CHAPTER 6: CRITICALITY EVALUATION

This chapter documents the criticality evaluation of the HI-STAR 100 System for the packaging and transportation of radioactive materials (spent nuclear fuel) in accordance with 10CFR71. The results of this evaluation demonstrate that, for the designated fuel assembly classes and basket configurations, an infinite number of HI-STAR 100 Systems with variations in internal and external moderation remain subcritical with a margin of subcriticality greater than 0.05Δk. This corresponds to a transport index of zero (0) and demonstrates compliance with 10CFR71 criticality requirements for normal and hypothetical accident conditions of transport.

The criticality design is based on favorable geometry, fixed neutron poisons (Boral), ~~and~~ an administrative limit on the maximum allowable enrichment, *and an administrative limit on the minimum average assembly burnup for the MPC-32*. Criticality safety of the HI-STAR 100 System does *not* rely on credit for: (1) fuel burnup *except for the MPC-32*; (2) fuel-related burnable absorbers; or (3) more than 75% of the manufacturer's minimum B-10 content for the Boral neutron absorber.

In addition to demonstrating that the criticality safety acceptance criteria are satisfied, this chapter describes the HI-STAR 100 System design structures and components important to criticality safety and limiting fuel characteristics in sufficient detail to identify the package accurately and provide a sufficient basis for the evaluation of the package.

6.1 DISCUSSION AND RESULTS

In conformance with the principles established in 10CFR71 [6.1.1], NUREG-1617 [6.1.2], and NUREG-0800 Section 9.1.2 [6.1.3], the results in this chapter demonstrate that the effective multiplication factor (k_{eff}) of the HI-STAR 100 System, including all biases and uncertainties evaluated with a 95% probability at the 95% confidence level, does not exceed 0.95 under all credible normal and hypothetical accident conditions of transport. This criterion provides a large subcritical margin, sufficient to assure the criticality safety of the HI-STAR 100 System when fully loaded with fuel of the highest permissible reactivity. In addition, the results of this evaluation demonstrate that the HI-STAR 100 System is in full compliance with the requirements outlined in the Standard Review Plan for Dry Cask Storage Systems, NUREG-1536.

Criticality safety of the HI-STAR 100 System depends on the following three principal design parameters:

1. The inherent geometry of the fuel basket designs within the MPC (and the flux-trap water gaps in the MPC-24),

2. The incorporation of permanent fixed neutron-absorbing panels (Boral) in the fuel basket structure, and

3. An administrative limit on the maximum average enrichment for PWR fuel and maximum planar-average enrichment for BWR fuel., *and*

4. *An administrative limit on the minimum average assembly burnup for PWR fuel in the MPC-32.*

The HI-STAR 100 System is designed such that the fixed neutron absorber (Boral) will remain effective for a period greater than 20 years, and there are no credible means to lose it. Therefore, there is no need to provide a surveillance or monitoring program to verify the continued efficacy of the neutron absorber.

Criticality safety of the HI-STAR 100 System does not rely on the use of any of the following credits:

- burnup of fuel, *except for the MPC-32*

- fuel-related burnable neutron absorbers

- more than 75 percent of the B-10 content for the fixed neutron absorber (Boral).

The following ~~two~~ interchangeable basket designs are available for use in the HI-STAR 100 System:

- a 24-cell basket (MPC-24), designed for intact PWR fuel assemblies with a specified maximum enrichment.

- *a 24-cell basket (MPC-24E/EF), designed for intact and damaged PWR fuel assemblies, and fuel debris (MPC-24EF only). This is a variation of the MPC-24, with increased ^{10}B content in the Boral and with four cells capable of accommodating either intact fuel or a damaged fuel container (DFC). The MPC-24E and MPC-24EF is designed for fuel assemblies with a specified maximum enrichment. Although the MPC-24E/EF is designed and analyzed for damaged fuel and fuel debris, it is only certified for intact fuel assemblies.*

- *a 24-cell basket (MPC-24E/EF Trojan), design for intact and damaged PWR fuel assemblies, and fuel debris (MPC-24EF Trojan only) from the Trojan Nuclear Plant (TNP). This is a variation of the MPC-24E/EF, with a slightly reduced height, and increased cell sizes for the cells designated for damaged fuel and fuel debris. This increased cell size is required to accommodate the Trojan specific Failed Fuel Cans and DFCs.*

- *a 32-cell basket (MPC-32), designed for intact PWR fuel assemblies of a specified minimum burnup, and*

- a 68-cell basket (MPC-68), designed for both intact and damaged BWR fuel assemblies with a specified maximum planar-average enrichment. Additionally, a variation in the MPC-68, designated MPC-68F, is designed for damaged BWR fuel assemblies and BWR fuel debris with a specified maximum planar-average enrichment.

During the normal conditions of transport, the HI-STAR 100 System is dry (no moderator), and thus, the reactivity is very low ($k_{eff} < 0.450$). However, the HI-STAR 100 System for loading and unloading operations, as well as for the hypothetical accident conditions, is flooded, and thus, represents the limiting case in terms of reactivity. The calculational models for these conditions conservatively include: full flooding with ordinary water, corresponding to the highest reactivity, and the worst case (most conservative) combination of manufacturing and fabrication tolerances.

The MPC-24EF contains the same basket as the MPC-24E. More specifically, all dimensions relevant to the criticality analyses are identical between the MPC-24E and MPC-24EF. Therefore, all criticality results obtained for the MPC-24E are valid for the MPC-24EF and no separate analyses for the MPC-24EF are necessary.

Confirmation of the criticality safety of the HI-STAR 100 Systems under flooded conditions, when filled with fuel of the maximum permissible reactivity for which they are designed, was accomplished with the three-dimensional Monte Carlo code MCNP4a [6.1.4]. Independent confirmatory calculations were made with NITAWL-KENO5a from the SCALE-4.3 package. KENO5a [6.1.5] calculations used the 238-group SCALE cross-section library in association with the NITAWL-II program [6.1.6], which adjusts the uranium-238 cross sections to compensate for resonance self-shielding effects. The Dancoff factors required by NITAWL-II were calculated with the CELLDAN code [6.1.13], which includes the SUPERDAN code [6.1.7] as a subroutine. K-factors for one-sided statistical tolerance limits with 95% probability at the 95% confidence level were obtained from the National Bureau of Standards (now NIST) Handbook 91 [6.1.8].

For the burnup credit calculations, CASMO~~-3~~*4*, a two-dimensional transport theory code [6.1.~~9~~*10*-6.1.12] for fuel assemblies, *was used to calculate the isotopic composition of the spent fuel. The criticality evaluations for burnup credit were performed with MCNP4a [6.1.4].*

To assess the incremental reactivity effects due to manufacturing tolerances, CASMO and MCNP4a [6.1.4] ~~was~~*were* used.~~ to assess the incremental reactivity effects due to manufacturing tolerances.~~ The CASMO~~-3~~ *and MCNP4a* calculations identify those tolerances that cause a positive reactivity effect, enabling the Monte Carlo code input to define the worst case (most conservative) conditions. CASMO~~-3~~ was not used for quantitative~~-information~~ *criticality evaluations*, but only to qualitatively indicate the direction and approximate magnitude of the reactivity effects of the manufacturing tolerances.

Benchmark calculations were made to compare the primary code packages (MCNP4a, *CASMO* and KENO5a) with experimental data, using ~~critical-~~experiments selected to encompass, insofar as practical, the design parameters of the HI-STAR 100 System. The most important parameters are (1) the enrichment, (2) the water-gap size (MPC-24) or cell spacing (*MPC-32 and* MPC-68), ~~and~~ (3) the ^{10}B loading of the neutron absorber panels, *and (4) the assembly burnup (MPC-32 only)*. Benchmark calculations are presented in Appendix 6.A *and Subsection 6.4.11.3.*.

Applicable codes, standards, and regulations, or pertinent sections thereof, include the following:

- U.S. Code of Federal Regulations, "Packaging and Transportation of Radioactive Materials," Title 10, Part 71.

- NUREG-1617, "Standard Review Plan for Transportation Packages for Spent Nuclear Fuel—~~Draft Report for Comment,~~" USNRC, Washington D.C., March ~~1998~~*2000.*

- U.S. Code of Federal Regulations, "Prevention of Criticality in Fuel Storage and Handling," Title 10, Part 50, Appendix A, General Design Criterion 62.

- USNRC Standard Review Plan, NUREG-0800, Section 9.1.2, Spent Fuel Storage, Rev. 3, July 1981.

- *USNRC Interim Staff Guidance 8 (ISG-8), Revision 1, "Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks", July 1999.*

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

- The MPCs are assumed to contain the most reactive ~~fresh~~ fuel authorized to be loaded into a specific basket design.

- No credit for fuel burnup is assumed, either in depleting the quantity of fissile nuclides or in producing fission product poisons, *except for fuel in the MPC-32.*

- The criticality analyses assume 75% of the manufacturer's minimum Boron-10 content for the Boral neutron absorber.

- The fuel stack density is assumed to be 96% of theoretical (10.522 g/cm^3) for all criticality analyses. The fuel stack density is approximately equal to 98% of the pellet density. Therefore, while the pellet density of some fuels might be slightly greater than 96% of theoretical, the actual stack density will still be less.

- *For fresh fuel,* ~~N~~*n*o credit is taken for the ^{234}U and ^{236}U in the fuel.

- When flooded, the moderator is assumed to be water at a temperature corresponding to the highest reactivity within the expected operating range (i.e., water density of 1.000 g/cc).

- Neutron absorption in minor structural members and *optional* heat conduction elements is neglected, i.e., spacer grids, basket supports, and *optional* aluminum heat conduction elements are replaced by water.

- The worst hypothetical combination of tolerances (most conservative values within the range of acceptable values), as identified in Section 6.3, is assumed.

- When flooded, the fuel rod pellet-to-clad gap regions are assumed to be flooded.

- Planar-averaged enrichments are assumed for BWR fuel. (Analyses are presented in Appendix 6.B to demonstrate that the use of planar-average enrichments produces conservative results.)

- Fuel-related burnable neutron absorbers, such as the Gadolinia normally used in BWR fuel and IFBA normally used in PWR fuel, are neglected.

- For evaluation of the *reactivity* bias, all benchmark calculations that result in a k_{eff} greater than 1.0 are conservatively truncated to 1.0000.

- For fuel assemblies that contain low-enriched axial blankets, the governing enrichment is that of the highest planar average, and the blankets are not included in determining the average enrichment.

- For intact fuel assemblies, as defined in Chapter 1, missing fuel rods must be replaced with dummy rods that displace a volume of water that is equal to, or larger than, that displaced by the original rods.

- *The burnup credit methodology for the MPC-32 contains significant additional conservative assumption specific to burnup credit, as listed below.*
  - *The same set of conservative / bounding assumptions is applied to all 32 fuel assemblies in the MPC-32 basket.*
  - *The core operating parameters are selected so that they bound more than 99% of the fuel assemblies.*
  - *The axial burnup profile was selected to bound all fuel assemblies.*
  - *For the criticality evaluations, guide tubes are assumed to be filled with water, i.e. the reactivity effect of any inserts into the assemblies in the cask, such as burnable poison rods (BPRs) or control rods (CRs), is conservatively neglected.*
  - *A cooling time of 5 years is assumed, even if the assembly has a longer cooling time and therefore a reduced reactivity.*
  - *Conservative correction factors are derived from isotopic benchmark calculations.*
  - *For all isotopes validated through commercial reactor critical experiments (CRCs) instead of isotopic benchmarks, credit is only taken for 75%.*
  - *Isotopes from the depletion calculations which do not have corresponding cross sections in MCNP4a are neglected.*

Results of the design basis criticality safety calculations for single unreflected, internally flooded casks (limiting cases) are listed in Tables 6.1.1 through 6.1.3 *and 6.1.5 through 6.1.7*, conservatively evaluated for the worst combination of manufacturing tolerances (as identified in Section 6.3), and including the calculational bias, uncertainties, and calculational statistics. For each of the MPC designs and fuel assembly classes†, Tables 6.1.1 through 6.1.3 *and 6.1.5 through 6.1.7* list the bounding maximum k_{eff} value, ~~and~~ the associated maximum allowable enrichment, *and the minimum required assembly average burnup (if applicable)*, as required by 10CFR71.33(b)(2). The maximum enrichment *and minimum burnup* acceptance criteria are defined in Chapter 1. Maximum k_{eff} values for each of the candidate fuel assemblies and basket configurations, that are bounded by those listed in Tables 6.1.1 through 6.1.3, are given in Section 6.2 *for the MPC-24 and MPC-68*. Calculations for fully reflected casks and for array configurations with various internal and external moderator densities and various cask-to-cask spacings showed negligible reactivity increases and are discussed in Section 6.4.

A table listing the maximum k_{eff} (including bias, uncertainties, and calculational statistics), calculated k_{eff}, standard deviation, and energy of the average lethargy causing fission (EALF) for each of the candidate fuel assemblies and basket configurations is provided in Appendix 6.C. These results confirm that the maximum k_{eff} values for the HI-STAR 100 System are below the limiting design criteria ($k_{eff} < 0.95$) when fully flooded and loaded with any of the candidate fuel assemblies and basket configurations. Analyses for the various conditions of flooding that support the conclusion that the fully flooded condition corresponds to the highest reactivity, and thus is most limiting, are presented in Section 6.4. The capability of the MPC-68F to safely accommodate Dresden-1 and Humboldt Bay damaged fuel (fuel assembly classes 6x6A, 6x6B, 6x6C, 7x7A, and 8x8A) is demonstrated in Subsection 6.4.4.

Hypothetical accident conditions of transport have also been evaluated and no hypothetical accident has been identified that would result in exceeding the design criteria limit on reactivity. For an infinite array of HI-STAR 100 Systems under flooded conditions, the physical separation between overpacks and the steel radiation shielding are each adequate to preclude any significant neutronic coupling between casks in an array configuration. Therefore, the transportation index based on criticality control is zero (0). Calculations are presented in Section 6.4 confirming this conclusion.

Calculational results, which address the following conditions:

- A single package, under the conditions of 10 CFR 71.55(b), (d), and (e);
- An array of undamaged packages, under the conditions of 10 CFR 71.59(a)(1); and
- An array of damaged packages, under the conditions of 10 CFR 71.59(a)(2)

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† For each array size (e.g., 6x6, 7x7, 14x14, etc.), the fuel assemblies have been subdivided into a number of assembly classes, where an assembly class is defined in terms of the (1) number of fuel rods; (2) pitch; (3) number and location of guide tubes (PWR) or water rods (BWR); and (4) cladding material. The assembly classes for BWR and PWR fuel are defined in Section 6.2.

are summarized in Table 6.1.4 *for the MPC-24 and MPC-68 basket designs. These two basket designs are representative for all baskets in the MPC regarding these conditions, as discussed in Section 6.4*. These results demonstrate that the HI-STAR 100 System is in full compliance with 10CFR71 (71.55(b), (d), and (e) and 71.59(a)(1) and (a)(2)).

Table 6.1.1

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-24

Fuel Assembly Class	**Maximum Allowable Enrichment (wt% ^{235}U)**	**Maximum† k_{eff}**
14x14A	4.6	*0.9296*
14x14B	4.6	*0.9228*
14x14C	4.6	*0.9287*
14x14D	4.0	*0.8507*
14x14E	*5.0*	*0.7627*
15x15A	4.1	*0.9204*
15x15B	4.1	*0.9388*
15x15C	4.1	*0.9361*
15x15D	4.1	*0.9367*
15x15E	4.1	*0.9368*
15x15F	4.1	*0.9395* ††
15x15G	4.0	*0.8876*
15x15H	3.8	*0.9337*
16x16A	4.6	*0.9287*
17x17A	4.0	*0.9368*
17x17B	4.0	*0.9324*
17x17C	4.0	*0.9336*

Note: These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† KENO5a verification calculation resulted in a maximum k_{eff} of ~~0.9466~~*0.9383*.

Table 6.1.2

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-68

Fuel Assembly Class	**Maximum Allowable Planar-Average Enrichment (wt% ^{235}U)**	**Maximum† k_{eff}**
6x6A	2.7††	0.7888†††
6x6B‡	2.7††	0.7824†††
6x6C	2.7††	0.8021†††
7x7A	2.7††	0.7974†††
7x7B	4.2	0.9386
8x8A	2.7††	0.7697†††
8x8B	4.2	0.9416
8x8C	4.2	0.9425
8x8D	4.2	0.9403
8x8E	4.2	0.9312
8x8F	*4.0*	*0.9411*

Note: These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† This calculation was performed for 3.0% planar-average enrichment, however, the authorized contents are limited to maximum planar-average enrichment of 2.7%. Therefore, the listed maximum k_{eff} value is conservative.

††† This calculation was performed for a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum ^{10}B loading of 0.0089 g/cm^2. The minimum ^{10}B loading in the MPC-68 is 0.0372 g/cm^2. Therefore, the listed maximum k_{eff} value is conservative.

‡ Assemblies in this class contain both MOX and UO_2 pins. The composition of the MOX fuel pins is given in Table 6.3.4. The maximum allowable planar-average enrichment for the MOX pins is given in the specification of authorized contents, Chapter 1.

Table 6.1.2 (continued)

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-68

Fuel Assembly Class	**Maximum Allowable Planar-Average Enrichment (wt% ^{235}U)**	**Maximum† k_{eff}**
9x9A	4.2	0.9417
9x9B	4.2	*0.9436*
9x9C	4.2	0.9395
9x9D	4.2	0.9394
9x9E	*4.0*	*0.9401*
9x9F	*4.0*	*0.9401*
9x9G	*4.2*	*0.9309*
10x10A	4.2	0.9457††
10x10B	4.2	0.9436
10x10C	4.2	*0.9433*
10x10D	4.0	0.9376
10x10E	4.0	0.9185

Note: These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† KENO5a verification calculation resulted in a maximum k_{eff} of 0.9453.

Table 6.1.3

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-68F

Fuel Assembly Class	**Maximum Allowable Planar-Average Enrichment (wt% ^{235}U)**	**Maximum† k_{eff}**
6x6A	2.7††	0.7888
6x6B†††	2.7	0.7824
6x6C	2.7	0.8021
7x7A	2.7	0.7974
8x8A	2.7	0.7697

Note:

1. These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

2. These calculations were performed for a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum ^{10}B loading of 0.0089 g/cm^2. The minimum ^{10}B loading in the MPC-68F is 0.010 g/cm^2. Therefore, the listed maximum k_{eff} values are conservative.

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† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† These calculations were performed for 3.0% planar-average enrichment, however, the authorized contents are limited to a maximum planar-average enrichment of 2.7%. Therefore, the listed maximum k_{eff} values are conservative.

††† Assemblies in this class contain both MOX and UO_2 pins. The composition of the MOX fuel pins is given in Table 6.3.4. The maximum allowable planar-average enrichment for the MOX pins is given in the specification of authorized contents, Chapter 1.

Table 6.1.4
SUMMARY OF THE CRITICALITY RESULTS FOR THE MOST REACTIVE ASSEMBLY FROM THE MOST REACTIVE ASSEMBLY CLASS IN ~~EACH OF~~ THE MPC-*24 and MPC-68*~~s~~ TO DEMONSTRATE COMPLIANCE WITH 10CFR71.55 AND 10CFR71.59

Case	% Internal Moderation	% External Moderation	Calculated $k_{eff} \pm 2\sigma$	MCNP4a Code Bias††	Maximum‡ k_{eff}
Single Package Under the Conditions of 10CFR71.55(b), (d), and (e)†					
MPC-24 (15x15F01)	100%	0%	*0.9350 ±0.0018*	0.0021 ± 0.0006	*0.9395*
MPC-24 (15x15F01)	100%	100%	*0.9345 ±0.0016*	0.0021 ± 0.0006	*0.9389*
MPC-68 (B10x10A01)	100%	0%	0.9414 ± 0.0016	0.0021 ± 0.0006	0.9457
MPC-68 (B10x10A01)	100%	100%	0.9399 ± 0.0016	0.0021 ± 0.0006	0.9442
MPC-68F (6x6C01)	100%	0%	0.7980 ± 0.0014	0.0021 ± 0.0006	0.8021
MPC-68F (6x6C01)	100%	100%	0.7990 ± 0.0016	0.0021 ± 0.0006	0.8033
An Infinite Close-Packed Triangular Array of Undamaged Packages Under the Conditions of 10CFR71.59(a)(1)					
MPC-24 (15x15F01)	0%	0%	*0.4267 ±0.0006*	0.0021 ± 0.0006	*0.4300*
MPC-68 (B10x10A01)	0%	0%	0.3633 ± 0.0005	0.0021 ± 0.0006	0.3665
MPC-68F (6x6C01)	0%	0%	0.3003 ± 0.0004	0.0021 ± 0.0006	0.3034
An Infinite Close-Packed Triangular Array of Damaged Packages Under the Conditions of 10CFR71.59(a)(2)					
MPC-24 (15x15F01)	100%	100%	*0.9362 ±0.0016*	0.0021 ± 0.0006	*0.9405*
MPC-68 (B10x10A01)	100%	100%	0.9404 ± 0.0016	0.0021 ± 0.0006	0.9447
MPC-68F (6x6C01)	100%	100%	0.7984 ± 0.0015	0.0021 ± 0.0006	0.8026

† The cases with 100% external moderation correspond to full water reflection of the containment system (refer to Subsection 6.4.2.1.1). The cases with 0% external moderation correspond to unreflected HI-STAR casks.
†† Development of the MCNP4a code bias and uncertainty are presented in Appendix 6.A.
‡ The maximum k_{eff} is equal to the sum of the calculated k_{eff}, two standard deviations, the code bias, and the uncertainty in the code bias.

Table 6.1.5

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-24E/EF

Fuel Assembly Class	***Maximum Allowable Enrichment (wt% ^{235}U)***	***Maximum† k_{eff}***
14x14A	*5.0*	*0.9380*
14x14B	*5.0*	*0.9312*
14x14C	*5.0*	*0.9356*
14x14D	*5.0*	*0.8875*
14x14E	*5.0*	*0.7651*
15x15A	*4.5*	*0.9336*
15x15B	*4.5*	*0.9465*
15x15C	*4.5*	*0.9462*
15x15D	*4.5*	*0.9440*
15x15E	*4.5*	*0.9455*
15x15F	*4.5*	*0.9468*
15x15G	*4.5*	*0.9054*
15x15H	*4.2*	*0.9423*
16x16A	*5.0*	*0.9341*
17x17A	*4.4*	*0.9447*
17x17B	*4.4*	*0.9421*
17x17C	*4.4*	*0.9433*

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.1.6

BOUNDING MAXIMUM k_{eff} VALUES IN THE MPC-24E/EF TROJAN

Fuel Assembly Class	***Maximum Allowable Enrichment (wt% ^{235}U)***	***Content***	***Maximum† k_{eff}***
17x17B	*3.7*	*Intact Fuel*	*0.9161*
17x17B	*3.7*	*Intact Fuel, Damaged Fuel and Fuel Debris*	*0.9377*

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.1.7

BOUNDING MAXIMUM k_{eff} VALUES IN THE MPC-32

Fuel Assembly Class	***Maximum Allowable Enrichment††* *(wt% ^{235}U)***	***Minimum Required Assembly Average Burnup††* *(GWd/MTU)***	***Maximum† k_{eff}***
15x15D, E, F, H	*2.0*	*4.77*	*0.945*
	3.0	*25.36*	*0.945*
	4.0	*36.87*	*0.945*
	5.0	*56.45*	*0.945*
17x17A, B, C	*2.0*	*3.83*	*0.945*
	3.0	*22.71*	*0.945*
	4.0	*37.18*	*0.945*
	5.0	*59.42*	*0.945*

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†† *Other combinations of maximum enrichment and minimum burnup have been evaluated which result in the same maximum k_{eff}. See Table 6.4.18 for a bounding polynomial function.*

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

6.2 SPENT FUEL LOADING

Specifications for the BWR and PWR fuel assemblies that were analyzed in this criticality evaluation are given in Tables 6.2.1 and 6.2.2, respectively. For the BWR fuel characteristics, the number and dimensions for the water rods are the actual number and dimensions. For the PWR fuel characteristics, the actual number and dimensions of the control rod guide tubes and thimbles are used. Table 6.2.1 lists ~~56~~*72* unique BWR assemblies while Table 6.2.2 lists ~~41~~*46* unique PWR assemblies, all of which were explicitly analyzed for this evaluation. Examination of Tables 6.2.1 and 6.2.2 reveals that there are a large number of minor variations in fuel assembly dimensions.

Due to the large number of minor variations in fuel assembly dimensions, the use of explicit dimensions in defining the authorized contents could limit the applicability of the HI-STAR 100 System. To resolve this limitation, bounding criticality analyses are presented in this section for a number of defined fuel assembly classes for both fuel types (PWR and BWR). The results of the bounding criticality analyses justify using bounding fuel dimensions for defining the authorized contents.

6.2.1 Definition of Assembly Classes

For each array size (e.g., 6x6, 7x7, 15x15, etc.), the fuel assemblies have been subdivided into a number of defined classes, where a class is defined in terms of the (1) number of fuel rods; (2) pitch; (3) number and locations of guide tubes (PWR) or water rods (BWR); and (4) cladding material. The assembly classes for BWR and PWR fuel are defined in Tables 6.2.1 and 6.2.2, respectively. It should be noted that these assembly classes are unique to this evaluation and are not known to be consistent with any class designations in the open literature.

For each assembly class, calculations have been performed for all of the dimensional variations for which data is available (i.e., all data in Tables 6.2.1 and 6.2.2). These calculations demonstrate that the maximum reactivity corresponds to:

- maximum active fuel length,
- maximum fuel pellet diameter,
- minimum cladding outside diameter (OD),
- maximum cladding inside diameter (ID),
- minimum guide tube/water rod thickness, and
- maximum channel thickness (for BWR assemblies only).

Therefore, for each assembly class, a bounding assembly was defined based on the above characteristics and a calculation for the bounding assembly was performed to demonstrate compliance with the regulatory requirement of $k_{eff} < 0.95$. In some assembly classes this bounding assembly corresponds directly to one of the actual (real) assemblies; while in most assembly classes, the bounding assembly is artificial (i.e., based on bounding dimensions from more than one of the actual assemblies). In classes where the bounding assembly is artificial, the reactivity of the actual (real) assemblies is typically much less than that of the bounding assembly; thereby providing additional conservatism. As a result of these analyses, the authorized contents (Chapter 1) are defined in terms of the bounding assembly parameters for each class.

