BSC

Design Calculation or Analysis Cover Sheet

Complete only applicable items.

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ACRONYMS AND ABBREVIATIONS

Acronyms

ANF	Advanced Nuclear Fuels
B&W	Babcock & Wilcox
BSC	Bechtel SAIC Company, LLC
BSS	Borated Stainless Steel
BWR	boiling water reactor
CSNF	commercial spent nuclear fuel
DOE	Department of Energy
DPC	dual-purpose canister
M&O	Management and Operations
MCNP	Monte Carlo N-Particle
MPC	multi-purpose canister
OFA	optimized fuel assembly
PWR	pressurized water reactor
SNF	spent nuclear fuel
STC	shielded transfer cask
TAD	transportation, aging and disposal
USL	upper subcritical limit
WHF	Wet Handling Facility

Abbreviations

˚C	degrees Celsius
cm^2	square centimeter
cm^3	cubic centimeters
cm	centimeter
ft	feet
g	grams
in.	inch
k_{eff}	effective neutron multiplication factor
kg	kilogram

L	liter
mg	milligram
mol	mole
nm	nanometer
wt.%	weight percent
yr	year

1. PURPOSE

The purpose of this calculation is to apply the process described in the TDR-DS0-NU-000001 Rev. 02, *Preclosure Criticality Analysis Process Report* (Ref. 2.2.25) to aid in establishing design and operational criteria important to criticality safety and to identify potential control parameters and their limits important to the criticality safety of commercial spent nuclear fuel (CSNF) handling operations in the Wet Handling Facility (WHF)

Based on representative assembly designs (Section 1.1.1), facility designs and operational detail (Section 1.1.2), conceptual transport, aging and disposal (TAD) designs (Section 3.1.2), and representative dual-purpose canisters (DPCs) (Section 6.1.4), parameters important to criticality safety are examined and, if needed, parameter limits are determined to ensure subcriticality for normal conditions and potential end states of Category 1 and Category 2 event sequences important to criticality, which are referred to as off-normal conditions throughout this calculation.

While the selected fuel assembly, TAD, and DPC designs are conservatively modeled, they are not necessarily bounding. The trends established in this calculation can, however, be expected to be similar for other fuel assembly, TAD, and DPC designs in regards to reactivity trends, parameters requiring controls, and control limits.

The results presented in Section 6.3 are all based on natural boron with a ^{10}B content of 19.9 atom percent except for the noted results in Section 6.3.5. These include the results presented in Figures 109 through 117.

1.1 SCOPE

The scope of this calculation is limited to specific waste form (or CSNF) characteristics, WHF facility design, and operational information as described in the following subsections.

1.1.1 CSNF Characteristics

The CSNF designs evaluated in this calculation are limited to four fuel assembly types. There are two pressurized water reactor (PWR) fuel assemblies Westinghouse (W) 17x17 OFA (optimized fuel assembly) and Babcock and Wilcox (B&W) 15x15 and two boiling water reactor (BWR) fuel assemblies (7x7 and 9x9). Details on these assemblies can be found in Sections 6.1.1and 6.1.2.

1.1.2 Facility Description

The WHF is located on the surface, east of the North Portal of the repository. The WHF provides the space, a pool, radiological confinement, structures, and internal systems that support receipt, wet and dry handling, transfer, and packaging of CSNF. The WHF receives truck and rail-based transportation casks containing uncanistered fuel assemblies, CSNF, and rail-based transportation casks containing DPCs. The WHF also receives shielded transfer casks (STCs) containing DPCs (Section 6.1.4) from the Receipt Facility. The CSNF from the transportation casks and DPCs is repackaged into TAD canisters (Section 6.1.3), and the sealed TAD canisters are transported to either the Aging Facility or the Canister Receipt and Closure Facilities.

The WHF receives DPCs contained in rail casks and STCs, and uncanistered spent nuclear fuel (SNF) contained in truck casks and rail casks in the transportation cask vestibule. DPCs that are received in aging overpacks or rail casks are unloaded and transferred into STCs prior to being processed in the pool room. DPCs in a STC are sampled, cooled, DPC lids cut, and the DPC filled with borated water prior to being lowered into the pool. Similarly, rail casks and truck casks containing uncanistered SNF are transferred directly to a preparation area for sampling and cooling prior to being placed in the pool. In the pool, SNF is retrieved from the DPC or cask and transferred to a TAD canister contained within a STC or to the fuel assembly staging rack (Sections 6.1.5 and 6.1.6). After the TAD canister loading is complete, the STC containing the loaded TAD canister is removed from the pool and sent to a closure station where the TAD canister is drained and closed. The loaded TAD canister in a STC is then transported to the Canister Receipt and Closure Facility via a site transporter or transferred from the STC into an aging overpack and then transported to the aging pad.

2. REFERENCES

This section presents the references used in this calculation. Where applicable, the document input reference system (DIRS) number is in parentheses at the end of the reference.

2.1 PROJECT PROCEDURES/DIRECTIVES

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General Applications. West Conshohocken, Pennsylvania: American Society for Testing and Materials. TIC: 259153 (DIRS 179346)

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2.2.9 BSC 2007. *Wet Handling Facility SNF Staging Racks in Pool Mechanical Equipment Envelope Sheet 1 of 3*. 050-M90-HTF0-00201-000 Rev. 00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071027.0020 (DIRS 183710)

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2.2.11 CRWMS M&O 1998. *Software Qualification Report for MCNP Version 4B2, A General Monte Carlo N-Particle Transport Code*. CSCI: 30033 V4B2LV. DI: 30033-2003, Rev. 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980622.0637 (DIRS 102836)

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2.2.24 BSC (Bechtel SAIC Company) 2005. Q-List. 000-30R-MGR0-00500-000-003. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20050929.0008. (DIRS 175539)

2.2.25 BSC 2007. *Preclosure Criticality Analysis Process Report*. TDR-DS0-NU-000001, Rev. 01, Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20070309.0001 (DIRS 182214)

2.3 DESIGN CONSTRAINTS

None.

2.4 DESIGN OUTPUTS

2.4.1 BSC 2007. *Preclosure Criticality Safety Analysis.* TDR-MGR-NU-000002, Las Vegas, Nevada: Bechtel SAIC Company

3. ASSUMPTIONS

3.1 ASSUMPTIONS THAT REQUIRE VERIFICATION

3.1.1 Upper Subcritical Limit

Assumption–The upper subcritical limit (USL) for all PWR and BWR CSNF configurations analyzed in this calculation is assumed to be 0.92, which includes a 0.05 administrative margin.

Rational–The largest bias and uncertainty for benchmarks applicable to PWR and BWR CSNF configurations, as summarized in Table 5 of the CAL-DS0-NU-000003 Rev. 00A, *Criticality Model* (Ref. 2.2.6), is 0.023. Range of applicability extension to cover the range of parameters for all normal and off-normal conditions may necessitate the use of additional benchmarks or the establishment of a penalty on the USL (Δk_{EROA}). The extension of the range of applicability is not expected to result in a bias and uncertainty larger than 0.03.

Use in the Calculation–This assumption is used throughout the calculations in Section 6.

Confirmation Status–This assumption requires confirmation by analysis. This assumption is tracked via CalcTrac (EG-DSK-3013 Rev. 02, *Desktop Information for Using CalcTrac.* Ref. 2.1.2).

3.1.2 TAD Canister Dimensions and Materials

Assumption–Certain dimensions and materials of construction of the TAD canister are not explicitly defined in WMO-TADCS-000001, Rev. 0 *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) and have been assumed as discussed in Section 6.1.3 in order to perform the analysis herein. These assumed values are summarized in Table 1and Table 2.

Table 1. Design Parameters Assumed for PWR TAD Canister Model

Design Parameter	MCNP Model		Design Criteria
TAD Canister Body			
Inner diameter of TAD canister	65.0 in.	165.10 cm	No specific criteria
Outer length/height of TAD canister[(3)]	211.5 in.	537.21 cm	211.5 in. (min), 212.0 in. (max)
TAD canister spacer	Not modeled		Required for TAD canisters less than 211.5 in. in height.
Inner length/height of TAD canister	210.5 in.	534.67 cm	No specific criteria
TAD canister base thickness	0.5 in.	1.27 cm	No specific criteria
TAD canister lid thickness	0.5 in.	1.27 cm	No specific criteria
Stainless steel type	Stainless Steel Type 316		Type 300-series stainless steel
TAD Canister Basket Structure			
Inner width of fuel assembly compartment	9.0 in.	22.86 cm	No specific criteria
Compartment Inner wall thickness	0.1875 in.	0.48 cm	No specific criteria
Compartment borated stainless steel panel arrangement[(4)]	4 panels around each compartment with a flux trap between		Panels must surround all four longitudinal sides of fuel assemblies
Compartment borated stainless steel panel thickness[(4)]	0.8 cm ((0.6 cm + (4 × 250 nm/yr × 10,000 yr)/2)		6 mm left after 10,000 yr 250 nm/yr of corrosion for every surface
Basket height	Full interior height of TAD canister [(2)]		The BSS plates are required to cover the entire active fuel region plus an allowance for any axial shift in the fuel assemblies
Compartment outer wall thickness	0.1875 in.	0.48 cm	No specific criteria
Outer width of fuel assembly compartment	10.38 in.	26.37 cm	No specific criteria
Spacing between compartments (surface-to-surface)	0.0 in. - 0.91 in.	0 – 2.32 cm	No specific criteria
Axial placement of fuel/basket in TAD canister[(1)]	Fuel/basket modeled to sit directly on the inside bottom of TAD canister		No specific criteria
Stainless steel type	Stainless Steel Type 316		Type 300-series stainless steel

NOTES: [(1)] Axial position selected purely for modeling convenience.

[(2)] The active fuel region is conservatively modeled as the same as the fuel assembly height and the basket height is modeled as the full interior height of the TAD canister.

[(3)] The minimum TAD canister height is allowed to be less than 211.5 in. with a spacer present (186 in.). The TAD canister spacer is not modeled in this calculation, therefore TAD canister heights less than 211.5 in. are not modeled.

[(4)] The basic arrangement of the basket includes a flux gap and utilizes two neutron absorber panels between fuel assemblies. This arrangement is allowed for in the *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14). The thickness of the panels is a direct result of this arrangement, the minimum thickness requirement, and the corrosion requirements.

BSS = borated stainless steel; max = maximum; min = minimum; yr = year

Source: *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14).

Table 2. Design Parameters Assumed for BWR TAD Canister Model

Design Parameter	MCNP Model		Design Criteria
TAD Canister Body			
Inner diameter of TAD canister	65.0 in.	165.10 cm	No specific criteria
Outer length/height of TAD canister[3]	211.5 in.	537.21 cm	211.5 in. (min), 212.0 in. (max)
TAD canister spacer	Not modeled		Required for TAD canisters less than 211.5 in. in height.
Inner length/height of TAD canister	210.5 in.	534.67 cm	No specific criteria
TAD canister base thickness	0.5 in.	1.27 cm	No specific criteria
TAD canister lid thickness	0.5 in.	1.27 cm	No specific criteria
Stainless steel type	Stainless Steel Type 316		Type 300-series stainless steel
TAD Canister Basket Structure			
Inner width of fuel assembly compartment	6.0 in.	15.24 cm	No specific criteria
Compartment inner wall thickness	0.125 in.	0.32 cm	No specific criteria
Compartment borated stainless steel panel arrangement[4]	4 panels around each compartment with a flux trap between		Panels must surround all four longitudinal sides of fuel assemblies
Compartment borated stainless steel panel thickness[4]	0.8 cm ((0.6 cm + (4 × 250 nm/yr × 10,000 yr)/2)		6 mm left after 10,000 yr 250 nm/yr of corrosion for every surface
Basket height	Same as fuel assembly [2]		The BSS plates are required to cover the entire active fuel region plus an allowance for any axial shift in the fuel assemblies
Compartment outer wall thickness	0.125 in.	0.32 cm	No specific criteria
Outer width of fuel assembly compartment	7.13 in.	18.11 cm	No specific criteria
Spacing between compartments (surface-to-surface)	0.0 in. - 0.58 in.	0 – 1.48 cm	No specific criteria
Axial placement of fuel/basket in TAD canister[1]	Fuel/basket modeled to sit directly on the inside bottom of TAD canister		No specific criteria
Stainless steel type	Stainless Steel Type 316		Type 300-series stainless steel

NOTES: [1] This placement is modeled purely for convenience.
[2] The active fuel region is modeled as the same height as fuel assembly. The fuel basket is modeled as the same height as the modeled active fuel region of the fuel.
[3] The minimum TAD canister height is allowed to be less than 211.5 in. with a spacer present (186 in.). The TAD canister spacer is not modeled in this calculation, therefore TAD canister heights less than 211.5 in. are not modeled.
[4] The basic arrangement of the basket includes a flux gap and utilizes two neutron absorber panels between fuel assemblies. This arrangement is allowed for in the *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14). The thickness of the panels is a direct result of this arrangement, the minimum thickness requirement, and the corrosion requirements.

BSS = borated stainless steel; max = maximum; min = minimum; yr = year

Source: *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14).

Rationale–The assumed dimensions and internal arrangement modeled configurations are allowed for per the *Transportation, Aging and Disposal System Performance Specification* (Ref. 2.2.14).

Use in the Calculation – Assumed dimensions and internal arrangement are utilized in the TAD canister and basket Monte Carlo N-Particle (MCNP) models.

Confirmation Status–The dimensions and internal arrangement of the TAD canister and basket must be verified. This assumption is tracked via CalcTrac (*Desktop Information for Using CalcTrac*, Ref. 2.1.2).

