water is stated in Note 1 of Table 2.1(c). The U-235 enrichment is based on the maximum U-235 enrichment of wt%, and repeated in Note 1 of Table 2.1(c). The calculated EALF for the design basis fuel assembly is within two EALF values in Table 2.1(c). Also, the maximum U-235 enrichment is within two U-235 enrichment values in Table 2.1(c). The bounding bias and bias uncertainty values for these two parameters (EALF and U-235 enrichment) are selected and compared to the bias and bias uncertainty of the 'all experiments' and 'all with pure water' (as provided in Table 2.1(b)). As can be seen, the set of bias and bias uncertainty of the 'all experiments' is largest, and is used in the maximum k_{eff} calculations.

2.2.2 CASMO-4

Fuel depletion analyses during core operation are performed with CASMO-4 Version 2.05.14 (using the 70-group cross-section library), which has been approved by the NRC for reactor analysis (depletion) when providing reactivity data for specific 3D simulator codes. CASMO-4 is a two-dimensional multigroup transport theory code based on the Method of Characteristics and it is developed by Studsvik of Sweden [4]. CASMO-4 is used to perform depletion calculations and to perform various sensitivity studies. The uncertainty on the isotopic composition of the fuel (i.e., the number density) is considered as discussed below (see Section 2.3.9). A validation for CASMO-4 to develop a bias and bias uncertainty is not necessary because the results of the CASMO-4 sensitivity studies are not used as input into the k_{eff} calculations. However, the code authors have validated CASMO-4 against MCNP and various critical experiments [5].

2.3 Analysis Methods

2.3.1 Design Basis Fuel Assembly

There are various fuel designs stored in the Dresden SFP. For the purpose of this analysis, the reactivity of each design is evaluated and the most reactive fuel bundle lattice is determined for use as the design basis fuel assembly (a single lattice (most reactive) along the entire active length) to determine k_{eff} at the 95/95 level. This approach follows the guidance in [6] and [7], and is further described below.

2.3.1.1 Peak Reactivity

The BWR fuel designs used at the Dresden Station use Gd as an integral burnable absorber. Initially, the Gd in the fuel assembly holds down the fresh fuel assembly reactivity and then, as core depletion occurs, the Gd begins to burnout until it is essentially fully depleted. As the Gd depletes the reactivity of the fuel assembly increases until it reaches a peak. This peak reactivity is the fuel assembly's most reactive condition. Note that most BWR fuel designs are composed of various axial lattices (including blankets) that can have different axial lengths, uranium loadings, fuel pin arrangements including partial or part-length rods, Gd pin locations and loading, etc. These various lattice components can all effect at what burnup the peak reactivity occurs and the magnitude of the peak reactivity. The axial lattices within a single fuel assembly can therefore all have different peak reactivity. Therefore, for each fuel design type, an assessment is made of every lattice to determine the bounding lattice (highest peak reactivity). These are the screening calculations described in Section 2.3.1.2 and are performed with CASMO-4 only. Note that using the CASMO-4 code is appropriate since all lattices are compared as axially infinite models.

Note that for the purposes of this analysis, the term "peak reactivity" is defined as the reactivity of a fuel assembly lattice in the SFP storage rack geometry as determined by MCNP5-1.51 (using CASMO-4 depletion calculation isotopic compositions which include residual Gd). This peak reactivity considers nominal fuel assembly and storage rack dimensions. For the purpose of determining the design basis fuel assembly and its bounding lattice (see Section 2.3.1.2 and Section 2.3.1.3), the core operating parameters (COP) are varied using four sets. For all further calculations using the design basis fuel assembly lattice bounding core operating parameters are used (see Section 2.3.2). Note that the fuel assembly orientation in the core with respect to its control blade does not change and therefore the CASMO-4 depletion calculations consider the only possible configuration.

2.3.1.1.1 Peak Reactivity and Fuel Assembly Burnup

Typically, a spent fuel assembly is characterized by its assembly average burnup (over all lattices or nodes). In this analysis methodology the fuel assembly average burnup is of no concern and is not credited for reactivity control. Rather, the methodology credits the residual Gd and other depletion isotopic compositions at the fuel assembly peak reactivity (most reactive lattice peak reactivity). While the peak reactivity occurs at some specific *lattice burnup*, the peak reactivity lattice burnup varies from lattice to lattice within a fuel design. Therefore, independent calculations with MCNP5-1.51 using pin specific compositions (see Section 2.3.1.1.2) are performed for *every lattice* that is selected as a result of the screening calculations (see Section 2.3.1.2) and all further design basis calculations using MCNP5-1.51. The MCNP5-1.51 calculations are performed over a burnup range to determine the burnup at peak reactivity for every lattice in the storage rack geometry. Since each lattice is considered at its peak reactivity (and therefore the lattice or nodal burnup at which that occurs), the fuel assembly average burnup or fuel assembly burnup profile is not applicable because the analysis already considers each lattice at its most reactive composition, independent of the fuel assembly average burnup.

2.3.1.1.2 Isotopic Compositions

The BWR fuel design lattices used at Dresden 2 and 3 have complex radial pin compositions. The radial variation includes enrichment, Gd rod location and loading, part length rods, etc. Furthermore, the fuel assemblies are asymmetric and are designed to a specific control blade orientation. All fuel compositions are at 0 hours cooling time with the exception of one study to show that this is conservative (see Section 2.3.1.4). For all calculations in the spent fuel pool racks, the Xe-135 concentration in the fuel is conservatively set to zero and the Np-239 isotope was considered as Pu-239.

2.3.1.2 Screening Calculations for the Design Basis Fuel Assembly

The SFP holds various legacy fuel assemblies designs, the current Optima2 design and the future ATRIUM 10XM design to be qualified for storage. For many of the legacy fuel designs, it is not necessary to perform calculations because they have a very low lattice average enrichment. Since it is known that the design basis lattice will have a high lattice average enrichment, a simple assessment of the legacy fuel population is all that is required to determine that they are bounded by the design basis lattice. Therefore, for legacy fuel designs with low lattice enrichments (i.e. less than about 1% U-235), engineering judgment is used to determine that these designs will not need screening calculations since they are well bounded by the more recent fuel designs with much higher lattice average enrichments.

For all of fuel design lattices that require screening calculations, the first step (Step 1) is to perform CASMO-4 calculations to determine the lattices that have the highest peak reactivity in the storage rack geometry (see Appendix A). For Step 1, an arbitrary value of $k_{inf} > 0.8500$ is used to determine the lattices that have the highest peak reactivity in the storage rack geometry. This arbitrary value was selected using engineering judgment.

Each of the Step 1 screening calculations using CASMO-4 includes the in core depletion and restart in SFP rack cell. Note that for the core depletion calculations, four sets of core operating parameters are used and the maximum reactivity over all four is determined (see Section A.2). These four sets of core operating parameters are presented in Table 5.2.(c) and have been selected to bound the effects of the most important parameters (i.e. void fraction, control blade use and temperatures).

Based on the results of Step 1, the most reactive fuel lattices are identified by selecting the subset of lattices that have a reactivity greater than 0.8500 (see Appendix A). The lattices which meet this criteria are then used for Step 2 calculations as described below.

2.3.1.3 Determination of the Design Basis Fuel Assembly Lattice

As discussed in Section 2.3.1.2, the Step 1 screening calculations are performed with CASMO-4 for each of the selected lattices. Based on the results of these screening calculations, the most reactive lattices are determined by comparison to the criteria of $k_{inf} > 0.8500$. Step 2 calculations are then performed using in-rack MCNP5-1.51 to determine the peak reactivity for each of the most reactive lattices selected in Step 1. See Appendix B.

Step 2 determines the peak reactivity for the most reactive lattices using MCNP5-1.51 calculations in the storage rack geometry. Note that the peak reactivity of the CASMO-4 depletion calculation model is used only for the screening calculations and is not the peak reactivity as determined by MCNP5-1.51 in rack models. MCNP5-1.51 calculations are performed over a burnup range to independently determine the peak reactivity.

The bounding set of COP determined by Step 1 in the CASMO-4 screening calculations is confirmed to be consistent with those in Step 2. See Appendix B.

The result of the Step 2 calculations are then compared, and the most reactive fuel assembly lattice is determined. Note that the results of the Step 2 lattice calculations in MCNP5-1.51 are useful to show important trends in the reactivity effect of lattice enrichment, Gd rod location, number and loading. These trends are expected to show that the most reactive lattices are those with the highest lattice average enrichment, lowest number of Gd rods and lowest Gd rod loading. The most reactive lattice is then used to construct a new lattice that is much more bounding by increasing the lattice average enrichment to the maximum value (i.e. 19.75 wt% U-235), decreasing the number of Gd rods to the minimum expected (i.e. 1) with the minimum expected Gd loading (i.e. 0.1%). This new constructed lattice is then used as the design basis fuel assembly lattice and is modeled along the entire active length for all calculations used to determine k_{eff} at the 95/95 level.

2.3.1.4 Design Basis Model

The analysis design basis MCNP5-1.51 model is a 2x2 array (and larger array sizes as noted below) that considers the formed and fabricated cell design of the storage racks. The storage rack cell wall, poison, and sheathing are all explicitly modeled along the active length of the design basis lattice. The BORAL panels are considered at their minimum thickness and loading. The design basis model explicitly considers the fuel pellet, pellet to cladding gap, cladding, water box and fuel assembly channel (unless otherwise noted below). Various studies are performed with the design basis model to determine the reactivity effect of SFP water, radial position of the fuel assembly within the storage cell, and radial orientation of the fuel in the 2x2 array with respect to the corner of the bundle which was adjacent to the control blade in the core. The reactivity impacts from these studies are discussed in detail in the sections below. The MCNP5-1.51 model uses periodic boundary conditions radially and 12 inches of water as axial reflectors. The assembly lattice is considered along the full active length. The storage rack is considered along the full active fuel length only.

The design basis model is used for all calculations used to show compliance with the regulatory limit. All calculations with the design basis model are presented in Appendix C. The design basis model differs slightly from the model used to determine the bounding lattice (i.e., the gaseous and volatile isotopes (see Table 5.4(b)) are removed from the spent fuel composition (see Appendix B).

Calculations are performed with the design basis model for the four sets of COP to confirm the selection of the bounding set from Appendix B. The design basis MCNP5-1.51 model is

presented in Figure 2.2. Note that all calculations are performed at zero hours cooling time. Justification of this cooling time is also presented in Appendix C.

The following cases are considered:

- Case 2.3.1.4.1: This is the design basis model. It is a 2x2 array cases MCNP5-1.51 with the fuel assembly centered in the rack cell. The COP used is the “min” set (see Table 5.2(c)). See Figure 2.2.
- Case 2.3.1.4.2: Same as Case 2.3.1.4.1 except that the COP used are in “nom” set.
- Case 2.3.1.4.3: Same as Case 2.3.1.4.1 except that the COP used are in “max” set.
- Case 2.3.1.4.4: Same as Case 2.3.1.4.1 except that the COP used are in “minr” set.
- Case 2.3.1.4.5: Same as Case 2.3.1.4.1 except that the isotopic compositions are at 72 hours cooling time.

The results of these calculations are presented in Table C.1. The results presented in Table C.1 also provide the bounding case from Appendix B so that a comparison can be made between the two calculations.

2.3.2 Core Operating Parameters

As previously discussed, CASMO-4 is used to perform depletion calculations to determine the spent fuel isotopic composition. The operating parameters for spent fuel depletion calculations are discussed in this Section. The core operating parameters which may have a significant impact on BWR spent fuel isotopic composition are void fraction, control blade history, moderator temperature, fuel temperature, and power density. Other parameters such as the effect of burnable absorbers and axial enrichment distribution are discussed in Section 2.3.3 and Section 2.3.4, respectively. For the purpose of determining the bounding set of COP for each lattice, four sets of COP are used (see Table 5.2(c)). The bounding set of COP is determined using both CASMO-4 and MCNP5-1.51 calculations (see Appendix A and Appendix B). The bounding set of COP for the design basis lattice is used for all design basis lattice calculations (see Appendix C).

2.3.3 Integral Reactivity Control Devices

The only type of burnable absorber used for the fuel assemblies covered in this analysis is Gd. The use of Gd does not increase the reactivity of the assembly, compared to an assembly lattice where all rods contain fuel and no Gd. As discussed in Section 2.3.1.1.1, the Gd in the fuel assembly holds down the fresh fuel assembly reactivity and then, as core depletion occurs, the Gd begins to burnout until it is essentially fully depleted. As the Gd depletes the reactivity of the fuel assembly increases until it reaches a peak. This peak reactivity is the fuel assembly's most reactive condition, which is used for design basis condition.

2.3.4 Axial and Planar Enrichment Variations

All calculations were performed with the design basis fuel assembly lattice pin specific enrichment(s), without any axial variation.

2.3.5 Fuel Assembly Eccentric Positioning and Fuel Assembly De-Channeling

The BWR fuel that is loaded in the SFP racks may not rest exactly in the center of the storage cell, therefore the potential reactivity effect of this eccentric positioning should be evaluated. The ATRIUM 10XM fuel assembly (the most reactive fuel assembly, as will be shown in Section 7) may be de-channelled, therefore the potential reactivity effect of de-channeling should be evaluated. These two parameters, storage cell eccentric positioning and the fuel assembly de-channeling may occur simultaneously and may impact the reactivity effect of each other. Therefore the two parameters should be evaluated together. Evaluations are therefore performed to determine the most limiting fuel radial location for fuel with and without a channel.

The following cases with the fuel assembly channel present are analyzed:

- Case 2.3.5.1: This is the reference for the 2x2 array cases, Case 2.3.5.2 and Case 2.3.5.3. The MCNP5-1.51 model used herein is a 2x2 array with the fuel assembly centered in the rack cell. This model is the same model as the design basis model. See Figure 2.2.
- Case 2.3.5.2: Every fuel assembly is positioned toward the center as shown in Figure 2.3.
- Case 2.3.5.3: Every fuel assembly is positioned toward one corner as shown in Figure 2.4.
- Case 2.3.5.4: This is the reference for Case 2.3.5.5 and Case 2.3.5.6. The MCNP5-1.51 model used herein is an 8x8 array with the fuel assembly centered in the rack cell. The model is the same as the design basis model but the array size is larger.
- Case 2.3.5.5: Every fuel assembly is positioned toward the center as shown in Figure 2.5.
- Case 2.3.5.6: Every fuel assembly is positioned toward one corner as shown in Figure 2.6.

The following cases with the fuel assembly channel NOT present are analyzed:

- Case 2.3.5.7: This is the reference for the 2x2 array cases, Case 2.3.5.8 and Case 2.3.5.9. The MCNP5-1.51 model used herein is a 2x2 array with the fuel assembly centered in the rack cell. This model is the same model as the design basis model except that the fuel channel has been removed.
- Case 2.3.5.8: Every fuel assembly is positioned toward the center as shown in Figure 2.7.