To demonstrate that the aforementioned characteristics are bounding, a parametric study was performed for a reference BWR assembly, designated herein as 8x8C04 (identified generally as a GE8x8R). The results of this study are shown in Table 6.2.3, and verify the positive reactivity effect associated with (1) increasing the pellet diameter, (2) maximizing the cladding ID (while maintaining a constant cladding OD), (3) minimizing the cladding OD (while maintaining a constant cladding ID), (4) decreasing the water rod thickness, (5) artificially replacing the Zircaloy water rod tubes with water, and (6) maximizing the channel thickness. These results, and the many that follow, justify the approach for using bounding dimensions for defining the authorized contents. Where margins permit, the Zircaloy water rod tubes (BWR assemblies) are artificially replaced by water in the bounding cases to remove the requirement for water rod thickness from the specification of authorized contents.

As mentioned, the bounding approach used in these analyses often results in a maximum k_{eff} value for a given class of assemblies that is much greater than the reactivity of any of the actual (real) assemblies within the class, and yet, is still below the 0.95 regulatory limit.

6.2.2 PWR Fuel Assemblies in the MPC-24

For PWR fuel assemblies (specifications listed in Table 6.2.2) the 15x15F01 fuel assembly at 4.1% enrichment has the highest reactivity (maximum k_{eff} of ~~0.9478~~*0.9395*). The 17x17A01 assembly (otherwise known as a Westinghouse 17x17 OFA) has a similar reactivity (see Table 6.2.17~~6~~) and was used throughout this criticality evaluation as a reference PWR assembly. The 17x17A01 assembly is a representative PWR fuel assembly in terms of design and reactivity and is useful for the reactivity studies presented in Sections 6.3 and 6.4. Calculations for the various PWR fuel assemblies in the MPC-24 are summarized in Tables 6.2.4 through 6.2.19 *and 6.2.43* for the fully flooded condition.

Tables 6.2.4 through 6.2.19 *and 6.2.43* show the maximum k_{eff} values for the assembly classes that are acceptable for storage in the MPC-24. All maximum k_{eff} values include the bias, uncertainties, and calculational statistics, evaluated for the worst combination of manufacturing tolerances. All calculations for the MPC-24 were performed for a ^{10}B loading of 0.020 g/cm^2, which is 75% of the minimum loading, 0.0267 g/cm^2, specified ~~on BM-1478, Bill of Materials~~ for *the* MPC-24~~-Assembly HI-STAR 100 PWR MPC,~~ in Section 1.4. The maximum allowable enrichment in the MPC-24 varies from 4.0 to 4.6 wt% ^{235}U, depending on the assembly class, and is defined in Tables 6.2.4 through 6.2.19 *and 6.2.43*. It should be noted that the maximum allowable enrichment does not vary within an assembly class. Table 6.1.1 summarizes the maximum allowable enrichments for each of the assembly classes that are acceptable for storage in the MPC-24.

Tables 6.2.4 through 6.2.19 *and 6.2.43* are formatted with the assembly class information in the top row, the unique assembly designations, dimensions, and k_{eff} values in the following rows above the bold double lines, and the bounding dimensions selected to define the authorized contents and corresponding bounding k_{eff} values in the final rows. Where the bounding assembly corresponds directly to one of the actual assemblies, the fuel assembly designation is listed in the bottom row in parentheses (e.g., Table 6.2.4). Otherwise, the bounding assembly is given a unique designation. For an assembly class that contains only a single assembly (e.g., 14x14D, see Table 6.2.7), the authorized contents dimensions are based on the assembly dimensions from that single assembly. All of the maximum k_{eff} values corresponding to the selected bounding dimensions are greater than or equal to those for the actual assembly dimensions and are below the 0.95 regulatory limit.

The results of the analyses for the MPC-24, which were performed for all assemblies in each class, further confirm the validity of the bounding dimensions established in Subsection 6.2.1. Thus, for all following calculations, namely analyses of the MPC-24E and MPC-32, only the bounding assembly in a class is analyzed.

6.2.3 BWR Fuel Assemblies in the MPC-68

For BWR fuel assemblies (specifications listed in Table 6.2.1) the artificial bounding assembly for the 10x10A assembly class at 4.2% enrichment has the highest reactivity (maximum k_{eff} of 0.9457). Calculations for the various BWR fuel assemblies in the MPC-68 are summarized in Tables 6.2.20 through 6.2.36 *and 6.2.44* for the fully flooded condition. In all cases, the gadolinia (Gd_2O_3) normally incorporated in BWR fuel was conservatively neglected.

For calculations involving BWR assemblies, the use of a uniform (planar-average) enrichment, as opposed to the distributed enrichments normally used in BWR fuel, produces conservative results. Calculations confirming this statement are presented in Appendix 6.B for several representative BWR fuel assembly designs. These calculations justify the specification of planar-average enrichments to define acceptability of BWR fuel for loading into the MPC-68.

Tables 6.2.20 through 6.2.36 *and 6.2.44* show the maximum k_{eff} values for assembly classes that are acceptable for storage in the MPC-68. All maximum k_{eff} values include the bias, uncertainties, and calculational statistics, evaluated for the worst combination of manufacturing tolerances. With the exception of assembly classes 6x6A, 6x6B, 6x6C, 7x7A, and 8x8A, which will be discussed in Section 6.2.4, all calculations for the MPC-68 were performed with a ^{10}B loading of 0.0279 g/cm^2, which is 75% of the minimum loading, 0.0372 g/cm^2, specified *for the MPC-68*~~on BM-1479, Bill of Materials for 68 Assembly HI-STAR 100 BWR MPC,~~ in Section

1.4. Calculations for assembly classes 6x6A, 6x6B, 6x6C, 7x7A, and 8x8A were conservatively performed with a ^{10}B loading of 0.0067 g/cm^2. The maximum allowable enrichment in the MPC-68 varies from 2.7 to 4.2 wt% ^{235}U, depending on the assembly class. It should be noted that the maximum allowable enrichment does not vary within an assembly class. Table 6.1.2 summarizes the maximum allowable enrichments for all assembly classes that are acceptable for storage in the MPC-68.

Tables 6.2.20 through 6.2.36 *and 6.2.44* are formatted with the assembly class information in the top row, the unique assembly designations, dimensions, and k_{eff} values in the following rows above the bold double lines, and the bounding dimensions selected to define the authorized contents and corresponding bounding k_{eff} values in the final rows. Where an assembly class contains only a single assembly (e.g., 8x8E, see Table 6.2.24), the authorized contents dimensions are based on the assembly dimensions from that single assembly. For assembly classes that are suspected to contain assemblies with thicker channels (e.g., 120 mils), bounding calculations are also performed to qualify the thicker channels (e.g. 7x7B, see Table 6.2.20). All of the maximum k_{eff} values corresponding to the selected bounding dimensions are shown to be greater than or equal to those for the actual assembly dimensions and are below the 0.95 regulatory limit.

For assembly classes that contain partial length rods (i.e., 9x9A, 10x10A, and 10x10B), calculations were performed for the actual (real) assembly configuration and for the axial segments (assumed to be full length) with and without the partial length rods. In all cases, the axial segment with only the full length rods present (where the partial length rods are absent) is bounding. Therefore, the bounding maximum k_{eff} values reported for assembly classes that contain partial length rods bound the reactivity regardless of the active fuel length of the partial length rods. As a result, the specification of authorized contents has no minimum requirement for the active fuel length of the partial length rods.

For BWR fuel assembly classes where margins permit, the Zircaloy water rod tubes are artificially replaced by water in the bounding cases to remove the requirement for water rod thickness from the specification of authorized contents. For these cases, the bounding water rod thickness is listed as zero.

As mentioned, the highest observed maximum k_{eff} value is 0.9457, corresponding to the artificial bounding assembly in the 10x10A assembly class. This assembly has the following bounding characteristics: (1) the partial length rods are assumed to be zero length (most reactive configuration); (2) the channel is assumed to be 120 mils thick; and (3) the active fuel length of the full length rods is 155 inches. Therefore, the maximum reactivity value is bounding compared to any of the real BWR assemblies listed.

6.2.4 Damaged BWR Fuel Assemblies and BWR Fuel Debris

In addition to storing intact PWR and BWR fuel assemblies, the HI-STAR 100 System is designed to store damaged BWR fuel assemblies and BWR fuel debris. Damaged fuel assemblies and fuel debris are defined in Chapter 1. Both damaged BWR fuel assemblies and BWR fuel debris are required to be loaded into Damaged Fuel Containers (DFCs) ~~prior to being loaded into the MPC~~. Two different DFC types with slightly different cross sections are considered. DFCs containing fuel debris must be stored in the MPC-68F. DFCs containing damaged fuel assemblies may be stored in either the MPC-68 or MPC-68F. The criticality evaluation of various possible damaged conditions of the fuel is presented in Subsection 6.4.4 for both DFC types.

Tables 6.2.37 through 6.2.41 show the maximum k_{eff} values for the six assembly classes that may be stored as damaged fuel or fuel debris. All maximum k_{eff} values include the bias, uncertainties, and calculational statistics, evaluated for the worst combination of manufacturing tolerances. All calculations were performed for a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum loading, 0.0089 g/cm^2. However, because the practical manufacturing lower limit for minimum ^{10}B loading is 0.01 g/cm^2, the minimum ^{10}B loading of 0.01 g/cm^2 is specified ~~on BM-1479, Bill of Materials for 68 Assembly HI-STAR 100 BWR MPC,~~ in Section 1.4, for the MPC-68F. As an additional level of conservatism in the analyses, the calculations were performed for an enrichment of 3.0 wt% ^{235}U, while the maximum allowable enrichment for these assembly classes is limited to 2.7 wt% ^{235}U in the specification of authorized contents. Therefore, the maximum k_{eff} values for damaged BWR fuel assemblies and fuel debris are conservative. Calculations for the various BWR fuel assemblies in the MPC-68F are summarized in Tables 6.2.37 through 6.2.41 for the fully flooded condition.

For the assemblies that may be stored as damaged fuel or fuel debris, the 6x6C01 assembly at 3.0 wt% ^{235}U enrichment has the highest reactivity (maximum k_{eff} of 0.8021). Considering all of the conservatism built into this analysis (e.g., higher than allowed enrichment and lower than actual ^{10}B loading), the actual reactivity will be lower.

Because the analysis for the damaged BWR fuel assemblies and fuel debris was performed for a minimum ^{10}B loading of 0.0089 g/cm^2, which conservatively bounds damaged BWR fuel assemblies in a standard MPC-68 with a minimum ^{10}B loading of 0.0372 g/cm^2, damaged BWR fuel assemblies may also be stored in the standard MPC-68. However, fuel debris is limited to the MPC-68F by the specification of authorized contents in Chapter 1.

Tables 6.2.37 through 6.2.41 are formatted with the assembly class information in the top row, the unique assembly designations, dimensions, and k_{eff} values in the following rows above the bold double lines, and the bounding dimensions selected to define the authorized contents and corresponding bounding k_{eff} values in the final rows. Where an assembly class contains only a single assembly (e.g., 6x6C, see Table 6.2.39), the authorized contents dimensions are based on the assembly dimensions from that single assembly. All of the maximum k_{eff} values corresponding to the selected bounding dimensions are greater than or equal to those for the actual assembly dimensions and are well below the 0.95 regulatory limit.

6.2.5 Thoria Rod Canister

Additionally, the HI-STAR 100 System is designed to store a Thoria Rod Canister in the MPC68 or MPC68F. The canister is similar to a DFC and contains 18 intact Thoria Rods placed in a separator assembly. The reactivity of the canister in the MPC68 or MPC68F is very low compared to the reactivity of the approved fuel assemblies (The ^{235}U content of these rods corresponds to UO_2 rods with an initial enrichment of approximately 1.7 wt% ^{235}U). It is therefore permissible to store the Thoria Rod Canister together with any other approved content in a MPC68 or MPC68F. Specifications of the canister and the Thoria Rods that are used in the criticality evaluation are given in Table 6.2.42. The criticality evaluation is presented in Subsection 6.4.6.

6.2.6 PWR Assemblies in the MPC-24E and MPC-24EF

The MPC-24E and MPC-24EF are variations of the MPC-24, which provide for transportation of higher enriched fuel than the MPC-24 through an increased ^{10}B loading in the Boral neutron absorber. The maximum allowable fuel enrichment varies between 4.2 and 5.0 wt% ^{235}U, depending on the assembly class. The maximum allowable enrichment for each assembly class is listed in Table 6.1.5, together with the maximum k_{eff} for the bounding assembly in the assembly class. All maximum k_{eff} values are below the 0.95 regulatory limit The 15x15F assembly class at 4.5% enrichment has the highest reactivity (maximum k_{eff} of 0.9468). The calculated k_{eff} and calculational uncertainty for each class is listed in Appendix 6.C.

6.2.7 PWR Intact Fuel, Damaged Fuel and Fuel Debris in the Trojan MPC-24E/EF

The Trojan MPC-24E and MPC-24EF are variations of the MPC-24E/EF, designed to transport Trojan intact and damaged PWR fuel assemblies (MPC-24E and MPC-24EF) and fuel debris (MPC-24EF only). Damaged PWR fuel assemblies and fuel debris are required to be loaded into PWR Damaged Fuel Containers (DFCs) or Failed Fuel Cans. Up to four DFCs may be loaded in the MPC-24E or MPC-24EF. The maximum enrichment for intact fuel, damaged fuel and fuel debris is 3.7 wt% ^{235}U. Only the assembly class 17x17B is certified for the Trojan MPC-24E/EF. The maximum k_{eff} is 0.9377, as listed in Table 6.1.6. The criticality evaluation of the damaged fuel is presented in Subsection 6.4.9.

6.2.8 PWR Assemblies in the MPC-32

Burnup credit is necessary to store PWR assemblies in the MPC-32, i.e. a required minimum average assembly burnup is specified as a function of the assembly initial enrichment. Only the *assembly classes 15x15D, E, F, H and 17x17A, B, C are certified for transportation in the MPC-32. The maximum initial enrichment in 5.0 wt% ^{235}U. The criticality evaluations for burnup credit are presented in Subsection 6.4.11.*

Table 6.2.1 (page 1 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
6x6A Assembly Class												
6x6A01	Zr	0.694	36	0.5645	0.0350	0.4940	110.0	0	n/a	n/a	0.060	4.290
6x6A02	Zr	0.694	36	0.5645	0.0360	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A03	Zr	0.694	36	0.5645	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A04	Zr	0.694	36	0.5550	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A05	Zr	0.696	36	0.5625	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A06	Zr	0.696	35	0.5625	0.0350	0.4820	110.0	1	0.0	0.0	0.060	4.290
6x6A07	Zr	0.700	36	0.5555	0.03525	0.4780	110.0	0	n/a	n/a	0.060	4.290
6x6A08	Zr	0.710	36	0.5625	0.0260	0.4980	110.0	0	n/a	n/a	0.060	4.290
6x6B (MOX) Assembly Class												
6x6B01	Zr	0.694	36	0.5645	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6B02	Zr	0.694	36	0.5625	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6B03	Zr	0.696	36	0.5625	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6B04	Zr	0.696	35	0.5625	0.0350	0.4820	110.0	1	0.0	0.0	0.060	4.290
6x6B05	Zr	0.710	35	0.5625	0.0350	0.4820	110.0	1	0.0	0.0	0.060	4.290
6x6C Assembly Class												
6x6C01	Zr	0.740	36	0.5630	0.0320	0.4880	77.5	0	n/a	n/a	0.060	4.542
7x7A Assembly Class												
7x7A01	Zr	0.631	49	0.4860	0.0328	0.4110	80	0	n/a	n/a	0.060	4.542

Table 6.2.1 (page 2 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
7x7B Assembly Class												
7x7B01	Zr	0.738	49	0.5630	0.0320	0.4870	150	0	n/a	n/a	0.080	5.278
7x7B02	Zr	0.738	49	0.5630	0.0370	0.4770	150	0	n/a	n/a	0.102	5.291
7x7B03	Zr	0.738	49	0.5630	0.0370	0.4770	150	0	n/a	n/a	0.080	5.278
7x7B04	Zr	0.738	49	0.5700	0.0355	0.4880	150	0	n/a	n/a	0.080	5.278
7x7B05	Zr	0.738	49	0.5630	0.0340	0.4775	150	0	n/a	n/a	0.080	5.278
7x7B06	Zr	0.738	49	0.5700	0.0355	0.4910	150	0	n/a	n/a	0.080	5.278
8x8A Assembly Class												
8x8A01	Zr	0.523	64	0.4120	0.0250	0.3580	110	0	n/a	n/a	0.100	4.290
8x8A02	Zr	0.523	63	0.4120	0.0250	0.3580	120	0	n/a	n/a	0.100	4.290

Table 6.2.1 (page 3 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
8x8B Assembly Class												
8x8B01	Zr	0.641	63	0.4840	0.0350	0.4050	150	1	0.484	0.414	0.100	5.278
8x8B02	Zr	0.636	63	0.4840	0.0350	0.4050	150	1	0.484	0.414	0.100	5.278
8x8B03	Zr	0.640	63	0.4930	0.0340	0.4160	150	1	0.493	0.425	0.100	5.278
8x8B04	Zr	0.642	64	0.5015	0.0360	0.4195	150	0	n/a	n/a	0.100	5.278
8x8C Assembly Class												
8x8C01	Zr	0.641	62	0.4840	0.0350	0.4050	150	2	0.484	0.414	0.100	5.278
8x8C02	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.000	no channel
8x8C03	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.080	5.278
8x8C04	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.100	5.278
8x8C05	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.120	5.278
8x8C06	Zr	0.640	62	0.4830	0.0320	0.4110	150	2	0.591	0.531	0.100	5.278
8x8C07	Zr	0.640	62	0.4830	0.0340	0.4100	150	2	0.591	0.531	0.100	5.278
8x8C08	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.493	0.425	0.100	5.278
8x8C09	Zr	0.640	62	0.4930	0.0340	0.4160	150	2	0.493	0.425	0.100	5.278
8x8C10	Zr	0.640	62	0.4830	0.0340	0.4100	150	2	0.591	0.531	0.120	5.278
8x8C11	Zr	0.640	62	0.4830	0.0340	0.4100	150	2	0.591	0.531	0.120	5.215
8x8C12	Zr	0.636	62	0.4830	0.0320	0.4110	150	2	0.591	0.531	0.120	5.215

Table 6.2.1 (page 4 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
8x8D Assembly Class												
8x8D01	Zr	0.640	60	0.4830	0.0320	0.4110	150	2 large/ 2 small	0.591/ 0.483	0.531/ 0.433	0.100	5.278
8x8D02	Zr	0.640	60	0.4830	0.0320	0.4110	150	4	0.591	0.531	0.100	5.278
8x8D03	Zr	0.640	60	0.4830	0.0320	0.4110	150	4	0.483	0.433	0.100	5.278
8x8D04	Zr	0.640	60	0.4830	0.0320	0.4110	150	1	1.34	1.26	0.100	5.278
8x8D05	Zr	0.640	60	0.4830	0.0320	0.4100	150	1	1.34	1.26	0.100	5.278
8x8D06	Zr	0.640	60	0.4830	0.0320	0.4110	150	1	1.34	1.26	0.120	5.278
8x8D07	Zr	0.640	60	0.4830	0.0320	0.4110	150	1	1.34	1.26	0.080	5.278
8x8D08	Zr	0.640	61	0.4830	0.0300	0.4140	150	3	0.591	0.531	0.080	5.278
8x8E Assembly Class												
8x8E01	Zr	0.640	59	0.4930	0.0340	0.4160	150	5	0.493	0.425	0.100	5.278
8x8F Assembly Class												
8x8F01	Zr	0.609	64	0.4576	0.0290	0.3913	150	4†	0.291†	0.228†	0.055	5.390
9x9A Assembly Class												
9x9A01	Zr	0.566	74	0.4400	0.0280	0.3760	150	2	0.98	0.92	0.100	5.278
9x9A02	Zr	0.566	66	0.4400	0.0280	0.3760	150	2	0.98	0.92	0.100	5.278
9x9A03	Zr	0.566	74/66	0.4400	0.0280	0.3760	150/90	2	0.98	0.92	0.100	5.278
9x9A04	Zr	0.566	~~74~~/66	0.4400	0.0280	0.3760	150/~~90~~	2	0.98	0.92	0.120	5.278

† Four rectangular water cross segments dividing the assembly into four quadrants

Table 6.2.1 (page 5 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
9x9B Assembly Class												
9x9B01	Zr	0.569	72	0.4330	0.0262	0.3737	150	1	1.516	1.459	0.100	5.278
9x9B02	Zr	0.569	72	0.4330	0.0260	0.3737	150	1	1.516	1.459	0.100	5.278
9x9B03	Zr	0.572	72	0.4330	0.0260	0.3737	150	1	1.516	1.459	0.100	5.278
9x9C Assembly Class												
9x9C01	Zr	0.572	80	0.4230	0.0295	0.3565	150	1	0.512	0.472	0.100	5.278
9x9D Assembly Class												
9x9D01	Zr	0.572	79	0.4240	0.0300	0.3565	150	2	0.424	0.364	0.100	5.278
9x9E Assembly Class†												
9x9E01	Zr	0.572	76	0.4170	0.0265	0.3530	150	5	0.546	0.522	0.120	5.215
9x9E02	Zr	0.572	48 28	0.4170 0.4430	0.0265 0.0285	0.3530 0.3745	150	5	0.546	0.522	0.120	5.215
9x9F Assembly Class†												
9x9F01	Zr	0.572	76	0.4430	0.0285	0.3745	150	5	0.546	0.522	0.120	5.215
9x9F02	Zr	0.572	48 28	0.4170 0.4430	0.0265 0.0285	0.3530 0.3745	150	5	0.546	0.522	0.120	5.215
9x9G Assembly Class												
9x9G01	*Zr*	*0.572*	*72*	*0.4240*	*0.0300*	*0.3565*	*150*	*1*	*1.668*	*1.604*	*0.120*	*5.278*

† The 9x9E and 9x9F fuel assembly classes represent a single fuel type containing fuel rods with different dimensions (SPC 9x9-5). In addition to the actual configuration (9x9E02 and 9x9F02), the 9x9E class contains a hypothetical assembly with only small fuel rods (9x9E01), and the 9x9F class contains a hypothetical assembly with only large rods (9x9F01). This was done in order to simplify the specification of this assembly in the CoC.

Table 6.2.1 (page 6 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
10x10A Assembly Class												
10x10A01	Zr	0.510	92	0.4040	0.0260	0.3450	155	2	0.980	0.920	0.100	5.278
10x10A02	Zr	0.510	78	0.4040	0.0260	0.3450	155	2	0.980	0.920	0.100	5.278
10x10A03	Zr	0.510	92/78	0.4040	0.0260	0.3450	155/90	2	0.980	0.920	0.100	5.278
10x10B Assembly Class												
10x10B01	Zr	0.510	91	0.3957	0.0239	0.3413	155	1	1.378	1.321	0.100	5.278
10x10B02	Zr	0.510	83	0.3957	0.0239	0.3413	155	1	1.378	1.321	0.100	5.278
10x10B03	Zr	0.510	91/83	0.3957	0.0239	0.3413	155/90	1	1.378	1.321	0.100	5.278
10x10C Assembly Class												
10x10C01	Zr	0.488	96	0.3780	0.0243	0.3224	150	5	1.227	1.165	0.055	5.457
10x10D Assembly Class												
10x10D01	SS	0.565	100	0.3960	0.0200	0.3500	83	0	n/a	n/a	0.08	5.663
10x10E Assembly Class												
10x10E01	SS	0.557	96	0.3940	0.0220	0.3430	83	4	0.3940	0.3500	0.08	5.663

Table 6.2.2 (page 1 of ~~3~~*4*)
PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Guide Tubes	Guide Tube OD	Guide Tube ID	Guide Tube Thickness
14x14A Assembly Class											
14x14A01	Zr	0.556	179	0.400	0.0243	0.3444	150	17	0.527	0.493	0.0170
14x14A02	Zr	0.556	179	0.400	0.0243	0.3444	150	17	0.528	0.490	0.0190
14x14A03	Zr	0.556	179	0.400	0.0243	0.3444	150	17	0.526	0.492	0.0170
14x14B Assembly Class											
14x14B01	Zr	0.556	179	0.422	0.0243	0.3659	150	17	0.539	0.505	0.0170
14x14B02	Zr	0.556	179	0.417	0.0295	0.3505	150	17	0.541	0.507	0.0170
14x14B03	Zr	0.556	179	0.424	0.0300	0.3565	150	17	0.541	0.507	0.0170
14x14B04	Zr	0.556	179	0.426	0.0310	0.3565	150	17	0.541	0.507	0.0170
14x14C Assembly Class											
14x14C01	Zr	0.580	176	0.440	0.0280	0.3765	150	5	1.115	1.035	0.0400
14x14C02	Zr	0.580	176	0.440	0.0280	0.3770	150	5	1.115	1.035	0.0400
14x14C03	Zr	0.580	176	0.440	0.0260	0.3805	150	5	1.111	1.035	0.0380
14x14D Assembly Class											
14x14D01	SS	0.556	180	0.422	0.0165	0.3835	144	16	0.543	0.514	0.0145

Table 6.2.2 (page 2 of 4)
PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	*Clad Material*	*Pitch*	*Number of Fuel Rods*	*Cladding OD*	*Cladding Thickness*	*Pellet Diameter*	*Active Fuel Length*	*Number of Guide Tubes*	*Guide Tube OD*	*Guide Tube ID*	*Guide Tube Thickness*
14x14E Assembly Class											
14x14E01†	*SS*	*0.453 and 0.411*	*162 3 8*	*0.3415 0.3415 0.3415*	*0.0120 0.0285 0.0200*	*0.313 0.280 0.297*	*102*	*0*	*n/a*	*n/a*	*n/a*
14x14E02†	*SS*	*0.453 and 0.411*	*173*	*0.3415*	*0.0120*	*0.313*	*102*	*0*	*n/a*	*n/a*	*n/a*
14x14E03†	*SS*	*0.453 and 0.411*	*173*	*0.3415*	*0.0285*	*0.0280*	*102*	*0*	*n/a*	*n/a*	*n/a*
15x15A Assembly Class											
15x15A01	Zr	0.550	204	0.418	0.0260	0.3580	150	*21*	0.533	0.500	0.0165

† *This is the fuel assembly used at Indian Point 1 (IP-1). This assembly is a 14x14 assembly with 23 fuel rods omitted to allow passage of control rods between assemblies. It has a different pitch in different sections of the assembly, and different fuel rod dimensions in some rods.*