3.2 ASSUMPTIONS THAT DO NOT REQUIRE VERIFICATION

3.2.1 Density of UO_2

Assumption–The density of the UO_2 fuel utilized in this calculation is conservatively assumed to be 10.751 g/cm^3. This is 98% of the 10.97 g/cm^3 theoretical density for naturally enriched UO_2 taken from the *CRC Handbook of Chemistry and Physics* (Ref. 2.2.18, p. 4-97).

Rationale–The fuel rods, as modeled herein, model the fuel as solid rods versus individual pellets. The individual pellets allow for some void space between the pellets which results in a lower effective density of UO_2 when modeled as a rod. Based upon a review of the uranium mass per fuel assembly, the active fuel length, fuel pellet diameter, and number of fuel rods per fuel assembly as given in CAL-DSU-NU-000017 Rev. 0A, *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8) and in CAL-DSU-NU-000013 Rev. 00A, *CSNF Assembly Type Sensitivity Evaluation for Pre- and Postclosure Criticality Analysis* (Ref. 2.2.7), the assumed density of 10.751 g/cm^3 is bounding of the determined UO_2 density. These determinations assumed that the given uranium mass is modeled in the given number of rods with a length equivalent to the active fuel length and are shown in Table 3 for B&W 15x15, W 17x17, and 7x7 BWR fuel assemblies. From Table 3 the maximum determined UO_2 density of these three fuel assemblies is 10.31 g/cm^3. For the 9x9 BWR fuel assembly, the density of the fuel pellets is given as 94.5% of theoretical density (TDR-UDC-NU-000001 Rev. 02, *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3,* Ref. 2.2.20, Table 2-3) which gives a density of 10.37 g/cm^3. These determined densities are all less than the 10.751 g/cm^3 used in this calculation. Therefore, the use of the 10.751 g/cm^3 models more fuel per assembly than is actually present which, for the purpose of the criticality safety calculations performed herein, is conservative.

Use in the Calculation–Used as part of the UO_2 material specification in Section 6.2.2.

Table 3. UO_2 Density Estimation for a Number of Fuel Assembly Types

Fuel Assembly Design Parameter[(3)]	B&W 15x15	W 17x17 (OFA)	7x7
Active fuel length - h_F (cm)	360.172	365.76	365.76
Fuel pellet outer diameter - D_P (cm)[(4)]	0.936244	0.784352	1.23952
U mass – M_U (kg per fuel assembly)	463.63	423.12	--[(1)]
Number of guide and instrument tubes	17	25	0
Fuel volume in rod (cm^3) $V_F = \pi \times \left(\frac{D_P}{2}\right)^2 \times h_F$	247.958	176.729	441.3602
Number of fuel rods - N_F	15^2-17=208	17^2-25=264	7^2=49
Fuel volume - $V_{Fuel}=V_F \times N_F$ (cm^3)	51575.24	46656.49	21626.64
UO_2 mass (kg) [(2)] – $M_{UO_2} = \frac{M_U}{wf_{^{235}U} + wf_{^{238}U}}$	525.99	480.03	222.98[(1)]
UO_2 density (g/cm^3) - $\rho_{UO_2} = \frac{M_{UO_2} \times 1000}{V_{Fuel}}$	10.199	10.289	10.310

NOTES: [(1)] The UO_2 mass is taken directly from Table 3 of EPRI NP-240, *Core Design and Operating Data for Cycles 1 and 2 of Quad Cities 1* (Ref. 2.2.17). The largest UO_2 value from this table is used here.

[(2)] The values of $wf_{^{235}U}$ and $wf_{^{238}U}$ are the weight fraction of each subscripted isotope in UO_2 with a uranium enrichment of 5 wt. % ^{235}U. These are based on the weight percent values determined in Section 6.2.2).

[(3)] Physical Parameters are per *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.8, Table 71) unless otherwise noted.

[(4)] Fuel pellet outer diameters per Tables 5-1 and 5-2 of *CSNF Assembly Type Sensitivity Evaluation for Pre- and Postclosure Criticality Analysis* (Ref. 2.2.7).

Source: *CSNF Assembly Type Sensitivity Evaluation for Pre- and Postclosure Criticality Analysis* (Ref. 2.2.7); *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.8, Table 71); *Storage, Transport,* and *Core Design and Operating Data for Cycles 1 and 2 of Quad Cities 1* (Ref. 2.2.17)

3.2.2 Stainless Steel Density in Borated Stainless Steel

Assumption–*Preliminary Transportation, Aging, and Disposal Canister System Performance Specification* (Ref. 2.2.14) requires the TAD canister to utilize Borated Stainless Steel Type S30464 as described in ASTM A887-89, *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application* (Ref. 2.2.2) as a neutron absorber. Since the ASTM A887-89 specification does not provide an overall density for the borated stainless steel, the density of the borated stainless steel is determined by assuming that the composition of the borated stainless steel is based on Stainless Steel Type 304.

Rationale–In comparing the chemical composition requirements of the Borated Stainless Steel Type S30464 with that of the Stainless Steel Type S30400, the chemical composition requirements are identical except for the boron content, nickel content, and the leftover iron content. This comparison is shown in Table 4. Given this, it is reasonable to utilize the density of Stainless Steel Type S30400 in determining the density of the Borated Stainless Steel Type S30464. This density is given as 7.94 g/cm^3 per *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens* (Ref. 2.2.3). The additional nickel content in the Borated Stainless Steel Type S30464 specification might result in a slightly higher overall density due to its higher density in comparison to the other elements. Ignoring this effect is conservative since the use of a slightly lower density results in a slight decrease in the boron concentration in the borated stainless steel and therefore its effectiveness as a neutron poison.

Table 4. Material Specifications for Stainless Steel Type S30400 and Borated Stainless Steel Type S30464

UNS Designation	C (wt. %)	Mn (wt. %)	P (wt. %)	S (wt. %)	Si (wt. %)	Cr (wt. %)	Ni (wt. %)	N (wt. %)
S30464(1)	0.08	2.00	0.045	0.030	0.75	18.0-20.0	12.0-15.0	0.10 max
S30400(2)	0.08	2.00	0.045	0.030	0.75	18.0-20.0	8.0-10.5	0.10

NOTE: max = maximum

Source: (1) Table 1 of *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application* (Ref. 2.2.2). (2) Table 1 of *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications* (Ref. 2.2.1).

Use in the Calculation–The Stainless Steel Type S30400 density is utilized in Section 6.2.4 as part of the determination of the density for borated stainless steel.

3.2.3 Depleted Uranium Composition

Assumption–Depleted uranium metal is modeled as naturally enriched uranium metal.

Rationale–Depleted uranium metal may be used as a radiation shield for the CSNF being processed in the WHF. The depleted uranium used for these shields would, by definition, have a ^{235}U content less than that found in naturally occurring uranium. The exact content, however, may vary depending on source. Therefore, for the purpose of this calculation, the ^{235}U content is conservatively set to that found in naturally occurring uranium with the balance being ^{238}U. From a criticality safety perspective, this is conservative because it assumes the presence of more fissile material in these shields (used as a reflector in this assessment) than is present in the actual shields.

Per *Nuclides and Isotopes* (Ref. 2.2.4), the ^{235}U abundance in natural uranium is 0.72 atom percent. The balance is ^{238}U (99.28 atom percent).

Use in the Calculation–The natural uranium isotopic content of ^{235}U is used to define the composition of depleted uranium which is used as a reflector in this calculation.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation is prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Ref. 2.1.1) and LS-PRO-0201, *Preclosure Safety Analysis Procedure* (Ref. 2.1.3). Therefore, the approved record version is designated as QA:QA. The commercial waste package system is classified as Safety Category in the 000-30R-MGR0-00500-000-003, *Q-List* (Ref. 2.2.24, Table A-1, p. A-4). Therefore, this calculation is subject to the applicable requirements of QA-DIR-10 Rev. 01, *Quality Management Directive* (Ref. 2.1.4).

4.2 USE OF SOFTWARE

4.2.1 MCNP

The baselined Monte MCNP code (Ref. 2.2.22) was used to calculate the effective neutron multiplication factor (k_{eff}) for various configurations associated with the WHF. The software specifications are as follows:

- Software Title: MCNP
- Version/Revision Number: Version 4B2LV
- Status/Operating System: Qualified/Microsoft Windows 2000 Service Pack 4
- Software Tracking Number: 10437-4B2LV-00
- Computer Type: Dell OPTIPLEX GX260 and GX270 Workstations.

The input and output files for the MCNP calculations are contained on a digital video disc attachment to this calculation report (Attachment 2) as described in Section 5. The MCNP software has been validated as being appropriate for use in modeling a range of radiation transport problems as documented in CSCI: 30033 V4B2LV. DI: 30033-2003, Rev. 01, *Software Qualification Report for MCNP Version 4B2, A General Monte Carlo N-Particle Transport Code* (Ref. 2.2.11). This range of validated problems includes using MCNP to determine k_{eff} of systems containing fissile material. The use of MCNP Version 4B2 was qualified for use under the Windows 2000 operating system by *Software Baseline Request for MCNP V4B2LV. STN 10437-4B2LV-00* (Ref. 2.2.23). The use of MCNP in determining k_{eff} values is further documented in LA-12625-M, Version 4B, *MCNP-A General Monte Carlo N-Particle Transport Code* (Ref. 2.2.5). The MCNP software was obtained from Software Configuration Management in accordance with the appropriate procedure IT-PRO-0011, *Software Management* (Ref. 2.1.6).

The software qualification report *Software Qualification Report for MCNP Version 4B2, A General Monte Carlo N-Particle Transport Code* (Ref. 2.2.11) was performed prior to the effective date of IT-PRO-0012, *Qualification of Software* (Ref.2.1.5), however, MCNP Version 4B2 was qualified software in the centralized baseline as of the effective date of IT-PRO-0012, *Qualification of Software* (Ref. 2.1.5) and is therefore considered acceptable and part of the established software baseline available for level 1 usage (*Qualification of Software*, Ref. 2.1.5, Paragraph 1.2.3).

4.2.2 EXCEL

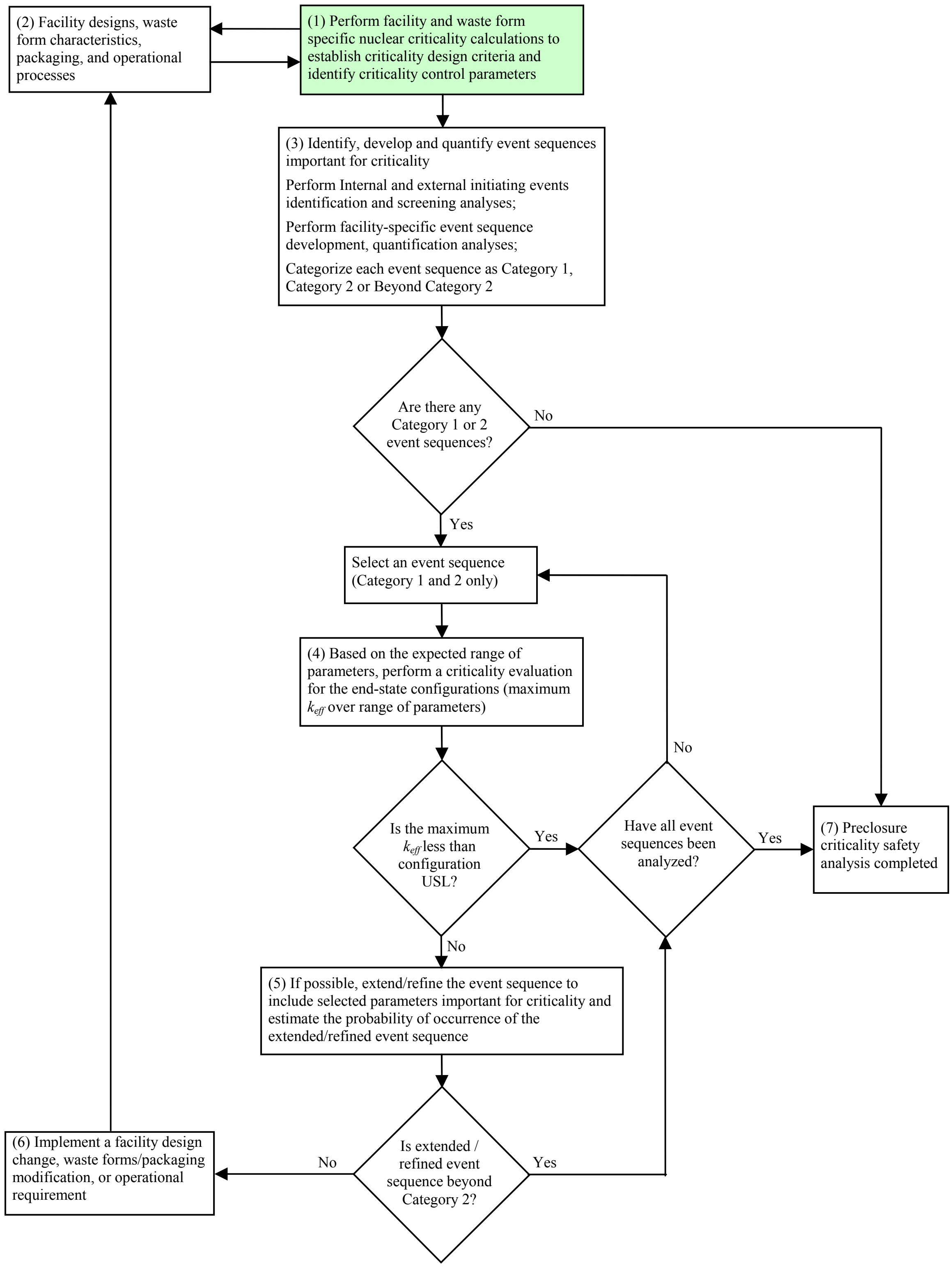
- Software Title: Excel
- Version/Revision number: Microsoft® Excel 2000 9.0.6926 SP-3 (on OPTIPLEX GX260 Workstation)
- Version/Revision number: Microsoft® Excel 2003 11.8120.8122 SP-2 (on OPTIPLEX GX620 Workstation)
- Computer Environment for Microsoft® Excel 2000: Software is installed on a DELL OPTIPLEX GX260 personal computer, running Microsoft Windows 2000, Service Pack 4.
- Computer Environment for Microsoft® Excel 2003: Software is installed on a DELL OPTIPLEX GX620 personal computer, running Microsoft Windows XP Professional, Version 2002, Service Pack 2.