- Case 2.3.5.9: Every fuel assembly is positioned toward one corner as shown in Figure 2.8.
- Case 2.3.5.10: This is the reference for Case 2.3.5.11 and Case 2.3.5.12. The MCNP5-1.51 model used herein is an 8x8 array with the fuel assembly centered in the rack cell. The model is the same as the design basis model but the array size is larger.
- Case 2.3.5.11: Every fuel assembly is positioned toward the center as shown in Figure 2.9.
- Case 2.3.5.12: Every fuel assembly is positioned toward one corner as shown in Figure 2.10.

The maximum positive reactivity effect of the MCNP5-1.51 calculations for the fuel eccentric positioning and de-channeling is added as the bias and the corresponding 95/95 uncertainty is statistically combined with other uncertainties to determine k_{eff} .

2.3.6 Fuel Bundle Orientation in SFP Rack Cell

As described in Section 2.3.1.1.2, fuel assemblies have various radial fuel enrichments and gadolinium distribution. Also, one corner of each fuel assembly is adjacent to the control blade during the depletion in the core. As a result, the fuel depletion is not uniform and therefore one fuel assembly corner may be more reactive than other corners and the fuel assembly orientation in the SFP storage cell may have an impact on reactivity.

Five cases are analyzed to assess the fuel assembly orientation variations and to determine the most limiting fuel orientation in SFP rack cell.

The MCNP5-1.51 model of the reference case is the design basis fuel in the 2x2 array, as shown in Figure 2.2. The MCNP5.1.51 models of the other four cases are the same as that of the reference case, except with different orientations. The following cases are considered:

- Case 2.3.6.1: This is the reference for the 2x2 array cases, Case 2.3.6.2 through Case 2.3.6.5. This model is the same model as the design basis model where the corner of the lattice adjacent to the control blades in the core is oriented towards the north west. See Figure 2.2.
- Case 2.3.6.2: The fuel assembly in each cell in the 2x2 array is oriented as shown in Figure 2.11.
- Case 2.3.6.3: The fuel assembly in each cell in the 2x2 array is oriented as shown in Figure 2.12.
- Case 2.3.6.4: The fuel assembly in each cell in the 2x2 array is oriented as shown in Figure 2.13.

- Case 2.3.6.5: The fuel assembly in each cell in the 2x2 array is oriented as shown in Figure 2.14.

Note that the evaluations use the same MCNP5-1.51 models with periodic boundary conditions used in the design basis calculation. The isotopic compositions of the fuel rods are the same as those of the design basis fuel assembly.

The maximum positive reactivity effect of the MCNP5-1.51 calculations for the fuel bundle orientation is added as the bias and the corresponding 95/95 uncertainty is statistically combined with other uncertainties to determine k_{eff} .

2.3.7 Reactivity Effect of Spent Fuel Pool Water Temperature

The Dresden Station SFP has a normal pool water temperature operating range below 150 °F. For the nominal condition, the criticality analyses are to be performed at the most reactive temperature and density [6]. Also, there are temperature-dependent cross section effects in MCNP5-1.51 that need to be considered. In general, both density and cross section effects may not have the same reactivity effect for all storage rack scenarios, since configurations with strong neutron absorbers typically show a higher reactivity at lower water temperature, while configurations without such neutron absorbers typically show a higher reactivity at a higher water temperature. For the SFP racks which credit neutron absorbers, the most reactive SFP water temperature and density is expected to be at 39.2 °F and 1 g/cc, respectively.

The standard cross section temperature in MCNP5-1.51 is 293.6 K. Cross sections are also available at other temperatures; however, not usually at the desired temperature for SFP criticality analysis. MCNP5-1.51 has the ability to automatically adjust the cross sections to the specified temperature when using the TMP card. Furthermore, MCNP5-1.51 has the ability to make a molecular energy adjustment for select materials (such as water) by using the S(α,β) card. The S(α,β) card is provided for certain fixed temperatures which are not always applicable to SFP criticality analysis. Rather, there are limited temperature options, i.e., 293.6 K and 350 K, etc. Additionally, MCNP5-1.51 does not have the ability to adjust the S(α,β) card for temperatures as it does for the TMP card discussed above. Therefore, additional studies are performed to show the impact of the S(α,β) card at the two available temperatures.

To determine the water temperature and density which result in the maximum reactivity, MCNP5-1.51 calculations are run using the bounding values. Additionally, S(α,β) calculations are performed for both upper and lower bounding S(α,β) values, if needed. Additional cases are added to cover the potential increase in temperature beyond normal conditions (i.e. accident condition).

The following cases are considered:

- Case 2.3.7.1 (reference case): Temperature of 39.2 °F (277.15 K) and a density of 1.0 g/cc are used to determine the reactivity at the low end of the temperature range. The S(α,β) card corresponds to a temperature of 68.81 °F (293.6 K).

- Case 2.3.7.2: Temperature of [REDACTED] °F ([REDACTED] K) and a corresponding density of [REDACTED] g/cc are used to determine the reactivity at the high end of the temperature range. The $S(\alpha,\beta)$ card corresponds to a temperature of 68.81 °F (293.6 K).
- Case 2.3.7.3: Temperature of [REDACTED] °F ([REDACTED] K) and a corresponding density of [REDACTED] g/cc. The $S(\alpha,\beta)$ card corresponds to a temperature of 170.33 °F (350 K).
- Case 2.3.7.4: Temperature of 212 °F (373.15 K) and a corresponding density of 0.95837 g/cc. The $S(\alpha,\beta)$ card corresponds to a temperature of 170.33 °F (350 K). This is a SFP water temperature accident condition.
- Case 2.3.7.5: Temperature of 212 °F (373.15 K) and a corresponding density of 0.95837 g/cc. The $S(\alpha,\beta)$ card corresponds to a temperature of 260.33 °F (400 K). This is a SFP water temperature accident condition.
- Case 2.3.7.6: Temperature of 255 °F (397.04 K) and a corresponding density of 0.84591 g/cc. The $S(\alpha,\beta)$ card corresponds to a temperature of 260.33 °F (400 K). In this model, it is assumed that the water modeled includes 10% void. Void is modeled as 10% decrease in density, compared to the density of water at 255 °F. This is a SFP water temperature accident condition.

The bounding water temperature and density (the temperature and its corresponding density which result in the maximum reactivity) of the above cases are applied to all further calculations so that the most reactive water temperature and density is considered. Note that the evaluations use the same MCNP5-1.51 models used in the design basis calculation. The pin specific isotopic compositions of the fuel rods are the same as those of the design basis fuel assembly.

2.3.8 Fuel and Storage Rack Manufacturing Tolerances

In order to determine the k_{eff} of the SFP at a 95% probability at a 95% confidence level, consideration is given to the effect of the BWR fuel and SFP storage rack manufacturing tolerances on reactivity. The reactivity effects of significant independent tolerance variations are combined statistically [6]. The evaluations use the same MCNP5-1.51 models used in the design basis calculation.

2.3.8.1 Fuel Manufacturing Tolerances

The BWR fuel tolerances for ATRIUM 10XM design basis lattice (which is the most reactive fuel design evaluated herein) are presented in Table 5.1(h). Fuel tolerance calculations are performed using the design basis fuel assembly lattice only because the reactivity of the design basis lattice is much greater than lattices from other fuel bundle designs. Therefore, only the tolerances applicable to that lattice are applicable. Separate CASMO-4 depletion calculations are performed for each fuel tolerance and the full value of the tolerance is applied for each case in both the depletion and in rack calculations. Pin specific compositions are used. The MCNP5-1.51 tolerance calculation is compared to the MCNP5-1.51 reference case (nominal parameter values) at the 95% probability at a 95% confidence level using the following equation:

$$\text{delta-}k_{\text{calc}} = (k_{\text{calc2}} - k_{\text{calc1}}) \pm 2 * \sqrt{(\sigma_1^2 + \sigma_2^2)}$$

The following fuel manufacturing tolerances cases are considered in this analysis:

- Case 2.3.8.1.1 (reference case): This is the reference for all the other fuel tolerance cases. This MCNP5-1.51 model is the same model as the design basis model. See Figure 2.2.
- Case 2.3.8.1.2: This is the fuel pellet density increase tolerance.
- Case 2.3.8.1.3: This is the fuel pellet diameter increase tolerance.
- Case 2.3.8.1.4: This is the fuel pellet diameter decrease tolerance.
- Case 2.3.8.1.5: This is the minimum cladding thickness tolerance. In this model, the maximum cladding inner diameter and minimum cladding outer diameter are applied together.
- Case 2.3.8.1.6: This is the increased rod pitch tolerance.
- Case 2.3.8.1.7: This is the decreased rod pitch tolerance.
- Case 2.3.8.1.8: This is the increased channel thickness tolerance.
- Case 2.3.8.1.9: This is the decreased channel thickness tolerance.
- Case 2.3.8.1.10: This is the increased fuel enrichment tolerance. All fuel pins have an increase in U-235 enrichment, including the Gd rods, of 0.05 wt% U-235.
- Case 2.3.8.1.11: This is the decreased Gd loading tolerance.

The maximum positive reactivity effect of the MCNP5-1.51 calculations for each tolerance is statistically combined with the other tolerance results, and this result is then statistically combined with other uncertainties when determining the k_{eff} value.

2.3.8.2 SFP Storage Rack Manufacturing Tolerances

The SFP rack tolerances are presented in Table 5.3. The full value of the tolerance is applied for each case. The MCNP5-1.51 tolerance calculation is compared to the MCNP5-1.51 reference case with a 95% probability at a 95% confidence level using the following equation:

$$\text{delta-}k_{\text{calc}} = (k_{\text{calc2}} - k_{\text{calc1}}) \pm 2 * \sqrt{(\sigma_1^2 + \sigma_2^2)}$$

The following rack manufacturing tolerances cases are considered in this analysis:

- Case 2.3.8.2.1 (reference case): This is the reference for all the other rack tolerance cases. This MCNP5-1.51 model is the same model as the design basis model. See Figure 2.2.
- Case 2.3.8.2.2: This is the increased storage cell inner diameter (ID) tolerance.
- Case 2.3.8.2.3: This is the decreased storage cell inner diameter tolerance.
- Case 2.3.8.2.4: This is the increased wall thickness tolerance. Note that the tolerance associated with the wall thickness is assumed to be 10% of the wall thickness.
- Case 2.3.8.2.5: This is the decreased wall thickness tolerance. Note that the tolerance associated with the wall thickness is assumed to be 10% of the wall thickness.
- Case 2.3.8.2.6: This is the increased storage cell pitch tolerance.
- Case 2.3.8.2.7: This is the decreased storage cell pitch tolerance.
- Case 2.3.8.2.8: This is the increased BORAL width tolerance.
- Case 2.3.8.2.9: This is the decreased BORAL width tolerance.

The maximum positive reactivity effect of the MCNP5-1.51 calculations for each tolerance is statistically combined with the other tolerance results, and this result is then statistically combined with other uncertainties when determining the k_{eff} value.

The evaluations use the same MCNP5-1.51 models used in the design basis calculation. The isotopic compositions of the fuel rods are the same as those of the design basis fuel assembly.

The poison thickness and loading are used at their minimum values for all calculations; i.e., they are treated as a bias instead of uncertainty, for conservatism and simplification.

2.3.9 Fuel Depletion Calculation Uncertainty

To account for the uncertainty of the number densities in the depletion calculations performed in CASMO-4, a 5% depletion uncertainty factor as described in [6] and [7] is used. Note that an additional uncertainty factor is used to account for the uncertainty in the cross sections; for fission products see Section 2.3.10.

The depletion uncertainty is applied by multiplying it with the reactivity difference (at 95%/95%) between the MCNP5-1.51 calculation with spent fuel at peak reactivity (includes residual Gd) and a corresponding MCNP5-1.51 calculation with fresh fuel (without Gd_2O_3).

The uncertainty is determined by the following:

$$\text{Uncertainty}_{\text{Isotopes}} = [(k_{\text{calc-2}} - k_{\text{calc-1}}) + 2 * \sqrt{(\sigma_{\text{calc-1}}^2 + \sigma_{\text{calc-2}}^2)}] * 0.05$$

with

$k_{calc-1} = k_{calc}$ with spent fuel

$k_{calc-2} = k_{calc}$ with fresh fuel

σ_{calc-1} = Standard deviation of k_{calc-1}

σ_{calc-2} = Standard deviation of k_{calc-2}

The following case is considered:

- Case 2.3.9.1 (reference case): This is the reference case. This MCNP5-1.51 model is the same model as the design basis model. See Figure 2.2.
- Case 2.3.9.2: This is the fresh fuel with no Gd case.

The result of the MCNP5-1.51 calculation for the fuel depletion calculation uncertainty is statistically combined with other uncertainties to determine k_{eff} .

2.3.10 Fission Products and Lumped Fission Products Uncertainty

Few relevant critical experiments are publicly available for fission products (FP) and minor actinides, and therefore direct validation similar to the actinide validation is not feasible and cannot be directly included in the MCNP5-1.51 benchmark bias and bias uncertainty. The uncertainty in the reactivity worth of FP and minor actinides isotopes is determined based on consideration of uncertainties of cross sections of FPs documented in [9]. The overall uncertainty is derived from the uncertainty associated with each individual isotope's cross section for all FPs and lumped fission products (LFP) and is determined at a 95% probability at a 95% confidence level. Based on the discussion and evaluation presented in [10], an uncertainty value of 1.5% is used for both the FPs and LFPs. Note that no statistical approach is used here, i.e., the uncertainty is applied equally to the effect of all FPs (including minor actinides) and LFPs. Also note that recent studies [11, 12] indicate that the total cross section uncertainty for 16 prominent fission products is only about 1.5% (one standard deviation) at 95% probability at a 95% confidence level.

The uncertainty is applied by multiplying it with the reactivity difference (at 95%/95%) between the MCNP5-1.51 calculation with all isotopes and a corresponding MCNP5-1.51 calculation where all FPs and LFPs have been removed. The MCNP-1.51 model is the same as the design basis model. The uncertainty of the calculations is calculated using the following equation:

$$\text{Uncertainty} = [(k_{calc-2} - k_{calc-1}) + 2 * \sqrt{(\sigma_{calc-1})^2 + (\sigma_{calc-2})^2}] * 1.5\%$$

with

$k_{calc-1} = k_{calc}$ with FPs and LFPs included

$k_{calc-2} = k_{calc}$ with FPs and LFPs removed

σ_{calc-1} = Standard Deviation of k_{calc-1}

σ_{calc-2} = Standard Deviation of k_{calc-2}

The following case is considered:

- Case 2.3.10.1 (reference case): This is the reference case. This MCNP5-1.51 model is the same model as the design basis model. See Figure 2.2.
- Case 2.3.10.2: This is the spent fuel with FP/LFP removed case.