Table 6.2.2 (page ~~2~~*3* of ~~3~~*4*)
PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Guide Tubes	Guide Tube OD	Guide Tube ID	Guide Tube Thickness
15x15B Assembly Class											
15x15B01	Zr	0.563	204	0.422	0.0245	0.3660	150	21	0.533	0.499	0.0170
15x15B02	Zr	0.563	204	0.422	0.0245	0.3660	150	21	0.546	0.512	0.0170
15x15B03	Zr	0.563	204	0.422	0.0243	0.3660	150	21	0.533	0.499	0.0170
15x15B04	Zr	0.563	204	0.422	0.0243	0.3659	150	21	0.545	0.515	0.0150
15x15B05	Zr	0.563	204	0.422	0.0242	0.3659	150	21	0.545	0.515	0.0150
15x15B06	Zr	0.563	204	0.420	0.0240	0.3671	150	21	0.544	0.514	0.0150
15x15C Assembly Class											
15x15C01	Zr	0.563	204	0.424	0.0300	0.3570	150	21	0.544	0.493	0.0255
15x15C02	Zr	0.563	204	0.424	0.0300	0.3570	150	21	0.544	0.511	0.0165
15x15C03	Zr	0.563	204	0.424	0.0300	0.3565	150	21	0.544	0.511	0.0165
15x15C04	Zr	0.563	204	0.417	0.0300	0.3565	150	21	0.544	0.511	0.0165
15x15D Assembly Class											
15x15D01	Zr	0.568	208	0.430	0.0265	0.3690	150	17	0.530	0.498	0.0160
15x15D02	Zr	0.568	208	0.430	0.0265	0.3686	150	17	0.530	0.498	0.0160
15x15D03	Zr	0.568	208	0.430	0.0265	0.3700	150	17	0.530	0.499	0.0155
15x15D04	Zr	0.568	208	0.430	0.0250	0.3735	150	17	0.530	0.500	0.0150
15x15E Assembly Class											
15x15E01	Zr	0.568	208	0.428	0.0245	0.3707	150	17	0.528	0.500	0.0140
15x15F Assembly Class											
15x15F01	Zr	0.568	208	0.428	0.0230	0.3742	150	17	0.528	0.500	0.0140

Table 6.2.2 (page ~~3~~*4* of ~~3~~*4*)

PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS

(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Guide Tubes	Guide Tube OD	Guide Tube ID	Guide Tube Thickness
15x15G Assembly Class											
15x15G01	SS	0.563	204	0.422	0.0165	0.3825	144	21	0.543	0.514	0.0145
15x15H Assembly Class											
15x15H01	Zr	0.568	208	0.414	0.0220	0.3622	150	17	0.528	0.500	0.0140
16x16A Assembly Class											
16x16A01	Zr	0.506	236	0.382	0.0250	0.3255	150	5	0.980	0.900	0.0400
16x16A02	Zr	0.506	236	0.382	0.0250	0.3250	150	5	0.980	0.900	0.0400
17x17A Assembly Class											
17x17A01	Zr	0.496	264	0.360	0.0225	0.3088	144	25	0.474	0.442	0.0160
17x17A02	Zr	0.496	264	0.360	0.0225	0.3088	150	25	0.474	0.442	0.0160
17x17A03	Zr	0.496	264	0.360	0.0250	0.3030	150	25	0.480	0.448	0.0160
17x17B Assembly Class											
17x17B01	Zr	0.496	264	0.374	0.0225	0.3225	150	25	0.482	0.450	0.0160
17x17B02	Zr	0.496	264	0.374	0.0225	0.3225	150	25	0.474	0.442	0.0160
17x17B03	Zr	0.496	264	0.376	0.0240	0.3215	150	25	0.480	0.448	0.0160
17x17B04	Zr	0.496	264	0.372	0.0205	0.3232	150	25	0.427	0.399	0.0140
17x17B05	Zr	0.496	264	0.374	0.0240	0.3195	150	25	0.482	0.450	0.0160
17x17B06	Zr	0.496	264	0.372	0.0205	0.3232	150	25	0.480	0.452	0.0140
17x17C Assembly Class											
17x17C01	Zr	0.502	264	0.379	0.0240	0.3232	150	25	0.472	0.432	0.0200
17x17C02	Zr	0.502	264	0.377	0.0220	0.3252	150	25	0.472	0.432	0.0200

Table 6.2.3
REACTIVITY EFFECT OF ASSEMBLY PARAMETER VARIATIONS
(all dimensions are in inches)

Fuel Assembly/ Parameter Variation	reactivity effect	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	water rod thickness	channel thickness
8x8C04 (GE8x8R)	reference	0.9307	0.0007	0.483	0.419	0.032	0.410	0.030	0.100
increase pellet OD (+0.001)	+0.0005	0.9312	0.0007	0.483	0.419	0.032	0.411	0.030	0.100
decrease pellet OD (-0.001)	-0.0008	0.9299	0.0009	0.483	0.419	0.032	0.409	0.030	0.100
increase clad ID (+0.004)	+0.0027	0.9334	0.0007	0.483	0.423	0.030	0.410	0.030	0.100
decrease clad ID (-0.004)	-0.0034	0.9273	0.0007	0.483	0.415	0.034	0.410	0.030	0.100
increase clad OD (+0.004)	-0.0041	0.9266	0.0008	0.487	0.419	0.034	0.410	0.030	0.100
decrease clad OD (-0.004)	+0.0023	0.9330	0.0007	0.479	0.419	0.030	0.410	0.030	0.100
increase water rod thickness (+0.015)	-0.0019	0.9288	0.0008	0.483	0.419	0.032	0.410	0.045	0.100
decrease water rod thickness (-0.015)	+0.0001	0.9308	0.0008	0.483	0.419	0.032	0.410	0.015	0.100
remove water rods (i.e., replace the water rod tubes with water)	+0.0021	0.9328	0.0008	0.483	0.419	0.032	0.410	0.000	0.100
remove channel	-0.0039	0.9268	0.0009	0.483	0.419	0.032	0.410	0.030	0.000
increase channel thickness (+0.020)	+0.0005	0.9312	0.0007	0.483	0.419	0.032	0.410	0.030	0.120

Table 6.2.4
MAXIMUM K_{EFF} VALUES FOR THE 14X14A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14A (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 179 fuel rods, 17 guide tubes, pitch=0.556, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14A01	*0.9295*	*0.9252*	*0.0008*	0.400	0.3514	0.0243	0.3444	150	0.017
14x14A02	*0.9286*	*0.9242*	*0.0008*	0.400	0.3514	0.0243	0.3444	150	0.019
14x14A03	*0.9296*	*0.9253*	*0.0008*	0.400	0.3514	0.0243	0.3444	150	0.017
Dimensions Listed for Authorized Contents				0.400 (min.)	0.3514 (max.)		0.3444 (max.)	150 (max.)	0.017 (min.)
bounding dimensions (14x14A03)	*0.9296*	*0.9253*	*0.0008*	0.400	0.3514	0.0243	0.3444	150	0.017

Table 6.2.5
MAXIMUM K_{EFF} VALUES FOR THE 14X14B ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14B (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 179 fuel rods, 17 guide tubes, pitch=0.556, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14B01	*0.9159*	*0.9117*	*0.0007*	0.422	0.3734	0.0243	0.3659	150	0.017
14x14B02	*0.9169*	*0.9126*	*0.0008*	0.417	0.3580	0.0295	0.3505	150	0.017
14x14B03	*0.9110*	*0.9065*	*0.0009*	0.424	0.3640	0.0300	0.3565	150	0.017
14x14B04	*0.9084*	*0.9039*	*0.0009*	0.426	0.3640	0.0310	0.3565	150	0.017
Dimensions Listed for Authorized Contents				0.417 (min.)	0.3734 (max.)		0.3659 (max.)	150 (max.)	0.017 (min.)
bounding dimensions (B14x14B01)	*0.9228*	*0.9185*	*0.0008*	0.417	0.3734	0.0218	0.3659	150	0.017

Table 6.2.6
MAXIMUM K_{EFF} VALUES FOR THE 14X14C ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14C (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 176 fuel rods, 5 guide tubes, pitch=0.580, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14C01	*0.9258*	*0.9215*	*0.0008*	0.440	0.3840	0.0280	0.3765	150	0.040
14x14C02	*0.9265*	*0.9222*	*0.0008*	0.440	0.3840	0.0280	0.3770	150	0.040
14x14C03	*0.9287*	*0.9242*	*0.0009*	0.440	0.3880	0.0260	0.3805	150	0.038
Dimensions Listed for Authorized Contents				0.440 (min.)	0.3880 (max.)		0.3805 (max.)	150 (max.)	0.038 (min.)
bounding dimensions (14x14C01)	*0.9287*	*0.9242*	*0.0009*	0.440	0.3880	0.0260	0.3805	150	0.038

Table 6.2.7
MAXIMUM K_{EFF} VALUES FOR THE 14X14D ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14D (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 180 fuel rods, 16 guide tubes, pitch=0.556, SS clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14D01	*0.8507*	*0.8464*	*0.0008*	0.422	0.3890	0.0165	0.3835	144	0.0145
Dimensions Listed for Authorized Contents				0.422 (min.)	0.3890 (max.)		0.3835 (max.)	144 (max.)	0.0145 (min.)

Table 6.2.8
MAXIMUM K_{EFF} VALUES FOR THE 15X15A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15A (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, *21* guide tubes, pitch=0.550, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15A01	*0.9204*	*0.9159*	*0.0009*	0.418	0.3660	0.0260	0.3580	150	0.0165
Dimensions Listed for Authorized Contents				0.418 (min.)	0.3660 (max.)		0.3580 (max.)	150 (max.)	0.0165 (min.)

Table 6.2.9
MAXIMUM K_{EFF} VALUES FOR THE 15X15B ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15B (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, 21 guide tubes, pitch=0.563, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15B01	*0.9369*	*0.9326*	*0.0008*	0.422	0.3730	0.0245	0.3660	150	0.017
15x15B02	*0.9338*	*0.9295*	*0.0008*	0.422	0.3730	0.0245	0.3660	150	0.017
15x15B03	*0.9362*	*0.9318*	*0.0008*	0.422	0.3734	0.0243	0.3660	150	0.017
15x15B04	*0.9370*	*0.9327*	*0.0008*	0.422	0.3734	0.0243	0.3659	150	0.015
15x15B05	*0.9356*	*0.9313*	*0.0008*	0.422	0.3736	0.0242	0.3659	150	0.015
15x15B06	*0.9366*	*0.9324*	*0.0007*	0.420	0.3720	0.0240	0.3671	150	0.015
Dimensions Listed for Authorized Contents				0.420 (min.)	0.3736 (max.)		0.3671 (max.)	150 (max.)	0.015 (min.)
bounding dimensions (B15x15B01)	*0.9388*	*0.9343*	*0.0009*	0.420	0.3736	0.0232	0.3671	150	0.015

Table 6.2.10
MAXIMUM K_{EFF} VALUES FOR THE 15X15C ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15C (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, 21 guide tubes, pitch=0.563, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15C01	*0.9255*	*0.9213*	*0.0007*	0.424	0.3640	0.0300	0.3570	150	0.0255
15x15C02	*0.9297*	*0.9255*	*0.0007*	0.424	0.3640	0.0300	0.3570	150	0.0165
15x15C03	*0.9297*	*0.9255*	*0.0007*	0.424	0.3640	0.0300	0.3565	150	0.0165
15x15C04	*0.9311*	*0.9268*	*0.0008*	0.417	0.3570	0.0300	0.3565	150	0.0165
Dimensions Listed for Authorized Contents				0.417 (min.)	0.3640 (max.)		0.3570 (max.)	150 (max.)	0.0165 (min.)
bounding dimensions (B15x15C01)	*0.9361*	*0.9316*	*0.0009*	0.417	0.3640	0.0265	0.3570	150	0.0165

Table 6.2.11
MAXIMUM K_{EFF} VALUES FOR THE 15X15D ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15D (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15D01	*0.9341*	*0.9298*	*0.0008*	0.430	0.3770	0.0265	0.3690	150	0.0160
15x15D02	*0.9367*	*0.9324*	*0.0008*	0.430	0.3770	0.0265	0.3686	150	0.0160
15x15D03	*0.9354*	*0.9311*	*0.0008*	0.430	0.3770	0.0265	0.3700	150	0.0155
15x15D04	*0.9339*	*0.9292*	*0.0010*	0.430	0.3800	0.0250	0.3735	150	0.0150
Dimensions Listed for Authorized Contents				0.430 (min.)	0.3800 (max.)		0.3735 (max.)	150 (max.)	0.0150 (min.)
bounding dimensions (15x15D04)	*0.9339*†	*0.9292*	*0.0010*	0.430	0.3800	0.0250	0.3735	150	0.0150

† *The k_{eff} value listed for the 15x15D03 case is slightly higher than that for the case with the bounding dimensions. However, the difference (0.0015) is well within the statistical uncertainties, and thus, the two values are statistically equivalent (within 2σ). Therefore, the 0.9354 value is listed in Table 6.1.1 as the maximum.*

Table 6.2.12
MAXIMUM K_{EFF} VALUES FOR THE 15X15E ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15E (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15E01	*0.9368*	*0.9325*	*0.0008*	0.428	0.3790	0.0245	0.3707	150	0.0140
Dimensions Listed for Authorized Contents				0.428 (min.)	0.3790 (max.)		0.3707 (max.)	150 (max.)	0.0140 (min.)

Table 6.2.13
MAXIMUM K_{EFF} VALUES FOR THE 15X15F ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15F (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15F01	*0.9395*†	*0.9350*	*0.0009*	0.428	0.3820	0.0230	0.3742	150	0.0140
Dimensions Listed for Authorized Contents				0.428 (min.)	0.3820 (max.)		0.3742 (max.)	150 (max.)	0.0140 (min.)

† KENO5a verification calculation resulted in a maximum k_{eff} of ~~0.9466~~*0.9378*.

Table 6.2.14
MAXIMUM K_{EFF} VALUES FOR THE 15X15G ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15G (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, 21 guide tubes, pitch=0.563, SS clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15G01	*0.8876*	*0.8833*	*0.0008*	0.422	0.3890	0.0165	0.3825	144	0.0145
Dimensions Listed for Authorized Contents				0.422 (min.)	0.3890 (max.)		0.3825 (max.)	144 (max.)	0.0145 (min.)

Table 6.2.15
MAXIMUM K_{EFF} VALUES FOR THE 15X15H ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15H (3.8% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15H01	*0.9337*	*0.9292*	*0.0009*	0.414	0.3700	0.0220	0.3622	150	0.0140
Dimensions Listed for Authorized Contents				0.414 (min.)	0.3700 (max.)		0.3622 (max.)	150 (max.)	0.0140 (min.)

Table 6.2.16
MAXIMUM K_{EFF} VALUES FOR THE 16X16A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

16x16A (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 236 fuel rods, 5 guide tubes, pitch=0.506, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
16x16A01	*0.9287*	*0.9244*	*0.0008*	0.382	0.3320	0.0250	0.3255	150	0.0400
16x16A02	*0.9263*	*0.9221*	*0.0007*	0.382	0.3320	0.0250	0.3250	150	0.0400
Dimensions Listed for Authorized Contents				0.382 (min.)	0.3320 (max.)		0.3255 (max.)	150 (max.)	0.0400 (min.)
bounding dimensions (16x16A01)	*0.9287*	*0.9244*	*0.0008*	0.382	0.3320	0.0250	0.3255	150	0.0400

Table 6.2.17
MAXIMUM K_{EFF} VALUES FOR THE 17X17A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

17x17A (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 264 fuel rods, 25 guide tubes, pitch=0.496, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
17x17A01	*0.9368*	*0.9325*	*0.0008*	0.360	0.3150	0.0225	0.3088	144	0.016
17x17A02	*0.9368*	*0.9325*	*0.0008*	0.360	0.3150	0.0225	0.3088	150	0.016
17x17A03	*0.9329*	*0.9286*	*0.0008*	0.360	0.3100	0.0250	0.3030	150	0.016
Dimensions Listed for Authorized Contents				0.360 (min.)	0.3150 (max.)		0.3088 (max.)	150 (max.)	0.016 (min.)
bounding dimensions (17x17A02)	*0.9368*	*0.9325*	*0.0008*	0.360	0.3150	0.0225	0.3088	150	0.016

Table 6.2.18
MAXIMUM K_{EFF} VALUES FOR THE 17X17B ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

17x17B (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 264 fuel rods, 25 guide tubes, pitch=0.496, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
17x17B01	*0.9288*	*0.9243*	*0.0009*	0.374	0.3290	0.0225	0.3225	150	0.016
17x17B02	*0.9290*	*0.9247*	*0.0008*	0.374	0.3290	0.0225	0.3225	150	0.016
17x17B03	*0.9243*	*0.9199*	*0.0008*	0.376	0.3280	0.0240	0.3215	150	0.016
17x17B04	*0.9324*	*0.9279*	*0.0009*	0.372	0.3310	0.0205	0.3232	150	0.014
17x17B05	*0.9266*	*0.9222*	*0.0008*	0.374	0.3260	0.0240	0.3195	150	0.016
17x17B06	*0.9311*	*0.9268*	*0.0008*	0.372	0.3310	0.0205	0.3232	150	0.014
Dimensions Listed for Authorized Contents				0.372 (min.)	0.3310 (max.)		0.3232 (max.)	150 (max.)	0.014 (min.)
bounding dimensions (17x17B06)	*0.9311*†	*0.9268*	*0.0008*	0.372	0.3310	0.0205	0.3232	150	0.014

† *The k_{eff} value listed for the 17x17B04 case is slightly higher than that for the case with the bounding dimensions. However, the difference (0.0013) is well within the statistical uncertainties, and thus, the two values are statistically equivalent (within 2σ). Therefore, the 0.9324 value is listed in Table 6.1.1 as the maximum.*

Table 6.2.19
MAXIMUM K_{EFF} VALUES FOR THE 17X17C ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

17x17C (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 264 fuel rods, 25 guide tubes, pitch=0.502, Zr clad									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
17x17C01	*0.9293*	*0.9250*	*0.0008*	0.379	0.3310	0.0240	0.3232	150	0.020
17x17C02	*0.9336*	*0.9293*	*0.0008*	0.377	0.3330	0.0220	0.3252	150	0.020
Dimensions Listed for Authorized Contents				0.377 (min.)	0.3330 (max.)		0.3252 (max.)	150 (max.)	0.020 (min.)
bounding dimensions (17x17C02)	*0.9336*	*0.9293*	*0.0008*	0.377	0.3330	0.0220	0.3252	150	0.020

Table 6.2.20
MAXIMUM K_{EFF} VALUES FOR THE 7X7B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

7x7B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 49 fuel rods, 0 water rods, pitch=0.738, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
7x7B01	0.9372	0.9330	0.0007	0.5630	0.4990	0.0320	0.4870	150	n/a	0.080
7x7B02	0.9301	0.9260	0.0007	0.5630	0.4890	0.0370	0.4770	150	n/a	0.102
7x7B03	0.9313	0.9271	0.0008	0.5630	0.4890	0.0370	0.4770	150	n/a	0.080
7x7B04	0.9311	0.9270	0.0007	0.5700	0.4990	0.0355	0.4880	150	n/a	0.080
7x7B05	0.9350	0.9306	0.0008	0.5630	0.4950	0.0340	0.4775	150	n/a	0.080
7x7B06	0.9298	0.9260	0.0006	0.5700	0.4990	0.0355	0.4910	150	n/a	0.080
Dimensions Listed for Authorized Contents				0.5630 (min.)	0.4990 (max.)		0.4910 (max.)	150 (max.)	n/a	0.120 (max.)
bounding dimensions (B7x7B01)	0.9375	0.9332	0.0008	0.5630	0.4990	0.0320	0.4910	150	n/a	0.102
bounding dimensions with 120 mil channel (B7x7B02)	0.9386	0.9344	0.0007	0.5630	0.4990	0.0320	0.4910	150	n/a	0.120

Table 6.2.21
MAXIMUM K_{EFF} VALUES FOR THE 8X8B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 63 or 64 fuel rods, 1 or 0 water rods, pitch† = 0.636-0.642, Zr clad												
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	Fuel rods	pitch	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8B01	0.9310	0.9265	0.0009	63	0.641	0.4840	0.4140	0.0350	0.4050	150	0.035	0.100
8x8B02	0.9227	0.9185	0.0007	63	0.636	0.4840	0.4140	0.0350	0.4050	150	0.035	0.100
8x8B03	0.9299	0.9257	0.0008	63	0.640	0.4930	0.4250	0.0340	0.4160	150	0.034	0.100
8x8B04	0.9236	0.9194	0.0008	64	0.642	0.5015	0.4295	0.0360	0.4195	150	n/a	0.100
Dimensions Listed for Authorized Contents				63 or 64	0.636-0.642	0.4840 (min.)	0.4295 (max.)		0.4195 (max.)	150 (max.)	0.034	0.120 (max.)
bounding (pitch=0.636) (B8x8B01)	0.9346	0.9301	0.0009	63	0.636	0.4840	0.4295	0.02725	0.4195	150	0.034	0.120
bounding (pitch=0.640) (B8x8B02)	0.9385	0.9343	0.0008	63	0.640	0.4840	0.4295	0.02725	0.4195	150	0.034	0.120
bounding (pitch=0.641) (B8x8B03)	0.9416	0.9375	0.0007	63	0.642	0.4840	0.4295	0.02725	0.4195	150	0.034	0.120

† This assembly class was analyzed and qualified for a small variation in the pitch and a variation in the number of fuel and water rods.

Table 6.2.22
MAXIMUM K_{EFF} VALUES FOR THE 8X8C ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8C (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 62 fuel rods, 2 water rods, pitch† = 0.636-0.641, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	pitch	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8C01	0.9315	0.9273	0.0007	0.641	0.4840	0.4140	0.0350	0.4050	150	0.035	0.100
8x8C02	0.9313	0.9268	0.0009	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.000
8x8C03	0.9329	0.9286	0.0008	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.800
8x8C04	0.9348††	0.9307	0.0007	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.100
8x8C05	0.9353	0.9312	0.0007	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.120
8x8C06	0.9353	0.9312	0.0007	0.640	0.4830	0.4190	0.0320	0.4110	150	0.030	0.100
8x8C07	0.9314	0.9273	0.0007	0.640	0.4830	0.4150	0.0340	0.4100	150	0.030	0.100
8x8C08	0.9339	0.9298	0.0007	0.640	0.4830	0.4190	0.0320	0.4100	150	0.034	0.100
8x8C09	0.9301	0.9260	0.0007	0.640	0.4930	0.4250	0.0340	0.4160	150	0.034	0.100
8x8C10	0.9317	0.9275	0.0008	0.640	0.4830	0.4150	0.0340	0.4100	150	0.030	0.120
8x8C11	0.9328	0.9287	0.0007	0.640	0.4830	0.4150	0.0340	0.4100	150	0.030	0.120
8x8C12	0.9285	0.9242	0.0008	0.636	0.4830	0.4190	0.0320	0.4110	150	0.030	0.120
Dimensions Listed for Authorized Contents				0.636-0.641	0.4830 (min.)	0.4250 (max.)		0.4160 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding (pitch=0.636) (B8x8C01)	0.9357	0.9313	0.0009	0.636	0.4830	0.4250	0.0290	0.4160	150	0.000	0.120
bounding (pitch=0.640) (B8x8C02)	0.9425	0.9384	0.0007	0.640	0.4830	0.4250	0.0290	0.4160	150	0.000	0.120
bounding (pitch=0.641) (B8x8C03)	0.9418	0.9375	0.0008	0.641	0.4830	0.4250	0.0290	0.4160	150	0.000	0.120

† This assembly class was analyzed and qualified for a small variation in the pitch.

†† KENO5a verification calculation resulted in a maximum k_{eff} of 0.9343.

Table 6.2.23
MAXIMUM K_{EFF} VALUES FOR THE 8X8D ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8D (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 60 fuel rods, 1-4 water rods†, pitch=0.640, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8D01	0.9342	0.9302	0.0006	0.4830	0.4190	0.0320	0.4110	150	0.03/0.025	0.100
8x8D02	0.9325	0.9284	0.0007	0.4830	0.4190	0.0320	0.4110	150	0.030	0.100
8x8D03	0.9351	0.9309	0.0008	0.4830	0.4190	0.0320	0.4110	150	0.025	0.100
8x8D04	0.9338	0.9296	0.0007	0.4830	0.4190	0.0320	0.4110	150	0.040	0.100
8x8D05	0.9339	0.9294	0.0009	0.4830	0.4190	0.0320	0.4100	150	0.040	0.100
8x8D06	0.9365	0.9324	0.0007	0.4830	0.4190	0.0320	0.4110	150	0.040	0.120
8x8D07	0.9341	0.9297	0.0009	0.4830	0.4190	0.0320	0.4110	150	0.040	0.080
8x8D08	0.9376	0.9332	0.0009	0.4830	0.4230	0.0300	0.4140	150	0.030	0.080
Dimensions Listed for Authorized Contents				0.4830 (min.)	0.4230 (max.)		0.4140 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (B8x8D01)	0.9403	0.9363	0.0007	0.4830	0.4230	0.0300	0.4140	150	0.000	0.120

† Fuel assemblies 8x8D01 through 8x8D03 have 4 water rods that are similar in size to the fuel rods, while assemblies 8x8D04 through 8x8D07 have 1 large water rod that takes the place of the 4 water rods. Fuel assembly 8x8D08 contains 3 water rods that are similar in size to the fuel rods.

Table 6.2.24
MAXIMUM K_{EFF} VALUES FOR THE 8X8E ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8E (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 59 fuel rods, 5 water rods, pitch=0.640, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8E01	0.9312	0.9270	0.0008	0.4930	0.4250	0.0340	0.4160	150	0.034	0.100
Dimensions Listed for Authorized Contents				0.4930 (min.)	0.4250 (max.)		0.4160 (max.)	150 (max.)	0.034 (min.)	0.100 (max.)

Table 6.2.25
MAXIMUM K_{EFF} VALUES FOR THE 8X8F ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8F (*4.0%* Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 64 fuel rods, 4 rectangular water cross segments dividing the assembly into four quadrants, pitch=0.609, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8F01	*0.9411*	*0.9366*	*0.0009*	0.4576	0.3996	0.0290	0.3913	150	0.0315	0.055
Dimensions Listed for Authorized Contents				0.4576 (min.)	0.3996 (max.)		0.3913 (max.)	150 (max.)	0.0315 (min.)	0.055 (max.)

Table 6.2.26
MAXIMUM K_{EFF} VALUES FOR THE 9X9A ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9A (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 74/66 fuel rods†, 2 water rods, pitch=0.566, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9A01 (axial segment with all rods)	0.9353	0.9310	0.0008	0.4400	0.3840	0.0280	0.3760	150	0.030	0.100
9x9A02 (axial segment with only the full length rods)	0.9388	0.9345	0.0008	0.4400	0.3840	0.0280	0.3760	150	0.030	0.100
9x9A03 (actual three-dimensional representation of all rods)	0.9351	0.9310	0.0007	0.4400	0.3840	0.0280	0.3760	150/90	0.030	0.100
9x9A04 (axial segment with only the full length rods)	0.9396	0.9355	0.0007	0.4400	0.3840	0.0280	0.3760	150	0.030	0.120
Dimensions Listed for Authorized Contents				0.4400 (min.)	0.3840 (max.)		0.3760 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (axial segment with only the full length rods) (B9x9A01)	0.9417	0.9374	0.0008	0.4400	0.3840	0.0280	0.3760	150	0.000	0.120

† This assembly class contains 66 full length rods and 8 partial length rods. In order to eliminate a requirement on the length of the partial length rods, separate calculations were performed for the axial segments with and without the partial length rods.