Microsoft Excel for Windows is used in calculations and analyses to process results using standard mathematical expressions, operations, and functions. It is also used to tabulate and chart results. The user-defined formulas, inputs, and results are documented in sufficient detail to allow an independent repetition of computations. Thus, Microsoft Excel is used only as a worksheet and not as a software routine. Microsoft Excel is an exempt software product in accordance with *Software Management* (Ref. 2.1.6).

The spreadsheet files for the Excel calculations are documented in Attachment 1 and are included in Attachment 2 (DVD). The Excel calculations and graphical presentations were verified by hand calculations and visual inspection.

4.3 ANALYSIS PROCESS

This calculation is performed in support of the criticality safety analysis process described in the *Preclosure Criticality Analysis Process Report* (Ref. 2.2.25). The criticality safety analysis process is summarized in Figure 1. This calculation specifically supports the function in the shaded box from Figure 1. This is accomplished by determining the effective neutron multiplication factor (k_{eff}) for normal and off-normal conditions related to the WHF and its operations which are pertinent to criticality safety. These results are then used to establish design criteria and/or parameter limitations/controls needed in order to ensure the configurations examined remain safely subcritical.



Source: *Preclosure Criticality Analysis Process Report* (Ref. 2.2.25).

Figure 1. Preclosure Criticality Safety Process Flow

Based upon the expected design and operation of the WHF as summarized in Section 1.1.2, the following basic set of physical configurations/conditions have been evaluated:

1. Single CSNF assembly in the WHF pool (Sections 6.1.1, 6.1.2, and 6.3.1).
   Parameters varied:
   - Pin pitch
   - Boron concentration
   - Reflector material.

2. CSNF assemblies in a borated water filled TAD canisters (Sections 6.1.3 and 6.3.2).
   Parameters varied:
   - Pin pitch
   - Boron concentration
   - Flux trap
   - Fuel bunching
   - Presence of fixed neutron absorber (borated stainless steel)
   - Axial reflector material.

3. CSNF assemblies in a borated water filled DPC (Sections 6.1.4 and 6.3.3).
   Parameters varied:
   - Pin pitch
   - Boron concentration
   - Flux trap - PWR version only
   - Fuel bunching
   - Presence of fixed neutron absorber (Boral)
   - Density of fixed neutron absorber (Boral) – BWR version only
   - Spacing between bottom of fuel assembly and inside bottom of DPC
   - Void fraction in borated water – B&W 15x15 and 7x7 only.

4. CSNF assemblies in a dry (unfilled) DPC (Sections 6.1.4 and 6.3.3).
   - Only normal undamaged conditions examined.

5. CSNF assemblies in the WHF pool staging racks (Sections 6.1.5, 6.1.6, and 0).
   Parameters varied:
   - Pin pitch
   - Boron concentration
   - Flux trap
   - Presence of fixed neutron absorber (Boral plates)
   - Fuel bunching – 17x17 OFA only
   - Undamaged fuel assembly on top of staging rack – 17x17 OFA only.

6. Simple geometries of water moderated UO_2 (Sections 6.1.7 and 6.3.5).
   Parameters varied:
   - Particle size (homogeneous/heterogeneous)
   - $H/^{235}U$

- Geometry (sphere, slab, hemisphere)
- UO_2 mass – sphere and hemisphere
- Thickness – slab only
- Boron concentration
- Reflector material.

The parameters selected to be varied for the above configurations were selected for one or more of the following reasons:

1. The parameter variation is expected to accommodate and/or bound an off-normal condition.
   - An example would be the dropping of a fuel assembly resulting in increased pin pitch, or the dropping of a DPC resulting in reduction in the flux trap gap.
2. The parameter variation covers an expected variation in normal conditions.
   - An example of this would be variation of the reflection conditions/materials.
3. The parameter variation is meant to establish safely subcritical limits for control parameters or other design parameters.
   - An example of this would be the variation in boron concentration or the variation in flux trap gap in the pool storage racks.
4. The parameter variation is meant to provide further understanding of the system characteristics.
   - All of the variations examined further the understanding of the system characteristics, however, some variations go beyond expected and/or credible limits to provide further understanding of the system reactivity. An example of this is the expanded range of $H/^{235}U$ (1 - 400 versus 75 – 400) examined for the homogeneous simple geometry cases. Another would be close fitting lead and natural U reflectors for the single fuel assemblies which are not expected for single fuel assemblies in the WHF pool.

Not every fuel type/storage type combination was evaluated in exactly the same way. This was done in order to reduce the overall number of models created/results processed and to focus further attention on those fuel type/storage type combinations that would most likely drive criticality safety design and parameter limitations.

In some cases the evaluation process was truncated as a result of recognizing that the reactivity of a particular fuel type/storage type was bounded by the reactivity of another. In these cases, it is discussed in the text of the appropriate results sections of Section 6.3.

In other cases, the range of evaluated parameters may be extended either beyond the expected, credible range and/or the range in which the optimum condition occurs. These results are included purely to provide some additional insight into the reactivity of the system.

5. LIST OF ATTACHMENTS

		Number of Pages
Attachment 1.	List of Files on the Attachment 2 DVD	1
Attachment 2.	Attachment DVD	N/A

6. BODY OF CALCULATION

6.1 MCNP STANDARD GEOMETRIC DESCRIPTIONS

6.1.1 PWR CSNF Assemblies

The WHF is to handle only CSNF with ^{235}U enrichments of not more than 5 wt.%. Two PWR fuel assembly types are evaluated herein. These are the B&W 15x15 and the Westinghouse 17x17 OFA. This section describes the pertinent physical parameters of these two fuel assemblies and the simplifications used in the MCNP models. These fuel assembly models are used to evaluate single fuel assemblies under varying reflector conditions and in subsequent models involving multiple fuel assemblies (described in subsequent sections).

The physical description of the Westinghouse 17x17 OFA comes from *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8), *Physical Descriptions of LWR Fuel Assemblies. Volume 3 of Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation* (Ref. 2.2.13, Appendix 2A), B00000000-01717-5705-00063 Rev. 01, *Summary Report of Commercial Reactor Criticality Data for McGuire Unit 1.* (Ref. 2.2.12), and UCRL-ID-108314, *Waste Form Characteristics Report Revision 1* (Ref. 2.2.21). The physical description of the B&W 15x15 comes from *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8), *Physical Descriptions of LWR Fuel Assemblies. Volume 3 of Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation* (Ref. 2.2.13, Appendix 2A), and *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3* (Ref. 2.2.20). The PWR fuel assembly models described in this section are used in the other models described in the following sections. Variations in these single fuel assembly models are performed to evaluate various potential end states of event sequences or parameter sensitivities and are discussed in the applicable sections of this calculation.

The fuel assembly models are simplified by modeling only the fuel, clad, guide, and instrument tubes. The stack of fuel pellets within a fuel rod is modeled as a simple cylinder of fuel with the same diameter as the fuel pellet. The density is not modified to account for any dished ends to the pellets. This modeling treatment may add a small amount of additional fissile material to the system. This simplifies the model and is conservative. The active fuel length is conservatively modeled as the full assembly length. The small gap between the outside of the fuel and the inside of the cladding is explicitly modeled and filled with water containing no boron. This is the case for all the models examined in this calculation that include fuel assemblies. In those cases where the fuel assemblies are moderated with borated water, the water in the fuel-clad gap is still modeled as water containing no boron.

The non-fuel ends of the fuel assemblies and the various spacer grids are not modeled. This is considered reasonable since these components are constructed of materials that have small interaction cross sections compared to other materials such as the fuel, moderators, and poisons which make these materials essentially invisible to neutrons and therefore insignificant in regards to criticality safety. The single fuel assemblies are surrounded by close fitting reflection material 30 cm thick.

The fuel cladding and instrument tube material for the B&W 15x15 is Zircaloy-4 per Table 2-2 from *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3* (Ref. 2.2.20). The fuel cladding material for the Westinghouse 17x17 OFA is Zircaloy-4 per *Physical Descriptions of LWR Fuel Assemblies. Volume 3 of Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation* (Ref. 2.2.13, Appendix 2A, p. 2A-15). The instrument and guide tube material is listed as Zircaloy-4 per *Waste Form Characteristics Report Revision 1* (Ref. 2.2.21, Table 2, p. 2.1.2.2-2).

The basic parameters used to model these fuel assemblies are given in Table 5. The basic pin map for the Westinghouse 17x17 OFA is taken from *Summary Report of Commercial Reactor Criticality Data for McGuire Unit 1* (Ref. 2.2.12, Figure 2-3). The basic pin map for the B&W 15x15 is taken from Figure 2-2 of *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3* (Ref. 2.2.20). Figures 2 through 5 are cross sections of the MCNP fuel assembly models.

Table 5. Basic Physical Parameters for the PWR Fuel Assemblies

Fuel Assembly Parameter	Westinghouse 17x17 OFA	B&W 15x15
Fuel rod pitch[1] (cm)	1.25984	1.44272
Assembly width[2] (cm)	21.42236	21.68144
Fuel pellet outer diameter[2] (cm)	0.784352	0.936244
Fuel rod outer diameter[1] (cm)	0.9144	1.0922
Fuel clad thickness[1] (cm)	0.05715	0.06731
Assembly length[2] (cm)	405.8031	420.6875
Guide tube outer diameter[1] (cm)	1.20396[3]	1.3462
Guide tube wall thickness[1] (cm)	0.04064	0.04064
Instrument tube outer diameter[1] (cm)	1.20396	1.38193
Instrument tube wall thickness[1] (cm)	0.04064	0.130895

Source: [1] *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.8, Table 71).
[2] *Physical Descriptions of LWR Fuel Assemblies. Volume 3 of Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation* (Ref. 2.2.13, Appendix 2A, p. 2A-11).
[3] Two values for the guide tube outer diameter are provided in *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8.). From Table 2-2 of *Summary Report of Commercial Reactor Criticality Data for McGuire Unit* 1(Ref. 2.2.12) the two values are for different heights in the core. The 1.20396 cm outer diameter runs through ~311 cm of the active fuel region while the smaller 1.08966 cm outer diameter portion runs through ~55 cm of the lower active fuel region. For modeling purposes, these tubes are simply modeled as one diameter throughout the fuel assembly at the value provided in the table.

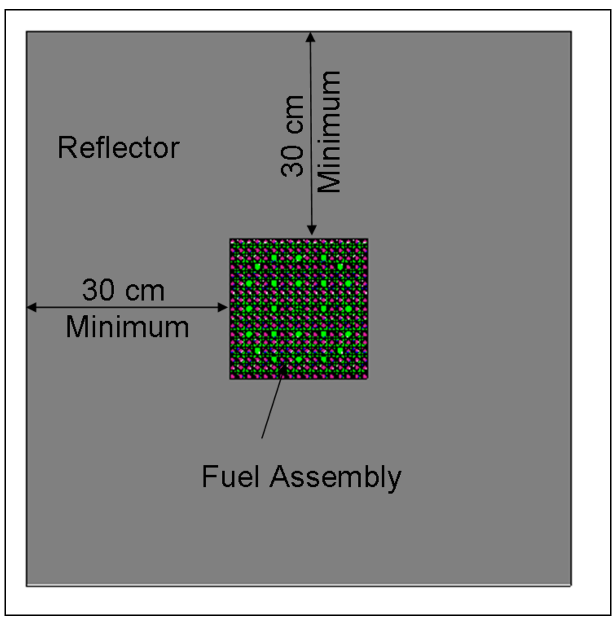


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Figure 2. Horizontal Cross Section of the Single Fuel Assembly MCNP Model for the Westinghouse 17x17 OFA (B&W 15x15 Model Similar)

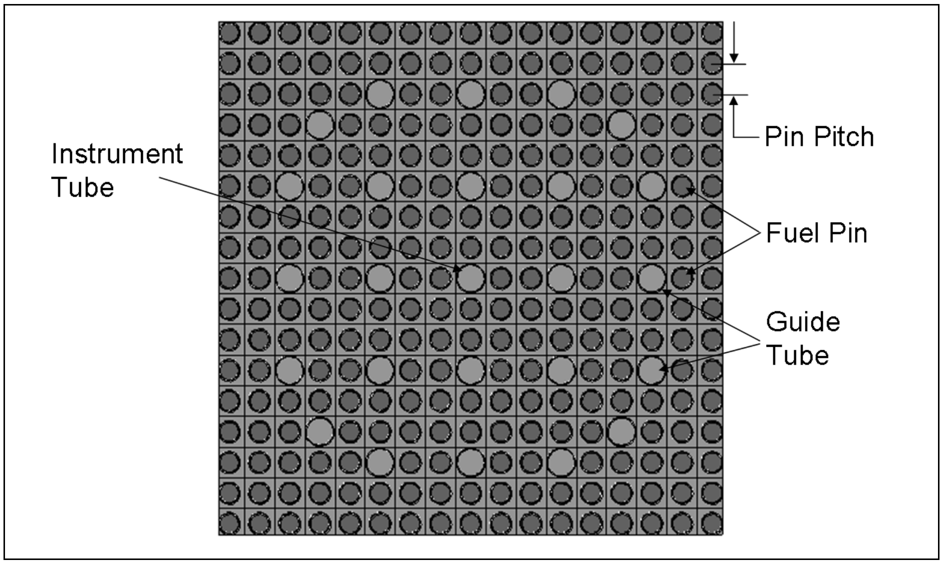

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Figure 3. Horizontal Cross Section of the Westinghouse 17x17 OFA MCNP Model Showing Pin Map