The result of the MCNP5-1.51 calculation for the FP and LFP calculation uncertainty is statistically combined with other uncertainties to determine k_{eff} .

All cases analyzed here have neutron spectra in the thermal energy range and the fission products are predominantly thermal absorbers. Additionally, fission processes are affected by the resonance integrals of the absorbers. The fission product cross section uncertainty is evaluated for the thermal neutron energy range and the resonance integral. The uncertainty is therefore directly applicable to the calculations performed here.

2.3.11 Depletion Related Fuel Assembly Geometry Changes

During irradiation the BWR fuel assembly may experience depletion related fuel geometry changes. These changes can be fuel rod growth and cladding creep, crud buildup, fuel rod bow and the fuel channel may bow and bulge. These fuel assembly geometry changes can affect the neutron spectrum during depletion by changing the fuel to moderator ratio. In the spent fuel pool, there are two potential impacts from the depletion related fuel geometry changes: first, the effect during depletion may lead to a different isotopic composition, second, the fuel geometry change itself can also impact reactivity by the change in the fuel to moderator ratio. The effect of these possible fuel geometry changes on the reactivity of the fuel in the SFP are discussed below.

Note that since the peak reactivity for the design basis fuel assembly is below ■ GWd/mtU (i.e. is about ■ GWd/mtU), there is no expected significant reactivity impact associated with any minimal fuel geometry changes which occur below that exposure value.

2.3.11.1 Fuel Rod Geometry Changes

Possible changes to the fuel rod geometry may occur as a result of fuel rod growth, cladding creep, and crud buildup. These geometry changes have the potential to change the fuel-to-moderator ratio in the geometry, thus potentially increasing reactivity, and are therefore discussed below.

2.3.11.1.1 Fuel Rod Growth and Cladding Creep

Fuel rod growth and cladding creep is not expected for the design basis lattice at the peak reactivity burnup (i.e. about ■ GWd/mtU). Therefore, no additional calculations are performed.

2.3.11.1.2 Fuel Rod Crud Buildup

Crud buildup on the fuel rod cladding decreases the amount of water around the fuel rods and thus increases the fuel-to-moderator ratio. The amount of crud buildup at peak reactivity is not expected to be significant. Therefore, no further evaluations are performed.

2.3.11.1.3 Fuel Rod Bow

Fuel rod bow is a depletion related geometry change that alters the fuel rod pitch. The effect of the fuel rod bow is similar to the fuel rod crud buildup (see Section 2.3.11.1.2). The reactivity impact of this geometry change to the fuel in the SFP is evaluated using the depletion related fuel rod pitch positive tolerance provided in Table 5.1(h).

The following fuel rod bow cases are considered:

- Case 2.3.11.1.3.1 (reference case): This is the reference case. This MCNP5-1.51 model is the same model as the design basis model. See Figure 2.2.
- Case 2.3.11.1.3.2: This is the fuel rod bow case. The isotopic compositions are taken from CASMO4 runs with this geometry change included. The geometry change is also included in the geometry of the MCNP5-1.51 model.

The results of the MCNP5-1.51 calculations are used to determine a bias and bias uncertainty. The bias and bias uncertainty are applied to the design basis results as discussed in Section 2.3.13.

The maximum positive reactivity effect of the MCNP5-1.51 calculations for the fuel rod bow is added as the bias and the corresponding 95/95 uncertainty is statistically combined with other uncertainties to determine k_{eff} .

2.3.11.2 Fuel Channel Bulging and Bowing

Fuel channel bulging and bowing is a depletion related geometry change that changes the proximity of the channel to the fuel rods. Since the proximity of the channel relative to the fuel rods may change, the temperature and density of the moderator during depletion may change (volume of moderator inside the channel may change). The reactivity effect of fuel channel bulging and bowing is evaluated using the channel outer exposed width tolerance presented in Table 5.1(h).

The following fuel channel bulging and bowing cases are considered:

- Case 2.3.11.2.1: This is the fuel channel bulging and bow case. The isotopic compositions are taken from CASMO4 runs with this geometry change included. The geometry change is also included in the geometry of the MCNP5-1.51 model.

The results of the MCNP5-1.51 calculations are used to determine a bias and bias uncertainty. The bias and bias uncertainty are applied to the design basis results as discussed in Section 2.3.13.

The maximum positive reactivity effect of the MCNP5-1.51 calculations for the fuel channel bulging and bowing is added as the bias and the corresponding 95/95 uncertainty is statistically combined with other uncertainties to determine k_{eff} .

2.3.12 SFP Storage Rack Interfaces

The Dresden SFP storage racks are all the high density egg crate design. BORAL panels are fixed to the outside of all fabricated cells and these fabricated cells are joined to create formed cells. Along the outside of each rack module, BORAL panels are not fixed to the locations where the formed cells reach the edge, thus there is no BORAL panel every other location. For each rack module, the fabricated cell is placed in each corner of the module so that there is always a BORAL panel beginning and ending each rack module edge. For the location where the formed cell is along the rack module edge there is a steel filler plate welded to cover the hole.

The rack design method creates a configuration where there may be no BORAL between two fuel bundles in adjacent rack modules, only the steel filler plates. Therefore, the reactivity effect of this interface condition is evaluated.

The following interface cases are considered:

- Case 2.3.12.1. The MCNP5-1.51 model is a 16x16 array model. The array is the same as the design basis model except that along every 8 columns of cells every other location has both BORAL panels removed. The two steel sheathings were left in the model to represent the steel plate. Thus, the steel plate thickness considered in the model is thinner than the actual steel plate (see Table 5.3). Note that in this model the gap between racks is not included in the model at all. All fuel is cell centered. See Figure 2.15.
- Case 2.3.12.2: This is the same as Case 2.3.12.1 except the fuel is eccentric towards the center of the model.

For the purpose of the interface calculations, two 16x16 array models that are larger arrays of the design basis model (one cell centered and one with the fuel eccentric towards the center of the model), are used as reference cases. The results of the MCNP5-1.51 calculations are used to determine a bias and bias uncertainty.

The maximum positive reactivity effect of the MCNP5-1.51 calculations for the storage rack interface is added as the bias and the corresponding 95/95 uncertainty is statistically combined with other uncertainties to determine k_{eff} .

2.3.13 Maximum k_{eff} Calculation for Normal Conditions

The calculation of the maximum k_{eff} of the SFP storage racks fully loaded with design basis fuel assemblies at their maximum reactivity is determined by adding all uncertainties and biases to the calculated reactivity. Note that the BORAL thickness and its B-10 loading are taken at their worst case values in all design basis cases.

k_{eff} is determined by the following equation:

$$k_{\text{eff}} = k_{\text{calc}} + \text{uncertainty} + \text{bias}$$

where uncertainty includes:

- Fuel manufacturing tolerances
- SFP storage rack manufacturing tolerances
- Fuel eccentricity bias uncertainty
- Fuel orientation bias uncertainty
- Fuel channel bow bias uncertainty
- Fuel rod bow bias uncertainty
- Depletion calculation uncertainty
- FPs and LFPs uncertainty
- MCNP5-1.51 bias uncertainty (95% probability at a 95% confidence level)
- MCNP5-1.51 calculations statistics (95% probability at a 95% confidence level, 2σ)
- Interface bias uncertainty

and the bias includes

- Fuel eccentricity bias
- Fuel orientation bias
- Fuel channel bow bias
- Fuel rod bow bias
- MCNP5-1.51 bias
- Interface bias

Note that each uncertainty is statistically combined with other uncertainties, while biases are added together in order to determine k_{eff} .

The approach used in this analysis takes credit for residual Gd at peak reactivity.

2.3.14 Fuel Movement, Inspection and Reconstitution Operations

Fuel movement procedures govern the movement and inspection of the fuel at all times that the fuel is onsite. The new fuel enters the SFP via the fuel prep machine (FPM). The FPM has a single fuel assembly capacity. There are two FPMs in each SFP, which could be loaded with fuel at the same time. However, the FPMs are greater than ■ feet apart, which is a low reactivity

configuration because of the distance between either FPM so no further analysis beyond the normal condition is necessary. The fuel is then picked up by the refueling platform, which also has a single fuel assembly capacity at any given time, and moved into a storage location in the storage rack. The fuel is always moved above the rack and never moved along the side of the rack. From the storage rack, the fuel is picked up by the refueling platform and moved through the refueling slot for transport to the core. The return trip uses the same process in reverse. All of these fuel movement operations involve a single fuel assembly that is never in close enough (i.e., directly adjacent) proximity to any other fuel that the configuration is not bounded by the analysis for normal conditions.

The FPM is not considered to be a long-term storage location for fuel but it is physically possible that a fuel assembly in the FPM could be approached by another fuel assembly in the refueling platform. The FPM is only single capacity; therefore, once a fuel assembly is in the FPM there is no normal operation that would allow the presence of another fuel assembly in close proximity to the FPM. This configuration (i.e., two fuel bundles in or around a FPM) is not considered a normal configuration.

Due to the location of the FPM, only one of the two refueling platforms can ever physically use the FPM at any given time. Furthermore, dimensions for distance from the FPMs to the nearest SFP rack is 11 inches, which is more than the dimensions of a fuel assembly.

2.3.15 Accident Condition

The accidents considered are:

- SFP temperature exceeding the normal range
- Dropped assemblies
- Missing BORAL Panel
- Rack movement
- Mislocated fuel assembly (a fuel assembly in the wrong location outside the storage rack, including the platform area)

Those are briefly discussed in the following sections.

Note that the double contingency principle as stated in [6] specifies that “two unlikely independent and concurrent incidents or postulated accidents are beyond the scope of the required analysis.” This principle precludes the necessity of considering the simultaneous occurrence of multiple accident conditions. The k_{eff} calculations performed for the accident conditions are done with a 95% probability at a 95% confidence level.

The accident conditions are considered at the 95/95 level using the total corrections from the design basis case. Note that the design basis lattice is used for the accident analyses.

2.3.15.1 Temperature and Water Density Effects

The SFP water temperature accident conditions for consideration are the increase in SFP water temperature above the maximum SFP operating temperature of ■■■ °F (the decrease in temperature was already considered for the temperature coefficient determination as discussed in Section 2.3.7). The increase in SFP temperature accident cases are discussed in Section 2.3.7 and are bounded by the calculations at reduced temperature.

2.3.15.2 Dropped Assembly – Horizontal

For the case in which a fuel assembly is assumed to be dropped on top of a rack, the fuel assembly will come to rest horizontally on top of the rack with a separation distance between the fueled portions of the two assemblies of more than 12 inches. Thus, the horizontally dropped assembly is decoupled from the fuel assemblies in the rack. This accident is also bounded by the mislocated case, where the mislocated assembly is closer to the assembly in the racks. Therefore, the horizontally dropped fuel assembly is not evaluated further in the report.

2.3.15.3 Dropped Assembly – Vertical into an Empty Storage Cell

It is also physically possible to vertically drop an assembly into a location that might be empty and such a drop may result in deformation of the rack baseplate. In that case some part of the active fuel length may extend beyond the BORAL panel out of the bottom of the rack. This potential configuration is physically similar to the normal condition of insertion and removal of fuel from the storage rack. In the normal condition of insertion and removal of a fuel assembly from the storage cell, the active fuel in the rack remains well within the length of the BORAL panels, while the part of the moving fuel bundle that is above the length of the BORAL panel is physically separated from the fuel in the rack by a sufficient amount of water to preclude neutron coupling. For the case where the fuel assembly is dropped into an empty cell, the fuel assembly could potentially break through the baseplate. The design of the rack is such that each storage cell location has a baseplate that is not connected with the adjacent cells. Therefore, this accident condition is physically the same as the normal condition of insertion and removal of fuel in the rack. However, this case is considered to show that there is no reactivity effect associated with this configuration.

The following vertical drop cases are considered:

- Case 2.3.15.3.1: This MCNP5-1.51 model is the same model as the design basis model but the array is 16x16. In the center location, the active length is extended below the active length of the other fuel by the thickness of the baseplate and the distance from the baseplate to the pool floor (see Table 5.3). All fuel is centered in the storage cell. See Figure 2.16.
- Case 2.3.15.3.2: Same as Case 2.3.15.3.1 but the fuel is eccentric in the storage cell towards the dropped fuel.

2.3.15.4 Missing BORAL Panel

The missing BORAL panel accident is considered to cover the potential that a BORAL panel may have been inadvertently not installed during construction of the rack or that a panel might become dislodged by some other accident force.

The following cases are considered:

- Case 2.3.15.4.1: This MCNP5-1.51 model is the same model as the design basis model but the array is 8x8. The cell in the center of the model has 1 BORAL panel removed. All fuel is centered in the storage cell. See Figure 2.17.
- Case 2.3.15.4.2: This is the same as Case 2.3.15.4.1 but the fuel is eccentric toward the missing BORAL panel.

2.3.15.5 Rack movement

The racks may move due to seismic activity and the gaps between racks may close. However, the design basis analysis already considers the interface of the racks without any gap, and therefore this condition is already analyzed.

2.3.15.6 Mislocated Fuel Assembly

The Dresden SFP layout was reviewed to determine the possible worst case locations for a mislocated fuel assembly. Five hypothetical locations where a fuel assembly may be mislocated are:

- Adjacent to the storage rack side where there is no BORAL panel
- In the corner between two racks
- In the corner between three racks
- Between the SFP rack and the FPM
- Between the two locations on the FPM.

The cited scenarios are evaluated, as follows.

2.3.15.6.1 Mislocated Fuel Assembly Adjacent to the Storage Rack

A fuel assembly may be mislocated adjacent to the storage rack in one of the alternating locations where there is no BORAL panel. The reactivity effect of this accident is discussed below.

The following cases are considered:

- Case 2.3.15.6.1.1: This MCNP5-1.51 model is the same model as the design basis model but the array is 80x80. The mislocated fuel assembly is placed adjacent to the storage rack on one side, aligned vertically with the fuel in the storage rack and in a location that is face adjacent to a location with no BORAL panel. The fuel in the storage rack is cell centered.

- Case 2.3.15.6.1.2: This is the same as Case 2.3.15.6.1.1 but the fuel in the storage rack is eccentrically positioned toward the center of the model.