Table 6.2.27
MAXIMUM K_{EFF} VALUES FOR THE 9X9B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 72 fuel rods, 1 water rod (square, replacing 9 fuel rods), pitch=0.569 to 0.572†, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	pitch	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9B01	*0.9380*	*0.9336*	*0.0008*	0.569	0.4330	0.3807	0.0262	0.3737	150	0.0285	0.100
9x9B02	*0.9373*	*0.9329*	*0.0009*	0.569	0.4330	0.3810	0.0260	0.3737	150	0.0285	0.100
9x9B03	*0.9417*	*0.9374*	*0.0008*	0.572	0.4330	0.3810	0.0260	0.3737	150	0.0285	0.100
Dimensions Listed for Authorized Contents				0.572	0.4330 (min.)	0.3810 (max.)		0.3740 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (B9x9B01)	*0.9436*	*0.9394*	*0.0008*	0.572	0.4330	0.3810	0.0260	0.3740††	150	0.000	0.120

† This assembly class was analyzed and qualified for a small variation in the pitch.

†† This value was conservatively defined to be larger than any of the actual pellet diameters.

Table 6.2.28

MAXIMUM K_{EFF} VALUES FOR THE 9X9C ASSEMBLY CLASS IN THE MPC-68

(all dimensions are in inches)

9x9C (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 80 fuel rods, 1 water rods, pitch=0.572, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9C01	0.9395	0.9352	0.0008	0.4230	0.3640	0.0295	0.3565	150	0.020	0.100
Dimensions Listed for Authorized Contents				0.4230 (min.)	0.3640 (max.)		0.3565 (max.)	150 (max.)	0.020 (min.)	0.100 (max.)

Table 6.2.29
MAXIMUM K_{EFF} VALUES FOR THE 9X9D ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9D (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 79 fuel rods, 2 water rods, pitch=0.572, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9D01	0.9394	0.9350	0.0009	0.4240	0.3640	0.0300	0.3565	150	0.0300	0.100
Dimensions Listed for Authorized Contents				0.4240 (min.)	0.3640 (max.)		0.3565 (max.)	150 (max.)	0.0300 (min.)	0.100 (max.)

Table 6.2.30
MAXIMUM K_{EFF} VALUES FOR THE 9X9E ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9E (*4.0%* Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 76 fuel rods, 5 water rods, pitch=0.572, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9E01	*0.9334*	*0.9293*	*0.0007*	0.4170	0.3640	0.0265	0.3530	150	0.0120	0.120
9x9E02	*0.9401*	*0.9359*	*0.0008*	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120
Dimensions Listed for Authorized Contents†				0.4170 (min.)	0.3640 (max.)		0.3530 (max.)	150 (max.)	0.0120 (min.)	0.120 (max.)
bounding dimensions (9x9E02)	*0.9401*	*0.9359*	*0.0008*	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120

† This fuel assembly, also known as SPC 9x9-5, contains fuel rods with different cladding and pellet diameters which do not bound each other. To be consistent in the way fuel assemblies are listed for Authorized Contents, two assembly classes (9x9E and 9x9F) are required to specify this assembly. Each class contains the actual geometry (9x9E02 and 9x9F02), as well as a hypothetical geometry with either all small rods (9x9E01) or all large rods (9x9F01). The Authorized Content lists the small rod dimensions for class 9x9E and the large rod dimensions for class 9x9F, and a note that both classes are used to qualify the assembly. The analyses demonstrate that all configurations, including the actual geometry, are acceptable.

Table 6.2.31
MAXIMUM K_{EFF} VALUES FOR THE 9X9F ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9F (*4.0%* Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 76 fuel rods, 5 water rods, pitch=0.572, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9F01	*0.9307*	*0.9265*	*0.0007*	0.4430	0.3860	0.0285	0.3745	150	0.0120	0.120
9x9F02	*0.9401*	*0.9359*	*0.0008*	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120
Dimensions Listed for Authorized Contents†				0.4430 (min.)	0.3860 (max.)		0.3745 (max.)	150 (max.)	0.0120 (min.)	0.120 (max.)
bounding dimensions (9x9F02)	*0.9401*	*0.9359*	*0.0008*	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120

† This fuel assembly, also known as SPC 9x9-5, contains fuel rods with different cladding and pellet diameters which do not bound each other. To be consistent in the way fuel assemblies are listed for Authorized Contents, two assembly classes (9x9E and 9x9F) are required to specify this assembly. Each class contains the actual geometry (9x9E02 and 9x9F02), as well as a hypothetical geometry with either all small rods (9x9E01) or all large rods (9x9F01). The Authorized Content lists the small rod dimensions for class 9x9E and the large rod dimensions for class 9x9F, and a note that both classes are used to qualify the assembly. The analyses demonstrate that all configurations, including the actual geometry, are acceptable.

Table 6.2.32
MAXIMUM K_{EFF} VALUES FOR THE 10X10A ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10A (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 92/78 fuel rods†, 2 water rods, pitch=0.510, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10A01 (axial segment with all rods)	0.9377	0.9335	0.0008	0.4040	0.3520	0.0260	0.3450	155	0.030	0.100
10x10A02 (axial segment with only the full length rods)	0.9426	0.9386	0.0007	0.4040	0.3520	0.0260	0.3450	155	0.030	0.100
10x10A03 (actual three-dimensional representation of all rods)	0.9396	0.9356	0.0007	0.4040	0.3520	0.0260	0.3450	155/90	0.030	0.100
Dimensions Listed for Authorized Contents				0.4040 (min.)	0.3520 (max.)		0.3455 (max.)	150†† (max.)	0.030 (min.)	0.120 (max.)
bounding dimensions (axial segment with only the full length rods) (B10x10A01)	0.9457†††	0.9414	0.0008	0.4040	0.3520	0.0260	0.3455‡	155	0.030	0.120

† This assembly class contains 78 full-length rods and 14 partial-length rods. In order to eliminate the requirement on the length of the partial length rods, separate calculations were performed for axial segments with and without the partial length rods.

†† Although the analysis qualifies this assembly for a maximum active fuel length of 155 inches, the specification for authorized contents limits the active fuel length to 150 inches. This is due to the fact that the Boral panels are 156 inches in length.

††† KENO5a verification calculation resulted in a maximum k_{eff} of 0.9453.

‡ This value was conservatively defined to be larger than any of the actual pellet diameters.

Table 6.2.33
MAXIMUM K_{EFF} VALUES FOR THE 10X10B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 91/83 fuel rods†, 1 water rods (square, replacing 9 fuel rods), pitch=0.510, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10B01 (axial segment with all rods)	0.9384	0.9341	0.0008	0.3957	0.3480	0.0239	0.3413	155	0.0285	0.100
10x10B02 (axial segment with only the full length rods)	0.9416	0.9373	0.0008	0.3957	0.3480	0.0239	0.3413	155	0.0285	0.100
10x10B03 (actual three-dimensional representation of all rods)	0.9375	0.9334	0.0007	0.3957	0.3480	0.0239	0.3413	155/90	0.0285	0.100
Dimensions Listed for Authorized Contents				0.3957 (min.)	0.3480 (max.)		0.3420 (max.)	150†† (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (axial segment with only the full length rods) (B10x10B01)	0.9436	0.9395	0.0007	0.3957	0.3480	0.0239	0.3420†††	155	0.000	0.120

† This assembly class contains 83 full length rods and 8 partial length rods. In order to eliminate a requirement on the length of the partial length rods, separate calculations were performed for the axial segments with and without the partial length rods.

†† Although the analysis qualifies this assembly for a maximum active fuel length of 155 inches, the specification for authorized contents limits the active fuel length to 150 inches. This is due to the fact that the Boral panels are 156 inches in length.

††† This value was conservatively defined to be larger than any of the actual pellet diameters.

Table 6.2.34
MAXIMUM K_{EFF} VALUES FOR THE 10X10C ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10C (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 96 fuel rods, 5 water rods (1 center diamond and 4 rectangular), pitch=0.488, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10C01	*0.9433*	*0.9392*	*0.0007*	0.3780	0.3294	0.0243	0.3224	150	0.031	0.055
Dimensions Listed for Authorized Contents				0.3780 (min.)	0.3294 (max.)		0.3224 (max.)	150 (max.)	0.031 (min.)	0.055 (max.)

Table 6.2.35
MAXIMUM K_{EFF} VALUES FOR THE 10X10D ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10D (4.0% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 100 fuel rods, 0 water rods, pitch=0.565, SS clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10D01	0.9376	0.9333	0.0008	0.3960	0.3560	0.0200	0.350	83	n/a	0.080
Dimensions Listed for Authorized Contents				0.3960 (min.)	0.3560 (max.)		0.350 (max.)	83 (max.)	n/a	0.080 (max.)

Table 6.2.36
MAXIMUM K_{EFF} VALUES FOR THE 10X10E ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10E (4.0% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 96 fuel rods, 4 water rods, pitch=0.557, SS clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10E01	0.9185	0.9144	0.0007	0.3940	0.3500	0.0220	0.3430	83	0.022	0.080
Dimensions Listed for Authorized Contents				0.3940 (min.)	0.3500 (max.)		0.3430 (max.)	83 (max.)	0.022 (min.)	0.080 (max.)

Table 6.2.37
MAXIMUM K_{EFF} VALUES FOR THE 6X6A ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

6x6A (3.0% Enrichment[†], Boral ^{10}B minimum loading of 0.0067 g/cm^2) 35 or 36 fuel rods[††], 1 or 0 water rods[††], pitch=0.694 to 0.710[††], Zr clad												
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	pitch	fuel rods	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
6x6A01	0.7539	0.7498	0.0007	0.694	36	0.5645	0.4945	0.0350	0.4940	110	n/a	0.060
6x6A02	0.7517	0.7476	0.0007	0.694	36	0.5645	0.4925	0.0360	0.4820	110	n/a	0.060
6x6A03	0.7545	0.7501	0.0008	0.694	36	0.5645	0.4945	0.0350	0.4820	110	n/a	0.060
6x6A04	0.7537	0.7494	0.0008	0.694	36	0.5550	0.4850	0.0350	0.4820	110	n/a	0.060
6x6A05	0.7555	0.7512	0.0008	0.696	36	0.5625	0.4925	0.0350	0.4820	110	n/a	0.060
6x6A06	0.7618	0.7576	0.0008	0.696	35	0.5625	0.4925	0.0350	0.4820	110	0.0	0.060
6x6A07	0.7588	0.7550	0.0007	0.700	36	0.5555	0.4850	0.03525	0.4780	110	n/a	0.060
6x6A08	0.7808	0.7766	0.0007	0.710	36	0.5625	0.5105	0.0260	0.4980	110	n/a	0.060
Dimensions Listed for Authorized Contents				0.710 (max.)	35 or 36	0.5550 (min.)	0.5105 (max.)	0.02225	0.4980 (max.)	120 (max.)	0.0	0.060 (max.)
bounding dimensions (B6x6A01)	0.7727	0.7685	0.0007	0.694	35	0.5550	0.5105	0.02225	0.4980	120	0.0	0.060
bounding dimensions (B6x6A02)	0.7782	0.7738	0.0008	0.700	35	0.5550	0.5105	0.02225	0.4980	120	0.0	0.060
bounding dimensions (B6x6A03)	0.7888	0.7846	0.0007	0.710	35	0.5550	0.5105	0.02225	0.4980	120	0.0	0.060

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

†† This assembly class was analyzed and qualified for a small variation in the pitch and a variation in the number of fuel and water rods.

Table 6.2.38
MAXIMUM K_{EFF} VALUES FOR THE 6X6B ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

6x6B (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 35 or 36 fuel rods†† (up to 9 MOX rods), 1 or 0 water rods††, pitch=0.694 to 0.710††, Zr clad												
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	pitch	fuel rods	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
6x6B01	0.7604	0.7563	0.0007	0.694	36	0.5645	0.4945	0.0350	0.4820	110	n/a	0.060
6x6B02	0.7618	0.7577	0.0007	0.694	36	0.5625	0.4925	0.0350	0.4820	110	n/a	0.060
6x6B03	0.7619	0.7578	0.0007	0.696	36	0.5625	0.4925	0.0350	0.4820	110	n/a	0.060
6x6B04	0.7686	0.7644	0.0008	0.696	35	0.5625	0.4925	0.0350	0.4820	110	0.0	0.060
6x6B05	0.7824	0.7785	0.0006	0.710	35	0.5625	0.4925	0.0350	0.4820	110	0.0	0.060
Dimensions Listed for Authorized Contents				0.710 (max.)	35 or 36	0.5625 (min.)	0.4945 (max.)		0.4820 (max.)	120 (max.)	0.0	0.060 (max.)
bounding dimensions (B6x6B01)	0.7822†††	0.7783	0.0007	0.710	35	0.5625	0.4945	0.0340	0.4820	120	0.0	0.060

Note:

1. These assemblies contain up to 9 MOX pins. The composition of the MOX fuel pins is given in Table 6.3.4.

† The ^{235}U enrichment of the MOX and UO_2 pins is assumed to be 0.711% and 3.0%, respectively.

†† This assembly class was analyzed and qualified for a small variation in the pitch and a variation in the number of fuel and water rods.

††† The k_{eff} value listed for the 6x6B05 case is slightly higher than that for the case with the bounding dimensions. However, the difference (0.0002) is well within the statistical uncertainties, and thus, the two values are statistically equivalent (within 1σ). Therefore, the 0.7824 value is listed in Tables 6.1.2 and 6.1.3 as the maximum.

Table 6.2.39
MAXIMUM K_{EFF} VALUES FOR THE 6X6C ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

6x6C (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 36 fuel rods, 0 water rods, pitch=0.740, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
6x6C01	0.8021	0.7980	0.0007	0.5630	0.4990	0.0320	0.4880	77.5	n/a	0.060
Dimensions Listed for Authorized Contents				0.5630 (min.)	0.4990 (max.)		0.4880 (max.)	77.5 (max.)	n/a	0.060 (max.)

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

Table 6.2.40
MAXIMUM K_{EFF} VALUES FOR THE 7X7A ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

7x7A (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 49 fuel rods, 0 water rods, pitch=0.631, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
7x7A01	0.7974	0.7932	0.0008	0.4860	0.4204	0.0328	0.4110	80	n/a	0.060
Dimensions Listed for Authorized Contents				0.4860 (min.)	0.4204 (max.)		0.4110 (max.)	80 (max.)	n/a	0.060 (max.)

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

Table 6.2.41
MAXIMUM K_{EFF} VALUES FOR THE 8X8A ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

8x8A (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 63 or 64 fuel rods††, 0 water rods, pitch=0.523, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	fuel rods	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8A01	0.7685	0.7644	0.0007	64	0.4120	0.3620	0.0250	0.3580	110	n/a	0.100
8x8A02	0.7697	0.7656	0.0007	63	0.4120	0.3620	0.0250	0.3580	120	n/a	0.100
Dimensions Listed for Authorized Contents				63	0.4120 (min.)	0.3620 (max.)		0.3580 (max.)	110 (max.)	n/a	0.100 (max.)
bounding dimensions (8x8A02)	0.7697	0.7656	0.0007	63	0.4120	0.3620	0.0250	0.3580	120	n/a	0.100

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

†† This assembly class was analyzed and qualified for a variation in the number of fuel rods.

Table 6.2.42

SPECIFICATION OF THE THORIA ROD CANISTER AND THE THORIA RODS

Canister ID	4.81"
Canister Wall Thickness	0.11"
Separator Assembly Plates Thickness	0.11"
Cladding OD	0.412"
Cladding ID	0.362"
Pellet OD	0.358"
Active Length	110.5"
Fuel Composition	1.8% UO_2 and 98.2% ThO_2
Initial Enrichment	93.5 wt% ^{235}U for 1.8% of the fuel
Maximum k_{eff}	0.1813
Calculated k_{eff}	0.1779
Standard Deviation	0.0004

Table 6.2.43
MAXIMUM K_{EFF} VALUES FOR THE 14X14E ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14E (5.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 173 fuel rods, 0 guide tubes, pitch=0.453 and 0.441, SS clad†									
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length††	guide tube thickness
14x14E01	0.7598	0.7555	0.0008	0.3415	0.3175 0.2845 0.3015	0.0120 0.0285 0.0200	0.3130 0.2800 0.2970	102	0.0000
14x14E02	0.7627	0.7586	0.0007	0.3415	0.3175	0.0120	0.3130	102	0.0000
14x14E03	0.6952	0.6909	0.0008	0.3415	0.2845	0.0285	0.2800	102	0.0000
Dimensions Listed in Certificate of Compliance				0.3415 (min.)	0.3175 (max.)		0.3130 (max.)	102 (max.)	0.0000 (min.)
Bounding dimensions (14x14E02)	0.7627	0.7586	0.0007	0.3415	0.3175	0.0120	0.3130	102	0.0000

† This is the IP-1 fuel assembly at Indian Point. This assembly is a 14x14 assembly with 23 fuel rods omitted to allow passage of control rods between assemblies. Fuel rod dimensions are bounding for each of the three types of rods found in the IP-1 fuel assembly.

†† Calculations were conservatively performed for a fuel length of 150 inches.

Table 6.2.44
MAXIMUM K_{EFF} VALUES FOR THE 9X9G ASSEMBLY CLASS IN THE MPC-68 and MPC-68FF
(all dimensions are in inches)

9x9G (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 72 fuel rods, 1 water rod (square, replacing 9 fuel rods), pitch=0.572, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9G01	0.9309	0.9265	0.0008	0.4240	0.3640	0.0300	0.3565	150	0.0320	0.120
Dimensions Listed in Certificate of Compliance				0.4240 (min.)	0.3640 (max.)		0.3565 (max.)	150 (max.)	0.0320 (min.)	0.120 (max.)

6.3 MODEL SPECIFICATION

In compliance with the requirements of 10CFR71.31(a)(1), 10CFR71.33(a)(5), and 10CFR71.33(b), this section provides a description of the HI-STAR 100 System in sufficient detail to identify the package accurately and provide a sufficient basis for the evaluation of the package.

6.3.1 Description of Calculational Model

Figures 6.3.1 ~~and~~*through* 6.3.3 show representative horizontal cross sections of the ~~two~~*four* types of cells used in the calculations, and Figures 6.3.4 ~~and~~*through* 6.3.6 illustrate the basket configurations used. ~~Two~~*Four* different MPC fuel basket designs were evaluated as follows:

- a 24 PWR assembly basket,
- *an optimized 24 PWR assembly basket (MPC-24E/EF and Trojan MPC-24E/EF),*
- *a 32 PWR assembly basket, and*
- a 68 BWR assembly basket.

For all basket designs, the same techniques and the same level of detail are used in the calculational models.

Full three-dimensional calculations were used, assuming the axial configuration shown in Figure 6.3.7, and conservatively neglecting the absorption in the overpack neutron shielding material (Holtite-A). Although the Boral neutron absorber panels are 156 inches in length, which is much longer than the active fuel length (maximum of 150 inches), they are assumed equal to the active fuel length in the calculations, *except for the Trojan MPC-24E/EF. Due to the reduced height of the Trojan MPCs, there is the potential of a misalignment of about 1 inch between the active length and the Boral at the bottom of the active region. Conservatively, a misalignment of 3 inches is assumed in the calculational model for the Trojan MPCs.* As shown on the ~~Design D~~*d*rawings in Section 1.4, ~~12~~*16* of the 24 periphery Boral panels on the MPC-24 have reduced width (i.e., 6.25 inches wide as opposed to 7.5 inches). However, ~~as shown in Figure 6.3.4,~~ the calculational models for the MPC-24 conservatively assume all of the periphery Boral panels are ~~5.0~~*6.25* inches in width.

The calculational model explicitly defines the fuel rods and cladding, the guide tubes (or water rods for BWR assemblies), the water-gaps and Boral absorber panels on the stainless steel walls of the basket cells. Under normal conditions of transport, when the MPC is dry, the resultant reactivity with the design basis fuel is very low (k_{eff} < 0.45). For the flooded condition (loading, unloading, and hypothetical accident condition), water was assumed to be present in the fuel rod pellet-to-clad gap regions (see Subsection 6.4.2.3 for justification). Appendix 6.D provides sample input files for ~~each of~~ the MPC-*24 and MPC-68* basket designs in the HI-STAR 100 System.

The water thickness above and below the fuel is intentionally maintained less than or equal to the actual water thickness. This assures that any positive reactivity effect of the steel in the MPC is conservatively included.

As indicated in Figures 6.3.1 ~~and~~*through* 6.3.3 and in Tables 6.3.1 and 6.3.2, calculations were made with dimensions assumed to be at their most conservative value with respect to criticality. CASMO-~~3~~*4 and MCNP4a* ~~was~~*were* used to determine the direction of the manufacturing tolerances which produced the most adverse effect on criticality. After the directional effect (positive effect with an increase in reactivity; or negative effect with a decrease in reactivity) of the manufacturing tolerances was determined, the criticality analyses were performed using the worst case tolerances in the direction which would increase reactivity.

CASMO-4 was used for one of each of the two principal basket designs, i.e. for the fluxtrap design MPC-24 and for the non-fluxtrap design MPC-68. The~~se~~ effects are shown in Table 6.3.1 which also identifies the approximate magnitude of the tolerances on reactivity. *The conclusions in Table 6.3.1 are directly applicable to the MPC-24E/EF and the MPC-32, due to the similarity in the basket designs.*

Additionaly, MCNP4a calculations are performed to evaluate the tolerances of the various basket dimensions of the MPC-68, MPC-24 and MPC-32 in further detail. The various basket dimensions are inter-dependent, and therefore cannot be individually varied (i.e., reduction in one parameter requires a corresponding reduction or increase in another parameter). Thus, it is not possible to determine the reactivity effect of each individual dimensional tolerance separately. However, it is possible to determine the reactivity effect of the dimensional tolerances by evaluating the various possible dimensional combinations. To this end, an evaluation of the various possible dimensional combinations was performed using MCNP4a. Calculated k_{eff} results (which do not include the bias, uncertainties, or calculational statistics), along with the actual dimensions, for a number of dimensional combinations are shown in Table 6.3.2 for the reference PWR and BWR fuel assemblies. ~~In Table 6.3.2, the box I.D. is the inner box dimension and the minimum, nominal, and maximum values correspond to those values permitted by the tolerances in the Design Drawings in Section 1.4. For each of the MPC designs, the reactivity effects of the tolerances are very small, generally within one standard deviation. The effect of the box wall thickness tolerance is negligible, being either slightly negative or within one standard deviation of the reference.~~*Each of the basket dimensions are evaluated for their minimum, nominal and maximum values. Due to the close similarity between the MPC-24 and MPC-24E,* *the basket dimensions are only evaluated for the MPC-24, and the same dimensional assumptions are applied to both MPC designs.*

Based on the MCNP4a and CASMO-~~3~~*4* calculations, the conservative dimensional assumptions listed in Table 6.3.3 were determined for the ~~two~~ MPC basket designs. Because the reactivity effect (positive or negative) of the manufacturing tolerances are not assembly dependent, these dimensional assumptions were employed for the criticality analyses.

The design parameters important to criticality safety are: fuel enrichment, the inherent geometry of the fuel basket structure, and the fixed neutron absorbing panels (Boral). None of these parameters are affected by the hypothetical accident conditions of transport.

During the hypothetical accident conditions of transport, the HI-STAR 100 System is assumed to be flooded to such an extent as to cause the maximum reactivity and to have full water reflection to such an extent as to cause the maximum reactivity. Further, arrays of packages under the hypothetical accident conditions must be evaluated to determine the maximum number of packages that may be transported in a single shipment. Thus, the only differences between the normal and hypothetical accident condition calculational models are the internal/external moderator densities and the boundary conditions (to simulate an infinite array of HI-STAR 100 Systems).

6.3.2 Cask Regional Densities

Composition of the various components of the principal designs of the HI-STAR 100 Systems are listed in Table 6.3.4. *In this table, only the composition of fresh fuel is listed. For a discussion on the composition of spent fuel for burnup credit in the MPC-32 see Subsection 6.4.11.*

The HI-STAR 100 System is designed such that the fixed neutron absorber (Boral) will remain effective for a period greater than 20 years, and there are no credible means to lose it. A detailed physical description, historical applications, unique characteristics, service experience, and manufacturing quality assurance of Boral are provided in Subsection 1.2.1.4.1.

The continued efficacy of the Boral is assured by acceptance testing, documented in Subsection 8.1.5.3, to validate the ^{10}B (poison) concentration in the Boral. To demonstrate that the neutron flux from the irradiated fuel results in a negligible depletion of the poison material, an MCNP4a calculation of the number of neutrons absorbed in the ^{10}B was performed. The calculation conservatively assumed a constant neutron source for 50 years equal to the initial source for the design basis fuel, as determined in Section 5.2, and shows that the fraction of ^{10}B atoms destroyed is only 2.6E-09 in 50 years. Thus, the reduction in ^{10}B concentration in the Boral by neutron absorption is negligible. In addition, *the structural* analysis ~~in Appendix 2.AD~~

demonstrates that the sheathing, which affixes the Boral panel, remains in place during all hypothetical accident conditions, and thus, the Boral panel remains permanently fixed. Therefore, there is no need to provide a surveillance or monitoring program to verify the continued efficacy of the neutron absorber.

Table 6.3.1

CASMO-~~3~~*4* CALCULATIONS FOR EFFECT OF TOLERANCES AND TEMPERATURE

Change in Nominal Parameter†	Δk for Maximum Tolerance		Action/Modeling Assumption
	MPC-24	**MPC-68‡**	
Reduce Boral Width to Minimum††	*N/A†††* *min. = nom. = 7.5" and 6.25"*	N/A††† min. = nom. = 4.75"	Assume minimum Boral width
Increase UO_2 Density to Maximum	*+0.0017* max. = 10.522 g/cc nom. = 10.412 g/cc	+0.0014 max. = 10.522 g/cc nom. = 10.412 g/cc	Assume maximum UO_2 density
Reduce Box Inside Dimension (I.D.) to Minimum	*-0.0005* min.= *8.86"* nom. = *8.92"*	See Table 6.3.2	Assume maximum box I.D. for the MPC-24
Increase Box Inside Dimension (I.D.) to Maximum	*+0.0007* max. = *8.98"* nom. = *8.92"*	-0.0030 max. = 6.113" nom. = 6.053"	Assume minimum box I.D. for the MPC-68
Decrease Water Gap to Minimum	*+0.0069* min. = 1.09" nom. = 1.15"	N/A	Assume minimum water gap in the MPC-24

† Reduction (or increase) in a parameter indicates that the parameter is changed to its minimum (or maximum) value.