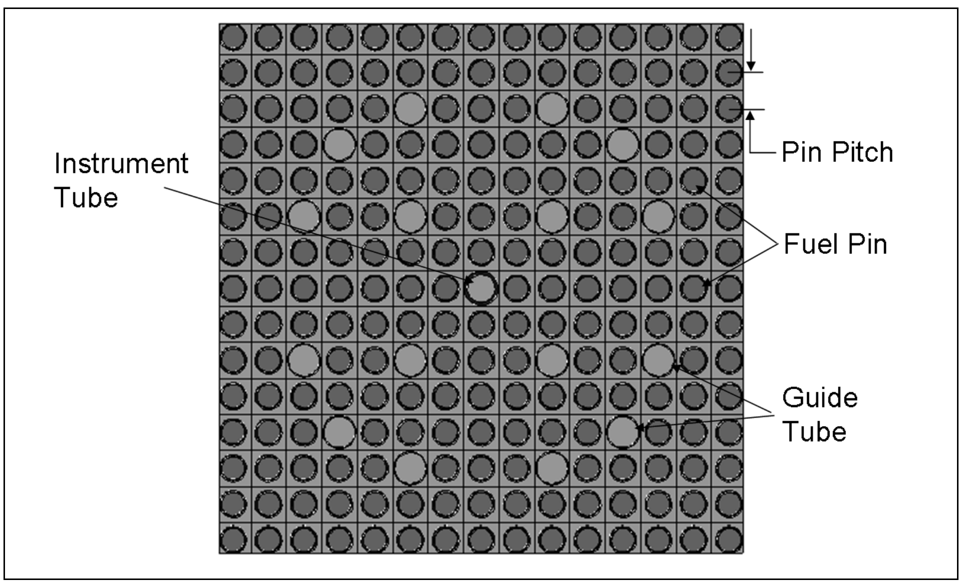

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Figure 4. Horizontal Cross Section of the B&W 15x15 Fuel Assembly MCNP Model Showing Pin Map

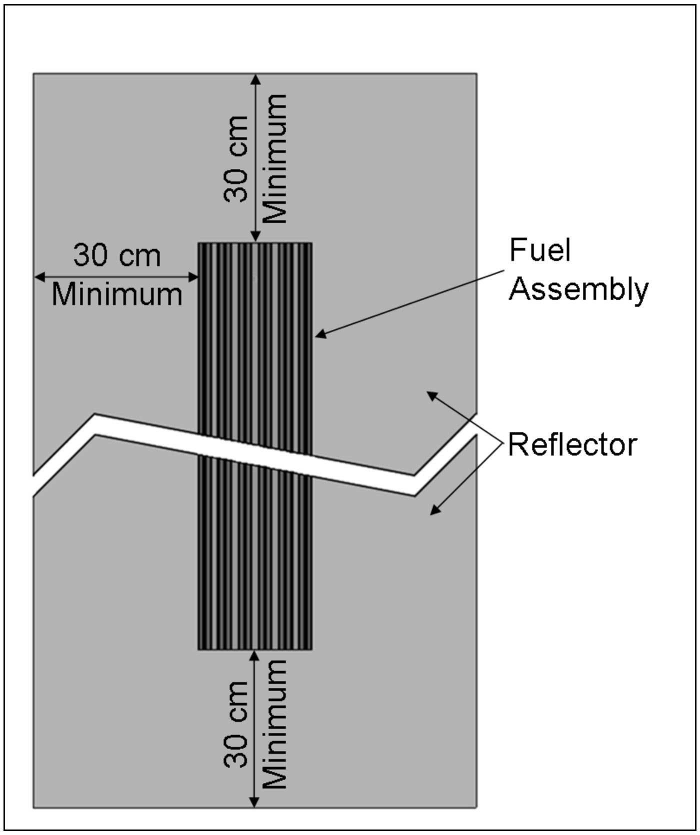

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Figure 5. Vertical Cross Section of the Westinghouse 17x17 OFA Single Fuel Assembly MCNP Model (B&W 15x15 Similar)

6.1.2 BWR CSNF Assemblies

Two BWR CSNF assemblies are examined in this calculation. These are the 7x7 and 9x9 BWR fuel assemblies described in *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8) and *Physical Descriptions of LWR Fuel Assemblies. Volume 3 of Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation* (Ref. 2.2.13, Appendix 2A). These fuel assembly descriptions are loosely based on the General Electric (GE) 7x7 and the Advanced Nuclear Fuels (ANF) 9x9 fuel assemblies. Some additional information for the 9x9 fuel assembly is taken from 32-5029393-00, *Commercial Reactor Reactivity Analysis for Grand Gulf, Unit 1* (Ref. 2.2.15). The BWR fuel assembly models described in this section are used in the other models described in the following sections. Variations in these models are performed to evaluate various potential end states of event sequences or parameter sensitivities and are discussed in the applicable sections of this calculation.

The fuel assembly models are simplified by modeling only the fuel, clad, water rods, and fuel assembly channel. The stack of fuel pellets within a fuel rod is modeled as a simple cylinder of fuel with the same diameter as the fuel pellet. The density is not modified to account for any dished ends to the pellets. This modeling treatment may add a small amount of additional fissile material to the system. This simplifies the model and is conservative. The non-fuel ends of the fuel assemblies and the various spacer grids are not modeled. These are made of materials that have small interaction cross sections compared to other materials such as the fuel, moderators, and poisons which make these materials essentially invisible to neutrons and therefore insignificant in regards to criticality safety. The active fuel length is conservatively modeled as the full fuel assembly length.

The fuel cladding and channel material for these fuel assemblies is Zircaloy-2 per *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8, Tables 73 and 74). The material of the 5 water rods of the ANF 9x9 fuel assembly is given as Zircaloy per *Commercial Reactor Reactivity Analysis for Grand Gulf, Unit 1* (Ref. 2.2.15, Table 9). For the same reasons as given above for the instrument tube material of the Westinghouse 17x17 OFA, the water tube material for the 9x9 is taken to be the same as the cladding material, Zircaloy-2.

The small gap between the outside of the fuel and the inside of the cladding is explicitly modeled and filled with water containing no boron. This is the case for all the models examined in this calculation that include fuel assemblies. In those cases where the fuel assemblies are moderated with borated water, the water in the fuel-clad gap is still modeled as water containing no boron.

The basic parameters used to model these fuel assemblies are given in Table 6. The pin map for the 7x7 is simply a 7x7 array of 49 fuel pins with no water rods. The basic pin map for the 9x9 is based upon the pin map for the ANF 9x9 taken from *Commercial Reactor Reactivity Analysis for Grand Gulf, Unit 1* (Ref. 2.2.15, Figures 24-27). Figures 6 and 7 are MCNP cross sections of the fuel assembly models showing the pin maps for these fuel assemblies. The cross sections of the basic single PWR fuel assembly model shown in Figures 2 and 5 from the previous section are representative of the single BWR fuel assembly MCNP models.

Table 6. Basic Physical Parameters for the BWR Fuel Assemblies

Fuel Assembly Parameter	**7x7**(1)	**9x9**(3)
Fuel rod pitch (cm)	1.87452	1.43002
Channel inner width (cm)	13.246	13.246
Channel thickness (cm)	0.3048	0.3048
Fuel pellet outer diameter (cm)	1.23952	0.95123(4)
Fuel rod outer diameter (cm)	1.43002	1.12522
Fuel clad thickness (cm)	0.08128	0.07747
Fuel assembly length (cm)	447.04(2)	447.18732(2)
Water rod outer diameter (cm)	N/A	1.38684
Water rod outer diameter (cm)	N/A	1.32588

NOTE: N/A = not applicable

Source: (1) *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.8, Table 74).
(2) *Physical Descriptions of LWR Fuel Assemblies. Volume 3 of Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation* (Ref. 2.2.13, Appendix 2A, p. 2A-12) as listed for the longest GE 7x7 or ANF 9x9.
(3) *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.8, Table 73).
(4) *CSNF Assembly Type Sensitivity Evaluation for Pre- and Postclosure Criticality Analysis* (Ref. 2.2.7, Table 5-2).

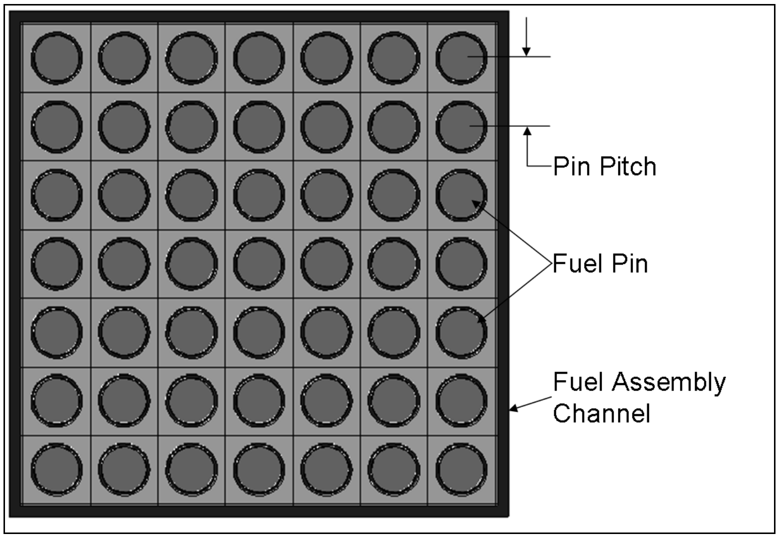

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Figure 6. Horizontal Cross Section of the 7x7 Fuel Assembly MCNP Model Showing Pin Map

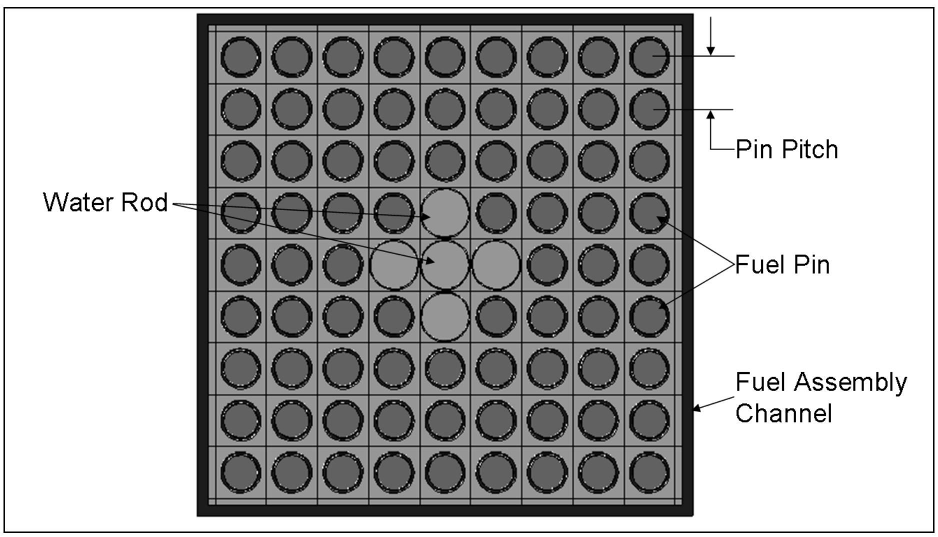

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Figure 7. Horizontal Cross Section of the 9x9 Fuel Assembly MCNP Model Showing Pin Map

6.1.3 TAD Canisters

The TAD canister is a right circular cylindrical structure meant to facilitate the storage and handling of CSNF. The TAD canister is capable of storing up to 21 PWR fuel assemblies or 44 BWR fuel assemblies. These, and other basic physical and performance requirements of the TAD canister, are provided in *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14).

TAD canisters are expected to be loaded in the WHF pool and are therefore evaluated herein. The following further describes the TAD canister, internal basket configurations, and the MCNP models of the TAD canister utilized in this evaluation.

6.1.3.1 Design Criteria

The *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) stipulates basic design criteria for the TAD canisters. The criteria pertinent to criticality safety are summarized below:

1. TAD canister outer diameter of 66.5 in. $\left(\frac{+\,0.0\,\text{in.}}{-\,0.5\,\text{in.}}\right)$

2. TAD canister height of 212.0 in. $\left(\frac{+\,0.0\,\text{in.}}{-\,0.5\,\text{in.}}\right)$

3. The maximum capacities of the PWR and BWR TAD canisters are 21 PWR CSNF assemblies or 44 BWR CSNF assemblies, respectively.

4. TAD canister cavity basket design shall include borated stainless steel neutron absorber panels which conform to the following specification:
   a. Have a minimum thickness of 0.433 in. (1.1 cm);
   b. Multiple plates may be used if corrosion assumptions (250 nm/year) are taken into account for all surfaces such that 6 mm remains after 10,000 years;
   c. Have a boron content within the range 1.1 weight percent (wt.%) to 1.2 wt.%;
   d. Extend along the full length of the active fuel region inclusive of any axial shifting of the fuel assemblies within the TAD canister; and
   e. Envelope all four longitudinal sides of each fuel assembly compartment.