2.3.15.6.2 Mislocated Fuel Assembly in the Corner between Two Racks

There are some places in the SFP, but outside of the racks, where the mislocated fuel assembly may be in the corner between two racks (thus the mislocated fuel assembly would be adjacent to the fuel assemblies in racks from two sides). To evaluate the effect of the mislocated fuel assembly in the corner between two racks, the following cases are evaluated:

- Case 2.3.15.6.2.1: This MCNP5-1.51 model is the same model as the design basis model but the array is 80x80 with a corner cut out to model the junction of two racks. The mislocated fuel assembly is in the corner between two racks. The two rack faces where the fuel assembly is mislocated do not have BORAL panels. This configuration is not physically possible because the racks are designed so that the BORAL panels are always in the first location along the outer edge. However, this model is conservative. The fuel in the storage rack is cell centered. See Figure 2.18.
- Case 2.3.15.6.2.2: The MCNP5-1.51 model is the same as Case 2.3.15.6.2.1, except with all fuel assemblies in the storage rack eccentric toward the misplaced fuel assembly.

2.3.15.6.3 Mislocated Fuel Assembly in the Corner between Three Racks

There is a location in the SFP where the mislocated fuel assembly may be in the corner between three racks (thus the mislocated fuel assembly would be adjacent to the fuel assemblies in racks from three sides, although there is a significant gap for the third face). To evaluate the effect of the mislocated fuel assembly in the corner between three racks, the following cases are evaluated:

- Case 2.3.15.6.3.1: This MCNP5-1.51 model is the same model as the design basis model but the array is 80x80 with a corner cut out to model the junction of three racks. The mislocated fuel assembly is in the corner between the three racks. The two rack faces where the fuel assembly is mislocated do not have BORAL panels. This configuration is not physically possible because the racks are designed so that the BORAL panels are always in the first location along the outer edge. However, this model is conservative. The fuel in the storage rack is cell centered. See Figure 2.19.
- Case 2.3.15.6.3.2: The MCNP5-1.51 model is the same as Case 2.3.15.6.3.1, except with all fuel assemblies in the storage rack eccentric toward the misplaced fuel assembly.
- Case 2.3.15.6.3.3: The MCNP5-1.51 model is the same as Case 2.3.15.6.3.1, except that the gap between the mislocated fuel assembly and the third rack is closed.
- Case 2.3.15.6.3.4: The MCNP5-1.51 model is the same as Case 2.3.15.6.3.3, except with all fuel assemblies in the storage rack eccentric toward the misplaced fuel assembly.

2.3.15.6.4 Mislocated Fuel Assembly in the FPM

The FPM is located adjacent to the SFP storage racks. The FPM has a fuel assembly capacity of two, where the pitch between the two locations on the FPM is specified in Table 5.3. There is a possibility that a fuel assembly could be mislocated between the two FPM locations or between the FPM locations and the storage rack. Note that the pitch is large enough to preclude neutron coupling between FPM locations. However, for conservatism, the evaluation of this potential mislocated fuel assembly accident condition considers that the distance between the two FPM locations is reduced to about 12 inches and one of them is face adjacent to a missing BORAL panel location. The gap between the FPM location and the storage rack is 12 inches.

The following FPM mislocated fuel assembly accident cases are considered:

- Case 2.3.15.6.4.1: The FPM mislocated MCNP5-1.51 model is a large 80x80 array. The model includes two FPM fuel assemblies. No FPM structural materials are considered. The mislocated fuel assembly is placed between the two FPM fuel assemblies with a small gap (position 1) to the closest location. The fuel is centered in the SFP storage rack cells. See Figure 2.20.
- Case 2.3.15.6.4.2: This is the same as Case 2.3.15.6.4.1 but the fuel is eccentric in the SFP storage rack cells toward the FPM.
- Case 2.3.15.6.4.3: This is the same as Case 2.3.15.6.4.1 but the mislocated fuel is at a distance (position 2) from the closest FPM location.
- Case 2.3.15.6.4.4: This is the same as Case 2.3.15.6.4.3 but the fuel is eccentric in the SFP storage rack cells towards the mislocated fuel assembly.
- Case 2.3.15.6.4.5: This is the same as Case 2.3.15.6.4.1 but the mislocated fuel is at a distance (position 3) from the closest FPM location.
- Case 2.3.15.6.4.6: This is the same as Case 2.3.15.6.4.5 but the fuel is eccentric in the SFP storage rack cells toward the mislocated fuel assembly.
- Case 2.3.15.6.4.7: This is the same as Case 2.3.15.6.4.1 but the mislocated fuel is at a distance (position 4) from the closest FPM location.
- Case 2.3.15.6.4.8: This is the same as Case 2.3.15.6.4.7 but the fuel is eccentric in the SFP storage rack cells toward the mislocated fuel assembly.
- Case 2.3.15.6.4.9: This is the same as Case 2.3.15.6.4.1 but the mislocated fuel is directly adjacent to the closest FPM location (position 5). See Figure 2.21
- Case 2.3.15.6.4.10: This is the same as Case 2.3.15.6.4.9 but the fuel is eccentric in the SFP storage rack cells toward the mislocated fuel assembly.

- Case 2.3.15.6.4.11: This is the same as Case 2.3.15.6.4.1 but the mislocated fuel is between the SFP rack and the FPM fuel. The mislocated fuel is directly adjacent to the SFP storage rack location without a BORAL panel (position 6). See Figure 2.22.
- Case 2.3.15.6.4.12: This is the same as Case 2.3.15.6.4.11 but the fuel is eccentric in the SFP storage rack cells toward the mislocated fuel assembly.
- Case 2.3.15.6.4.13: This is the same as Case 2.3.15.6.4.11 but the mislocated fuel is directly adjacent to the closest FPM location (position 7). See Figure 2.23.
- Case 2.3.15.6.4.14: This is the same as Case 2.3.15.6.4.13 but the fuel is eccentric in the SFP storage rack cells toward the mislocated fuel assembly.

2.3.16 Reconstituted Fuel Assemblies

The SFP contains various reconstituted assemblies. The entire population of previously reconstituted fuel has been examined to determine if the reconstitution may have created a more reactive lattice than those which have been evaluated for this analysis. The evaluation of the population of reconstituted fuel shows that most of the fuel is very old low reactivity legacy fuel and that there has been no reconstituted bundles that may pose a risk of not being bounded by the analysis. The evaluation also showed that there is a small set of newer Optima2 fuel bundles that have been reconstituted. However, the enrichment of these bundles is less than wt% U-235, and therefore clearly bounded by the analysis. Therefore, all previously reconstituted fuel is considered bounded by the analysis and no further analysis is required. All future reconstituted bundles will have to be evaluated to determine if they are bounded by the analysis.

3. ACCEPTANCE CRITERIA

Codes, standard, and regulations or pertinent sections thereof that are applicable to these analyses include the following:

- Code of Federal Regulations, Title 10, Part 50, Appendix A, General Design Criterion 62, "Prevention of Criticality in Fuel Storage and Handling."
- Code of Federal Regulations, Title 10, Part 50.68, "Criticality Accident Requirements."
- USNRC Standard Review Plan, NUREG-0800, Section 9.1.1, Criticality Safety of Fresh and Spent Fuel Storage and Handling, Revision 3 – March 2007.
- L. Kopp, "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," NRC Memorandum from L. Kopp to T. Collins, August 19, 1998.
- ANSI ANS-8.17-1984, Criticality Safety Criteria for the Handling, Storage and Transportation of LWR Fuel Outside Reactors (withdrawn in 2004).
- USNRC, NUREG/CR-6698, Guide for Validation of Nuclear Criticality Safety Calculational Methodology, January 2001.
- DSS-ISG-2010-01, Revision 0, Staff Guidance Regarding the Nuclear Criticality Safety Analysis for Spent Fuel Pools.

4. ASSUMPTIONS

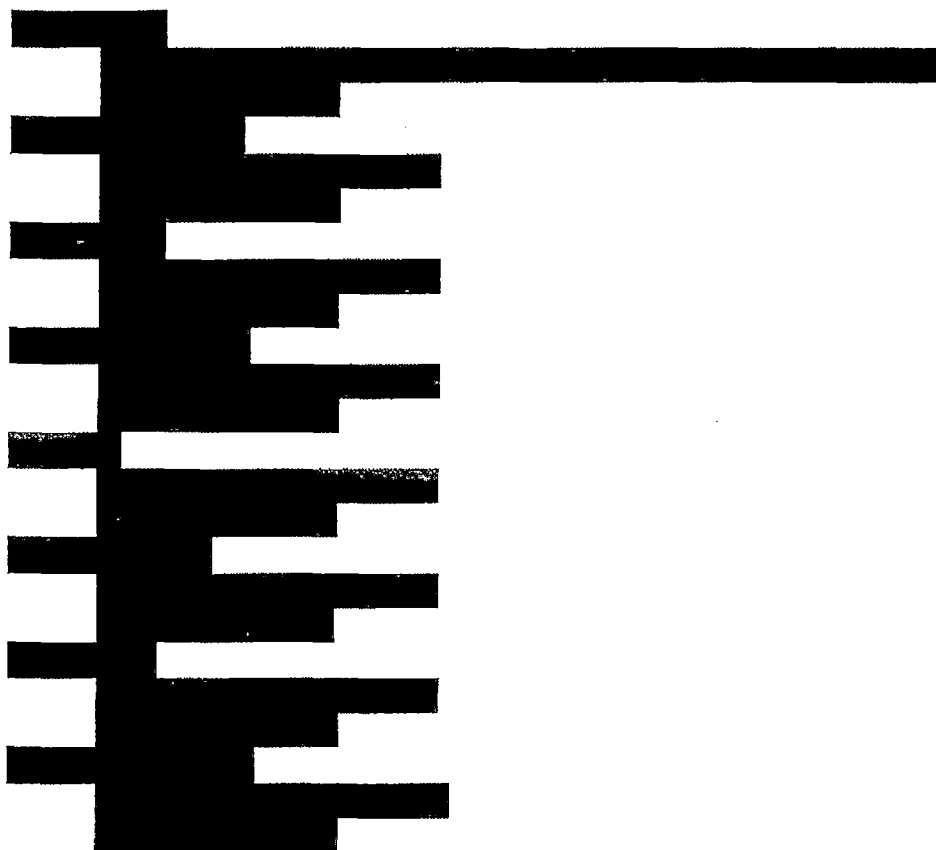
The analyses apply a number of assumptions, either for conservatism or to simplify the calculation approach. Important aspects of applying those assumptions are as follows:

1. Bounding or sufficiently conservative inputs and assumptions are used essentially throughout the entire analyses, and as necessary studies are presented to show that the selected inputs and parameters are in fact conservative or bounding.
2. Neutron absorption in minor structural members of the fuel assembly is neglected, e.g., spacer grids are replaced by water.
3. The neutron absorber length in the rack is more than the active region of the fuel, but it is modeled to be the same length.
4. The fuel density is assumed to be equal to the pellet density for the design basis calculations, and is conservatively modeled as a solid right cylinder over the entire active length, neglecting dishing and chamfering. This is acceptable since the amount of fuel modeled is more than the actual amount.
5. All models are laterally infinite arrays of the respective configuration, neglecting lateral leakage. The exception is where the model boundaries are water, as specified.
6. All fuel cladding materials are modeled as pure zirconium, while the actual fuel cladding consists of one of several zirconium alloys. This is acceptable since the model neglects the trace elements in the alloy which provide additional neutron absorption.
7. The SFP storage rack cell ID and cell wall thickness tolerances are assumed values presented in Table 5.3.

5. INPUT DATA

5.1 Fuel Assembly Specification

The SFP racks are designed to accommodate various fuel assembly types used in Dresden Unit 2 and Unit 3. A subset of these fuel designs are presented here for information purposes (the much older fuel designs are not shown):



The specifications for the above fuel assemblies designs are presented in Table 5.1. Note that the fuel assembly tolerance information is provided for the bounding fuel design only. As it can be seen in Section 7.1, the reactivity difference between the reactivity of the bounding lattice from the most reactive fuel design and the next most reactive design is large enough to preclude tolerance calculations for both designs.

Additional Specification of the ATRIUM 10XM

² Note: This is the expected actual IMPAE; the design basis lattice uses 4.95 wt% U-235.



5.2 Reactor and SFP Operating Parameters

The reactor core and SFP operating parameters are provided in Table 5.2(a). The reactor control blade data are provided in Table 5.2(b). The reactor control parameters used in CASMO-4 screening and design basis calculations are provided in Table 5.2(c).

5.3 Storage Rack Specification

The spent fuel pool rack parameters are provided in Table 5.3. The rack cells are constructed by fixing BORAL panels to the outside of a fabricated steel cell box with sheathing. The fabricated cells are then joined to create formed cells. On the exterior of every rack module, the location of the formed cells along the exterior without BORAL is closed with a filler plate. Thus, beginning at the corner of each module, the first location has BORAL and then every other location does not have BORAL.

The SFP layout is shown in Figure 5.1.

5.4 Material Compositions

The MCNP5-1.51 material specification is provided in Table 5.4(a) for non-fuel materials, and Table 5.4(b) specifies isotopes followed in the fuel pellet.

6. COMPUTER CODES

The following computer codes were used in this analysis.

- MCNP5-1.51 [1] is a three-dimensional continuous energy Monte Carlo code developed at Los Alamos National Laboratory. This code offers the capability of performing full three dimensional calculations for the loaded storage racks. MCNP5-1.51 was run on the PCs at Holtec.
- CASMO-4 [4] is a two-dimensional multigroup transport theory code developed by Studsvik. CASMO-4 is used to perform the depletion calculation for the pin-specific approach, and for various studies. CASMO-4 was run on the PCs at Holtec.

7. ANALYSIS RESULTS

7.1 *Determination of the Design Basis Fuel Assembly Lattice*

As discussed in Section 2.3.1, a complete evaluation of the legacy fuel bundles, current fuel bundle designs and future fuel bundle designs (i.e. the ATRIUM 10XM design) has been performed. Based on the method described in Section 2.3.1, and the discussion presented in Appendix A, CASMO-4 screening calculations were performed for all Optima2 lattices, all ATRIUM 10XM lattices, three ATRIUM 9B lattices and one GE14 lattice. The results of the screening calculations determined a subset of lattices with an in-rack CASMO-4 reactivity greater than 0.8500. The subset of most reactive lattices has been further evaluated using MCNP5-1.51 to determine the bounding lattice. This evaluation is documented in Appendix B.