‡ *Calculations for the MPC-68 were performed with CASMO-3 [6.3.1 – 6.3.4].*

†† ~~Although the most prevalent Boral width for the MPC-24 is 7.50" +0.125, -0", the analyses conservatively assumed the Boral width to be 7.4375". Further, the analyses conservatively assumed the periphery Boral width to be 5.0".~~

††† The Boral width for the MPC-68 is 4.75" +0.125", -0" , *the Boral widths for the MPC-24 are 7.5" +0.125", -0" and 6.25" +0.125" –0"* (i.e., the nominal and minimum values are the same).

Table 6.3.1 (continued)

CASMO-~~3~~4 CALCULATIONS FOR EFFECT OF TOLERANCES AND TEMPERATURE

Change in Nominal Parameter	**Δk Maximum Tolerance**		**Action/Modeling Assumption**
	MPC-24	**MPC-68**‡	
Increase in Temperature 20°C 40°C 70°C 100°C	 Ref. *-0.0030* *-0.0089* *-0.0162*	 Ref. -0.0039 -0.0136 -0.0193	Assume 20°C
10% Void in Moderator 20°C with no void 20°C 100°C	 Ref. *-0.0251* *-0.0412*	 Ref. -0.0241 -0.0432	Assume no void
Removal of Flow Channel (BWR)	N/A	-0.0073	Assume flow channel present for MPC-68

‡ *Calculations for the MPC-68 were performed with CASMO-3 [6.3.1 – 6.3.4].*

Table 6.3.2

MCNP4a EVALUATION OF BASKET MANUFACTURING TOLERANCES†

Pitch		**Box I.D.**		**Box Wall Thickness**		**MCNP4a Calculated k_{eff}**
MPC-24†† (17x17A01 @ 4.0% Enrichment)						
nominal	*(10.906")*	maximum	*(8.98")*	nominal	(5/16")	*0.9325±0.0008*†††
minimum	*(10.846")*	nominal	*(8.92")*	nominal	(5/16")	*0.9300±0.0008*
nominal	*(10.906")*	nom. *−0.04"*	*(8.88")*	nom. + 0.05"	(0.3625")	*0.9305±0.0007*
MPC-68 (8x8C04 @ 4.2% Enrichment)						
minimum	(6.43")	minimum	(5.993")	nominal	(1/4")	0.9307±0.0007
nominal	(6.49")	nominal	(6.053")	nominal	(1/4")	0.9274±0.0007
maximum	(6.55")	maximum	(6.113")	nominal	(1/4")	0.9272±0.0008
nom. + 0.05"	(6.54")	nominal	(6.053")	nom. + 0.05"	(0.30")	0.9267±0.0007

Note: Values in parentheses are the actual value used.

† Tolerance for pitch and box I.D. are ± 0.06".
Tolerance for box wall thickness is +0.05", -0.00".

†† All calculations for the MPC-24 assume minimum water gap thickness (1.09").

††† Numbers are 1σ statistical uncertainties.

Table 6.3.2 (cont.)

MCNP4a EVALUATION OF BASKET MANUFACTURING TOLERANCES†

Pitch	***Box I.D.***	***Box Wall Thickness***	***MCNP4a Calculated k_{eff}***
MPC-32 (17x17A @ 4.0% Enrichment and 40 GWd/MTU)			
minimum (9.158")	*minimum (8.69")*	*nominal (9/32")*	*0.9350±0.0007*
nominal (9.218")	*nominal (8.75")*	*nominal (9/32")*	*0.9331±0.0006*
maximum (9.278")	*maximum (8.81")*	*nominal (9/32")*	*0.9304±0.0006*
nominal+0.05" (9.268")	*nominal (8.75")*	*nominal+0.05" (0.331")*	*0.9311±0.0006*
minimum+0.05"(9.208")	*minimum (8.69")*	*nominal+0.05" (0.331")*	*0.9331±0.0007*
maximum (9.278")	*Maximum-0.05" (8.76")*	*nominal+0.05" (0.331")*	*0.9333±0.0007*

Notes:

1. *Values in parentheses are the actual value used.*

† Tolerance for pitch and box I.D. are ± 0.06".
Tolerance for box wall thickness is +0.05", -0.00".

Table 6.3.3

BASKET DIMENSIONAL ASSUMPTIONS

Basket Type	**Pitch**	**Box I.D.**	**Box Wall Thickness**	**Water-Gap Flux Trap**
MPC-24	nominal (10.906")	maximum (8.98")	nominal (5/16")	minimum (1.09")
MPC-24E	*nominal (10.847")*	*maximum (8.81", 9.11" for DFC Positions, 9.36" for DFC Positions in Trojan MPC)*	*nominal (5/16")*	*minimum (1.076", 0.776" for DFC Positions, 0.526" for DFC Positions in Trojan MPC)*
MPC-32	*minimum (9.158")*	*minimum (8.69")*	*nominal (9/32")*	*N/A*
MPC-68	minimum (6.43")	minimum (5.993")	nominal (1/4")	N/A

Table 6.3.4

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

MPC-24		
UO_2 4.0% ENRICHMENT, DENSITY (g/cc) = 10.522		
Nuclide	**Atom-Density**	**Wgt. Fraction**
8016	4.693E-02	1.185E-01
92235	9.505E-04	3.526E-02
92238	2.252E-02	8.462E-01
BORAL (0.02 g ^{10}B/cm sq), DENSITY (g/cc) = 2.660		
Nuclide	**Atom-Density**	**Wgt. Fraction**
5010	8.707E-03	5.443E-02
5011	3.512E-02	2.414E-01
6012	1.095E-02	8.210E-02
13027	3.694E-02	6.222E-01
MPC-32		
BORAL (0.0279 g ^{10}B/cm sq), DENSITY (g/cc) = 2.660		
Nuclide	***Atom-Density***	***Wgt. Fraction***
5010	*8.071E-03*	*5.089E-02*
5011	*3.255E-02*	*2.257E-01*
6012	*1.015E-02*	*7.675E-02*
13027	*3.805E-02*	*6.467E-01*

Table 6.3.4 (continued)

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

MPC-68		
UO_2 4.2% ENRICHMENT, DENSITY (g/cc) = 10.522		
Nuclide	**Atom-Density**	**Wgt. Fraction**
8016	4.697E-02	1.185E-01
92235	9.983E-04	3.702E-02
92238	2.248E-02	8.445E-01
UO_2 3.0% ENRICHMENT, DENSITY (g/cc) = 10.522		
Nuclide	**Atom-Density**	**Wgt. Fraction**
8016	4.695E-02	1.185E-01
92235	7.127E-04	2.644E-02
92238	2.276E-02	8.550E-01
MOX FUEL†, DENSITY (g/cc) = 10.522		
Nuclide	**Atom-Density**	**Wgt. Fraction**
8016	4.714E-02	1.190E-01
92235	1.719E-04	6.380E-03
92238	2.285E-02	8.584E-01
94239	3.876E-04	1.461E-02
94240	9.177E-06	3.400E-04
94241	3.247E-05	1.240E-03
94242	2.118E-06	7.000E-05

† The Pu-238, which is an absorber, was conservatively neglected in the MOX description for analysis purposes.

Table 6.3.4 (continued)

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

BORAL (0.0279 g ^{10}B/cm sq), DENSITY (g/cc) = 2.660		
Nuclide	**Atom-Density**	**Wgt. Fraction**
5010	8.071E-03	5.089E-02
5011	3.255E-02	2.257E-01
6012	1.015E-02	7.675E-02
13027	3.805E-02	6.467E-01
FUEL IN THORIA RODS, DENSITY (g/cc) = 10.522		
Nuclide	**Atom-Density**	**Wgt. Fraction**
8016	4.798E-02	1.212E-01
92235	4.001E-04	1.484E-02
92238	2.742E-05	1.030E-03
90232	2.357E-02	8.630E-01

Table 6.3.4 (continued)

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

COMMON MATERIALS		
ZR CLAD, DENSITY (g/cc) = 6.550		
Nuclide	**Atom-Density**	**Wgt. Fraction**
40000	4.323E-02	1.000E+00
MODERATOR (H_2O), DENSITY (g/cc) = 1.000		
Nuclide	**Atom-Density**	**Wgt. Fraction**
1001	6.688E-02	1.119E-01
8016	3.344E-02	8.881E-01
STAINLESS STEEL, DENSITY (g/cc) = 7.840		
Nuclide	**Atom-Density**	**Wgt. Fraction**
24000	1.761E-02	1.894E-01
25055	1.761E-03	2.001E-02
26000	5.977E-02	6.905E-01
28000	8.239E-03	1.000E-01
ALUMINUM, DENSITY (g/cc) = 2.700		
Nuclide	**Atom-Density**	**Wgt. Fraction**
13027	6.026E-02	1.000E+00

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED

FIGURE 6.3.1; TYPICAL CELL IN THE CALCULATION MODEL (PLANAR CROSS-SECTION) WITH REPRESENTATIVE FUEL IN THE MPC-24 BASKET
(SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY **USED** FOR CRITICALITY **ANALYSES.**

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED

FIGURE 6.3.1A; TYPICAL CELL IN THE CALCULATION MODEL (PLANAR CROSS-SECTION) WITH REPRESENTATIVE FUEL IN THE MPC-24E & MPC-24E/EF TROJAN BASKET
(SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.3.2; TYPICAL CELL IN THE CALCULATION MODEL (PLANAR CROSS-SECTION) WITH REPRESENTATIVE FUEL IN THE MPC-32 BASKET (SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.3.3; TYPICAL CELL IN THE CALCULATION MODEL (PLANAR CROSS-SECTION) WITH REPRESENTATIVE FUEL IN THE MPC-68 BASKET (SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

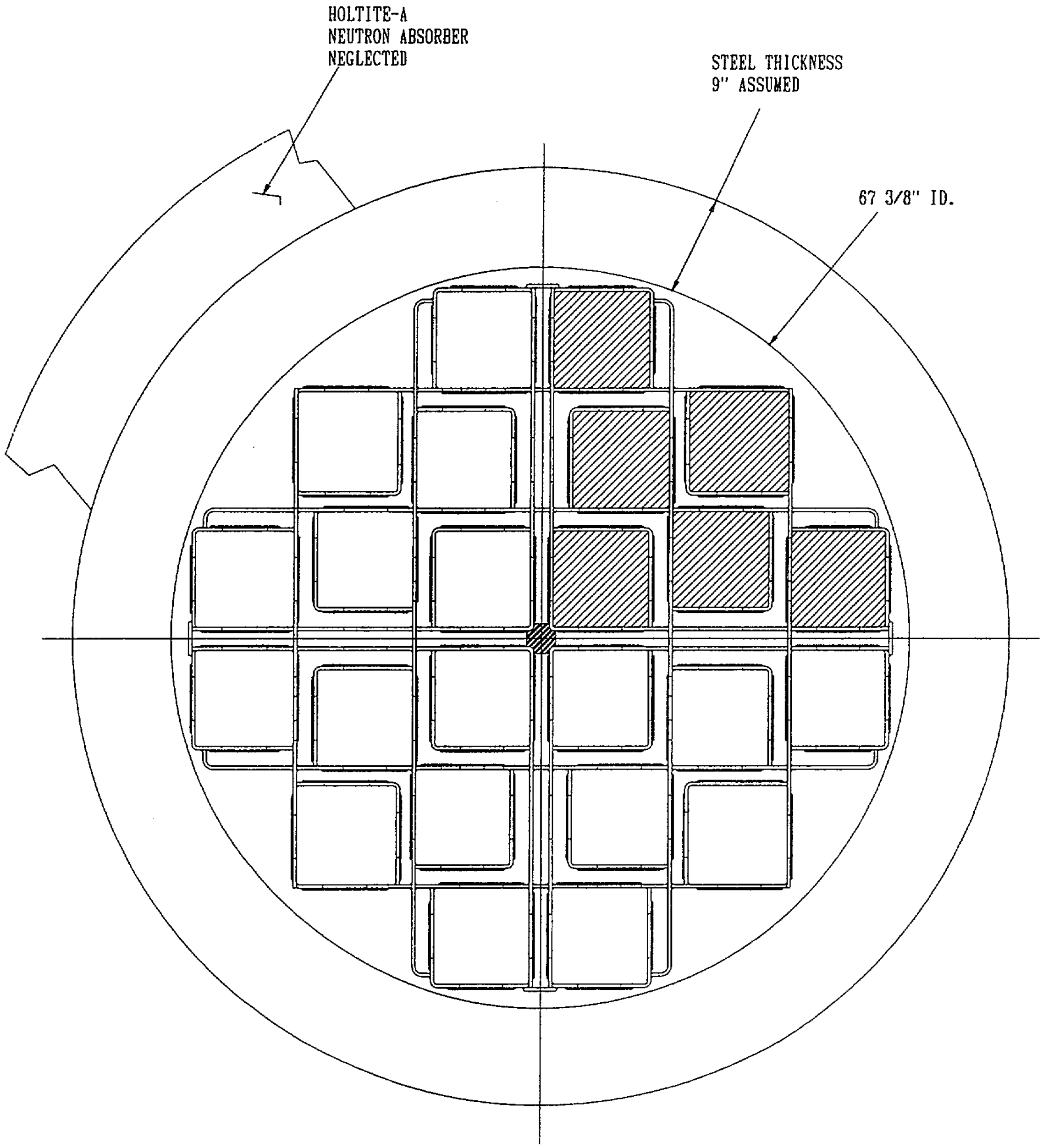

FIGURE 6.3.4; CALCULATION MODEL (PLANAR CROSS-SECTION) WITH FUEL ILLUSTRATED IN ONE QUADRANT OF THE MPC-24, MPC-24E AND MPC-24E/EF TROJAN.

(SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.3.5; CALCULATION MODEL (PLANAR CROSS-SECTION) WITH FUEL ILLUSTRATED IN ONE QUADRANT OF THE MPC-32.
SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.3.6; CALCULATION MODEL (PLANAR CROSS-SECTION) WITH FUEL ILLUSTRATED IN ONE QUADRANT OF THE MPC-68
SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.3.7; SKETCH OF THE CALCULATIONAL MODEL IN THE AXIAL DIRECTION

6.4 CRITICALITY CALCULATIONS

6.4.1 Calculational or Experimental Method

The principal method for the criticality analysis is the general three-dimensional continuous energy Monte Carlo N-Particle code MCNP4a [6.1.4] developed at the Los Alamos National Laboratory. MCNP4a was selected because it has been extensively used and verified and has all of the necessary features for this analysis. MCNP4a calculations used continuous energy cross-section data based on ENDF/B-V, as distributed with the code [6.1.4]. Independent verification calculations were performed with NITAWL-KENO5a [6.1.5], which is a three-dimensional multigroup Monte Carlo code developed at the Oak Ridge National Laboratory. The KENO5a calculations used the 238-group cross-section library, which is based on ENDF/B-V data and is distributed as part of the SCALE-4.3 package [6.4.1], in association with the NITAWL-II program [6.1.6], which adjusts the uranium-238 cross sections to compensate for resonance self-shielding effects. The Dancoff factors required by NITAWL-II were calculated with the CELLDAN code [6.1.13], which includes the SUPERDAN code [6.1.7] as a subroutine.

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. The MCNP4a criticality output contains a great deal of useful information that may be used to determine the acceptability of the problem convergence. This information was used in parametric studies to develop appropriate values for the aforementioned criticality parameters to be used in the criticality calculations for this submittal. Based on these studies, a minimum of 5,000 histories were simulated per cycle, a minimum of 20 cycles were skipped before averaging, a minimum of 100 cycles were accumulated, and the initial source was specified as uniform over the fueled regions (assemblies). Further, the output was examined to ensure that each calculation achieved acceptable convergence. These parameters represent an acceptable compromise between calculational precision and computational time. Appendix 6.D provides sample input files for ~~each of~~ the MPC-*24 and MPC-68* basket~~s~~ in the HI-STAR 100 System.

CASMO-~~3~~*4* [6.1.~~9~~*11*-6.1.12] was used for determining the small incremental reactivity effects of manufacturing tolerances. Although CASMO-~~3~~ has been extensively benchmarked, these calculations are used only to establish direction of reactivity uncertainties due to manufacturing tolerances (and their magnitude). This allows the MCNP4a calculational model to use the worst combination of manufacturing tolerances. Table 6.3.1 shows results of the CASMO-~~3~~ calculations. *Additionally, CASMO-4 was used to determine the isotopic composition of spent fuel for burnup credit in the MPC-32 (see Subsection 6.4.11).*

6.4.2 Fuel Loading or Other Contents Loading Optimization

The basket designs are intended to safely accommodate the candidate fuel assemblies with enrichments indicated in Tables 6.1.1 ~~and 6.1.2~~ *through 6.1.3 and 6.1.5 through 6.1.7*. The calculations were based on the assumption that the HI-STAR 100 System was fully flooded with water. In all cases, the calculations include bias and calculational uncertainties, as well as the reactivity effects of manufacturing tolerances, determined by assuming the worst case geometry.

Nominally, the fuel assemblies would be centrally positioned in each MPC basket cell. However, the consequence of eccentric positioning was also evaluated and found to be negligible. To simulate eccentric positioning (and possible closer approach to the thick steel shield), calculations were made analytically decreasing the inner radius of the steel until it was 1 cm away[†] from the nearest fuel. Results showed a minor increase in reactivity of 0.0026 Δk maximum (MPC-68) which implies that the effect of eccentric location of fuel will be negligible at the actual reflector spacing.

The evaluations of all credible conditions of moderation and partial flooding have been performed for one of each of the two principal basket designs: flux-trap and non-flux-trap design. The MPC-24 (PWR fuel) and the MPC-68 (BWR fuel) are analyzed for the flux-trap and non-flux-trap design, respectively. The results presented in this subsection show a consistent behavior of the different basket designs and fuel types for different moderation conditions. Consequently, the conclusions drawn in this subsection are directly applicable to the remaining baskets, namely the MPC-24E/EF (flux-trap design, PWR), MPC-32 (non-flux-trap design, PWR) and MPC-68F (non-flux-trap design, BWR), and no further evaluations are required for these baskets.

6.4.2.1 Internal and External Moderation

As required by 10CFR71.55, calculations in this section demonstrate that the HI-STAR 100 System remains subcritical for all credible conditions of moderation.

With a neutron absorber present (i.e., the Boral sheets on the steel walls of the storage compartments), the phenomenon of a peak in reactivity at a hypothetical low moderator density

† PNL critical experiments have shown a small positive reactivity effect of thick steel reflectors, with the maximum effect at 1 cm distance from the fuel. In the cask designs, the fuel is mechanically prohibited from being positioned at a 1 cm spacing from the overpack steel.

(sometimes called "optimum" moderation) does not occur to any significant extent. In a definitive study, Cano, et al. [6.4.2] has demonstrated that the phenomenon of a peak in reactivity at low moderator densities does not occur when strong neutron absorbing material is present or in the absence of large water spaces between fuel assemblies in storage. Nevertheless, calculations for a single reflected cask and for infinite arrays of casks were made to confirm that the phenomenon does not occur with low density water inside or outside the HI-STAR 100 Systems.

6.4.2.1.1 Single Package Evaluation

10CFR71.55 (b), (d), and (e) require the HI-STAR 100 System to be subcritical when surrounded by water providing external moderation to the most reactive credible extent and with internal moderation present to such an extent as to cause maximum reactivity. In accordance with these regulations, calculations for the ~~two~~ MPC-*24 and MPC-68* ~~designs~~ in a square array with internal and external moderators of various densities are shown in Table 6.4.1. These calculations assumed 60 cm spacing between cask surfaces, with the neutron shield (Holtite-A) absent in accordance with the requirements of 10CFR71.55(e) for hypothetical accidents conditions. For comparison purposes, a calculation for a single unreflected cask (Case 1) is also included in Table 6.4.1. At 100% external moderator density, Case 2 corresponds to a single fully-flooded cask, fully reflected by water. Figure 6.4.9 plots calculated k_{eff} values ($\pm 2\sigma$) as a function of internal moderator density for both MPC designs with 100% external moderator density (i.e., full water reflection).

Results listed in Table 6.4.1 and plotted in Figure 6.4.9 support the following conclusions:

- For each type of MPC, the calculated k_{eff} for a fully-flooded cask is independent of the external moderator (the small variations in the listed values are due to statistical uncertainties which are inherent to the calculational method (Monte Carlo)), and

- For each type of MPC, reducing the internal moderation results in a monotonic reduction in reactivity, with no evidence of any optimum moderation. Thus, the fully flooded condition corresponds to the highest reactivity, and the phenomenon of optimum low-density moderation does not occur and is not applicable to the HI-STAR 100 System.

- The maximum k_{eff} results for each of the MPC designs are below the regulatory criticality safety limit (k_{eff}<0.95), and thus, these results demonstrate that the HI-STAR 100 System meets the requirements of 10CFR71.55.

To satisfy the requirement of 10CFR71.55(b)(3), calculations were performed with close full reflection of the containment system (which corresponds to the 2.5 inch thick inner shell of the overpack) by water on all sides. These calculations were performed with the most reactive assembly from the most reactive assembly class in ~~each of~~ the MPC-*24 and MPC-68* ~~designs~~ and are summarized in Table 6.4.9. Similar to the calculations presented in Table 6.4.1, these calculations were performed for an infinite square array with 60 cm spacing between containment surfaces (i.e., inner shells).

Therefore, in accordance with 10CFR71.35, this evaluation demonstrates that a single HI-STAR 100 System satisfies the criticality safety requirements for the normal conditions of transport (10CFR71.43(f), 10CFR71.51(a)(1), 10CFR71.55(b) and 10CFR71.55(d)) and the hypothetical accident conditions of transport (10CFR71.55(e)).

6.4.2.1.2 Evaluation of Package Arrays

In terms of reactivity, the normal conditions of transport (i.e., no internal or external moderation) are bounded by the hypothetical accident conditions of transport. Therefore, the calculations in this section evaluate arrays of HI-STAR 100 Systems under hypothetical accident conditions (i.e, internal and external moderation by water to the most reactive credible extent and no neutron shield present).

In accordance with 10CFR71.59 requirements, calculations were performed to simulate an infinite three-dimensional square array of internally fully-flooded (highest reactivity) casks with varying cask spacing and external moderation density. The MPC-24 was used for this analysis. The maximum k_{eff} results of these calculations are listed in Table 6.4.2 and confirm that the individual casks in a square-pitched array are independent of external moderation and cask spacing. The maximum value listed in Table 6.4.2 is ~~0.9453~~*0.9389*, which is statistically equivalent (within ~~one~~*three* standard deviation*s*) to the reference value (~~0.9449~~*0.9368* shown in Table 6.4.1) for a single unreflected fully flooded cask.

To further investigate the reactivity effects of array configurations, calculations were also performed to simulate an infinite three-dimensional hexagonal (triangular-pitched) array of internally fully-flooded (highest reactivity) MPC-24 casks with varying cask spacing and external moderation density. The maximum k_{eff} results of these calculations are listed in Table 6.4.3 and confirm that the individual casks in a hexagonal (triangular pitched) array are effectively independent of external moderation and cask spacing. The maximum value listed in Table 6.4.3 is ~~0.9455~~*0.9381*, which is statistically equivalent (within ~~one~~*two* standard deviation*s*) to the reference value (~~0.9449~~*0.9368* shown in Table 6.4.1) for a single unreflected fully flooded cask.

To assure that internal moderation does not result in increased reactivity, hexagonal array calculations were also performed for 10% internal moderator with 10% and 100% external moderation for varying cask spacing. Maximum k_{eff} results are summarized in Table 6.4.4 and confirm the very low values of k_{eff} for low values of internal moderation.

The results presented thus far indicate that neutronic interaction between casks is not enhanced by the neighboring casks or the water between the neighboring casks, and thus, the most reactive arrangement of casks corresponds to a tightly packed array with the cask surfaces touching. Therefore, calculations were performed for an infinite hexagonal (triangular pitched) array of touching casks (neglecting the Holtite-A neutron shield). These calculations were performed for both MPC designs, in the internally flooded (highest reactivity) and internally dry conditions, with and without external flooding. The results of these calculations are listed in Table 6.4.5. For *both* ~~each of~~ the MPC-*24 and MPC-68*~~-designs~~, the maximum k_{eff} values are shown to be statistically equivalent (within one standard deviation) to that of a single internally flooded unreflected cask and are below the regulatory limit of 0.95. Therefore, the transportation index for criticality control is zero because an infinite number of HI-STAR 100 casks will remain subcritical (k_{eff}<0.95) under both normal and hypothetical accident conditions of transport. This analysis demonstrates that the HI-STAR 100 System is in full compliance with 10CFR71.35 and 10CFR71.59. To further demonstrate that the transport index for criticality control is zero, these infinite array calculations were repeated with the most reactive assembly from the most reactive assembly class in ~~each of~~ the MPC-*24 and MPC-68*~~-designs~~. The results are listed in Table 6.1.4 and support the conclusion that the HI-STAR 100 System specifically meets the requirements of 10CFR71.59(a)(2).

The thick steel wall of the overpack is more than sufficient to preclude neutron coupling between casks, consistent with the findings of Cano, et al. Neglecting the Holtite-A neutron shielding in the calculational model provides further assurance of conservatism in the calculations.

6.4.2.2 Partial Flooding

To demonstrate that the HI-STAR 100 System would remain subcritical if water were to leak into the containment system, as required by 10CFR71.55, calculations in this section address partial flooding in the HI-STAR 100 System and demonstrate that the fully flooded condition is the most reactive.

The reactivity changes during the flooding process were evaluated in both the vertical and horizontal positions for ~~all MPC~~ *the MPC-24 and MPC-68* designs. For these calculations, the cask is partially filled (at various levels) with full density (1.0 g/cc) water and the rem*a*inder of the cask is filled with steam consisting of ordinary water at partial density (0.002 g/cc). Results of these calculations are shown in Table 6.4.6. In all cases, the reactivity increases monotonically as the water level rises, confirming that the most reactive condition is fully flooded.

6.4.2.3 Clad Gap Flooding

The reactivity effect of flooding the fuel rod pellet-to-clad gap regions, in the fully flooded condition, has been investigated. Table 6.4.7 presents maximum k_{eff} values that demonstrate the positive reactivity effect associated with flooding the pellet-to-clad gap regions. These results confirm that it is conservative to assume that the pellet-to-clad gap regions are flooded. For all cases that involve flooding, the pellet-to-clad gap regions are assumed to be flooded.