Other pertinent, but less important to criticality safety, criteria include:

5. Required use of type 300-series stainless steel for the construction of the TAD canister and structural internals (i.e., the basket) but excluding neutron absorbing materials associated with the basket structure; and
6. Prohibiting the use of organic or hydrocarbon based materials in the TAD canister construction.

Using the above design criteria, two basic MCNP models were generated for the PWR and BWR TAD canister design configurations. A description of each basic MCNP model is provided in the following sections. In order to create these models, dimensional values not explicitly provided in the performance specification *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) were assumed (See Assumption 3.1.2). These assumed values are called out in the following sections and are compliant with the requirements of *Transportation,* *Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14.). Materials employed for the two base MCNP models are detailed in Section 6.2.4.

6.1.3.2 PWR TAD Canisters

The design parameters used for the PWR TAD Canister MCNP model are summarized in Table 7. For ease of comparison, the basic design criteria (Section 6.1.3.1) are also detailed.

From Table 7 it is seen that design parameters additional to those detailed as design criteria in *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) are specified. These were needed in order to produce a complete design model in MCNP. In addition, values were selected within a range of possible values in order to reduce the complexity of the calculation. These values are considered typical values for similarly designed containers used to transport PWR CSNF and are considered appropriate for this analysis.

In the case of the borated stainless steel panel thickness, panel arrangement, and the basket height, the design criteria *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) allows for many variations. For the purposes of this calculation, an arrangement was selected that is considered typical, while being allowed for under the design criteria. This typical arrangement includes having fuel compartments with borated stainless steel panels on all four sides and a gap (flux trap) between adjacent compartments.

The thickness of the individual panels is based on a minimum required thickness of 0.6 cm after 10,000 years given a corrosion rate of 250 nm/year applied to each surface (*Transportation, Aging and Disposal Canister System Performance Specification,* Ref. 2.2.14, Section 3.1.5). For two panels between adjacent fuel assemblies there would be four surfaces resulting in the need for an additional 1 cm of total thickness to account for corrosion (250×10^{-9} m/year-surface $\times 10{,}000$ years $\times$ 4 surfaces $\times$ 100 cm/m). This gives a total minimum thickness of two panels between adjacent fuel assemblies of 1.6 cm. Therefore, the minimum thickness of an individual panel is modeled here as 0.8 cm.

The basket height is required to be such that the borated stainless steel panels cover the active fuel region and also account for any axial shifting of the fuel assemblies within the TAD canister. For the purpose of this calculation, the basket height is modeled as the interior height of the TAD canister.

Figures 8 through 11 are cross sections of the basic PWR TAD Canister MCNP model. The TAD canisters are conservatively modeled in an infinite hexagonal planar array. This is accomplished in MCNP by utilizing periodic boundaries surrounding the TAD canister in a hexagonal shape as depicted in Figure 8. Close fitting end reflectors 30 cm thick of varying materials are also modeled as depicted in Figure 11. The interstitial spaces between adjacent canisters in the infinite array are modeled as void in order to maximize the neutron interaction between canisters.

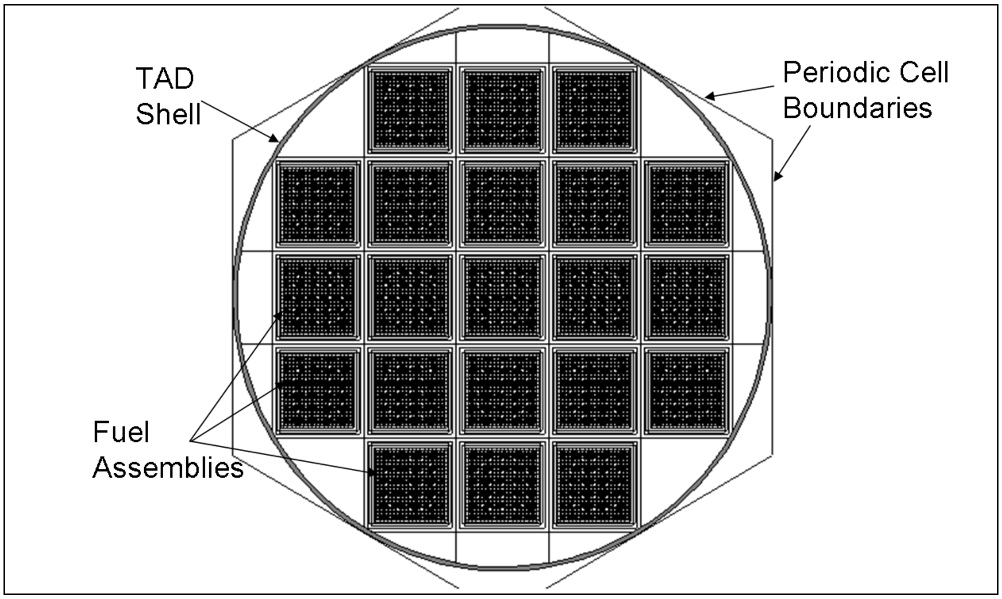
Table 7. Design Parameters Considered for PWR TAD Canister Model

Design Parameter	MCNP Model		Design Criteria
TAD Canister Body			
Outer diameter of TAD canister	66.0 in.	167.64 cm	66.0 in. (min), 66.5 in. (max)
Inner diameter of TAD canister[1]	65.0 in.	165.10 cm	No specific criteria
Outer length/height of TAD canister[4]	211.5 in.	537.21 cm	211.5 in. (min), 212.0 in. (max)
TAD canister spacer[1]	Not modeled		Required for TAD canisters less than 211.5 in. in height.
Inner length/height of TAD canister[1]	210.5 in.	534.67 cm	No specific criteria
TAD canister base thickness[1]	0.5 in.	1.27 cm	No specific criteria
TAD canister lid thickness[1]	0.5 in.	1.27 cm	No specific criteria
TAD Canister Basket Structure			
Number of fuel assembly compartments	21		21
Inner width of fuel assembly compartment[1]	9.0 in.	22.86 cm	No specific criteria
Compartment inner wall thickness[1]	0.1875 in.	0.48 cm	No specific criteria
Compartment borated stainless steel panel arrangement[5]	4 panels around each compartment with a flux trap between		Panels must surround all four longitudinal sides of fuel assemblies
Compartment borated stainless steel panel thickness[5]	0.8 cm ((0.6 cm + (4 × 250 nm/yr × 10,000 yr)/2)		6 mm left after 10,000 yr 250 nm/yr of corrosion for every surface
Basket height	Full interior height of TAD canister [3]		The BSS plates are required to cover the entire active fuel region plus an allowance for any axial shift in the fuel assemblies
Compartment outer wall thickness[1]	0.1875 in.	0.48 cm	No specific criteria
Outer width of fuel assembly compartment[1]	10.38 in.	26.37 cm	No specific criteria
Spacing between compartments (surface-to-surface) [1]	0.0 in. - 0.91 in.	0 - 2.32 cm	No specific criteria
Axial placement of fuel in TAD canister[2]	Fuel modeled to sit directly on the inside bottom of TAD canister		No specific criteria

NOTES: (1) These values are assumed per Assumption 3.1.2.
(2) This placement is modeled purely for convenience.
(3) The basket height is modeled as the full interior height of the TAD canister.
(4) The minimum TAD canister height is allowed to be less than 211.5 in. with a spacer present (186 in.). The TAD canister spacer is not modeled in this calculation, therefore TAD canister heights less than 211.5 in. are not modeled.
(5) The basic arrangement of the basket includes a flux gap and utilizes two neutron absorber panels between fuel assemblies. This arrangement is allowed for in the *Transport, Aging, and Disposal Canister System Performance Specification* (Ref. 2.2.14). The thickness of the panels is a direct result of this arrangement, the minimum thickness requirement, and the corrosion requirements.

BSS = borated stainless steel; max = maximum; min = minimum; yr = year

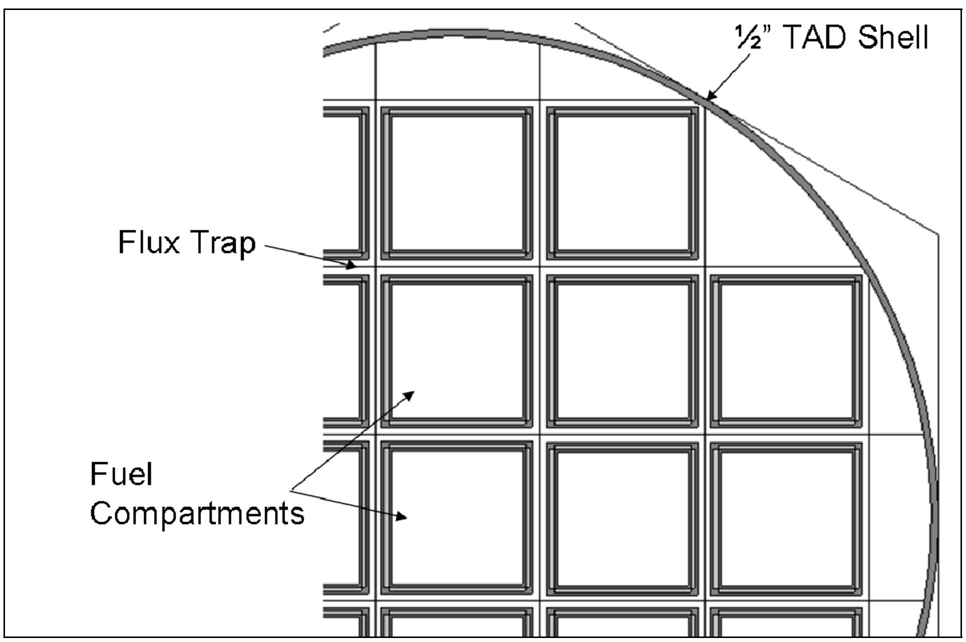
Source: *Transport, Aging, and Disposal Canister System Performance Specification* (Ref. 2.2.14).



NOTE: TAD = transportation, aging, and disposal canister

Source: Original to this document.

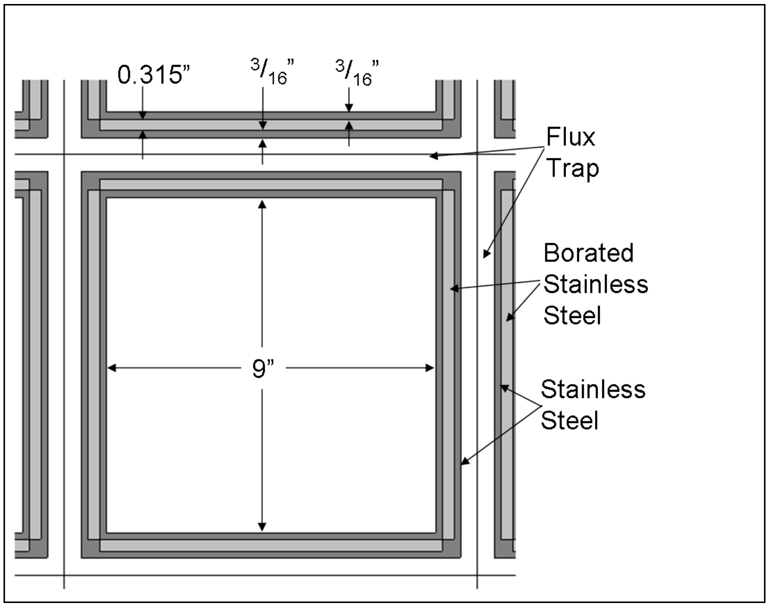
Figure 8. Horizontal Cross Section of Basic PWR TAD Canister MCNP Model



NOTES: " = inch; TAD = transportation, aging, and disposal canister

Source: Original to this document.

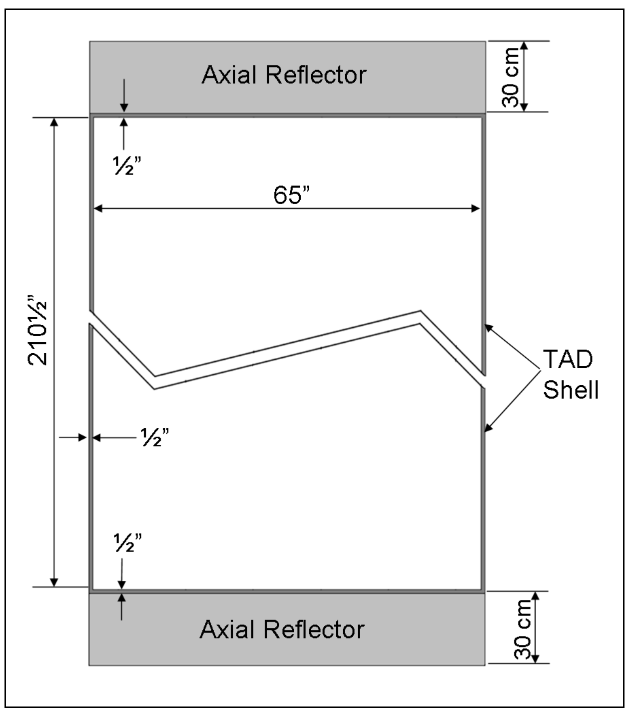
Figure 9. Expanded Horizontal Cross Section of the Basic PWR TAD Canister MCNP Model (Fuel Assemblies Not Shown for Clarity)



NOTE: " = inch

Source: Original to this document.

Figure 10. Horizontal Cross Section of the Basic PWR TAD Canister MCNP Fuel Compartment (Fuel Assembly Not Shown for Clarity)



NOTE: " = inch; TAD = transportation, aging, and disposal canister

Source: Original to this document.