The results presented in Appendix B show that the most reactive ATRIUM 10XM lattice is, as expected, the lattice with the combination of the highest lattice average enrichment, least number of Gd rods, and lowest Gd rod loading. This lattice is shown to be the ATRIUM 10XM lattice [REDACTED] (see Figure 7.1). As discussed in Section 2.3.1.3, this lattice was then used to construct a lattice with the maximum possible lattice average enrichment of [REDACTED] wt% UO_2 , a lower number of Gd rods ([REDACTED]), and the Gd loading was left at the minimum expected ([REDACTED] %). This constructed lattice was then labeled the ATRIUM 10XM Lattice [REDACTED] (see Figure 7.2). An alternate version has also been constructed which is an equivalent lattice with two alternate Gd rod locations, ATRIUM 10XM Lattice [REDACTED] (see Figure 7.3). Calculations were then performed and document in Appendix B to compare the reactivity of these lattices. As can be seen in Appendix B Table B.1, the ATRIUM 10XM lattice [REDACTED] has an statistically equivalent reactivity to the ATRIUM 10XM lattice [REDACTED] (the only difference between the two lattices is the location of two Gd rods). The ATRIUM 10XM lattice [REDACTED] was selected as the design basis lattice for simplicity and is used for all design basis calculations to show compliance with the regulatory limit.

7.2 *Core Operating Parameters*

As discussed in Section 2.3.2, the effects of the core operating parameters on the reactivity were evaluated both during the design basis lattice screening calculations in Appendix A and Appendix B, as well as in the final design basis models calculations presented in Appendix C, Table C.1. As can be seen from the results in Appendix C, Table C.1 the bounding COP for the design basis lattice is the "min" set (see Table 5.2(c)). Therefore, all design basis calculations use the "min" set of COP. Since the bounding configuration is determined for the various design basis calculations, there is no bias and bias uncertainty associated with COP.

7.3 *Fuel Assembly Eccentric Positioning and Fuel Assembly De-Channeling*

As discussed in Section 2.3.5, the reactivity effect of the fuel assembly position in the storage cell and the reactivity effect of the channel have been evaluated. The results of these calculations are presented in Appendix C, Table C.2. The result show that the bounding fuel

assembly position is cell centered and the bounding condition is channeled fuel. Therefore, all design basis calculations consider the fuel cell centered and with a channel with the exception of specific cases that are otherwise noted. Since the bounding configuration is determined for the various design basis calculations, there is no bias and bias uncertainty associated with fuel assembly eccentric positioning and fuel assembly de-channeling (i.e. the value is zero as presented in Table 7.1 and 7.2).

7.4 Fuel Bundle Orientation in the SFP Rack Cell

As discussed in Section 2.3.6, the reactivity effect of the fuel assembly orientation (i.e. orientation of the in core control blade corner) has been evaluated. The results of these calculations are presented in Appendix C, Table C.3. The results of these calculations show that Case 2.3.6.2 has a small bias and bias uncertainty. This small bias and bias uncertainty are therefore considered in the determination of k_{eff} (see Table 7.1 and 7.2).

7.5 Reactivity Effect of Spent Fuel Pool Water Temperature

As discussed in Section 2.3.7, the effects of water temperature, and the corresponding water density and temperature adjustments ($S(\alpha, \beta)$) were evaluated for SFP racks. The results of these calculations are presented in Appendix C, Table C.4.

The results of the SFP temperature and density calculations show that as expected (for poisoned racks) the most reactive water temperature and density for the SFP racks is a temperature of 39.2 °F at a density of 1 g/cc, and these values are used for all calculations in SFP racks with the exception of specific accident conditions.

7.6 Fuel and Storage Rack Manufacturing Tolerances

7.6.1 Fuel Manufacturing Tolerances

As discussed in Section 2.3.8.1, the effect of the BWR fuel tolerances on reactivity was determined. The results of these calculations are presented in Appendix C, Table C.5. The maximum positive delta-k value for each tolerance is statistically combined.

The maximum statistical combination of fuel assembly tolerances is used to determine k_{eff} in Table 7.1 and Table 7.2.

7.6.2 SFP Storage Rack Manufacturing Tolerances

As discussed in Section 2.3.8.2, the effect of the manufacturing tolerances on reactivity of the SFP racks was determined. The results of these calculations are presented in Appendix C, Table C.6. The maximum positive delta-k value for each tolerance is statistically combined.

The maximum statistical combination of the SFP rack tolerances is used to determine k_{eff} in Table 7.1 and Table 7.2.

7.6.3 Fuel Depletion Calculation Uncertainty

As discussed in Section 2.3.9, the uncertainty of the number densities in the depletion calculations was evaluated. The results of these calculations are presented in Appendix C, Table C.7. As can be seen in Appendix C, Table C.7, the depletion uncertainty is calculated as 5% of the reactivity difference between the design basis case and a calculation with fresh fuel and no Gd.

The depletion uncertainty is included in the statistical combination of uncertainties used to determine k_{eff} in Table 7.1 and Table 7.2.

7.6.4 Fission Products and Lumped Fission Products Uncertainty

As discussed in Section 2.3.10, the uncertainty of the FP and LFP in the depletion calculations was evaluated. The results of these calculations are presented in Appendix C, Table C.8. As can be seen in Appendix C, Table C.8, the FP and LFP uncertainty is calculated as █% of the reactivity difference between the design basis case and a calculation with no FP or LFP.

The FP and LFP uncertainty is included in the statistical combination of uncertainties used to determine k_{eff} in Table 7.1 and Table 7.2.

7.6.5 Depletion Related Fuel Assembly Geometry Changes

As discussed in Section 2.3.11, the reactivity effect of depletion related fuel assembly geometry changes has been evaluated. These evaluations are discussed further below.

7.6.5.1 Fuel Rod Geometry Changes

As discussed in Section 2.3.11.1, the reactivity effect of fuel rod geometry changes is evaluated. These evaluations consider fuel rod growth and cladding creep, fuel rod crud buildup and fuel rod bow and are discussed below. As previously discussed, the fuel assembly is not expected to undergo significant depletion related geometry changes at peak reactivity (i.e. about █ GWd/mtU). However, specific effects are evaluated as discussed below.

7.6.5.1.1 Fuel Rod Growth, Cladding Creep and Fuel Rod Crud Buildup

As discussed in Section 2.3.11.1.1 and Section 2.3.11.1.2, the effect of the fuel rod growth, cladding creep and fuel rod crud buildup on reactivity was not evaluated due to the low burnup at peak reactivity.

7.6.5.1.2 Fuel Rod Bow

As discussed in Section 2.3.11.1.3, the reactivity effect of the fuel rod bow was evaluated by calculation. The fuel rod bow calculation results are presented in Appendix C, Table C.9. The

results presented in Appendix C, Table C.9 show a small bias and bias uncertainty. This bias and bias uncertainty are considered in the determine of k_{eff} as presented in Table 7.1 and 7.2.

7.6.5.2 Fuel Channel Bulging and Bowing

As discussed in Section 2.3.11.2, the reactivity effect of fuel channel bulging and bowing was evaluated by calculation. The fuel channel bow calculation results are presented in Appendix C, Table C.9. The results presented in Appendix C, Table C.9 show a small bias and bias uncertainty. This bias and bias uncertainty are considered in the determine of k_{eff} as presented in Table 7.1 and 7.2.

7.7 SFP Storage Rack Interfaces

As discussed in Section 2.3.12, the reactivity effect of the SFP storage rack interfaces, specifically the interface of one storage rack module with another storage rack model has been evaluated. The calculation results are presented in Appendix C, Table C.10. The results presented in Appendix C, Table C.10 show a bias and bias uncertainty. This bias and bias uncertainty are considered in the determine of k_{eff} as presented in Table 7.1 and 7.2.

7.8 Maximum k_{eff} Calculations for Normal Conditions

As discussed in Section 2.3.13, the maximum k_{eff} for normal conditions is calculated. The results are tabulated in Table 7.1. The results show that the maximum k_{eff} for the normal conditions in the SFP racks is less than 0.95 at a 95% probability and at a 95% confidence level.

7.9 Fuel Movement, Inspection and Reconstitution Operation.

As discussed in Section 2.3.14, the fuel movement, inspection and reconstitution operations are normal conditions that are bounded by the analysis. No further evaluations are required.

7.10 Abnormal and Accident Conditions

As discussed in Sections 2.3.15, the effects of various accident conditions has been evaluated. The results of these calculations are presented in Appendix C, Table C.4 (increased SFP temperature only) and Appendix C, Table C.11 (all other accidents). The maximum reactivity accident has been determined to be [REDACTED]

[REDACTED]. The calculated results of this accident are used, along with all applicable biases and uncertainties, to show compliance with the regulatory limit in Table 7.2. As it can be seen in Table 7.2, the maximum calculated reactivity is less than 0.95 at a 95% probability and at a 95% confidence level.

8. CONCLUSION

The criticality analysis for the storage of BWR assemblies in the Dresden SFP racks with BORAL has been performed. The results for the normal condition show that k_{eff} is [REDACTED] with the storage racks fully loaded with fuel of the highest anticipated reactivity, which is the [REDACTED], at a temperature corresponding to the highest reactivity. The results for the bounding accident condition, i.e. the [REDACTED], show that k_{eff} is [REDACTED] with the storage racks fully loaded with fuel of the highest anticipated reactivity, which is [REDACTED], at a temperature corresponding to the highest reactivity. The maximum calculated reactivity for both normal and accident conditions include a margin for uncertainty in reactivity calculations with a 95% probability at a 95% confidence level. Reactivity effects of abnormal and accident conditions have been evaluated to assure that under all credible abnormal and accident conditions, the reactivity will not exceed the regulatory limit of 0.95.

9. REFERENCES

- [1] "MCNP - A General Monte Carlo N-Particle Transport Code, Version 5," Los Alamos National Laboratory, LA-UR-03-1987, April 24, 2003 (Revised 2/1/2008).
- [2] "Nuclear Group Computer Code Benchmark Calculations," Holtec Report HI-2104790 Revision 1.
- [3] Guide for Validation of Nuclear Criticality Safety Calculational Methodology, NUREG/CR-6698, January 2001.
- [4] M. Edenius, K. Ekberg, B.H. Forssén, and D. Knott, "CASMO-4 A Fuel Assembly Burnup Program User's Manual," Studsvik/SOA-95/1; and J. Rhodes, K. Smith, "CASMO-4 A Fuel Assembly Burnup Program User's Manual," SSP-01/400, Revision 5, Studsvik of America, Inc. and Studsvik Core Analysis AB (proprietary).
- [5] D. Knott, "CASMO-4 Benchmark Against Critical Experiments," SOA-94/13, Studsvik of America, Inc., (proprietary); and D. Knott, "CASMO-4 Benchmark Against MCNP," SOA-94/12, Studsvik of America, Inc., (proprietary).
- [6] L.I. Kopp, "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," NRC Memorandum from L. Kopp to T. Collins, August 19, 1998.
- [7] DSS-ISG-2010-01, Staff Guidance Regarding the Nuclear Criticality Safety Analysis for Spent Fuel Pools, Revision 0.
- [8] HI-2002444, Latest Revision, "Final Safety Analysis Report for the HI-STORM 100 Cask System", USNRC Docket 72-1014.
- [9] "Atlas of Neutron Resonances", S.F. Mughabghab, 5th Edition, National Nuclear Data Center, Brookhaven National Laboratory, Upton, USA.
- [10] "Sensitivity Studies to Support Criticality Analysis Methodology," HI-2104598 Rev. 1, October 2010.
- [11] "Spent Nuclear Fuel Burnup Credit Analysis Validation", ORNL Presentation to NRC, September 21, 2010.
- [12] An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses—Criticality (k_{eff}) Predictions, NUREG/CR-7109, April 2012.

Table 2.1(a)
Summary of the Area of Applicability of the MCNP5-1.51 Benchmark

Parameter	Analysis	Validated by Benchmark	Validation Gaps	Extrapolation
Fuel assemblies	UO ₂ and MOX fuel	U-235, U-238, Pu-239, Pu-240, Pu-241, Pu-242, Am-241	none	N/A
Initial fuel enrichments	Up to [REDACTED] wt% U-235,	< 5 wt% U-235, 1.5 to 20 wt% Pu	none	N/A
Fuel density	[REDACTED] g/cc	9.2 to 10.7 g/cc	none	N/A
Burnup range	< [REDACTED] GWd/mtU	0 and 37.5 GWd/mtU	none	N/A
Moderator material	H ₂ O	H ₂ O	none	N/A
Neutron poison	B-10 (rack insert) Gd (residual)	B-SS, BORAL, Boraflex, Cadmium or Gadolinium [†]	none	N/A
Interstitial material	Steel	Steel or Lead	none	N/A
Fuel cladding	Zr alloy	Zr alloy	none	N/A
Reflector	Periodic boundary, water reflectors	Reflective or periodic boundary, water reflectors	none	N/A
Lattice type	Square	Square, triangle	none	N/A
Neutron energy	Thermal spectrum	Thermal spectrum	none	N/A
EALF (eV)	[REDACTED]	[REDACTED]	none	N/A

[†] The set of benchmarked experiments include the experiments with Gd₂O₃ rods and gadolinium dissolved in water. However, it's acceptable because the isotope composition and distribution (Gd₂O₃ rods) is similar.

Table 2.1(b)
Analysis of the MCNP5-1.51 calculations [2]

Experiment Description	No. of exp.	Bias	Bias Uncertainty	Normality $\chi^2 (P_d(\chi^2; d))$	Linear Correlation	Residuals Normality, $(P_d(\chi^2; d))$
All experiments	■	■	■	■	■	■
All with Pure water	■	■	■	■	■	■
					■	■

Note 1: The single sided lower tolerance factor for ■ samples was conservatively used.

Table 2.1(c)
Bias and Bias Uncertainty as a Function of Independent Parameter for SFP Racks Filled with Pure Water [2]

[illegible]

Note 1: For U-235 enrichment of [REDACTED] wt% (maximum fuel enrichment used in the analysis which has the largest bias uncertainty) and EALF of [REDACTED] (larger than the maximum EALF determined in the analysis), the bolded numbers show the bounding bias and bias uncertainty values.

Note 2: The positive biases (which mean decrease in reactivity) are truncated to zero [3].