6.4.2.4 Preferential Flooding

~~Preferential or uneven flooding within the HI-STAR 100 System was not evaluated because such a condition is not credible for any of the MPC basket designs loaded in the HI-STAR 100 System.~~ *Two different potential conditions of preferential flooding are considered: preferential flooding of the MPC basket itself (i.e. different water levels in different basket cells), and preferential flooding involving Damaged Fuel Containers.*

Preferential flooding of *the MPC basket itself for* any of the MPC fuel basket designs is not possible because flow holes are present on all four walls of each basket cell and on the two flux trap walls at both the top and bottom of the MPC basket. The flow holes are sized to ensure that they cannot be blocked by crud deposits. Because the fuel cladding temperatures remain below their design limits (as demonstrated in Chapter 3) and the inertial loading remains below 63g's (Section 2.9), the cladding remains intact. For damaged BWR fuel assemblies and BWR fuel debris, the assemblies or debris are pre-loaded into stainless steel Damaged Fuel Containers fitted with *250x250*~~-micron~~ fine mesh screens *(20x20 for Trojan FFC)* which prevent damaged fuel assemblies or fuel debris from blocking the basket flow holes. Therefore, the flow holes cannot be blocked and the MPC fuel baskets cannot be preferentially flooded.

However, when DFCs are present in the MPC, a condition could exist during the draining of the MPC, where the DFCs are still partly filled with water while the remainder of the MPC is dry. This condition would be the result of the water tension across the mesh screens. The maximum water level inside the DFCs for this condition is calculated from the dimensions of the mesh screen and the surface tension of water. The wetted perimeter of the screen openings is up to 50 ft per square inch of screen. With a surface tension of water of 0.005 lbf/ft, this results in a maximum pressure across the screen of 0.25 psi, corresponding to a maximum water height in the DFC of 7 inches. For added conservativism, a value of 12 inches is used. Assuming this condition, calculations are performed for the two possible DFC configurations:

- *MPC-68 or MPC-68F with 68 DFCs (Assembly Classes 6x6A/B/C, 7x7A and 8x8A)*
- *MPC-24E or MPC-24EF with 4 DFCs*

For each configuration, the case resulting in the highest maximum k_{eff} for the fully flooded condition (see Subsection 6.4.9) is re-analyzed assuming the preferential flooding condition. For these analyses, the lower 12 inches of the active fuel in the DFCs and the water region below the active fuel (see Figure 6.3.7) are filled with full density water (1.0 g/cc). The remainder of the cask is filled with steam consisting of ordinary water at partial density (0.002 g/cc). Table 6.4.10 *lists the maximum k_{eff} for the configurations in comparison with the maximum k_{eff} for the fully flooded condition. For all configurations, the preferential flooding condition results in a lower maximum k_{eff} than the fully flooded condition. Thus, the preferential flooding condition is bounded by the fully flooded condition.*

In summary, it is concluded that the MPC fuel baskets cannot be preferentially flooded, and that the potential preferential flooding conditions involving DFCs are bounded by the result for the fully flooded condition listed in Subsection 6.4.9.

6.4.2.5 Hypothetical Accidents Conditions of Transport

The analyses presented in Section 2.7 of Chapter 2 and Section 3.5 of Chapter 3 demonstrate that the damage resulting from the hypothetical accident conditions of transport are limited to a loss of the neutron shield material as a result of the hypothetical fire accident. Because the criticality analyses do not take credit for the neutron shield material (Holtite-A), this condition has no effect on the criticality analyses.

As reported in Table 2.7.1, the minimum factor of safety for *all MPCs* ~~the MPC-24~~ as a result of the hypothetical accident conditions of transport *is larger than 1.0*~~are 1.17~~ against the Level D allowables for Subsection NG, Section III of the ASME Code. Therefore, because the maximum box wall stresses are well within the ASME Level D allowables, the flux-trap gap change *in the MPC-24 and MPC-24E/EF* will be insignificant compared to the characteristic dimension of the flux trap.

In summary, the hypothetical transport accidents have no adverse effect on the geometric form of the package contents important to criticality safety, and thus, are limited to the effects on internal and external moderation evaluated in Subsection 6.4.2.1.

6.4.3 Criticality Results

Results of the criticality safety calculations for the condition of flooding with water to the most reactive credible extent are presented in Section 6.2 *and Subsection 6.4.11,* and summarized in Section 6.1. These data, along with the analysis in Subsection 6.4.2.1, confirm that for each of the candidate fuel assemblies and basket configurations the effective multiplication factor (k_{eff}), including all biases and uncertainties at a 95-percent confidence level, do not exceed 0.95 under all credible normal and hypothetical accident conditions of transport. Therefore, compliance with 10CFR71.55 for single packages and 10CFR71.59 for package arrays in both normal and hypothetical accident conditions of transport is demonstrated for all of the fuel assembly classes and basket configurations listed in Tables 6.1.1 through 6.1.3 *and 6.1.5 through 6.1.7.* A table listing the maximum k_{eff} (including bias, uncertainties, and calculational statistics), calculated

k_{eff}, standard deviation, and energy of the average lethargy causing fission (EALF) for each of the candidate fuel assemblies and basket configurations is provided in Appendix 6.C

Additional calculations (CASMO-~~3~~*4*) at elevated temperatures confirm that the temperature coefficients of reactivity are negative as shown in Table 6.3.1. This confirms that the calculations for the storage baskets are conservative.

In calculating the maximum reactivity, the analysis used the following equation:

$$k_{eff}^{max} = k_c + K_c\sigma_c + Bias + \sigma_B$$

where:

⇒ ***k****c* is the calculated k_{eff} under the worst combination of tolerances;

⇒ ***K****c* is the K multiplier for a one-sided statistical tolerance limit with 95% probability at the 95% confidence level [6.1.8]. Each final k_{eff} value calculated by MCNP4a (or KENO5a) is the result of averaging 100 (or more) cycle k_{eff} values, and thus, is based on a sample size of 100. The K multiplier corresponding to a sample size of 100 is 1.93. However, for this analysis a value of 2.00 was assumed for the K multiplier, which is larger (more conservative) than the value corresponding to a sample size of 100;

⇒ σ_c is the standard deviation of the calculated k_{eff}, as determined by the computer code (MCNP4a or KENO5a);

⇒ ***Bias*** is the systematic error in the calculations (code dependent) determined by comparison with critical experiments in Appendix 6.A; and

⇒ σ_B is the standard error of the bias (which includes the K multiplier for 95% probability at the 95% confidence level; see Appendix 6.A).

Appendix 6.A presents the critical experiment benchmarking and the derivation of the bias and standard error of the bias (95% probability at the 95% confidence level).

6.4.4 Damaged Fuel Container *for BWR Fuel*

Both damaged BWR fuel assemblies and BWR fuel debris are required to be loaded into Damaged Fuel Containers (DFCs)~~ prior to being loaded into the MPC~~. Two different DFC types with slightly different cross sections are analyzed. DFCs containing fuel debris must be stored in the MPC-68F. DFCs containing damaged fuel assemblies may be stored in either the MPC-68 or MPC-68F. Evaluation of the capability of storing damaged fuel and fuel debris (loaded in DFCs) is limited to very low reactivity fuel in the MPC-68F. Because the MPC-68 has a higher specified ^{10}B loading, the evaluation of the MPC-68F conservatively bounds the storage of damaged BWR fuel assemblies in a standard MPC-68 Although the maximum planar-average enrichment of the damaged fuel is limited to 2.7% ^{235}U as specified in Chapter 1, analyses have been made for three possible scenarios, conservatively assuming fuel†† of 3.0% enrichment. The scenarios considered included the following:

1. Lost or missing fuel rods, calculated for various numbers of missing rods in order to determine the maximum reactivity. The configurations assumed for analysis are illustrated in Figures 6.4.1 through 6.4.7.
2. Broken fuel assembly with the upper segments falling into the lower segment creating a close-packed array (described as a 8x8 array). For conservatism, the array analytically retained the same length as the original fuel assemblies in this analysis. This configuration is illustrated in Figure 6.4.8.
3. Fuel pellets lost from the assembly and forming powdered fuel dispersed through a volume equivalent to the height of the original fuel. (Flow channel and clad material assumed to disappear).

Results of the analyses, shown in Table 6.4.8, confirm that, in all cases, the maximum reactivity is well below the regulatory limit. There is no significant difference in reactivity between the two DFC types. Collapsed fuel reactivity (simulating fuel debris) is low because of the reduced moderation. Dispersed powdered fuel results in low reactivity because of the increase in ^{238}U neutron capture (higher effective resonance integral for ^{238}U absorption).

The loss of fuel rods results in a small increase in reactivity (i.e., rods assumed to collapse, leaving a smaller number of rods still intact). The peak reactivity occurs for 8 missing rods, and a smaller (or larger) number of intact rods will have a lower reactivity, as indicated in Table 6.4.8.

The analyses performed and summarized in Table 6.4.8 provides the relative magnitude of the effects on the reactivity. This information in combination with the maximum k_{eff} values listed in Table 6.1.3 and the conservatism in the analyses, demonstrate that the maximum k_{eff} of the damaged fuel in the most adverse post-accident condition will remain well below the regulatory requirement of $k_{eff} < 0.95$.

Appendix 6.D provides sample input files for the damaged fuel analysis.

6.4.5 Fuel Assemblies with Missing Rods

For fuel assemblies that are qualified for damaged fuel storage, missing and/or damaged fuel rods are acceptable. However, for fuel assemblies to meet the limitations of intact fuel assembly

†† 6x6A01 and 7x7A01 fuel assemblies were used as representative assemblies.

storage, missing fuel rods must be replaced with dummy rods that displace a volume of water that is equal to, or larger than, that displaced by the original rods.

6.4.6 Thoria Rod Canister

The Thoria Rod Canister is similar to a DFC with an internal separator assembly containing 18 intact fuel rods. The configuration is illustrated in Figure 6.4.10. The k_{eff} value for an MPC-68F filled with Thoria Rod Canisters is calculated to be 0.1813. This low reactivity is attributed to the relatively low content in ^{235}U (equivalent to UO_2 fuel with an enrichment of approximately 1.7 wt% ^{235}U), the large spacing between the rods (the pitch is approximately 1", the cladding OD is 0.412") and the absorption in the separator assembly. Together with the maximum k_{eff} values listed in Tables 6.1.2 and 6.1.3 this result demonstrates, that the k_{eff} for a Thoria Rod Canister loaded into the MPC68 or the MPC68F together with other approved fuel assemblies or DFCs will remain well below the regulatory requirement of $k_{eff} < 0.95$.

6.4.7 Sealed Rods Replacing BWR Water Rods

Some BWR fuel assemblies contain sealed rods filled with a non-fissile instead of water rods. Compared to the configuration with water rods, the configuration with sealed rods has a reduced amount of moderator, while the amount of fissile material is maintained. Thus, the reactivity of the configuration with sealed rods will be lower compared to the configuration with water rods. Any configuration containing sealed rods instead of water rods is therefore bounded by the analysis for the configuration with water rods and no further analysis is required to demonstrate the acceptability. Therefore, for all BWR fuel assemblies analyzed, it is permissible that water rods are replaced by sealed rods filled with a non-fissile material.

6.4.8 Neutron Sources in Fuel Assemblies

Fuel assemblies containing start-up neutron sources are permitted for storage in the HI-STAR 100 System. The reactivity of a fuel assembly is not affected by the presence of a neutron source (other than by the presence of the material of the source, which is discussed later). This *is* true because in a system with a keff less than 1.0, any given neutron population at any time, regardless of its origin or size, will decrease over time. Therefore, a neutron source of any strength will not increase reactivity, but only the neutron flux in a system, and no additional criticality analyses are required. Sources are inserted as rods into fuel assemblies, i.e. they replace either a fuel rod or water rod (moderator). Therefore, the insertion of the material of the source into a fuel assembly will not lead to an increase of reactivity either.

6.4.9 *PWR Damaged Fuel and Fuel Debris*

The MPC-24E, MPC-24EF, and Trojan MPC-24E and MPC-24EF are designed to contain damaged fuel and fuel debris, loaded into Damaged Fuel Containers (DFCs) or Failed Fuel Cans (FFCs). There is one generic DFC for the MPC-24E/EF, and two containers, a Holtec DFC and a Trojan FFC for the Trojan MPC-24E/EF. In this section, the term "DFC" is used to specify either of these components. In any case, the number of DFCs is limited to 4, and the permissible locations of the DFCs are shown in Figure 6.4.11.

Only the Trojan MPC-24E/EF is certified for damaged fuel and fuel debris. However, the generic MPC-24E/EF is also designed to accommodate damaged fuel debris, and the majority of criticality evaluations for damaged fuel and fuel debris are performed for the generic MPC-24E/EF, with only a smaller number of calculations performed for the Trojan MPCs. Therefore, criticality evaluations for both the generic MPC-24E/EF and the Trojan MPC-24E/EF are presented in this subsection.

Damaged fuel assemblies are assemblies with known or suspected cladding defects greater than pinholes or hairlines, or with missing rods, but excluding fuel assemblies with gross defects (for a full definition see the Certificate of Compliance). Therefore, apart from possible missing fuel rods, damaged fuel assemblies have the same geometric configuration as intact fuel assemblies and consequently the same reactivity. Missing fuel rods can result in a slight increase of reactivity. After a drop accident, however, it can not be assumed that the initial geometric integrity is still maintained. For a drop on either the top or bottom of the cask, the damaged fuel assemblies could collapse. This would result in a configuration with a reduced length, but increased amount of fuel per unit length. For a side drop, fuel rods could be compacted to one side of the DFC. In either case, a significant relocation of fuel within the DFC is possible, which creates a greater amount of fuel in some areas of the DFC, whereas the amount of fuel in other areas is reduced. Fuel debris can include a large variety of configurations ranging from whole fuel assemblies with severe damage down to individual fuel pellets.

In the cases of fuel debris or relocated damaged fuel, there is the potential that fuel could be present in axial sections of the DFCs that are outside the basket height covered with Boral. However, in these sections, the DFCs are not surrounded by any intact fuel, only by basket cell walls, non-fuel hardware and water. Studies have shown that this condition does not result in any significant effect on reactivity, compared to a condition where the damaged fuel and fuel debris is restricted to the axial section of the basket covered by Boral. All calculations for damaged fuel and fuel debris are therefore performed assuming that fuel is present only in the axial sections covered by Boral, and the results are directly applicable to any situation where damaged fuel and fuel debris is located outside these sections in the DFCs.

To address all the situations listed above and identify the configuration or configurations leading to the highest reactivity, it is impractical to analyze a large number of different geometrical configurations for each of the fuel classes. Instead, a bounding approach is taken which is based on the analysis of regular arrays of bare fuel rods without cladding. Details and results of the analyses are discussed in the following sections.

All calculations for generic damaged fuel and fuel debris are performed using a full cask model with the maximum permissible number of Damaged Fuel Containers. For the MPC-24E and MPC-24EF, the model consists of 20 intact assemblies, and 4 DFCs in the locations shown in Figure 6.4.11. The bounding assumptions regarding the intact assemblies and the modeling of the damaged fuel and fuel debris in the DFCs are discussed in the following sections.

6.4.9.1 Bounding Intact Assemblies

Intact PWR assemblies stored together with DFCs in the MPC-24E/EF are limited to a maximum enrichment of 4.0 wt% ^{235}U, regardless of the fuel class. Results presented in Table 6.1.5 for the MPC-24E/EF loaded with intact assemblies only are for different enrichments for each class, ranging between 4.2 and 5.0 wt% ^{235}U, making it difficult to directly identify the bounding assembly. However, the assembly class 15x15H is among the classes with the highest reactivity, but has the lowest initial enrichment. Therefore, the 15x15H assembly is used as the intact PWR assembly for all calculations with DFCs.

The Trojan MPC-24E/EF is only certified for the assembly class 17x17B, which bounds the fuel types used at the Trojan plant. Consequently, the assembly class 17x17B is used as the intact assembly in all calculations for the Trojan MPC-24E/EF.

6.4.9.2 Bare Fuel Rod Arrays

A conservative approach is used to model both damaged fuel and fuel debris in the DFCs, using arrays of bare fuel rods:

- *Fuel in the DFCs is arranged in regular, rectangular arrays of bare fuel rods, i.e. all cladding and other structural material in the DFC is replaced by water.*

- *The active length of these rods is chosen to be the maximum active fuel length of all fuel assemblies listed in Section 6.2, which is 150 inch for PWR fuel.*

- *To ensure the configuration with optimum moderation and highest reactivity is analyzed, the amount of fuel per unit length of the DFC is varied over a large range. This is achieved by changing the number of rods in the array and the rod pitch. The number of rods are varied* *between 64 (8x8) and 729 (27x27) for PWR fuel.*

- *Analyses are performed for the minimum, maximum and typical pellet diameter of the fuel.*

This is a very conservative approach to model damaged fuel, and to model fuel debris configurations such as severely damaged assemblies and bundles of individual fuel rods, as the absorption in the cladding and structural material is neglected.

This is also a conservative approach to model fuel debris configurations such as bare fuel pellets due to the assumption of an active length of 150 inch. For some of the analyzed cases, this assumption results in more uranium mass being modeled in the DFCs than is permitted by the uranium mass loading restrictions in the CoC.

To demonstrate the level of conservatism, additional analyses are performed with the DFC containing various realistic assembly configurations such as intact assemblies, assemblies with missing fuel rods and collapsed assemblies, i.e. assemblies with increased number of rods and decreased rod pitch.

As discussed in Subsection 6.4.9, all calculations are performed for full cask models, containing the maximum permissible number of DFCs together with intact assemblies.

Graphical presentations of the calculated maximum k_{eff} *for each case as a function of the fuel mass per unit length of the DFC are shown in Figure 6.4.12. The results for the bare fuel rods show a distinct peak in the maximum* k_{eff} *at about 3.5 kg*UO_2*/inch.*

The realistic assembly configurations are typically about 0.01 (delta-k) or more below the peak results for the bare fuel rods, demonstrating the conservatism of this approach to model damaged fuel and fuel debris configurations such as severely damaged assemblies and bundles of fuel rods.

For fuel debris configurations consisting of bare fuel pellets only, the fuel mass per unit length would be beyond the value corresponding to the peak reactivity. For example, for DFCs filled with a mixture of 60 vol% fuel and 40 vol% water the fuel mass per unit length is 7.92 kgUO_2*/inch for the PWR DFC. The corresponding reactivities are significantly below the peak reactivies. The difference is about 0.01 (delta-k) or more for PWR fuel. Furthermore, the filling height of the DFC would be less than 70 inches in these examples due to the limitation of the fuel mass per basket position, whereas the calculation is conservatively performed for a height of 150 inch. These results demonstrate that even for the fuel debris configuration of bare fuel pellets, the model using bare fuel rods is a conservative approach.*

6.4.9.3 *Results for MPC-24E and MPC-24EF*

The MPC-24E is designed for the storage of up to four DFCs with damaged fuel in the four outer fuel baskets cells shaded in Figure 6.4.11. The MPC-24EF allows storage of up to four DFCs with damaged fuel or fuel debris in these locations. These locations are designed with a larger box ID to accommodate the DFCs. For an enrichment of 4.0 wt% ^{235}U *for the intact fuel, damaged fuel and fuel debris, the results for the various configurations outlined in Subsection 6.4.9.2 are summarized in Figure 6.4.12 and in Table 6.4.11. Figure 6.4.12 shows the maximum* k_{eff}*, including bias and calculational uncertainties, for various actual and hypothetical damaged fuel and fuel debris configurations as a function of the fuel mass per unit length of the DFC. For the intact assemblies, the 15x15H assembly class was chosen (see Subsection 6.4.9.1). Table 6.4.11 lists the highest maximum* k_{eff} *for the various configurations. All maximum* k_{eff} *values are below the 0.95 regulatory limit.*

6.4.9.4 *Results for Trojan MPC-24E and MPC-24EF*

For the Tojan MPC-24E/EF, bare fuel rod arrays with arrays sizes between 11x11 and 23x23 were analyzed as damaged fuel/fuel debris, with a pellet diameter corresponding to the 17x17B assembly class. The highest maximum k_{eff} *value is shown in Table 6.1.6, and is below the 0.95 regulatory limit. The realistic damaged fuel assembly configurations in the DFC, such as assemblies with missing rods, were not analyzed in the Trojan MPC-24E/EF since the evaluations for the generic MPC-24E/EF demonstrate that these conditions are bounded by the fuel debris model using bare fuel pellets.*

6.4.10 *Non-fuel Hardware in PWR Fuel Assemblies*

Non-fuel hardware such as Thimble Plugs (TPs), Burnable Poison Rod Assemblies (BPRAs), Rod Cluster Control Assemblies (RCCAs) and similar devices are permitted for storage with the PWR fuel assemblies in the Trojan MC-24E/EF. Non-fuel hardware is inserted in the guide tubes of the assemblies. For pure water, the reactivity of any PWR assembly with inserts is bounded by (i.e. lower than) the reactivity of the same assembly without the insert. This is due to the fact that the insert reduces the amount of moderator in the assembly, while the amount of fissile material remains unchanged.

Therefore, from a criticality safety perspective, non-fuel hardware inserted into PWR assemblies are acceptable for all allowable PWR types, and, depending on the assembly class, can increase the safety margin.

6.4.11 Burnup Credit for MPC-32

Two principal MPC basket designs are used for PWR fuel, the MPC-24 and MPC-32, providing space for 24 and 32 fuel assemblies, respectively. The MPC-24 contains flux traps (water gaps with neutron poison panels on each side), which significantly reduce the neutronic coupling between adjacent fuel assemblies when the MPC is flooded with water. Due to these flux traps, fresh fuel assemblies with enrichments between 4.0 and 5.0 % enrichment (depending on the assembly type) can be loaded into the MPC-24 without exceeding the regulatory limit on reactivity. In the high density MPC-32 there is only a single neutron poison panel between two adjacent fuel assemblies, and no water gap. The reactivity of the MPC-32 is therefore higher than the reactivity of the MPC-24 for the same fuel, and additional measures are necessary to ensure the reactivity of the MPC-32 is below the regulatory limit when the MPC is flooded. However, it is desirable to use the MPC-32 instead of the MPC-24 whenever possible, since this reduces the number of loading and transport campaigns. This will result in a reduced dose to the general public and the plant personnel. This is a result of the increased self shielding of assemblies inside the basket in the MPC-32, and the reduced number of loading campaigns.

After being loaded, the MPC is a seal welded enclosure for the fuel basket and its contents, and is designed in accordance with the ASME codes for pressure vessels. The evaluations documented in Chapter 2, Section 2.7 demonstrate that there is no credible event or accident which would result in a breach of the boundary to allow water to enter the MPC. Therefore even under accident conditions the MPC cavity remains dry and the reactivity is below the regulatory limit by a large safety margin, with a typical k_{eff} for a dry system of less than 0.5. However, no application is made to exclude the potential presence of water in the MPC. Instead, water is assumed to be present in the MPC for the criticality evaluations, and it is shown that the reduction in reactivity due to the burnup of the fuel is sufficient to ensure that the reactivity does not exceed the regulatory limit even under this postulated condition. The result of the evaluation is a minimum burnup requirement as a function of initial enrichment to ensure criticality safety.

During loading, the MPC is submerged in the spent fuel pool and filled with pool water. The pool water of the PWR spent fuel pools contains neutron poison (soluble boron), which results in a lower reactivity compared to the flooding with pure water. The loading condition is therefore bounded by the burnup credit evaluations assuming pure water in the MPC, and no further criticality analyzes are required for the MPC during loading.

The NRC Interim Staff Guidance (ISG) 8, Rev. 1 permits the use of burnup credit to qualify PWR assemblies for transportation in a spent fuel cask. The ISG 8 recommends a number of requirements and restrictions that have to be fulfilled and applied when evaluating burnup credit. Figure 6.4.20 shows burnups and enrichments of unloaded WE 17x17 assemblies, together with limiting burnup curves from burnup credit calculations. The dotted line in this figure represents the minimum burnup requirement based on scoping calculations for the MPC-

32 performed in strict compliance with ISG 8 Rev. 1. Note that not all assemblies above this dotted line would be acceptable. Assemblies exposed to burnable poison would have to be excluded per ISG 8. Therefore, due to the limitations in ISG 8 regarding burnup, cooling time, isotope selection and assembly selection, only about 25% of the unloaded assemblies would qualify for transport in the MPC-32. This is not sufficient to make effective use of the advantages of the MPC-32. Note that the reactivity control incorporated into the MPC-32 basket in the form neutron poison plates is already at the highest possible level and can therefore not be improved any further. The burnup credit methodology presented here generally follows the recommendations of ISG 8. However, in some areas, where it was deemed necessary in order to achieve the designated goal of making effective use of the MPC-32, the methodology uses alternative or additional methods. Subsection 6.4.11.7 provides a comparison between the analyses provided here and the ISG-8. It references the applicable subsection for each of the requirements and restrictions. When alternatives are used, it provides the motivation and justification for the approach taken. The resulting minimum burnup requirement is shown in Figure 6.4.20 as a solid line. The majority of the assemblies, up to about 90%, and including assemblies exposed to burnable poisons, are qualified for transportation in the MPC-32 using the methodologies presented here.

Outline of the Burnup Credit Calculations and Evaluations

The following is a brief summary of the burnup credit evaluation.

[illegible]

The presentation and discussion of the burnup credit evaluations is separated into two parts, the current Subsection 6.4.11 and a number of appendices (Appendix 6.E through 6.L). This Section 6.4.11 and its subsections outline the principles, methodologies, major assumptions, principal results and conclusions of the burnup credit evaluations for the MPC-32. Technical details, justifications and additional explanations are contained in the appendices. The information in the appendices are appropriately referenced in this section.

The overall process of establishing burnup credit for the MPC-32 can be broadly divided into six distinct tasks, some of them with a number of subtasks. The tasks and subtasks, together with the corresponding section number where the task is described, are listed below.