Figure 11. Vertical Cross Section of the TAD Canister Shell

6.1.3.3 BWR TAD Canisters

The design parameters used for the BWR TAD Canister MCNP model are summarized in Table 8. For ease of comparison, the basic design criteria (Section 6.1.3.1) are also detailed.

From Table 8 it is seen that design parameters additional to those detailed as design criteria in *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) are specified. Similar to the PWR TAD Canister analysis, the nominal values considered for these parameters reflect typical design practices for BWR CSNF transportation packages and are considered appropriate for this analysis.

In the case of the borated stainless steel panel thickness, panel arrangement, and the basket height, the design criteria in *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) allows for many variations. For the purposes of this calculation, an arrangement was selected that is considered typical while being allowed for under the design criteria. This typical arrangement includes having fuel compartments with borated stainless steel panels on all four sides and a gap (flux trap) between adjacent compartments.

The thickness of the individual panels is based on a minimum required thickness of 0.6 cm after 10,000 years given a corrosion rate of 250 nm/year applied to each surface (*Transportation, Aging and Disposal Canister System Performance Specification,* Ref. 2.2.14, Section 3.1.5). For two panels between adjacent fuel assemblies there would be four surfaces resulting in the need for an additional 1 cm of total thickness to account for corrosion (250×10^{-9} m/year-surface × 10,000 years × 4 surfaces × 100 cm/m). This gives a total minimum thickness of two panels between adjacent fuel assemblies of 1.6 cm. Therefore, the minimum thickness of an individual panel is modeled here as 0.8 cm.

The basket height is required to be such that the borated stainless steel panels cover the active fuel region and also account for any axial shifting of the fuel assemblies within the TAD canister. For the purpose of this calculation, the basket height is modeled as the modeled height of the active fuel region.

Table 8. Design Parameters Considered for BWR TAD Canister Model

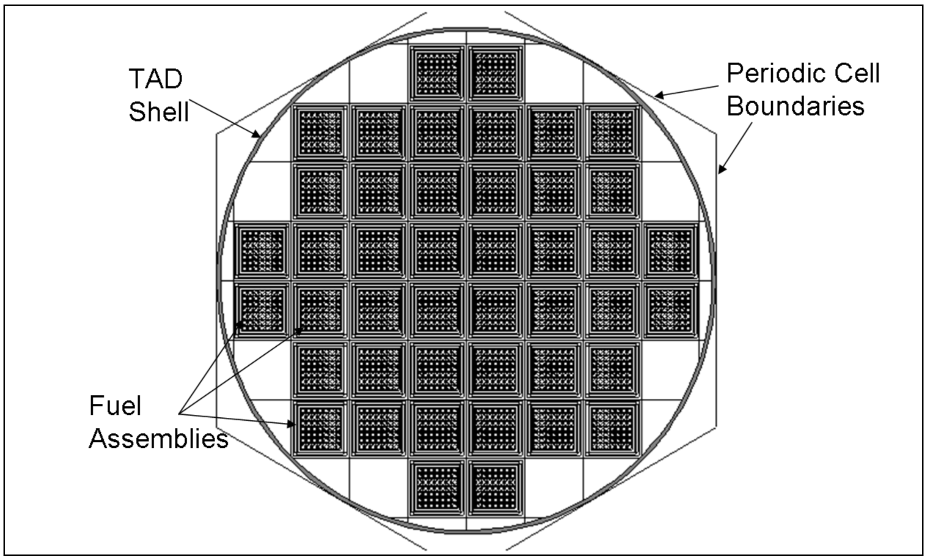
Design Parameter	MCNP Model		Design Criteria
TAD Canister Body			
Outer diameter of TAD canister	66.0 in.	167.64 cm	66.0 in. (min), 66.5 in. (max)
Inner diameter of TAD canister(1)	65.0 in.	165.10 cm	No specific criteria
Outer length/height of TAD canister(4)	211.5 in.	537.21 cm	211.5 in. (min), 212.0 in. (max)
TAD canister spacer(1)	Not modeled		Required for TAD canisters less than 211.5 in. in height.
Inner length/height of TAD canister(1)	210.5 in.	534.67 cm	No specific criteria
TAD canister base thickness(1)	0.5 in.	1.27 cm	No specific criteria
TAD canister lid thickness(1)	0.5 in.	1.27 cm	No specific criteria
TAD Canister Basket Structure			
Number of fuel assembly compartments	44		44
Inner width of fuel assembly compartment(1)	6.0 in.	15.24 cm	No specific criteria
Compartment inner wall thickness(1)	0.125 in.	0.32 cm	No specific criteria
Compartment borated stainless steel panel arrangement(5)	4 panels around each compartment with a flux trap between		Panels must surround all four longitudinal sides of fuel assemblies
Compartment borated stainless steel panel thickness(5)	0.8 cm ((0.6 cm + (4 × 250 nm/yr × 10,000 yr)/2)		6 mm left after 10,000 yr 250 nm/yr of corrosion for every surface
Basket height	Same as fuel assembly (3)		The BSS plates are required to cover the entire active fuel region plus an allowance for any axial shift in the fuel assemblies
Compartment outer wall thickness(1)	0.125 in.	0.32 cm	No specific criteria
Outer width of fuel assembly compartment(1)	7.13 in.	18.11 cm	No specific criteria
Spacing between compartments (surface-to-surface) (1)	0.0 in. - 0.58 in.	0 – 1.48 cm	No specific criteria
Axial placement of fuel/basket in TAD canister(2)	Fuel/basket modeled to sit directly on the inside bottom of TAD canister		No specific criteria

NOTES: (1) These values are assumed per Assumption 3.1.2.
(2) This placement is modeled purely for convenience.
(3) The active fuel region is modeled as the same height as the fuel assembly. The fuel basket is modeled as the same height as the modeled active fuel region of the fuel.
(4) The minimum TAD canister height is allowed to be less than 211.5 in. with a spacer present (186 in.). The TAD canister spacer is not modeled in this calculation, therefore TAD canister heights less than 211.5 in. are not modeled.
(5) The basic arrangement of the basket includes a flux gap and utilizes two neutron absorber panels between fuel assemblies. This arrangement is allowed for in the *Transport, Aging, and Disposal Canister System Performance Specification* (Ref. 2.2.14). The thickness of the panels is a direct result of this arrangement, the minimum thickness requirement, and the corrosion requirements.

yr = year; BSS = borated stainless steel; max = maximum; min = minimum

Source: *Transport, Aging, and Disposal Canister System Performance Specification* (Ref. 2.2.14).

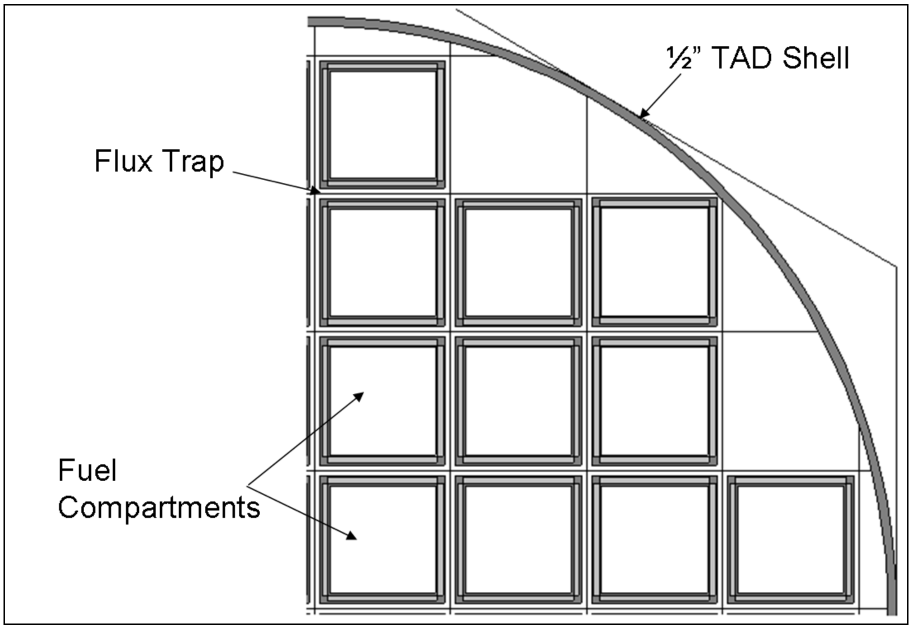
Figures 12 through 14 are cross sections of the basic BWR TAD Canister MCNP model. The axial cross section of the BWR TAD Canister MCNP model is the same as the PWR TAD canister cross section shown in Figure 11. The TAD canisters are conservatively modeled in an infinite hexagonal planar array. This is accomplished in MCNP by utilizing periodic boundaries surrounding the TAD canister in a hexagonal shape as depicted in Figure 12. The interstitial spaces between adjacent canisters in the infinite array are modeled as void in order to maximize the neutron interaction between canisters.



NOTE: TAD = transportation, aging, and disposal canister

Source: Original to this document.

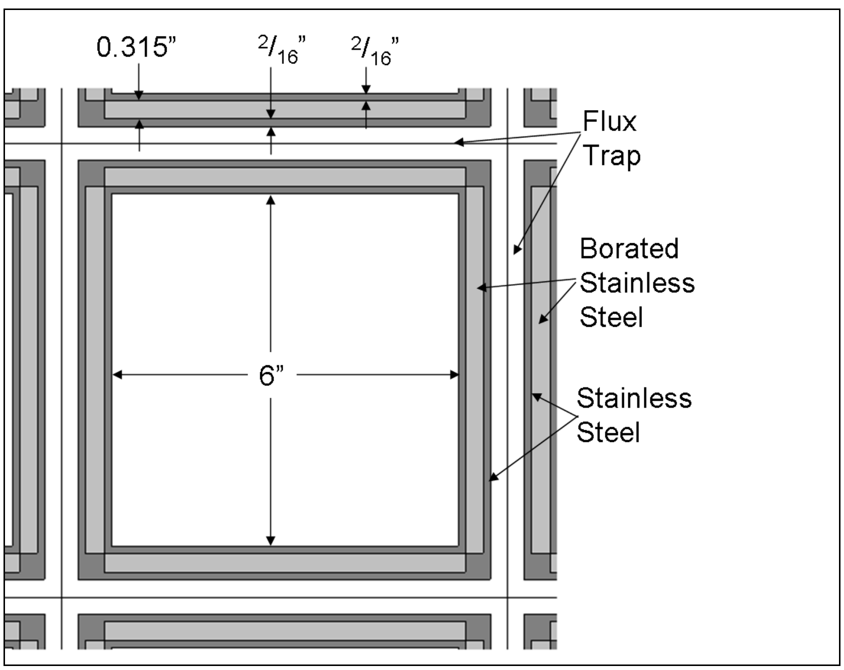
Figure 12. Horizontal Cross Section of Basic BWR TAD Canister MCNP Model



NOTES: " = inch; TAD = transportation, aging, disposal canister

Source: Original to this document.

Figure 13. Expanded Horizontal Cross Section of the BWR TAD Canister MCNP Model (Fuel Assemblies Not Shown for Clarity)



NOTE: " = inch

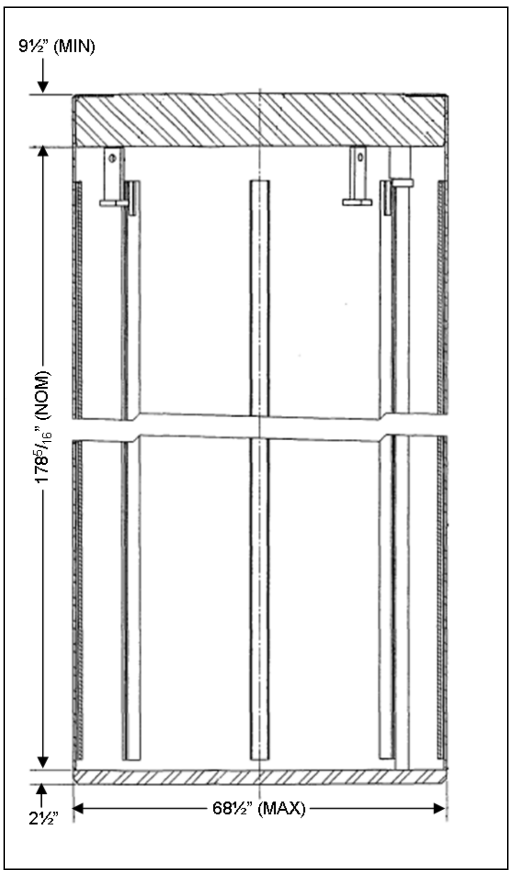
Source: Original to this document.

Figure 14. Horizontal Cross Section of the BWR TAD Canister Fuel Compartment (Fuel Assembly Not Shown for Clarity)

6.1.4 Dual Purpose Canisters

The DPC is the inner canister of a CSNF transport cask system. DPCs provide a structural support and confinement system into which various arrangements of CSNF assemblies are placed. These arrangements are supported and controlled by a fuel basket made up of fuel compartments, fixed neutron poisons (e.g., Boral plates), and flux traps. For the purpose of this calculation, the DPC and fuel baskets evaluated are based on the HOLTEC HI-STAR 100 Multi-Purpose Canister (MPC) and the associated MPC-24 (PWR) and MPC-68 (BWR) fuel baskets as described in *Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261* (Ref. 2.2.16).

The DPC is a steel cylinder with a wall thickness of ½ inch (*Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261,* Ref. 2.2.16, Section 1.4, Drawing 3923, Sheet 2). The outside diameter is given as 68½ inches maximum. The nominal value for the outside diameter of the DPC used in the MCNP models is 68 inches. The basic dimensions are shown in Figure 15, as taken from *Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261* (Ref. 2.2.16, Section 1.4, Drawing 3923, Sheet 3).