[REDACTED]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Case No.	Age	Sex	Occupation	Marital Status	Religion	Education	Income	Assets	Liabilities	Net Worth	Notes
1	25	M	Teacher	Married	Catholic	High School	\$12,000	\$5,000	\$7,000		
2	30	F	Homemaker	Married	Protestant	College	\$15,000	\$8,000	\$7,000		
3	35	M	Engineer	Single	Jewish	University	\$20,000	\$10,000	\$10,000		
4	40	F	Nurse	Married	Muslim	High School	\$18,000	\$9,000	\$9,000		
5	45	M	Doctor	Married	Hindu	University	\$25,000	\$12,000	\$13,000		
6	50	F	Retired	Married	Buddhist	College	\$10,000	\$4,000	\$6,000		
7	55	M	Farmer	Married	Christian	High School	\$8,000	\$3,000	\$5,000		
8	60	F	Homemaker	Married	Protestant	High School	\$6,000	\$2,000	\$4,000		
9	65	M	Retired	Married	Catholic	University	\$11,000	\$5,000	\$6,000		
10	70	F	Retired	Married	Jewish	College	\$9,000	\$4,000	\$5,000		
11	75	M	Retired	Married	Muslim	High School	\$7,000	\$3,000	\$4,000		
12	80	F	Retired	Married	Hindu	High School	\$5,000	\$2,000	\$3,000		
13	85	M	Retired	Married	Buddhist	High School	\$4,000	\$1,000	\$3,000		
14	90	F	Retired	Married	Christian	High School	\$3,000	\$1,000	\$2,000		
15	95	M	Retired	Married	Protestant	High School	\$2,000	\$1,000	\$1,000		

[illegible]

Table 5.2(a)
Reactor Core and Spent Fuel Pool Parameters

Description (Unit)	Value
<u>Reactor</u>	
Licensed thermal power (MW _{th})	
Power density (W/gU)	
Maximum fuel pin temperature (K)	
Moderator temperature range (°F)	
Moderator saturation temperature (°F)	
Design basis core average void fraction (%)	
Maximum bundle core exit void fraction (%)	
<u>Spent fuel pool</u>	
Maximum temperature (°F)	

Table 5.2(b)
Reactor Control Blade Data

Description (Unit)		Nominal Value	
GE standard initial equipment			

Table 5.2(c)
Reactor Core Parameters used for CASMO-4 Screening and Design Basis Calculations

Description (Unit)	Screening Calculations				Design Basis Calculations
	Minimum Value "min"	Minimum Value with Control Blades Inserted "minr"	Nominal Value "nom"	Maximum Value "max"	
Power density (W/gU)					
Fuel temperature (K)					
Moderator temperature (°F)					
Void fraction (%)					
Control blade					

[†] It is assumed that the minimum power density is 15% less than the nominal value.

^{††} It is assumed that the minimum fuel temperature is half of the maximum value. Also, the nominal fuel temperature is the average of the maximum and minimum values.

^{†††} The nominal moderator temperature is the average of the maximum and minimum values.

Table 5.3
SFP Storage Rack Parameters and Dimensions

Description (Unit)	Nominal Value	Tolerance
<u>SFP Racks</u>		
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
<u>BORAL</u>		
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
<u>Fuel Prep Machine Platform^{†††}</u>		
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]

[†]These are assumed values.

^{††}This is the design value. The value used in the interface model (see Section 2.3.12) is [REDACTED] inches.

^{†††} This representation of the fuel prep machine (FPM) is a simplification. There are two physically separate FMPs in the SFP each with a capacity of one assembly.

Table 5.4(a)
Non-Fuel Material Compositions

Element	MCNP ZAID [1]	Weight Fraction
Steel (density = [REDACTED] g/cc) [8]†		
Cr	24050.70c	[REDACTED]
	24052.70c	[REDACTED]
	24053.70c	[REDACTED]
	24054.70c	[REDACTED]
Mn	25055.70c	[REDACTED]
Fe	26054.70c	[REDACTED]
	26056.70c	[REDACTED]
	26057.70c	[REDACTED]
	26058.70c	[REDACTED]
Ni	28058.70c	[REDACTED]
	28060.70c	[REDACTED]
	28061.70c	[REDACTED]
	28062.70c	[REDACTED]
	28064.70c	[REDACTED]
Zr (density = 6.55 g/cc) [8]†		
Zr	40090.70c	0.50706120
	40091.70c	0.11180900
	40092.70c	0.17278100
	40094.70c	0.17891100
	40096.70c	0.02943790
Pure water (density = 1.0 g/cc) [8]†		
H	1001.70c	0.11188600
	1002.70c	0.00002572
O	8016.70c	0.88579510
	8017.70c	0.00229319
BORAL (density = [REDACTED] g/cc)		
B	5010.70c	[REDACTED]
	5011.70c	[REDACTED]
C	6000.70c	[REDACTED]
Al	13027.70c	[REDACTED]

† The material composition was expanded to represent the full list of natural isotopes for each chemical element.

Table 5.4(b)
Summary of the Fuel and Fission Product Isotopes Used in Calculations

CASMO Isotope	MCNP5 ZAIID	CASMO Isotope	MCNP5 ZAIID
U-234	92234.70c	Xe-131 [†]	54131.70c
U-235	92235.70c	Cs-133 [†]	55133.70c
U-236	92236.70c	Cs-134 [†]	55134.70c
U-238	92238.70c	Cs-135 [†]	55135.70c
U-239	92239.70c	Cs-137 [†]	55137.70c
Np-237	93237.70c	Nd-143	60143.70c
Np-239	added to Pu-239	Nd-145	60145.70c
Pu-238	94238.70c	Pm-147	61147.70c
Pu-239	94239.70c	Pm-148	61148.70c
Pu-240	94240.70c	Pm-149	61149.70c
Pu-241	94241.70c	Sm-147	62147.70c
Pu-242	94242.70c	Sm-149	62149.70c
Am-241	95241.70c	Sm-150	62150.70c
Am-242m	95242.70c	Sm-151	62151.70c
Am-243	95243.70c	Sm-152	62152.70c
Cm-242	96242.70c	Eu-153	63153.70c
Cm-243	96243.70c	Eu-154	63154.70c
Cm-244	96244.70c	Eu-155	63155.70c
Cm-245	96245.70c	Gd-152	64152.70c
Cm-246	96246.70c	Gd-154	64154.70c
Kr-83 [†]	36083.70c	Gd-155	64155.70c
Rh-103	45103.70c	Gd-157	64157.70c
Rh-105	45105.70c	Gd-160	64160.70c
Ag-109	47109.70c	O-16	8016.70c
I-135 [†]	53135.70c	Gd-158	64158.70c
Gd-156	64156.70c	LFP1/LFP2	

[†] Note: These isotopes are removed for all design basis applications because they are either gaseous or volatile nuclides.

Table 7.1
Maximum k_{eff} Calculation for Normal Conditions in SFP Racks

Parameter	Value
<i>Uncertainties[†]</i>	
Fuel tolerance uncertainty, from Table C.5	██████
Rack tolerance uncertainty, from Table C.6	██████
Fuel eccentricity and de-channeling bias uncertainty, from Table C.2	██████
Fuel orientation bias uncertainty, from Table C.3	██████
Fuel channel bow bias uncertainty, from Table C.9	██████
Fuel rod bow bias uncertainty, from Table C.9	██████
Depletion uncertainty, from Table C.7	██████
FP/LFP uncertainty, from Table C.8	██████
MCNP5-1.51 code bias uncertainty (95%/95%), from Table 2.1(b)	██████
MCNP5-1.51 calculations statistics (95%/95%, 2σ), from Table C.1	██████
Interface bias uncertainty, from Table C.10	██████
Statistical combination of uncertainties	██████
<i>Biases</i>	
Fuel eccentricity and de-channeling bias, from Table C.2	██████
Fuel orientation bias, from Table C.3	██████
Fuel channel bow bias, from Table C.9	██████
Fuel rod bow bias, from Table C.9	██████
MCNP5-1.51 code bias, from Table 2.1(b)	██████
Interface bias, from Table C.10	██████
<i>Determination of k_{eff}</i>	
Calculated MCNP5-1.51 k_{calc} , from Table C.1	██████
Maximum k_{eff}	██████
Regulatory Limit	0.9500
Margin to Limit	██████

[†] The provided value is the 95%/95% delta k_{calc} uncertainty.

Note 1: The negative biases were conservatively truncated.

Table 7.2

Maximum k_{eff} Calculation for Abnormal and Accident Conditions in SFP Racks

Parameter	Value
<i>Uncertainties[†]</i>	
Fuel tolerance uncertainty, from Table C.5	██████
Rack tolerance uncertainty, from Table C.6	██████
Fuel eccentricity and de-channeling bias uncertainty, from Table C.2	██████
Fuel orientation bias uncertainty, from Table C.3	██████
Fuel channel bow bias uncertainty, from Table C.9	██████
Fuel rod bow bias uncertainty, from Table C.9	██████
Depletion uncertainty, from Table C.7	██████
FP/LFP uncertainty, from Table C.8	██████
MCNP5-1.51 code bias uncertainty (95%/95%), from Table 2.1(b)	██████
MCNP5-1.51 calculations statistics (95%/95%, 2σ), from Table C.11	██████
Interface bias uncertainty, from Table C.10	██████
Statistical combination of uncertainties	██████
<i>Biases</i>	
Fuel eccentricity and de-channeling bias, from Table C.2	██████
Fuel orientation bias, from Table C.3	██████
Fuel channel bow bias, from Table C.9	██████
Fuel rod bow bias, from Table C.9	██████
MCNP5-1.51 code bias, from Table 2.1(b)	██████
Interface bias, from Table C.10	██████
<i>Determination of k_{eff}</i>	
Calculated MCNP5-1.51 k_{calc} , from Table C.11	██████
Maximum k_{eff}	██████
Regulatory Limit	0.9500
Margin to Limit	██████

[†] The provided value is the 95%/95% delta k_{calc} uncertainty.

Note 1: The negative biases were conservatively truncated.

Figure 2.1
A representation of the Design Basis CASMO-4 Model with the Design Basis Lattice.

This figure is proprietary.

Figure 2.2
A 2-D Representation of the MCNP5-1.51 Design Basis Model with the Design Basis Lattice,
Case 2.3.1.4.1

This figure is proprietary.

Figure 2.3
A 2-D Representation of the 2x2 Channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.2

This figure is proprietary.

Figure 2.4
A 2-D Representation of the 2x2 Channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.3

This figure is proprietary.

Figure 2.5
A 2-D Representation of the 8x8 Channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.5.

This figure is proprietary.

Figure 2.6
A 2-D Representation of the 8x8 Channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.6.

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Figure 2.7
A 2-D Representation of the 2x2 De-channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.8.

This figure is proprietary.

Figure 2.8
A 2-D Representation of the 2x2 De-channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.9.

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Figure 2.9
A 2-D Representation of the 8x8 De-channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.11

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Figure 2.10
A 2-D Representation of the 8x8 De-channeled Fuel Eccentric Positioning MCNP5-1.51 Model,
Case 2.3.5.12

This figure is proprietary.

Figure 2.11
A 2-D Representation of the 4x4 Fuel Orientation MCNP5-1.51 Model, Case 2.3.6.2

This figure is proprietary.

Figure 2.12
A 2-D Representation of the 4x4 Fuel Orientation MCNP5-1.51 Model, Case 2.3.6.3

This figure is proprietary.

Figure 2.13
A 2-D Representation of the 4x4 Fuel Orientation MCNP5-1.51 Model, Case 2.3.6.4

This figure is proprietary.

Figure 2.14
A 2-D Representation of the 4x4 Fuel Orientation MCNP5-1.51 Model, Case 2.3.6.5

This figure is proprietary.

Figure 2.15
A Partial 2-D Representation of the MCNP5-1.51 Interface Model, Case 2.3.12.1

This figure is proprietary.

Figure 2.16
A partial 2-D Representation of the 16x16 Vertical Fuel Drop Accident MCNP5-1.51 Model,
Case 2.3.15.3.1

This figure is proprietary.

Figure 2.17

A partial 2-D Representation of the 8x8 Missing BORAL Panel Accident MCNP5-1.51 Model,
Case 2.3.15.4.1

This figure is proprietary.

Figure 2.18
A partial 2-D Representation of the 80x80 Mislocated in a Corner of Two Racks Accident
MCNP5-1.51 Model, Case 2.3.15.6.2.1

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Figure 2.19
A partial 2-D Representation of the 80x80 Mislocated in a Corner of Three Racks Accident
MCNP5-1.51 Model, Case 2.3.15.6.3.1

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Figure 2.20
A partial 2D representation of the SFP Platform Mislocated Fuel Assembly Accident MCNP5-
1.51 Model, Position 1 (Case 2.3.15.6.4.1)

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Figure 2.21
A partial 2D representation of the SFP Platform Mislocated Fuel Assembly Accident MCNP5-
1.51 Model, Position 5 (Case 2.3.15.6.4.9)

This figure is proprietary.

Figure 2.22
A partial 2D representation of the SFP Platform Mislocated Fuel Assembly Accident MCNP5-
1.51 Model, Position 6 (Case 2.3.15.6.4.11)

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Figure 2.23
A partial 2D representation of the SFP Platform Mislocated Fuel Assembly Accident MCNP5-
1.51 Model, Position 7 (Case 2.3.15.6.4.13)

This figure is proprietary.

Layout of the SFP

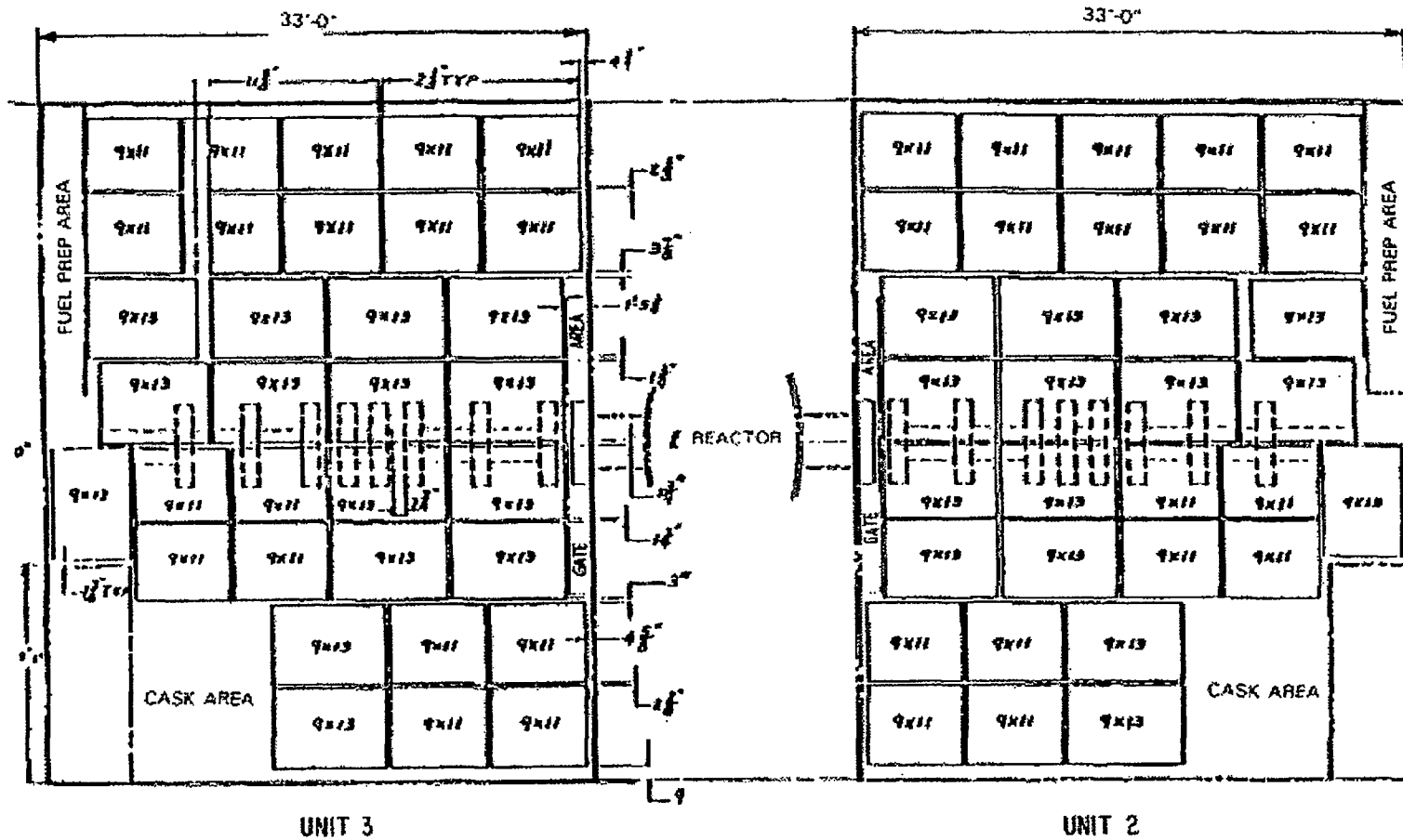


Figure 7.1

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Figure 7.2

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Figure 7.3

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Appendix A

CASMO-4 Screening Calculations for Determination of the Design
Basis Fuel Assembly

(Number of Pages 43)

A.1 Introduction

The purpose of Appendix A is to present the results of the Step 1 CASMO-4 screening calculations (see Section 2.3.1.2 in the main report).