1. *Selection of Fuel Assemblies (6.4.11.1)*
2. *Depletion Calculations (6.4.11.2)*
    a. *Core Operating Parameters (6.4.11.2.1)*
    b. *Fuel Inserts and Burnable Poisons (6.4.11.2.2)*
    c. *CASMO calculations (6.4.11.2.3)*
3. *Benchmarks (6.4.11.3)*
    a. *Isotopic Benchmarks (6.4.11.3.1)*
    b. *Criticality Benchmarks (6.4.11.3.2)*
    c. *Commercial Reactor Critical Benchmarks (6.4.11.3.3)*
4. *Criticality Calculations (6.4.11.4)*
    a. *Axial Burnup Distribution (6.4.11.4.1)*
    b. *Planar Burnup Distribution (6.4.11.4.2)*
    c. *Transfer of Isotopic Compositions (6.4.11.4.3)*
    d. *MCNP Calculations (6.4.11.4.4)*
5. *Establish Loading Curves (6.4.11.5)*
6. *Evaluation of Remaining Safety Margins (6.4.11.6)*

6.4.11.1 <u>Selection of Fuel Assemblies</u>

[illegible]

6.4.11.2 Depletion Calculations

6.4.11.2.1 Core Operating Parameters

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[redacted]

6.4.11.2.2 Fuel Inserts and Burnable Poisons

[redacted]

Burnable Poison Rods

[illegible]

Control Rods

[illegible]

[redacted]

Axial Power Shaping Rods

[redacted]

Integral Burnable Absorbers

[redacted]

Approach used in the Burnup Credit Evaluation

[redacted]

[illegible]

6.4.11.2.3 CASMO Calculations

[illegible]

[redacted]

6.4.11.3 Benchmarks

[redacted]

6.4.11.3.1 Isotopic Benchmarks

[redacted]

[redacted]

6.4.11.3.2 Criticality Benchmarks

[redacted]

6.4.11.3.3 *Commercial Reactor Critical Benchmarks*

6.4.11.4 *Criticality Calculations*

6.4.11.4.1 *Axial Burnup Distribution*

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† *The design basis calculations for burnup credit conservatively use the highest enrichment in the assembly as the governing enrichment.*

6.4.11.4.2 Tilted Burnup Distribution

6.4.11.4.3 Transfer of Isotopic Compositions

6.4.11.4.4 MCNP Calculations

[illegible]

6.4.11.5 *Establish Loading Curves*

6.4.11.6 *Remaining Safety Margin*

6.4.11.6.1 *Summary of Conservatisms*

[redacted]

6.4.11.6.2 *Equivalent B-10 Amount for CASMO isotopes without MCNP Cross Section*

6.4.11.6.3 *Best Estimate Isotopic Compositions in CRCs*

6.4.11.6.4 *MPC-32 Calculations with Best Estimate Isotopic Compositions*

6.4.11.6.5 *Evaluation of Uncertainties with Best Estimate Isotopic Compositions*

6.4.11.7 Comparison with ISG-8 Rev. 1

In Table 6.4.22, a cross reference is presented between ISG-8 and the approach outlined here. For each of the recommendations in the ISG, the table lists the section or sections of this chapter where the implementation of the recommendation is discussed, or where an alternative to the recommendation is presented. Additionally, the alternatives to, and extensions of the ISG-8 recommendation are summarized below.

6.4.11.7.1 Actinide Only Burnup Credit

[illegible]

[redacted]

6.4.11.7.3 *Burnable Absorbers*

[redacted]

6.4.11.7.4 *Burnup Measurements*

6.4.11.8 *Burnup Credit Summary*

The burnup credit evaluations demonstrate that with the minimum burnups as specified by the formulas in Table 6.4.18, the reactivity in the MPC-32 is below the regulatory limit of 0.95. The evaluations also show that the results still contain substantial safety margins, sufficient to offset potential uncertainties in the condition of the fuel assemblies. The methodology generally follows ISG-8 Rev. 1, with additional benchmarks for alternative approaches.

Table 6.4.1

MAXIMUM REACTIVITIES WITH REDUCED WATER DENSITIES FOR CASK ARRAYS†
WITH MPC-24 AND MPC-68

	Water Density		**MCNP4a Maximum k_{eff} ††**	
Case Number	**Internal**	**External**	**MPC-24 (17x17A01 @ 4.0%)**	**MPC-68 (8x8C04 @ 4.2%)**
1	100%	single cask	*0.9368*	0.9348
2	100%	100%	*0.9354*	0.9339
3	100%	70%	*0.9362*	0.9339
4	100%	50%	*0.9352*	0.9347
5	100%	20%	*0.9372*	0.9338
6	100%	10%	*0.9380*	0.9336
7	100%	5%	*0.9351*	0.9333
8	100%	0%	*0.9342*	0.9338
9	70%	0%	*0.8337*	0.8488
10	50%	0%	*0.7426*	0.7631
11	20%	0%	*0.5606*	0.5797
12	10%	0%	*0.4834*	0.5139
13	5%	0%	*0.4432*	0.4763
14	10%	100%	*0.4793*	0.4946

† For an infinite square array of casks with 60 cm spacing between cask surfaces.

†† Maximum k_{eff} includes the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.2

REACTIVITY EFFECTS OF SPACING AND WATER MODERATOR DENSITY FOR SQUARE ARRAYS OF MPC-24 CASKS
(17x17A01 @ 4.0% E)

	Cask-to-Cask External Spacing (cm)				
External Moderator Density (%)	2	10	20	40	60
5	*0.9352*	*0.9389*	*0.9356*	*0.9345*	*0.9351*
10	*0.9366*	*0.9353*	*0.9338*	*0.9357*	*0.9380*
20	*0.9368*	*0.9371*	*0.9359*	*0.9366*	*0.9372*
50	*0.9363*	*0.9363*	*0.9371*	*0.9352*	*0.9352*
100	*0.9355*	*0.9369*	*0.9354*	*0.9354*	*0.9354*

Note:

1. All values are maximum k_{eff} which include the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.3

REACTIVITY EFFECTS OF SPACING AND WATER MODERATOR DENSITY FOR HEXAGONAL (TRIANGULAR-PITCHED) ARRAYS OF MPC-24 CASKS
(17x17A01 @ 4.0% E)

	Cask-to-Cask External Spacing (cm)				
External Moderator Density (%)	2	10	20	40	60
5	*0.9358*	*0.9365*	*0.9369*	*0.9354*	*0.9354*
10	*0.9363*	*0.9372*	*0.9351*	*0.9368*	*0.9372*
20	*0.9354*	*0.9357*	*0.9345*	*0.9358*	*0.9381*
50	*0.9347*	*0.9361*	*0.9371*	*0.9365*	*0.9370*
100	*0.9373*	*0.9381*	*0.9354*	*0.9354*	*0.9354*

Note:

1. All values are maximum k_{eff} which include the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.4

REACTIVITY EFFECTS OF SPACING AND EXTERNAL MODERATOR DENSITY FOR HEXAGONAL (TRIANGULAR-PITCHED) ARRAYS OF MPC-24 CASKS (17x17A01 @ 4.0% E) INTERNALLY FLOODED WITH WATER OF 10% FULL DENSITY

	Cask-to-Cask External Spacing (cm)				
External Moderator Density (%)	2	10	20	40	60
10	*0.4818*	*0.4808*	*0.4798*	*0.4795*	*0.4789*
100	*0.4798*	*0.4788*	*0.4781*	*0.4793*	*0.4793*

Note:

1. All values are maximum k_{eff} which include the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.5

CALCULATIONS FOR HEXAGONAL (TRIANGULAR-PITCHED) ARRAYS OF TOUCHING CASKS *WITH MPC-24 AND MPC-68*

MPC-24 (17x17A01 @ 4.0% ENRICHMENT)		
Internal Moderation (%)	External Moderation (%)	Maximum k_{eff}
0	0	*0.3910*
0	100	*0.3767*
100	0	*0.9366*
100	100	*0.9341*
MPC-68 (8x8C04 @ 4.2% ENRICHMENT)		
Internal Moderation (%)	External Moderation (%)	Maximum k_{eff}
0	0	0.4036
0	100	0.3716
100	0	0.9351
100	100	0.9340

Note:

1. All values are maximum k_{eff} which include bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.6

REACTIVITY EFFECTS OF PARTIAL CASK FLOODING *FOR MPC-24 AND MPC-68*

MPC-24 (17x17A01 @ 4.0% ENRICHMENT)			
Flooded Condition (% Full)	Vertical Orientation	Flooded Condition (% Full)	Horizontal Orientation
25	*0.9157*	25	*0.8766*
50	*0.9305*	50	*0.9240*
75	*0.9330*	75	*0.9329*
100	*0.9368*	100	*0.9368*
MPC-68 (8x8C04 @ 4.2% ENRICHMENT)			
Flooded Condition (% Full)	Vertical Orientation	Flooded Condition (% Full)	Horizontal Orientation
25	0.9132	23.5	0.8586
50	0.9307	50	0.9088
75	0.9312	76.5	0.9275
100	0.9348	100	0.9348

Notes:

1. All values are maximum k_{eff} which include bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.7

REACTIVITY EFFECT OF FLOODING THE PELLET-TO-CLAD GAP *FOR MPC-24 AND MPC-68*

Pellet-to-Clad Condition	**MPC-24 17x17A01 4.0% Enrichment**	**MPC-68 8x8C04 4.2% Enrichment**
dry	*0.9295*	0.9279
flooded	*0.9368*	0.9348

Notes:

1. All values are maximum k_{eff} which includes bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.8

MAXIMUM k_{eff} VALUES† IN THE DAMAGED FUEL CONTAINER

Condition	MCNP4a Maximum†† k_{eff}	
	DFC Dimensions: ID 4.93" THK. 0.12"	DFC Dimensions:ID 4.81" THK. 0.11"
6x6 Fuel Assembly		
6x6 Intact Fuel	0.7086	0.7016
w/32 Rods Standing	0.7183	0.7117
w/28 Rods Standing	0.7315	0.7241
w/24 Rods Standing	0.7086	0.7010
w/18 Rods Standing	0.6524	0.6453
Collapsed to 8x8 array	0.7845	0.7857
Dispersed Powder	0.7628	0.7440
7x7 Fuel Assembly		
7x7 Intact Fuel	0.7463	0.7393
w/41 Rods Standing	0.7529	0.7481
w/36 Rods Standing	0.7487	0.7444
w/25 Rods Standing	0.6718	0.6644

† These calculations were performed with a planar-average enrichment of 3.0% and a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum ^{10}B loading of 0.0089 g/cm^2. The minimum ^{10}B loading in the MPC-68F is 0.010 g/cm^2. Therefore, the listed maximum k_{eff} values are conservative.

†† Maximum k_{eff} includes bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.9

MAXIMUM k_{eff} VALUES FOR THE MOST REACTIVE ASSEMBLY FROM THE MOST REACTIVE ASSEMBLY CLASS IN ~~EACH OF~~ THE MPCs *-24 AND MPC-68* WITH FULL WATER REFLECTION ON THE SURFACE OF THE CONTAINMENT BOUNDARY

Case	Maximum k_{eff}
MPC-24 (15x15F01 @ 4.1%)	*0.9389*
MPC-68 (B10x10A01 @ 4.2%)	0.9442
MPC-68F (6x6C01 @ 3.0%)	0.8033

Note:

1. Maximum k_{eff} values include bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.10

REACTIVITY EFFECT OF PREFERENTIAL FLOODING OF THE DFCs

DFC Configuration	Preferential Flooding	Fully Flooded
MPC-68 or MPC-68F with 68 DFCs (Assembly Classes 6x6A/B/C, 7x7A and 8x8A)	0.6560	0.7857
MPC-24E or MPC-24EF with 4 DFCs (All PWR Assembly Classes)	0.7895	0.9480

Notes:

1. All values are maximum k_{eff} which includes bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.11

MAXIMUM k_{eff} VALUES IN THE GENERIC PWR DAMAGED FUEL CONTAINER FOR A MAXIMUM INITIAL ENRICHMENT OF 4.0 wt% ^{235}U.

Model Configuration inside the DFC	**Maximum k_{eff}**
Intact Assemblies (2 assemblies analyzed)	0.9340
Assemblies with missing rods (4 configurations analyzed)	0.9350
Collapsed Assemblies (6 configurations analyzed)	0.9360
Regular Arrays of Bare Fuel Rods (36 configurations analyzed)	0.9480

Table 6.4.12

CORE OPERATING PARAMETERS USED IN BURNUP CREDIT EVALUATIONS.

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 6.4.13

ISOTOPIC CORRECTION FACTOR DERIVED FROM ISOTOPIC BENCHMARK CALCULATIONS

Table 6.4.14

BIAS AND BIAS UNCERTAINTY FOR MCNP4a BASED ON DIFFERENT SETS OF CRITICAL EXPERIMENTS

Critical Experiments	Bias	Bias Uncertainty at the 95% confidence level
Set of 56 experiments (48 with UO_2 fuel, 8 with MOX fuel)	0.0021	0.0006
Set of 87 experiments (48 with UO_2 fuel, 39 with MOX fuel)	0.0015	0.0005

Table 6.4.15

CASMO-4 ISOTOPES, CORRESPONDING MCNP4a CROSS SECTION IDENTIFIER AND CORRECTION FACTORS

Table 6.4.16

DESIGN BASIS MATERIAL SPECIFICATION FOR WE 17x17 FUEL WITH 4.0 wt% ^{235}U INITIAL ENRICHMMENT AND 37.5 GWd/MTU BURNUP

Table 6.4.17

MINIMUM ASSEMBLY AVERAGE BURNUP FOR VARIOUS ASSEMBLY CLASSES AND INITIAL ENRICHMENTS IN THE MPC-32

Enrichment (wt% ^{235}U)	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Assembly Class	Minimum Assembly Average Burnup (GWd/MTU)						
15x15D	4.06	16.18	24.75	31.25	36.59	46.52	56.04
15x15E	3.91	16.32	24.72	31.35	36.62	46.19	56.35
15x15F	4.77	16.60	25.36	31.82	36.87	46.74	56.38
15x15H	4.04	16.50	24.86	31.29	36.75	46.65	56.45
Polynom for 15x15D/E/F/H (Table 6.4.18)	4.96	16.74	25.49	32.02	37.16	46.74	56.59
17x17A	1.18	11.76	20.93	28.51	35.20	45.89	56.57
17x17B	3.03	13.35	22.71	30.27	36.35	47.24	58.48
17x17C	3.83	13.75	22.62	30.46	37.18	47.85	59.42
Polynom for 17x17A/B/C (Table 6.4.18)	3.92	14.17	22.91	30.47	37.19	48.41	59.46

Table 6.4.18
POYNOMIAL FUNCTIONS FOR THE MINIMUM BURNUP AS A FUNCTION OF INITIAL ENRICHMENT

Assembly Classes	Burnup B (GWd/MTU) as a Function of the Initial Enrichment E (wt% ^{235}U)
15x15D, E, F, H	E <= 4.0 wt% : $B = (1.1018) * E^3 - (14.3434) * E^2 + (71.3106) * E - 89.1034$ E > 4.0 wt% and E <= 5.0 wt% : $B = (1.1018) * E^3 - (14.3434) * E^2 + (81.3106) * E - 129.1034$
17x17A, B, C	E <= 4.0 wt% : $B = (0.4483) * E^3 - (6.3861) * E^2 + (42.401) * E - 58.9255$ E > 4.0 wt% and E <= 5.0 wt% : $B = (0.4483) * E^3 - (6.3861) * E^2 + (52.401) * E - 98.9255$

Table 6.4.19

COMPARISON OF BURNUP CREDIT DESIGN BASIS CALCULATION (B&W 15x15) WITH ANALYSIS USING BEST ESTIMATE ISOTOPIC COMPOSITIONS

Initial Enrichment (wt% ^{235}U)	**Burnup (GWd/MTU)**	**Maximum k_{eff}**		**Margin (delta-k)**
		Design Basis Calculation	**Best Estimate Isotopic Composition**	
2.0	5.0	0.9440	0.9307	0.0133
3.0	25.0	0.9471	0.9139	0.0332
4.0	37.5	0.9409	0.8957	0.0452
5.0	47.5	0.9410	0.8849	0.0561

Table 6.4.20

COMPARISON OF BURNUP CREDIT DESIGN BASIS CALCULATION (B&W 15x15) WITH ANALYSIS USING BEST ESTIMATE ISOTOPIC COMPOSITIONS AND REDUCED BURNUP

Initial Enrichment (wt% ^{235}U)	**Design Basis Calculation**		**Best Estimate Isotopic Composition**		**Margin (delta-k)**
	Burnup (GWd/MTU)	**Maximum k_{eff}**	**Burnup (GWd/MTU)**	**Maximum k_{eff}**	
2.0	5.0	0.9440	4.25	0.9352	0.0088
3.0	25.0	0.9471	21.25	0.9385	0.0086
4.0	37.5	0.9409	31.88	0.9375	0.0034
5.0	47.5	0.9410	40.38	0.9338	0.0072

Table 6.4.21

COMPARISON OF BURNUP CREDIT DESIGN BASIS CALCULATION (B&W 15x15) WITH ANALYSIS USING BEST ESTIMATE ISOTOPIC COMPOSITIONS AND ASSUMING FULLY INSERTED CONTROL RODS

Initial Enrichment (wt% ^{235}U)	**Burnup (GWd/MTU)**	**Maximum k_{eff}**		**Margin (delta-k)**
		Design Basis Calculation	**Best Estimate Isotopics, Fully Inserted Control Rods**	
2.0	5.0	0.9440	0.9357	0.0083
3.0	25.0	0.9471	0.9274	0.0197
4.0	37.5	0.9409	0.9111	0.0298
5.0	47.5	0.9410	0.9005	0.0405

Table 6.4.22

ISG-8 REV. 1 TO SECTION NUMBER CROSS REFERENCE

ISG-8 Recommendation	**Corresponding Section**
…limit the amount of burnup credit to that available from actinide compositions …	6.4.11.7.1, 6.4.11.3.3
…limit the amount of burnup credit … to an assembly-average burnup value of 40 GWd/MTU or less.	6.4.11.7.2
…should assume an out-of-reactor cooling time of five years …	6.4.11.2.3
…restricted to assemblies that have not used burnable absorbers.	6.4.11.7.3
The initial enrichment … should not be more than 4.0 wt% ^{235}U unless a loading offset is applied.	6.4.11.5
…ensure that the analysis methodologies …are properly validated.	6.4.11.3.1/2/3
Bias and uncertainties associated with predicting the actinide compositions should be determined from benchmarks of applicable fuel assay measurements.	6.4.11.3.1
Bias and uncertainties associated with the calculation of k-effective should be derived from benchmark experiments that represent important features of the cask design and spent fuel contents.	6.4.11.3.2, 6.4.11.3.3
The particular set of nuclides used to determine the k-effective value should be limited to that established by the validation process.	6.4.11.3.1, 6.4.11.3.3
The bias and uncertainties should applied in a way that ensures conservatism in the licensing safety analysis.	6.4.11.3.1/2/3
…fuel design and in-reactor operating parameters selected to provide conservative estimates of the k-effective value …	6.4.11.2.1
…cask models, appropriate analysis assumptions, and code inputs that allow adequate representation of the physics.	6.3, 6.4.1, 6.4.11.4.4
…account for the axial and horizontal variation of the burnup within a spent fuel assembly …	6.4.11.4.1, 6.4.11.4.2
…consider the more reactive actinide compositions of fuels burned with fixed absorbers or with control rods fully or partially inserted …	6.4.11.2.2
…account for local reactivity effects at the less-burned axial ends of the fuel region.	6.4.11.4.1, 6.4.11.4.2
…should prepare one or more loading curves …	6.4.11.5
Loading curves should be estabalished based on a 5-year cooling time …	6.4.11.2.3, 6.4.11.5
Administrative procedures should include an assembly measurement that confirms the reactor record burnup.	6.4.11.7.4

Table 6.4.22 (continued)

ISG-8 REV. 1 TO SECTION NUMBER CROSS REFERENCE

ISG-8 Recommendation	**Corresponding Section**
…provide design-specific analyses that estimate the additional reactivity margins …	6.4.11.6.3
…methods used for determining these estimated reactivity margins should be verified using available experimental data …and computational benchmarks …	6.4.11.6.2
…margins should be evaluated over the full range ofinitial enrichments and burnups …	6.4.11.6.3
…margins should then be assessed against estimates of … uncertainties not directly evaluated …and…potential nonconservatisms …	6.4.11.6.4

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FAILED FUEL CALCULATION MODEL (PLANAR CROSS-SECTION)
WITH 6X6 ARRAY WITH 4 MISSING RODS IN THE MPC-68 BASKET
(SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.2; FAILED FUEL CALCULATION MODEL (PLANAR CROSS-SECTION) WITH 6X6 ARRAY WITH 8 MISSING RODS IN THE MPC-68 BASKET SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.3; FAILED FUEL CALCULATION MODEL (PLANAR CROSS-SECTION) WITH 6X6 ARRAY WITH 12 MISSING RODS IN THE MPC-68 BASKET (SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DI1ENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.4; FAILED FUEL CALCULATION MODEL (PLANAR CROSS-SECTION) WITH 6X6 ARRAY WITH 18 MISSING RODS IN THE MPC-68 BASKET (SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.5; FAILED FUEL CALCULATION MODEL (PLANAR CROSS-SECTION) WITH 7X7 ARRAY WITH 8 MISSING RODS IN THE MPC-68 BASKET (SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.6; **FAILED FUEL CALCULATION** MODEL (PLANAR **CROSS-SECTION)** WlLTH **7X7** ARRAY WlITH **13 MISSING** RODS **IN** THE **MPC-68** BASKET
SEE CHAPTER **1** FOR TRUE BASKET **DIMENSIONS**

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.7; FAILED **FUEL CALCULATION** MODEL (PLANAR **CROSS-SECTION)** WiITH **7X7** ARRAY W~ITHl 24 **MISSING** RODS **IN**THE **MPC-68** BASKET **(SEE** CHAPTER 1 FOR TRUE BASKET **DIMENSIONS)**

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.8; FAILED FUEL CALCULATION MODEL (PLANAR CROSS-SECTION) WITH DAMAGED FUEL COLLAPSED INTO 8X8 ARRAY IN THE MPC-68 BASKET
SEE CHAPTER I FOR TRUE BASKET DIMENSIONS

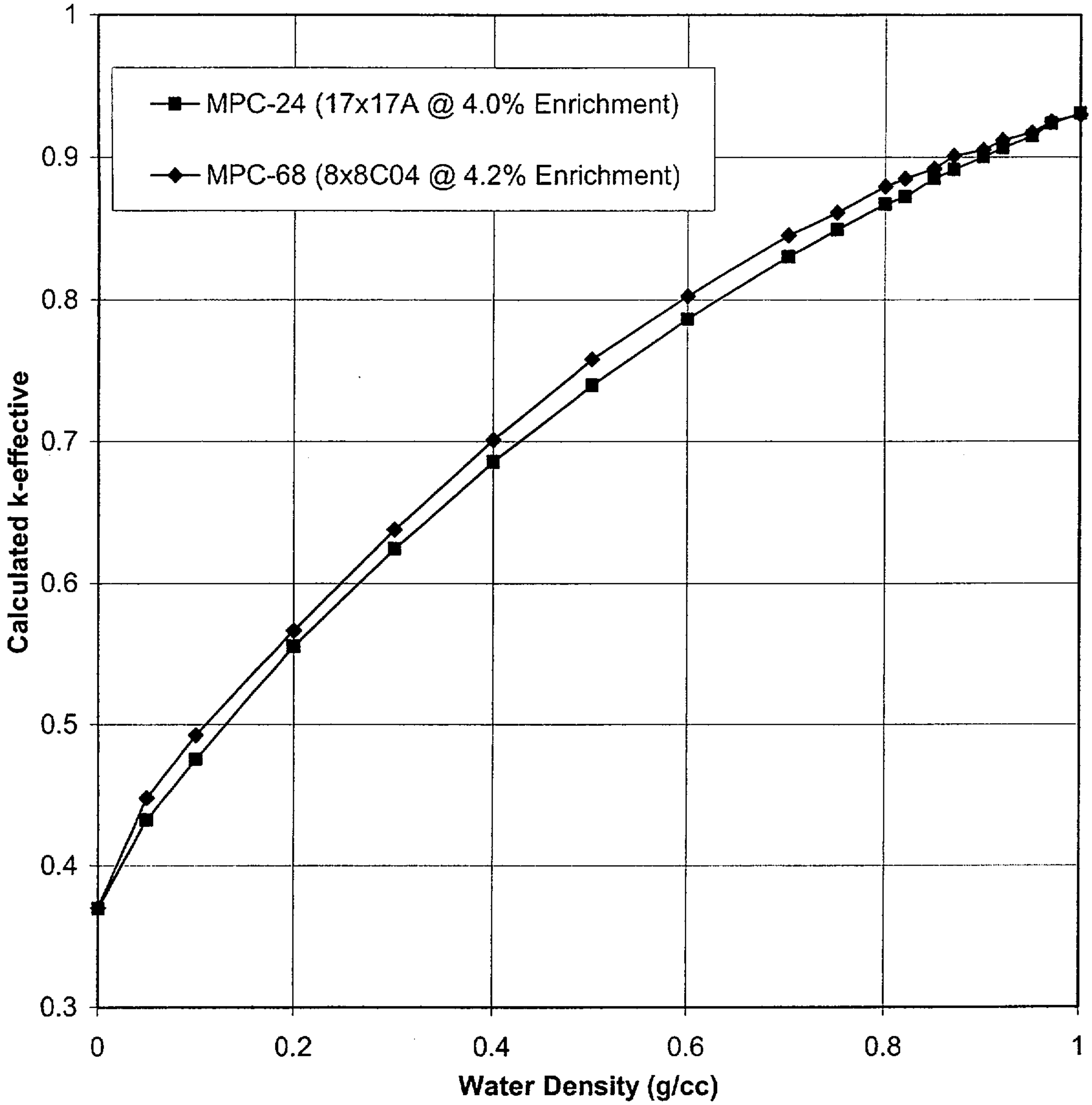

FIGURE 6.4.9; CALCULATED K-EFFECTIVE AS A FUNCTION OF INTERNAL MODERATOR DENSITY

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

FIGURE 6.4.10; THORIA ROD CANISTER (PLANAR CROSS-SECTION)
WITH 18 THORIA RODS IN THE MPC-68 BASKET
(SEE CHAPTER I FOR TRUE BASKET DIMENSIONS