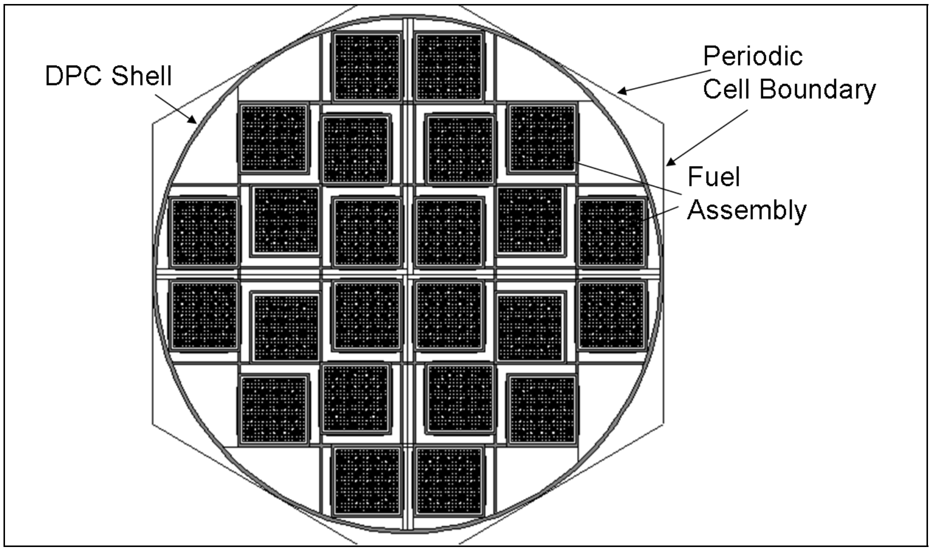


NOTES: " = inch; MAX = maximum; MIN = minimum; NOM = nominal

Source: *Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261* (Ref. 2.2.16, Section 1.4, Drawing 3923, Sheet 3).

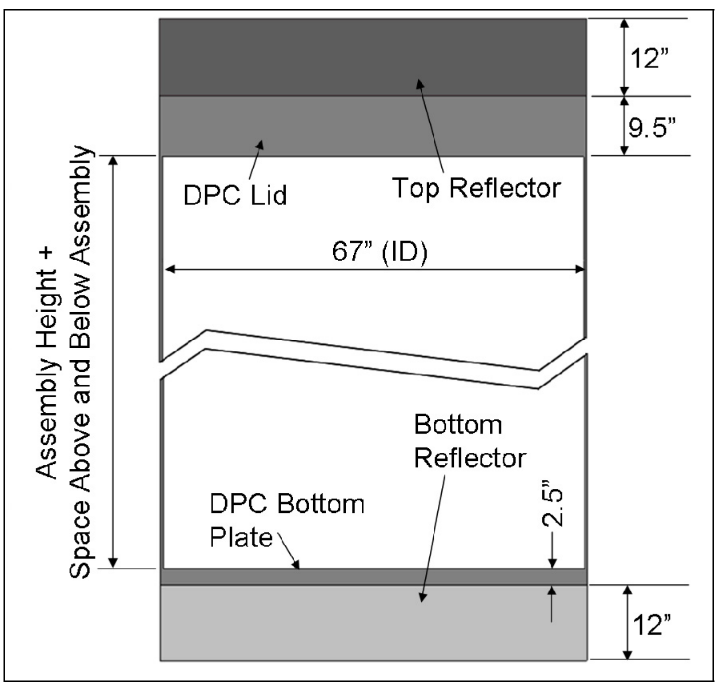
Figure 15. Basic Dimensions of the DPC

The DPC is modeled in a hexagonal array that is infinite in the X-Y plane. This is accomplished by the use of close fitting periodic boundaries surrounding the DPC. The interstitial spaces between adjacent canisters are modeled as void in order to maximize the neutron interaction between canisters. The ends of the DPC have close fitting reflectors 12 inches thick. Figures 16 and 17 are cross sections that show the basic DPC MCNP model.



Source: Original to this document.

Figure 16. Horizontal Cross Section of PWR DPC MCNP Model



NOTE: “ = inch

Source: Original to this document.

Figure 17. Vertical Cross Section of the DPC Shell and End Reflectors

The nominal interior height of the DPC is 178 $^{5}/_{16}$ inches (*Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261,* Ref. 2.2.16, Section 1.4, Drawing 3923, Sheet 3). This height is maintained constant with the amount of space above and below the fuel assemblies varied by changing the axial placement (height within the DPC) of the fuel assemblies.

6.1.4.1 PWR DPC Fuel Basket

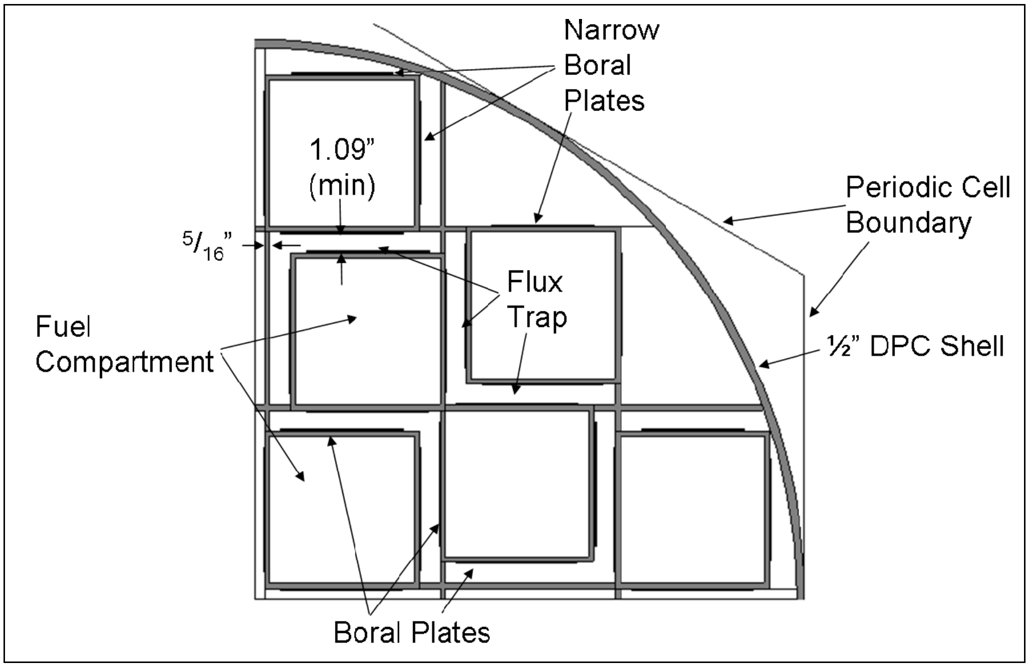
The PWR DPC fuel basket, for the purpose of this calculation, is based on the MPC-24 fuel basket described in *Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261* (Ref. 2.2.16, Section 1.4, Drawing 3926). This fuel basket consists of 24 square fuel compartments with steel clad Boral plates located on the outside of the four fuel compartment walls. The walls of the fuel compartments are $^{5}/_{16}$-inch thick.

The Boral plates are nominally 0.075 inches thick and 156 inches in length. The Boral plates are 7½ inches wide except for those on the periphery of the basket which are 6¼ inches wide. The steel clad is nominally 0.024 inches thick. The Boral plates start approximately 3 inches from the bottom of the basket structure (*Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261*, Ref. 2.2.16, Section 1.4, Drawing 3926). Spacers are used to ensure that the active fuel region aligns with the Boral plates (Ref. 2.2.16, p. 1.2-22).

The Boral plates are not modeled at the design height of 156 inches. As discussed in Section 6.1.1, the active fuel heights of the fuel assemblies are conservatively modeled as the overall heights of the fuel assemblies. This results in the active fuel regions being significantly longer than the as designed Boral plates. The Boral plates and spacers are, however, designed to ensure the entire active fuel region of the fuel is covered. Therefore, for the purpose of the MCNP model, the Boral plates are modeled as the same length as the modeled active fuel region (i.e., the fuel assembly length).

The flux trap is the minimum space between Boral plates. The flux trap is initially modeled as its minimum value of 1.09 inches (*Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261*, Ref. 2.2.16, Section 1.4, Drawing 3926) and then reduced to approximately zero (0.001 cm) to determine its effect on the reactivity of the system.

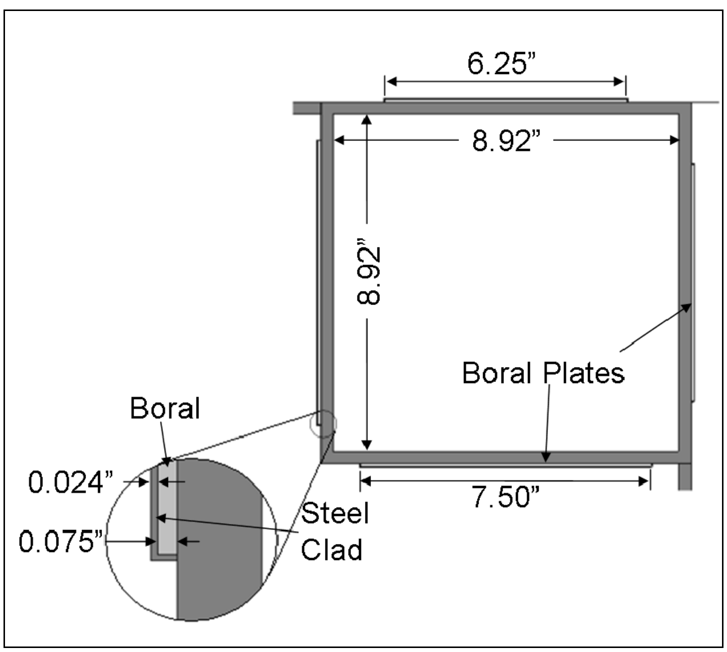
Figure 16 shows the PWR DPC basket in the DPC MCNP model. Figures 18 and 19 are cross sections showing additional details of the PWR DPC MCNP model. Figure 20 shows the basic PWR DPC model with the fuel basket flux traps fully collapsed.



NOTE: “ = inch

Source: Original to this document.

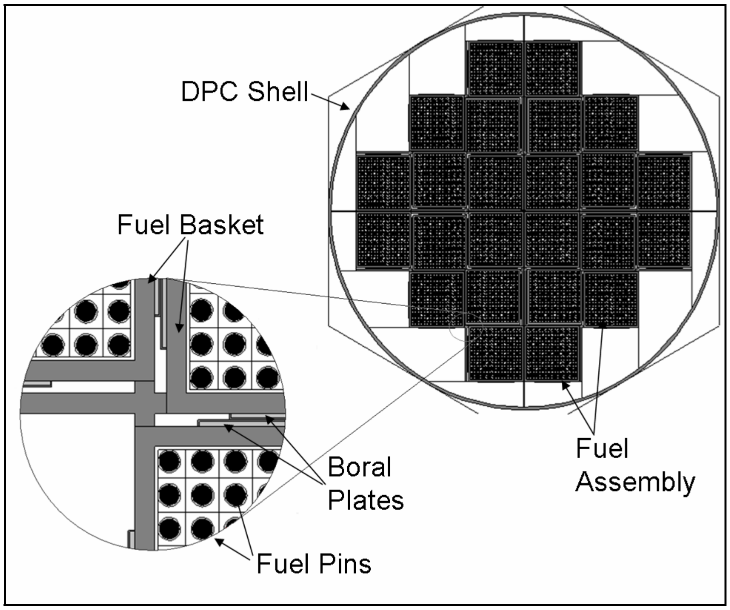
Figure 18. Expanded Horizontal Cross Section of the PWR DPC MCNP Model (Fuel Assemblies Not Shown for Clarity)



NOTE: “ = inch

Source: Original to this document.

Figure 19. Horizontal Cross Section of the PWR DPC MCNP Model Showing a Peripheral Fuel Compartment (Fuel Assembly Not Shown for Clarity)

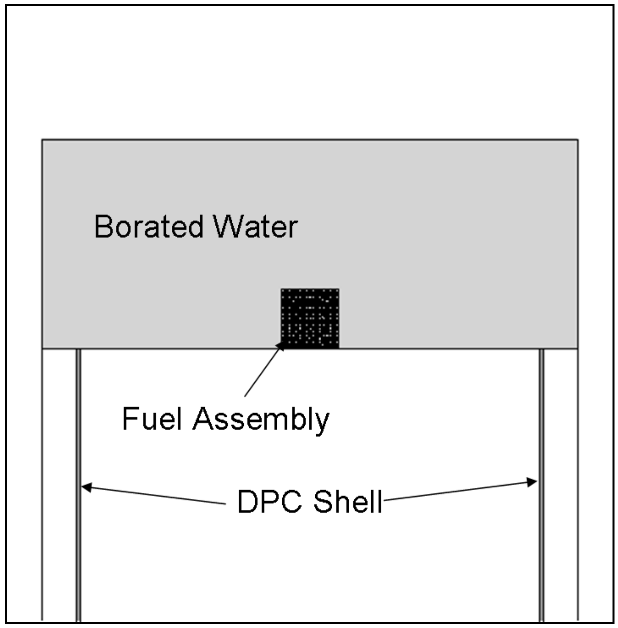


Source: Original to this document.