A.2 Methodology

The CASMO-4 screening calculations are performed using CASMO-4 depletion calculations and in-rack restart k_{inf} calculations for four sets of core operating parameters (COP) (minimum COP, minimum COP with control blades inserted, nominal COP and maximum COP), see Table 5.2(c) in the main report. The screening calculations are performed in order to determine the peak reactivity for every Optima2, every ATRIUM 10XM lattice, a GE14 lattice and three ATRIUM 9B lattices. The other legacy fuel lattices (i.e. [REDACTED], etc.) all have an average enrichment less than [REDACTED] wt% U-235. Engineering judgment is used to screen these lattices from further consideration because their reactivity will be bounded by the other fuel designs with average enrichments greater than [REDACTED] wt% U-235. All lattices with natural uranium are neglected because of their low reactivity.

The screening calculations determine the peak reactivity for each of the four sets of COP for each lattice. Using the maximum overall value from the four sets of COP for each lattice, the results are further screened to select the subset of most reactive lattices (and the two most reactive fuel designs). For the purpose of determining the most reactive subset of lattices, the lattices with an in-rack k_{inf} of 0.8500 or greater are selected for further analysis in the main report (see Section 2.3.1.3 in the main report).

A.3 Assumptions

No assumptions are made specifically for the screening calculations that are different than those listed in Section 4 of the main report..

A.4 Acceptance Criteria

In order to screen out low reactivity lattices from unnecessary additional calculations, the entire set of lattices are screened for in-rack reactivity k_{inf} values of 0.8500 or more. The criteria of $k_{inf} > 0.8500$ is chosen based on the overall range of reactivity seen in the results presented in this Appendix.

A.5 Input Data

All input data has been specified in Section 5 of the main report.































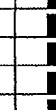

























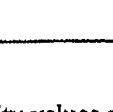






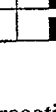
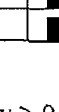
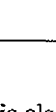
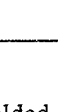
A.6 Results

The results of the CASMO-4 screening calculations are presented in Table A.1 for the ATRIUM 10XM design, Table A.2 for the Optima2 design, Table A.3 for the ATRIUM 9B design and Table A.4 for the GE14 design. The results presented in Table A.1 through A.4 are screened for lattices with an in-rack peak reactivity greater than 0.8500. The results of this screening are presented in Table A.5.

A.7 Conclusion














































































































































Based on the results presented in Table A.5, the most reactive lattices from the ATRIUM 10XM and Optima2 fuel designs are selected because they meet the acceptance criteria of an in-rack restart peak reactivity greater than 0.8500. These lattices are considered for additional calculations as described in Section 2.3.1.3 in the main report.

Table A.1 Results of the CASMO-4 in-rack k_{inf} Screening Calculations for the ATRIUM 10XM Fuel Design (1 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-mirr"	peak	Bounding COP
										
										
										
										
										
										











































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header “gwd” represents “GWD/mtU”.

Table A.1 continued (2 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										







































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (3 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										

















































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (4 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
									0.8500	0.8500
										
										
										
									0.8500	0.8500
										
										
										
									0.8500	0.8500
										
										
										
									0.8500	0.8500
										
										
										
									0.8500	0.8500
										
										
										






























































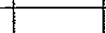
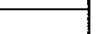

































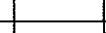
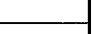





















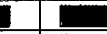










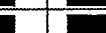










Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (5 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

















































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (6 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										







































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (7 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										







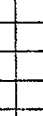
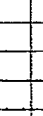








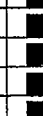
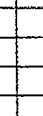
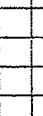









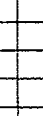
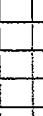









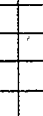
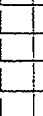




Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (8 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										











































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (9 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										














































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (10 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										








































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (11 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.1 continued (12 of 12)

	Burnup (gwd)	kinf "-min"	Burnup (gwd)	kinf "-nom"	Burnup (gwd)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded.

Also, in the table header "gwd" represents "GWD/mtU".

(1 of 25)

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header “gwd” represents “GWD/mtU”.

Table A.2 continued (2 of 25)

[illegible]



































































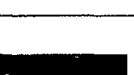














Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header “gwd” represents “GWD/mtU”.

Table A.2 continued (3 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP




























































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header “gwd” represents “GWD/mtU”.

Table A.2 continued (4 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
				<						




















































































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header “gwd” represents “GWD/mtU”.

Table A.2 continued (5 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										




































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (6 of 25)

	Bumup (GWD/MTU)	kinf "-min"	Bumup (GWD/MTU)	kinf "-nom"	Bumup (GWD/MTU)	kinf "-max"	Bumup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										




































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (7 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minor"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										









































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (8 of 25)

	Burnup (GWD/MTU)	k _{inf} "-min"	Burnup (GWD/MTU)	k _{inf} "-nom"	Burnup (GWD/MTU)	k _{inf} "-max"	Burnup (gwd)	k _{inf} "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										




















































































































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (9 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (10 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

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Table A.2 continued (12 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
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	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	
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	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (13 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP













































































































































Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (14 of 25)

[REDACTED]	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
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[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (15 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (16 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.2 continued (17 of 25)

		Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".


































































































Table A.2 continued (18 of 25)

	Bumup (GWD/MTU)	kinf "-min"	Bumup (GWD/MTU)	kinf "-nom"	Bumup (GWD/MTU)	kinf "-max"	Bumup (gwd)	kinf "-minr"	peak	Bounding COP

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

















































































































































































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		Bumup (GWD/MTU)	kinf "-min"	Bumup (GWD/MTU)	kinf "-nom"	Bumup (GWD/MTU)	kinf "-max"	Bumup (gwd)	kinf "-min"	peak	Bounding COP
											
											
											
											
											
											
											
											
											
											

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Table A.2 continued (21 of 25)




































































































































































	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-minr"	peak	Bounding COP

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Table A.2 continued (23 of 25)

	Burnup (GWD/MTU)	kinf "-min"	Burnup (GWD/MTU)	kinf "-nom"	Burnup (GWD/MTU)	kinf "-max"	Burnup (gwd)	kinf "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Any lattice that meets the criteria of peak reactivity > 0.8500 is also bolded. Also, in the table header "gwd" represents "GWD/mtU".











































































































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	Bumup (GWD/MTU)	kinf "-min"	Bumup (GWD/MTU)	kinf "-nom"	Bumup (GWD/MTU)	kinf "-max"	Bumup (gwd)	kinf "-minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										


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Table A.3 Results of the CASMO-4 in-rack k_{inf} Screening Calculations for the ATRIUM 9B Fuel Design

	Burnup (gwd)	k_{inf} "-min"	Burnup (gwd)	k_{inf} "-nom"	Burnup (gwd)	k_{inf} "-max"	Burnup (gwd)	k_{inf} "-min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.4 Results of the CASMO-4 in-rack k_{inf} Screening Calculations for the GE14 Fuel Design

Lattice	Burnup (gwd)	k_{inf} "-min"	Burnup (gwd)	k_{inf} "-nom"	Burnup (gwd)	k_{inf} "-max"	Burnup (gwd)	k_{inf} "-minr"	peak	Bounding COP
										

Note: the peak reactivity values are bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table A.5 Subset of Most Reactive Lattices

Fuel Bundle Design	Lattice	Peak Reactivity	COP Set
ATRIUM 10XM	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
Optima2	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]

Appendix B
MCNP5-1.51 Screening Calculations for Determination of the Design
Basis Fuel Assembly

(Number of Pages 5)

B.1 Introduction

The purpose of Appendix B is to present the results of the Step 2 MCNP5-1.51 screening calculations (see Section 2.3.1.3 in the main report) to determine the design basis lattice for use in the analysis.

B.2 Methodology

The MCNP5-1.51 screening calculations are performed with the design basis rack model (see Section 2.3.1.3 for four sets of COP (minimum COP, minimum COP with control blades inserted, nominal COP and maximum COP), see Table 5.2(c) in the main report. The screening calculations are performed in order to determine the in rack peak reactivity for the set of most reactive lattices as determined in Step 1 (see Appendix A).

The screening calculations determine the peak reactivity for each of the four sets of COP for each lattice using the maximum overall value from the four sets of COP for each lattice.

B.3 Assumptions

All assumptions are listed in Section 4 of the main report.

B.4 Acceptance Criteria

There are no acceptance criteria.

B.5 Input Data

The input data is specified in Section 5 of the main report.

B.6 Results













































































































































The results of the MCNP5-1.51 screening calculations are presented in Table B.1 for each of the lattices selected during Step 1 (see Appendix A, the results presented in Table A.5 show that the lattice with a uniform U-235 enrichment of [REDACTED]% and [REDACTED] Gd rods is bounding).

B.7 Conclusion

Based on the results presented in Table B.1, the most reactive lattice is [REDACTED]. Although this lattice is statistically equivalent (it is actually within 1 sigma) to lattice [REDACTED], lattice [REDACTED] is selected as the design basis lattice. The design basis lattice is selected for additional calculations as described in Section 2.3.1.3 in the main report.

Table B.1 (1 of 3)
















































































































































































Summary of the MCNP5-1.51 Step 2 Calculations to Determine the Design Basis Lattice

Lattice Name	Burnup (gwd)	kcalc "min"	Burnup (gwd)	kcalc "nom"	Burnup (gwd)	kcalc "max"	Burnup (gwd)	kcalc "min"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: the peak reactivity values are bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table B.1 (2 of 3)

Summary of the MCNP5-1.51 Step 2 Calculations to Determine the Design Basis Lattice

Lattice Name	Burnup (gwd)	kcalc "min"	Burnup (gwd)	kcalc "nom"	Burnup (gwd)	kcalc "max"	Burnup (gwd)	kcalc "minr"	peak	Bounding COP
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										
										

Note: The peak reactivity values are bolded. The bounding lattice is also bolded. Also, in the table header "gwd" represents "GWD/mtU".

Table B.1 (3 of 3)

Summary of the MCNP5-1.51 Step 2 Calculations to Determine the Design Basis Lattice

Lattice Name	Burnup (gwd)	kcalc "min"	Burnup (gwd)	kcalc "nom"	Burnup (gwd)	kcalc "max"	Burnup (gwd)	kcalc "minr"	peak	Bounding COP
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		
	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]		

Note: The peak reactivity values are bolded. Also, in the table header "gwd" represents "GWD/mtU".

Appendix C
MCNP5-1.51 Design Basis Calculations
(Number of Pages 20)

C.1 Introduction

The purpose of Appendix C is to present the results of the design basis lattice calculations (see Section 2.3.1.3 in the main report). The results of these calculations are used to show compliance with the regulatory limit (see Section 3 in the main report).

C.2 Methodology

The MCNP5-1.51 design basis lattice calculations are performed with the bounding set of COP (see Section 2.3.2 in the main report). The following sets of calculations are performed for the burnup range of [REDACTED] GWD/mtU so that the peak reactivity can be established for each case:

- Design basis model (see Section 2.3.1.4 in the main report)
- Eccentric positioning and the impact of the fuel bundle channel (see Section 2.3.5 in the main report)
- Fuel bundle orientation in the storage rack (see Section 2.3.6 in the main report)
- Impact of SFP water temperature (see Section 2.3.7 in the main report)
- Fuel manufacturing tolerances (see Section 2.3.8.1 in the main report)
- Storage rack manufacturing tolerances (see Section 2.3.8.2 in the main report)
- Depletion uncertainty calculations (see Section 2.3.9 in the main report)
- FP/LFP uncertainty calculations (see Section 2.3.10 in the main report)
- Fuel assembly geometry changes bias calculations (see Section 2.3.11 in the main report)
- Storage rack interface calculations (see Section 2.3.12 in the main report)
- Accident condition calculations (see Section 2.3.15 in the main report)

C.3 Assumptions

All assumptions are listed in Section 4 of the main report.

C.4 Acceptance Criteria

There are no acceptance criteria specific to this appendix.

C.5 Input Data

All input data is listed in Section 5 of the main report.

C.6 Results

The results of the MCNP5-1.51 design basis lattice calculations are presented in the following tables:

- Design basis model results are presented in Table C.1. The results presented in Table C.1 show that the reactivity effect of the RAD card and the exclusion of the gaseous and volatile isotopes (see Section 2.3.1.4 in the main report) is conservative. Furthermore, these calculations confirm the bounding set of COP for the design basis lattice (see Section 2.3.2 in the main report). Therefore, all further design basis lattice calculations include the use of the RAD card changes and the bounding set of COP.