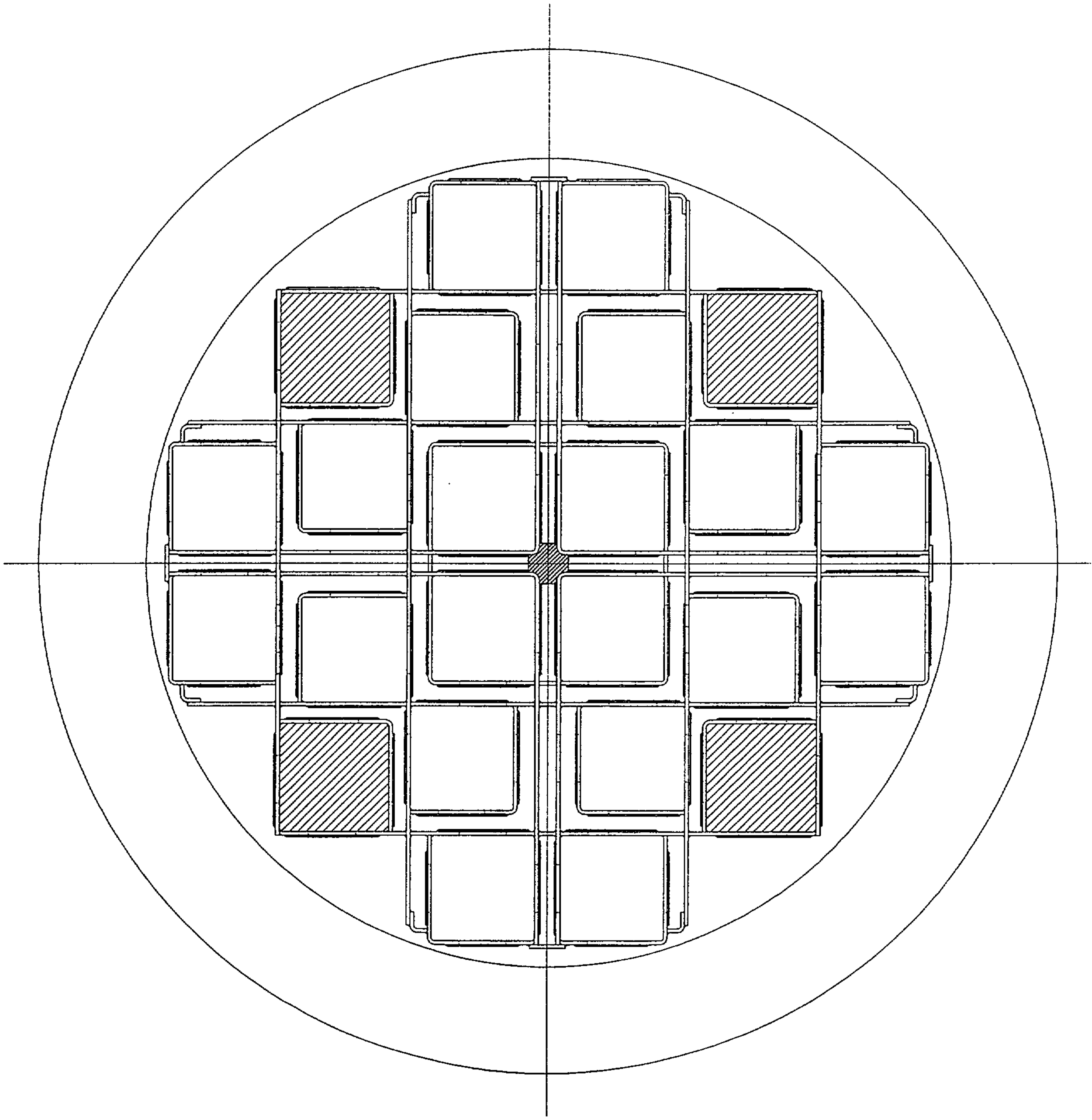

FIGURE 6.4.11: LOCATIONS OF THE DAMAGED FUEL CONTAINERS
IN THE MPC-24E/EF

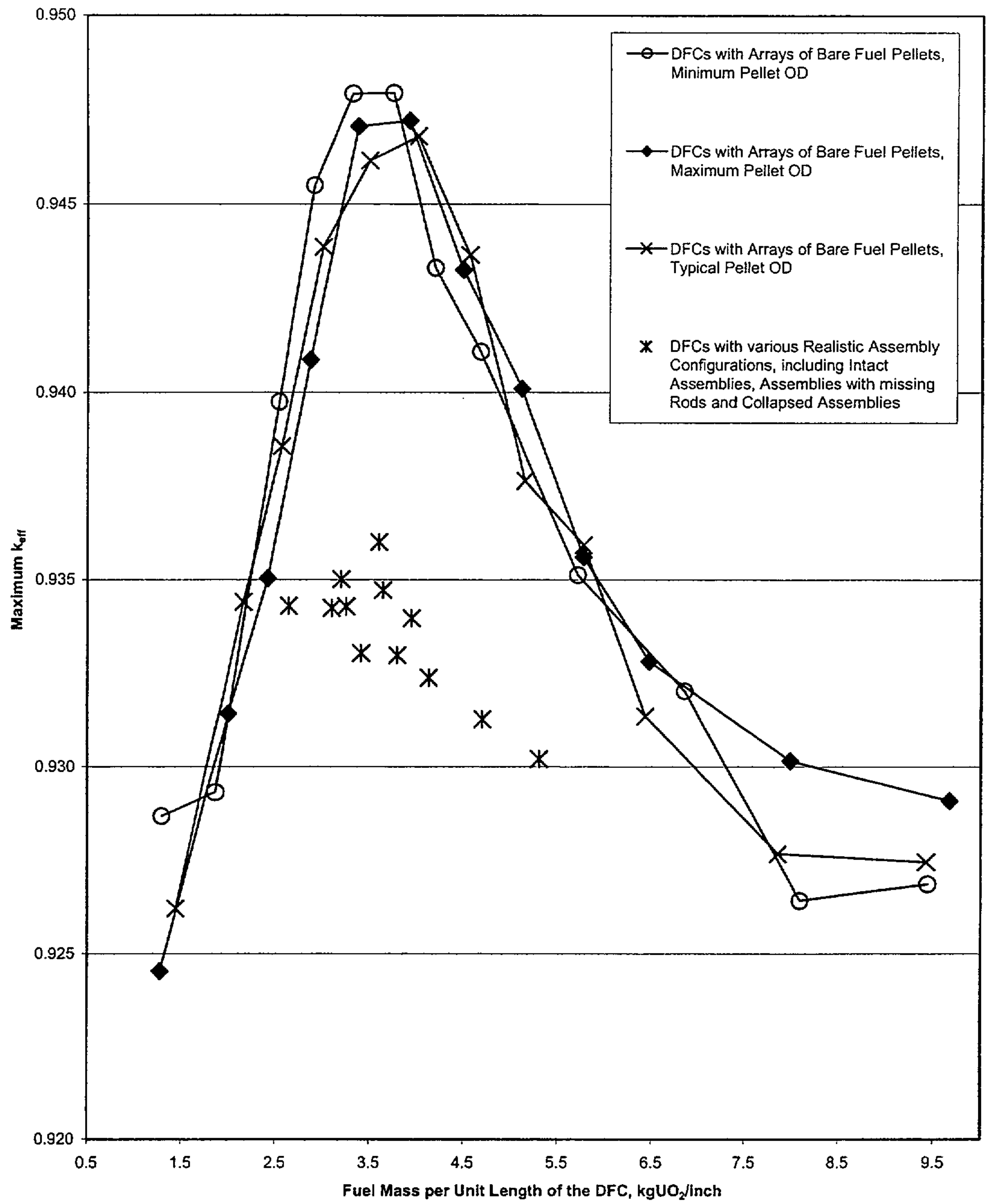

FIGURE 6.4.12: MAXIMUM K_{EFF} FOR THE MPC-24E/EF WITH GENERIC PWR DAMAGED FUEL CONTAINER, INITIAL ENRICHMENT OF 4.0 WT% FOR DAMAGED AND INTACT FUEL.

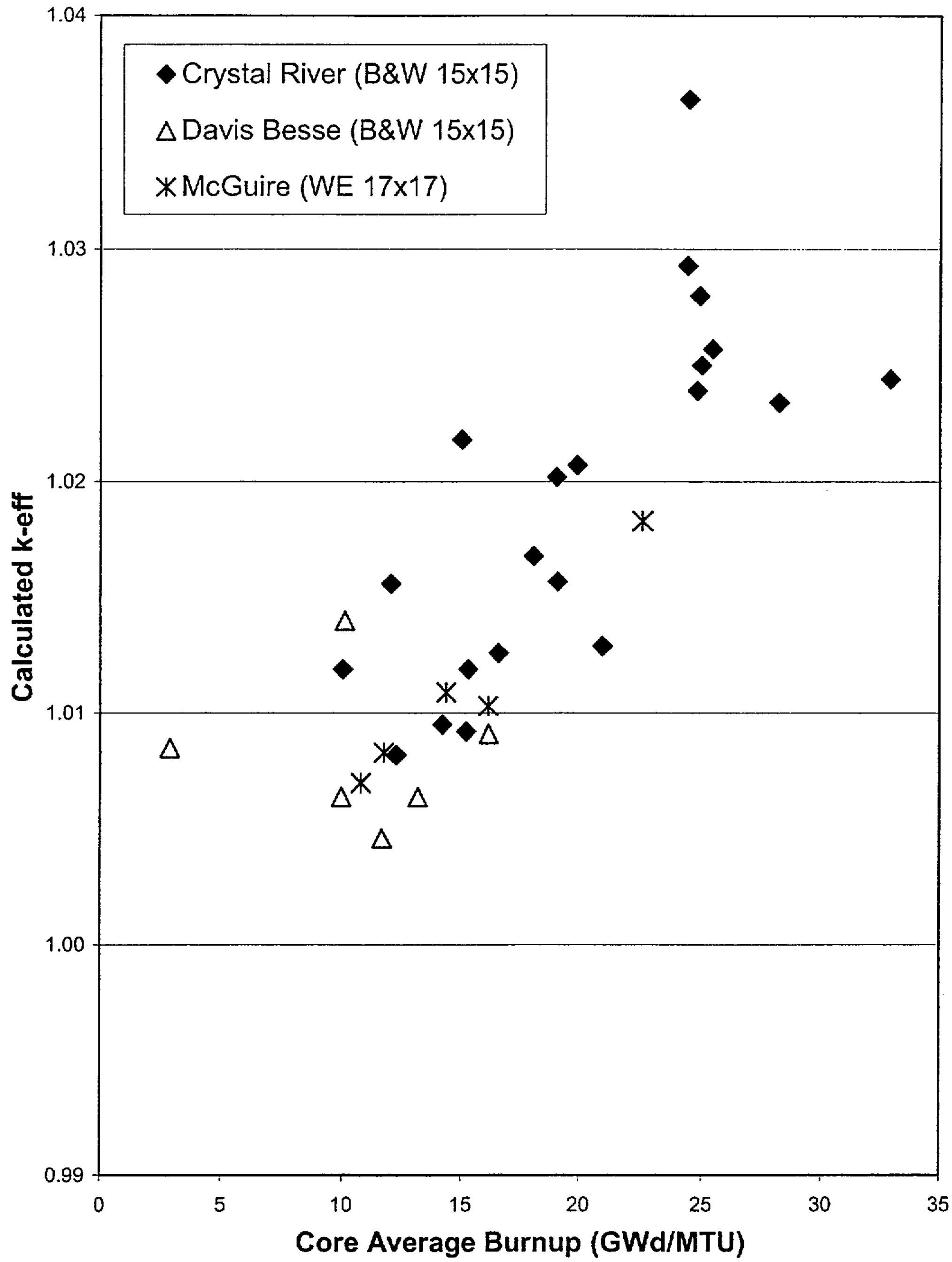

FIGURE 6.4.13: RESULTS OF REACTOR CRITICAL BENCHMARK CALCULATIONS

FIGURE 6.4.14: HOLTEC PROPRIETARY INFORMATION

FIGURE 6.4.15: HOLTEC PROPRIETARY INFORMATION

FIGURE 6.4.16: HOLTEC PROPRIETARY INFORMATION

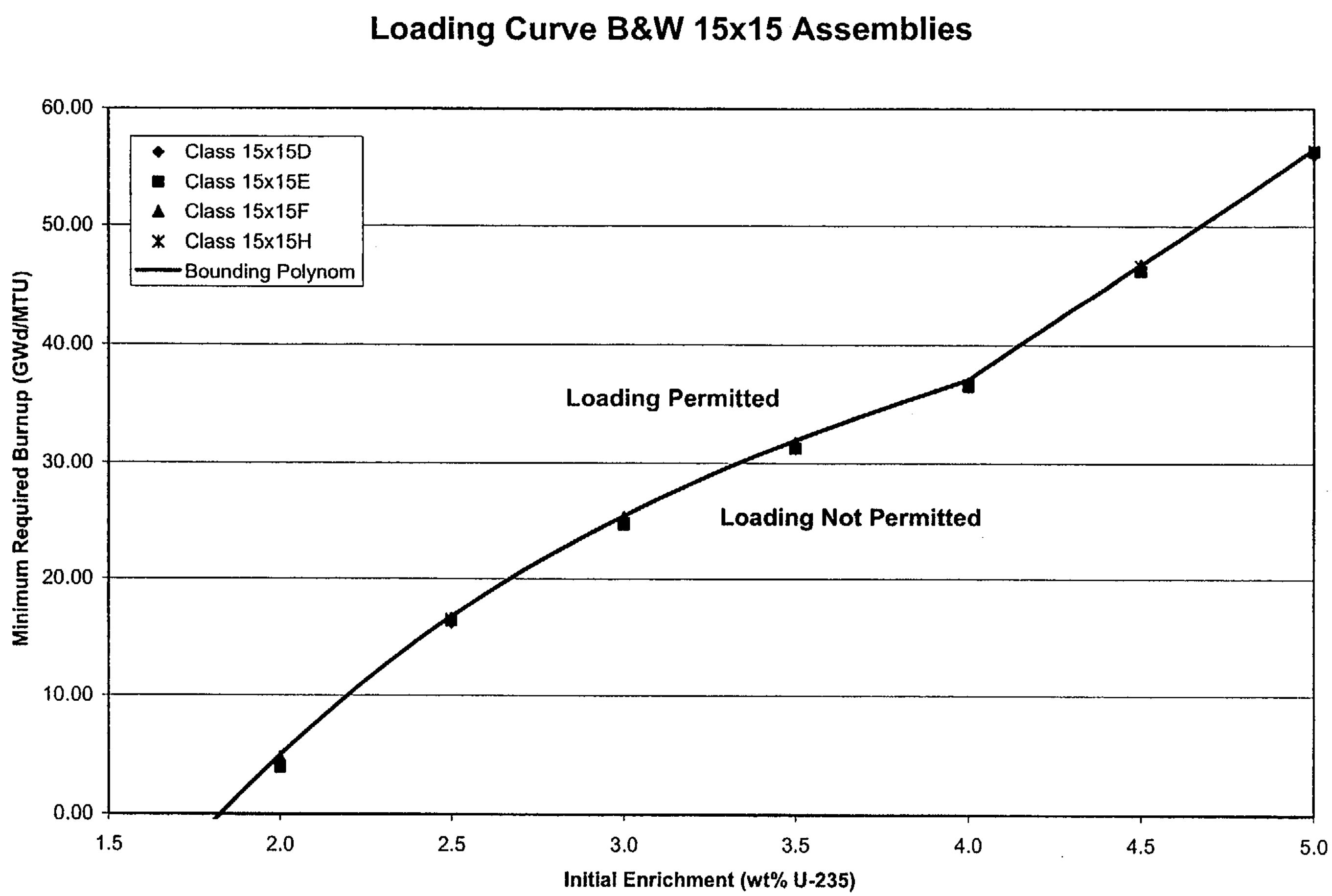

FIGURE 6.4.17: MINIMUM REQUIRED BURNUP AS A FUNCTION OF INITIAL ENRICHMENT FOR B&W 15x15 ASSEMBLIES IN THE MPC-32

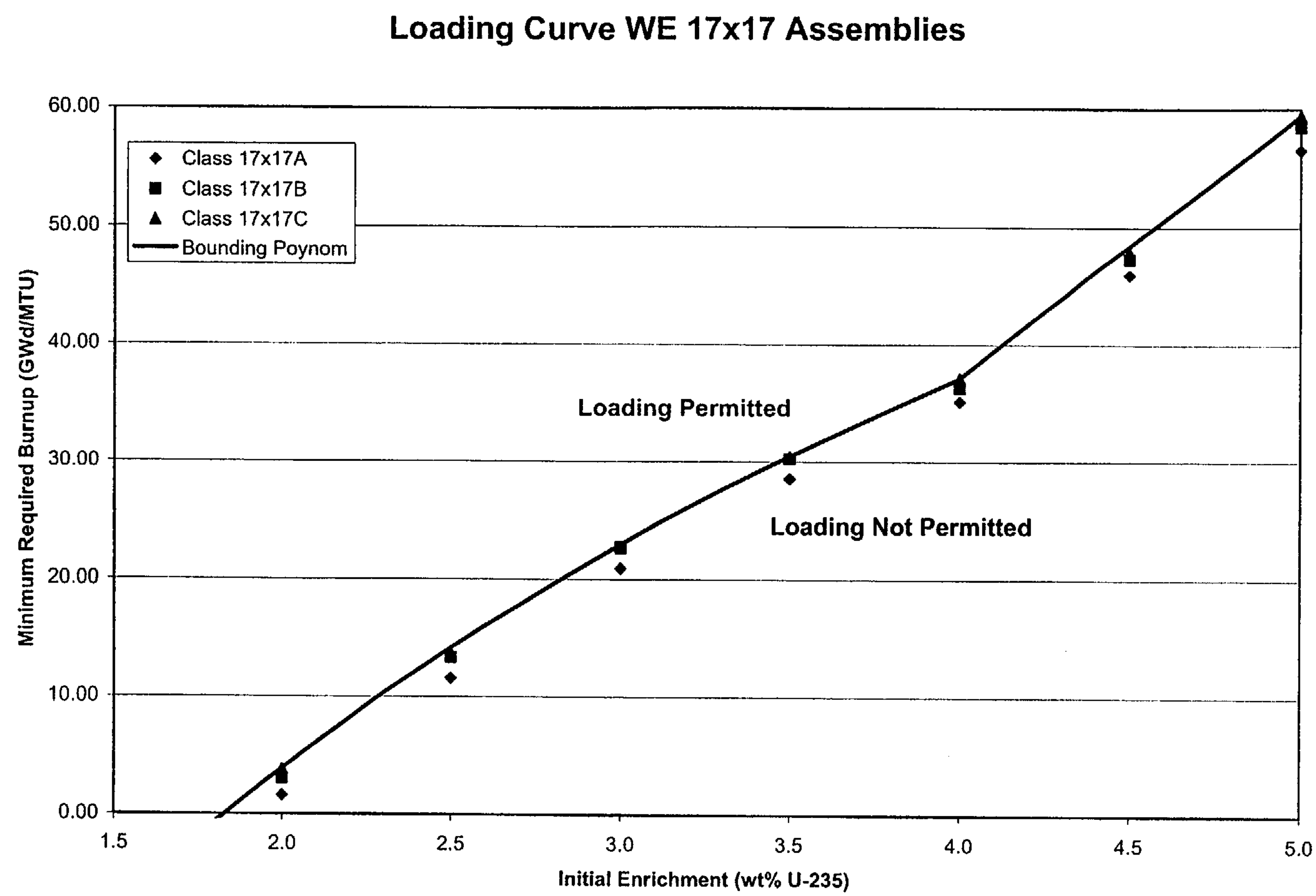

FIGURE 6.4.18: MINIMUM REQUIRED BURNUP AS A FUNCTION OF INITIAL ENRICHMENT FOR WE 17x17 ASSEMBLIES IN THE MPC-32

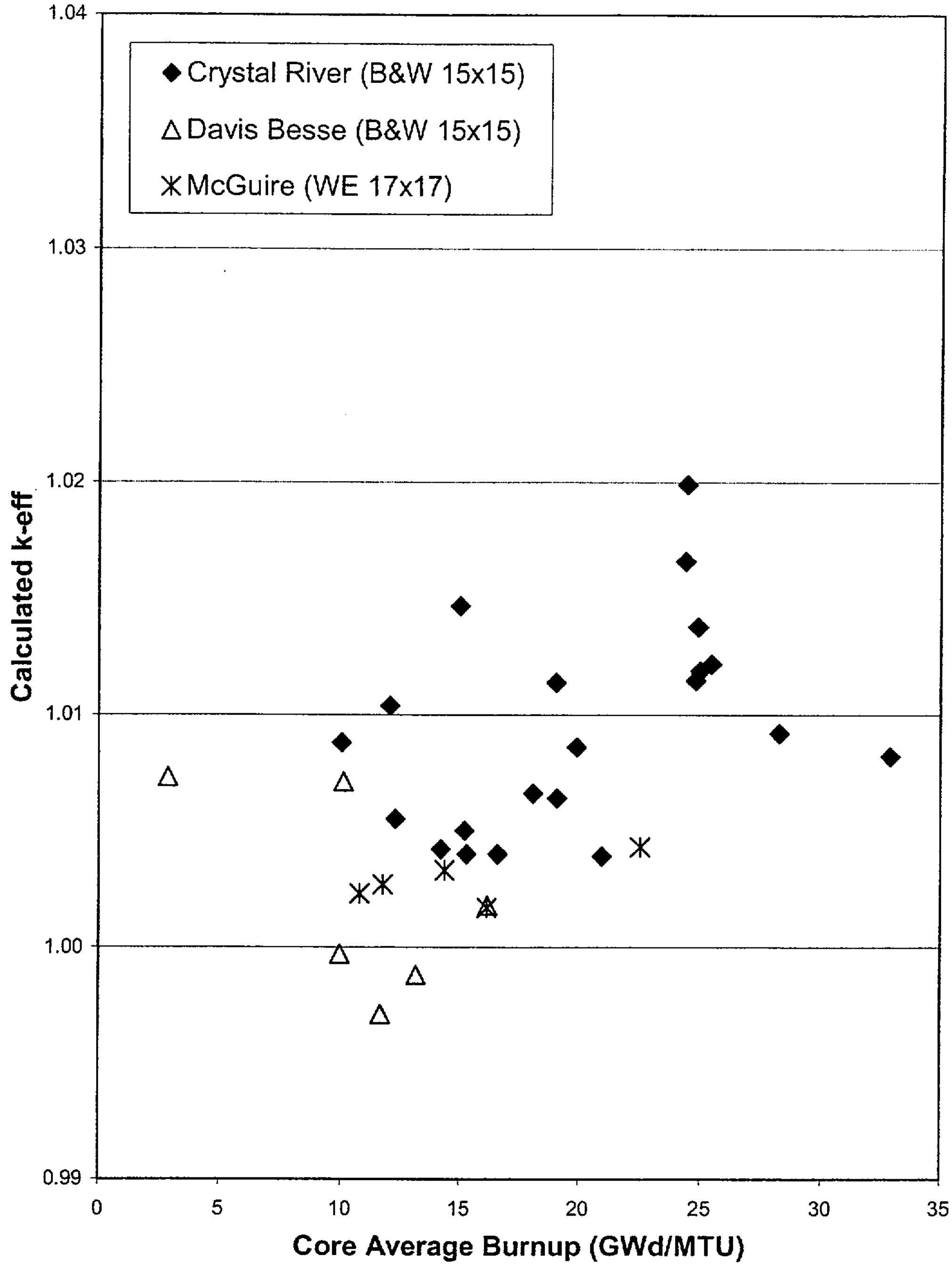

FIGURE 6.4.19: RESULTS OF REACTOR CRITICAL BENCHMARK CALCULATIONS WITH BEST ESTIMATE ISOTOPIC COMPOSITIONS

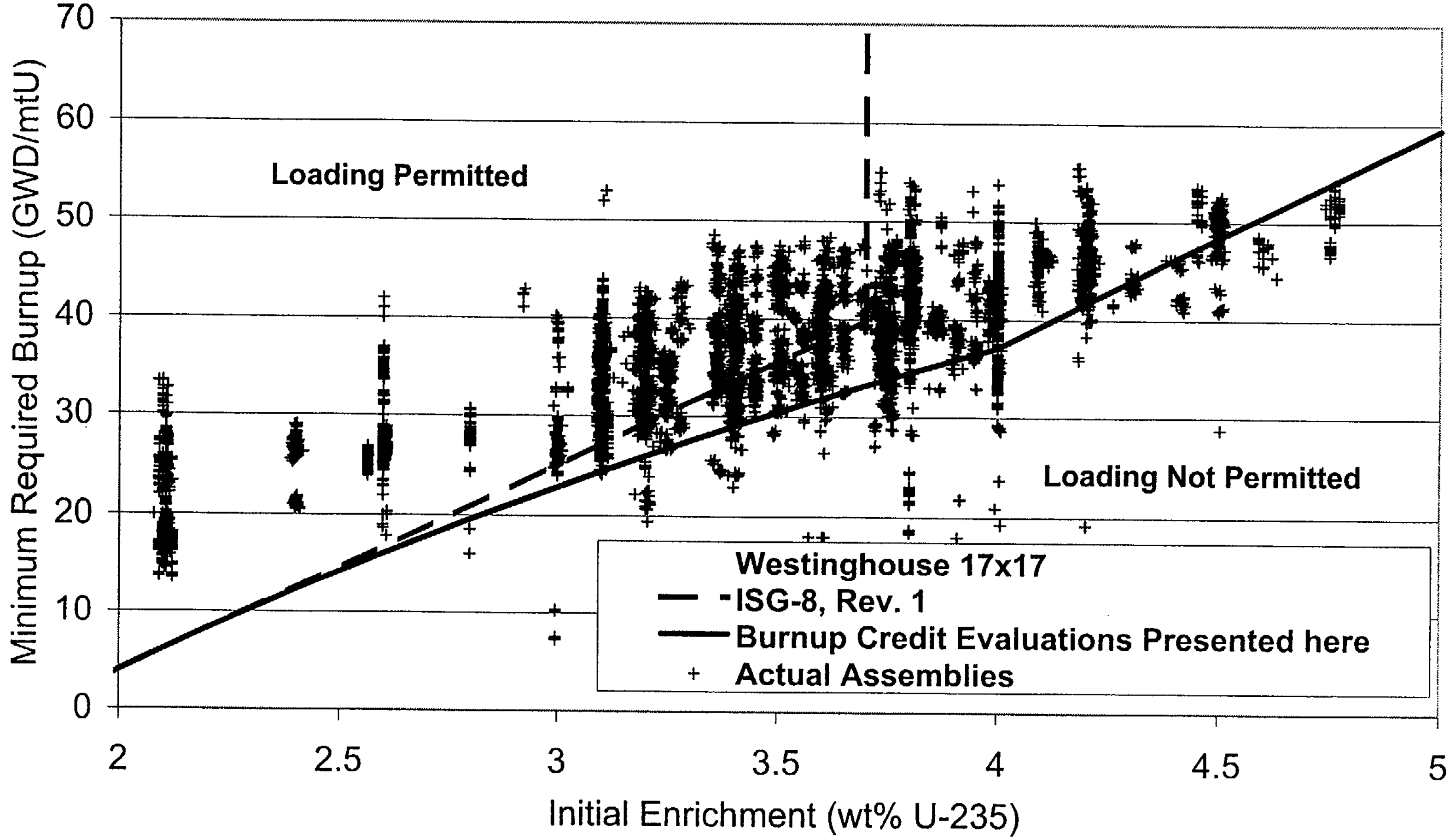

FIGURE 6.4.20: BURNUP CREDIT LOADING CURVES COMPARED TO BURNUP AND ENRICHMENT OF UNLOADED ASSEMBLIES