- Eccentric positioning and the impact of the fuel bundle channel results are presented in Table C.2. The results presented in Table C.2 show that the cell centered fuel assembly and inclusion of the fuel assembly channel is conservative. Therefore, all further calculations are performed with the fuel assembly cell centered and the fuel assembly channel included (with the exception of interface and accident calculations as discussed in Section 2.3.12 and 2.3.15 of the main report).
- Fuel bundle orientation in the storage rack results are presented in Table C.3. The results presented in Table C.3 show that the reactivity difference between the reference case (design basis model) and each alternative orientation is within the 2σ . However, the reactivity difference between Case 2.3.6.2 (maximum positive effect) and the reference case is applied as a bias and bias uncertainty to the final calculated reactivity as presented in the main report.
- Impact of SFP water temperature results are presented in Table C.4. The results presented in Table C.4 show that the minimum SFP water temperature and maximum water density and use of the $S(\alpha,\beta)$ card at 293.6 K is conservative. Therefore, all design basis lattice calculations are performed with the minimum SFP water temperature, maximum water density and $S(\alpha,\beta)$ card at 293.6 K with the exception of specific accident cases as discussed in Section 2.3.15 of the main report.
- Fuel manufacturing tolerances results are presented in Table C.5. The results presented in Table C.5 for each fuel manufacturing tolerance are statistically combined. The fuel manufacturing tolerance calculations that result in a decrease in reactivity are excluded from the statistical combination. The statistical combination results are included in the total uncertainty calculation in the main report as discussed in Section 2.3.13 of the main report.
- Storage rack manufacturing tolerances results are presented in Table C.6. The results presented in Table C.6 for each storage rack manufacturing tolerance are statistically combined. The storage rack manufacturing tolerance calculations that result in a decrease in reactivity are excluded from the statistical combination. The statistical combination results are included in the total uncertainty calculation in the main report as discussed in Section 2.3.13 of the main report.
- Depletion uncertainty calculations results are presented in Table C.7. The results presented in Table C.7 show the calculation of the 5% depletion uncertainty factor. This factor is 5% of the reactivity difference between [REDACTED] wt% U-235 fresh fuel with no Gd and the design basis case at peak reactivity. This 5% factor is included in the total uncertainty calculation in the main report as discussed in Section 2.3.13 of the main report.
- FP/LFP uncertainty calculations results are presented in Table C.8. The results presented in Table C.8 show the calculation of the [REDACTED]% FP/LFP uncertainty factor. This factor is [REDACTED]% of the reactivity difference between the design basis fuel with no LFP or FP at peak reactivity and the design basis case at peak reactivity. This [REDACTED]% factor is included in the total uncertainty calculation in the main report as discussed in Section 2.3.13 of the main report.
- Fuel assembly geometry changes bias calculations results are presented in Table C.9. The results presented in Table C.9 show the calculation of the bias and bias uncertainty for both the fuel rod bow and the fuel channel bow calculations. The fuel assembly geometry change bias and bias uncertainty are included in the total uncertainty

calculation and total bias calculation in the as discussed in Section 2.3.13 of the main report.

- Storage rack interface calculations results are presented in Table C.10. The results presented in Table C.10 show that the interface results in a small bias and bias uncertainty. The storage rack interface bias and bias uncertainty are included in the total uncertainty calculation and total bias calculation in the as discussed in Section 2.3.13 of the main report.
- Accident condition calculations results are presented in Table C.11. The results presented in Table C.11 show that the bounding accident is the "[REDACTED]" case. The results of this accident are presented in the main report as discussed in Section 2.3.15.

C.7 Conclusion

The results of the calculations presented in this appendix are used in the main report to show compliance with the regulatory requirements.

Table C.1

MCNP5-1.51 Design Basis Lattice () Model Results

Case	Burnup (gwd)	kcalc	2 Sigma
Design Basis Model (no gaseous/volatiles) "min" COP (Case 2.3.1.4.1)	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
Design Basis Model (no gaseous/volatiles) "nom" COP (Case 2.3.1.4.2)	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
Design Basis Model (no gaseous/volatiles) "max" COP (Case 2.3.1.4.3)	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
Design Basis Model (no gaseous/volatiles) "minr" COP (Case 2.3.1.4.4)	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
Appendix B Model (gaseous/volatiles included) "min" COP	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
Design Basis Model (no gaseous/volatiles) "min" COP and 72 Hours Cooling Time (Case 2.3.1.4.5)	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000
	1.0	1.000	1.000

Note: the maximum reactivity result is bolded for each case. Also, in the table header "gwd" represents "GWD/mtU".

Table C.2

MCNP5-1.51 Design Basis Lattice () Results for the In Rack Fuel Assembly Eccentric Positioning and Fuel Assembly Channel Reactivity Effect

Case	Burnup (gwd)	kcalc	2 Sigma	Case	Burnup (gwd)	kcalc	2 Sigma	Bounding Case
Channeled Calculations				De-Channeled Calculations				
2x2 Channeled Reference, Cell Centered (Case 2.3.5.1)				2x2 De-Channeled Reference, Cell Centered (Case 2.3.5.7)				Channeled
2x2 Channeled, All Fuel Eccentric Towards Center (Case 2.3.5.2)				2x2 De-Channeled, All Fuel Eccentric Towards Center (Case 2.3.5.8)				Channeled
2x2 Channeled, All Fuel Eccentric Towards One Corner (Case 2.3.5.3)				2x2 De-Channeled, All Fuel Eccentric Towards One Corner (Case 2.3.5.9)				Channeled
8x8 Channeled Reference Cell Centered Case (Case 2.3.5.4)				8x8 De-Channeled Reference Cell Centered Case (Case 2.3.5.10)				Channeled
8x8 Channeled, All Fuel Eccentric Towards Center (Case 2.3.5.5)				8x8 De-Channeled, All Fuel Eccentric Towards Center (Case 2.3.5.11)				Channeled
8x8 Channeled, All Fuel Eccentric Towards One Corner (Case 2.3.5.6)				8x8 De-Channeled, All Fuel Eccentric Towards One Corner (Case 2.3.5.12)				Channeled

Note: in the table header "gwd" represents "GWD/mtU".

Table C.3

MCNP5-1.51 Design Basis Lattice () Results for the In Rack Fuel
Assembly Orientation Reactivity Effect

Case	Burnup (gwd)	kcalc	2 Sigma	Max kcalc	Bias	Bias Uncertainty
Reference, (Case 2.3.6.1)						
Rotation One, (Case 2.3.6.2)						
Rotation Two, (Case 2.3.6.3)						
Rotation Three, (Case 2.3.6.4)						
Rotation Four, (Case 2.3.6.5)						

Note: in the table header "gwd" represents "GWD/mtU".

Table C.4

MCNP5-1.51 Design Basis Lattice () Results for the SFP Temperature Reactivity Effect

Case	Temp K	Water Density g/cc	S(α,β) K	Burnup (gwd)	kcalc	Max
Reference, (case 2.3.7.1)						
Temperature Case One, (Case 2.3.7.2)						
Temperature Case Two, (Case 2.3.7.3)						
Temperature Case Three, (Case 2.3.7.4)						
Temperature Case Four, (Case 2.3.7.5)						
Temperature Case Five, (Case 2.3.7.6)						

Note: in the table header "gwd" represents "GWD/mtU".

Table C.5 (1 of 2)

MCNP5-1.51 Design Basis Lattice () Results for the Fuel Assembly
Manufacturing Tolerances Reactivity Effect

Case	Burnup (gwd)	kcalc	Max	95/95 Unc
Reference (Case 2.3.8.1.1/2.3.1.4.1)				
Increased UO2 Pellet Density (Case 2.3.8.1.2)				
Increased Pellet OD (Case 2.3.8.1.3)				
Decreased Pellet OD (Case 2.3.8.1.4)				
Minimum Clad Thickness (Case 2.3.8.1.5)				
Increased Rod Pitch (Case 2.3.8.1.6)				
Decreased Rod Pitch (Case 2.3.8.1.7)				

Note: in the table header "gwd" represents "GWD/mtU".

Table C.5 (2 of 2)

Case	Bumup (gwd)	kcalc	Max	95/95 Unc
Increased Channel Thickness (Case 2.3.8.1.8)				
Decreased Channel Thickness (Case 2.3.8.1.9)				
Increased Fuel Enrichment (Case 2.3.8.1.10)				
Decreased Gd Loading (Case 2.3.8.1.11)				
Statistical Uncertainty				

Note: in the table header "gwd" represents "GWD/mfU".

Table C.6

MCNP5-1.51 Design Basis Lattice () Results for the Storage Rack
Manufacturing Tolerances Reactivity Effect

Case	Burnup (gwd)	k _{eff}	Max	95/95 Unc
Reference (Case 2.3.8.2.1/2.3.1.4.1)				
Increased Cell ID (Case 2.3.8.2.2)				
Decreased Cell ID (Case 2.3.8.2.3)				
Increased Wall Thickness (Case 2.3.8.2.4)				
Decreased Wall Thickness (Case 2.3.8.2.5)				
Increased Cell Pitch (Case 2.3.8.2.6)				
Decreased Cell Pitch (Case 2.3.8.2.7)				
Increased BORAL Width (Case 2.3.8.2.8)				
Decreased BORAL Width (Case 2.3.8.2.9)				
Statistical Combination				

Note: in the table header "gwd" represents "GWD/mtU".

Table C.7

MCNP5-1.51 Design Basis Lattice () Results for the Fuel Depletion
Uncertainty

Case	Burnup (gwd)	kcalc	2 Sigma	95/95 Depletion Unc
Reference, (Case 2.3.9.1)				
Fresh Fuel, No Gd (Case 2.3.9.2)				

Note: in the table header “gwd” represents “GWD/mtU”.

Table C.8

MCNP5-1.51 Design Basis Lattice () Results for the Fission Product and Lumped Fission Products Uncertainty

Case	Burnup (gwd)	kcalc	2 Sigma	95/95 Depletion Unc
Reference, (Case 2.3.10.1)				
LFP/FP Removed (Case 2.3.10.2)				

Note: in the table header "gwd" represents "GWD/mtU".

Table C.9

MCNP5-1.51 Design Basis Lattice () Results for the Fuel Depletion
Geometry Related Changes Reactivity Bias

Case	Burnup (gwd)	kcalc	2 Sigma	Bias	95/95 Bias Uncertainty
Reference, (Case 2.3.11.1.3.1)					
Fuel Rod Bow Bias (Case 2.3.11.1.3.2)					
Fuel Channel Bow Bias (Case 2.3.11.2.1)					

Note: in the table header "gwd" represents "GWD/mtU".

Table C.10
MCNP5-1.51 Design Basis Lattice () Results for the Interface
Calculations

Case	Burnup (gwd)	kcalc	2 Sigma	Bias	Bias Uncertainty
Reference 16x16 Model, Cell Centered	I			■	■
	■				
	■				
	■				
	■				
16x16 Interface Model, (Case 2.3.12.1)	I			■	■
	■				
	■				
	■				
	■				
Reference 16x16 Model, Eccentric Loading	I			■	■
	■				
	■				
	■				
	■				
16x16 Interface Model, Eccentric Loading, (Case 2.3.12.2)	I			■	■
	■				
	■				
	■				
	■				

Note: in the table header "gwd" represents "GWD/mtU".

Table C.11 (1 of 5)

MCNP5-1.51 Design Basis Lattice () Results for the Accident Calculation

Case	Bumup (gwd)	kcalc	2 Sigma
Vertical Drop into an Empty Storage Cell, Cell Centered (Case 2.3.15.3.1)			
Vertical Drop into an Empty Storage Cell, Eccentric Fuel (Case 2.3.15.3.2)			
Missing BORAL Panel, Cell Centered Fuel (Case 2.3.15.4.1)			
Missing BORAL Panel, Eccentrically Positioned Fuel (Case 2.3.15.4.2)			
Mislocated Adjacent To Rack, Cell Centered Fuel (Case 2.3.15.6.1.1)			
Mislocated Adjacent To Rack, Eccentric Positioned Fuel toward Mislocated Fuel Assembly (Case 2.3.15.6.1.2)			
Mislocated in the Corner of Two Racks, Cell Centered Fuel (Case 2.3.15.6.2.1)			
Mislocated in the Corner of Two Racks, Eccentric Positioned Fuel toward Mislocated Fuel Assembly (Case 2.3.15.6.2.2)			









































































Note: in the table header "gwd" represents "GWD/mtU".

Table C.11 (2 of 5)

Case	Burnup (gwd)	kcalc	Σ Sigma
Mislocated in the Corner of Three Racks, Actual Rack Gaps, Cell Centered Fuel (Case 2.3.15.6.3.1)			
Mislocated in the Corner of Three Racks, Actual Rack Gaps, Eccentric Fuel (Case 2.3.15.6.3.2)			
Mislocated in the Corner of Three Racks, Closed Rack Gaps, Cell Centered Fuel (Case 2.3.15.6.3.3)			
Mislocated in the Corner of Three Racks, Closed Rack Gaps, Eccentric Fuel (Case 2.3.15.6.3.4)			

















































Note: in the table header "gwd" represents "GWD/mtU".

Table C.11 (3 of 5)

Case	Burnup (gwd)	kcalc	2 Sigma
Mislocated Fuel Assembly Platform Area, Position 1, Cell Centered Fuel (Case 2.3.15.6.4.1)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 1, Eccentric Fuel (Case 2.3.15.6.4.2)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 2, Cell Centered Fuel (Case 2.3.15.6.4.3)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 2, Eccentric Fuel (Case 2.3.15.6.4.4)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 3, Cell Centered Fuel (Case 2.3.15.6.4.5)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 3, Eccentric Fuel (Case 2.3.15.6.4.6)			
			
			
			

Note: in the table header "gwd" represents "GWD/mtU".

Table C.11 (4 of 5)

Case	Burnup (gwd)	kcalc	Σ Sigma
Mislocated Fuel Assembly Platform Area, Position 4, Cell Centered Fuel (Case 2.3.15.6.4.7)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 4, Eccentric Fuel (Case 2.3.15.6.4.8)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 5, Cell Centered Fuel (Case 2.3.15.6.4.9)			
			
			
			
Mislocated Fuel Assembly Platform Area, Position 5, Eccentric Fuel (Case 2.3.15.6.4.10)			
			
			
			

Note: in the table header “gwd” represents “GWD/mtU”.

Table C.11 (5 of 5)

Case	Burnup (gwd)	kcalc	Σ Sigma
Mislocated Fuel Assembly Platform Area, Position 6, Cell Centered Fuel (Case 2.3.15.6.4.11)			
Mislocated Fuel Assembly Platform Area, Position 6, Eccentric Fuel (Case 2.3.15.6.4.12)			
Mislocated Fuel Assembly Platform Area, Position 7, Cell Centered Fuel (Case 2.3.15.6.4.13)			
Mislocated Fuel Assembly Platform Area, Position 7, Eccentric Fuel (Case 2.3.15.6.4.14)			

Note: in the table header "gwd" represents "GWD/mtU".