Figure 20. Horizontal Cross Section of PWR DPC MCNP Model with the Flux Traps Fully Collapsed

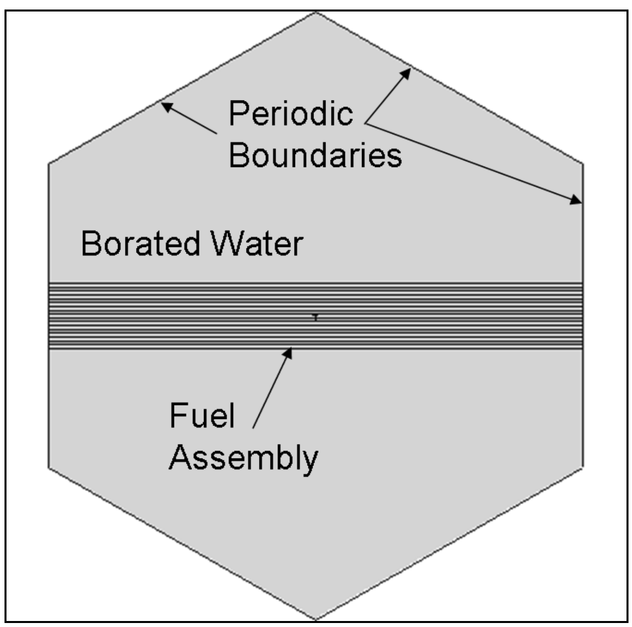
Two additional models were created to deal with specific off-normal conditions related to the PWR DPCs in the WHF. The first model includes an undamaged fuel assembly lying horizontally on top of an undamaged DPC. This model assumes the DPC lid is removed. The model includes only a section of a fuel assembly with a length approximately equal to the diameter of the DPC (67 inches). However, because the model utilizes periodic boundary conditions on the enclosing hexagonal surfaces, the fuel assembly on top of the DPC is effectively modeled as an infinitely long fuel assembly. Figures 21 and 22 are cross sections of this MCNP model. This model evaluates only a single set of conditions. It does not evaluate other off-normal conditions in combination with the fuel assembly on top of the DPC (e.g., it does not include flux trap collapse).

The second model involves positioning the fuel assemblies in off-center positions within the fuel compartments. This allows for fuel in adjacent compartments to be closer to one another and therefore may result in increases in the system reactivity. Figure 23 shows horizontal cross sections of the two fuel bunching patterns examined.



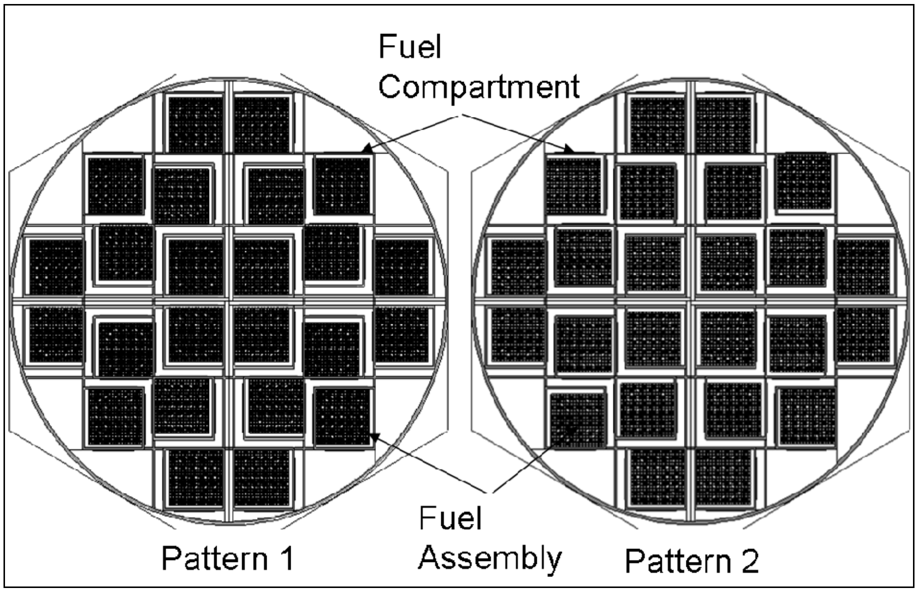
Source: Original to this document.

Figure 21. Vertical Cross Section of the Upper Portion of PWR DPC with a Fuel Assembly on Top (Internal Structure of DPC Not Shown for Clarity)



Source: Original to this document.

Figure 22. Horizontal Cross Section of PWR DPC MCNP Model with Fuel Assembly on Top



Source: Original to this document.

Figure 23. Horizontal Cross Sections of the PWR DPC MCNP Models Showing the Fuel Bunching Patterns Examined

6.1.4.2 BWR DPC Fuel Basket

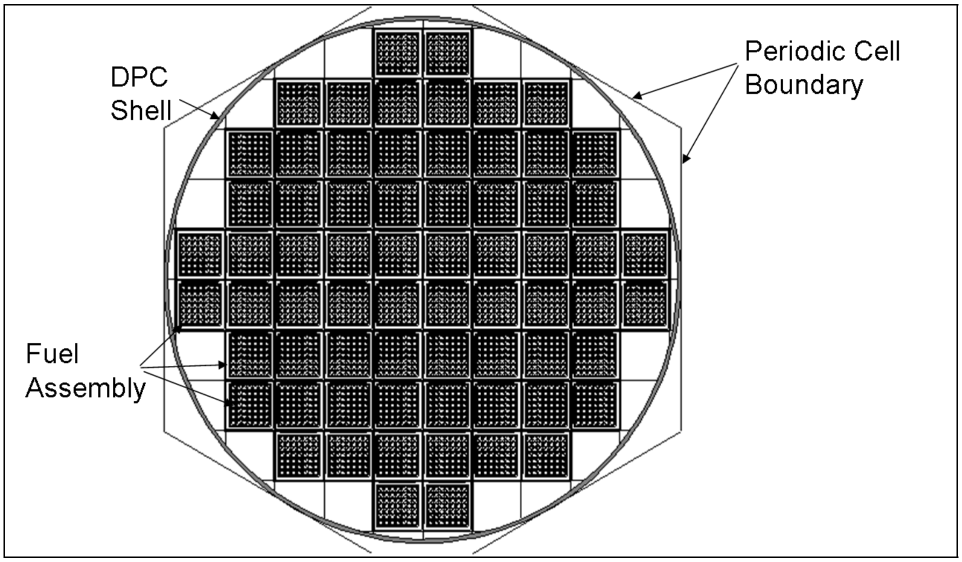
The BWR DPC fuel basket, for the purpose of this calculation, is based on the MPC-68 fuel basket (*Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261*, Ref. 2.2.16, Section 1.4, Drawing 3928).

The MPC-68 fuel basket consists of a square pitched lattice of 68 fuel compartments with two steel clad Boral plates attached to the interior walls of each fuel compartment except for the fuel compartments on the periphery of the basket which may have fewer plates depending on location. The fuel compartment lattice has a center-to-center pitch of 6.49 inches with compartment walls ¼-inch thick.

The Boral plates are nominally 0.101 inches thick and 156 inches in length. The Boral plates are 4¾ inches wide. The steel clad is nominally 0.075 inches thick. The Boral plates start approximately 5 inches from the bottom of the basket structure (*Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261*, Ref. 2.2.16, Section 1.4, Drawing 3926, Sheet 2). Spacers are used to ensure that the active fuel region aligns with the Boral plates (Ref. 2.2.16, p. 1.2-22).

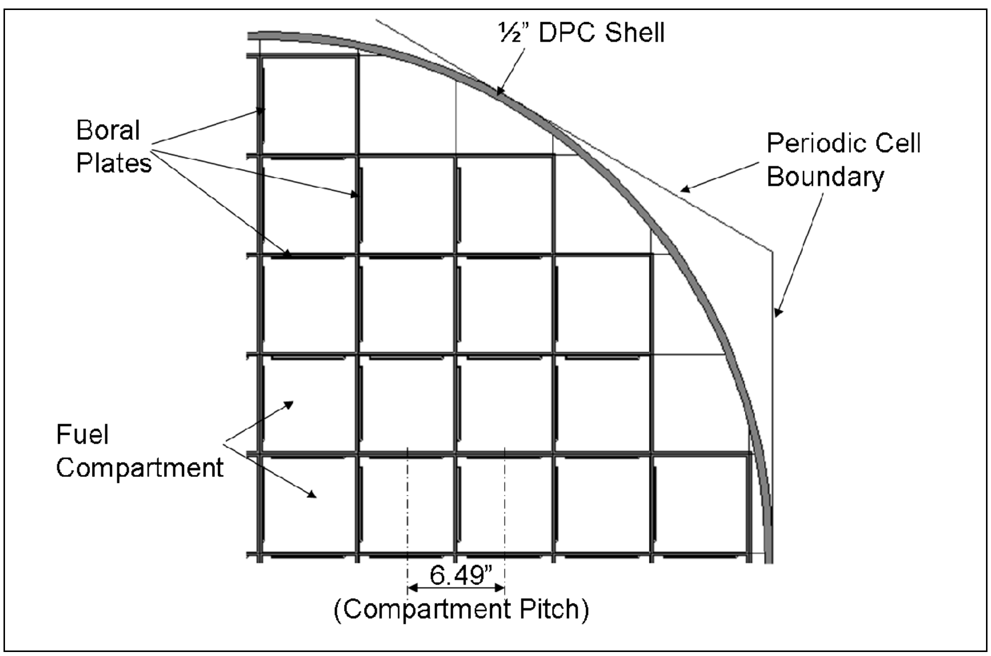
As with the PWR DPC fuel basket, the Boral plates of the BWR DPC fuel basket are not modeled at the design height of 156 inches. As discussed in Section 6.1.1, the active fuel heights of the fuel assemblies are conservatively modeled as the overall heights of the fuel assemblies. This results in the active fuel regions being significantly longer than the as designed Boral plates. The Boral plates and spacers are, however, designed to ensure the entire active fuel region of the fuel is covered. Therefore, for the purpose of the MCNP model, the Boral plates are modeled as the same length as the modeled active fuel region (i.e., the fuel assembly length).

Figures 24 through 26 are cross sections of the MCNP models showing additional details of the BWR DPC MCNP model.



Source: Original to this document.

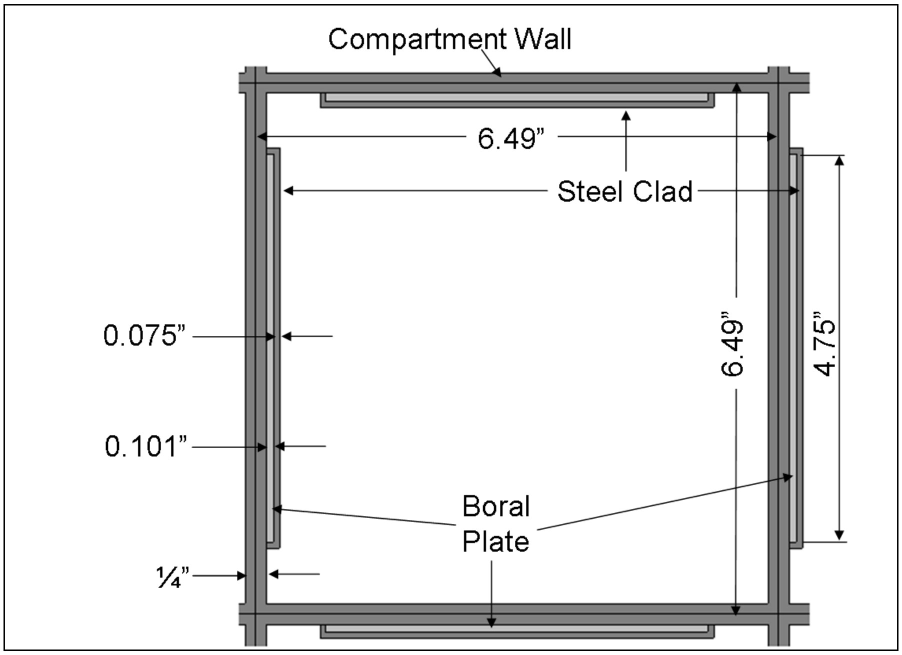
Figure 24. Horizontal Cross Section of BWR DPC Model



NOTE: " = inch

Source: Original to this document.

Figure 25. Expanded Horizontal Cross Section of the BWR DPC MCNP Model (Fuel Assemblies Not Shown for Clarity)

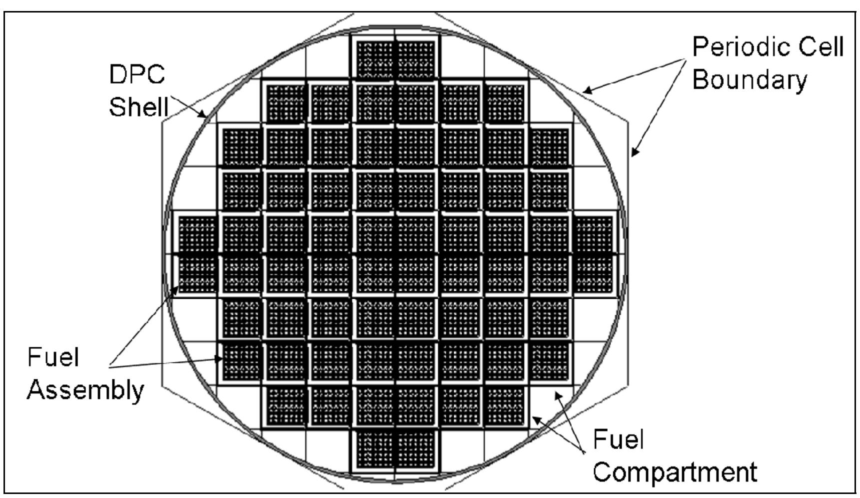


NOTE: “ = inch

Source: Original to this document.

Figure 26. Horizontal Cross Section of the BWR DPC MCNP Model Fuel Compartment (Fuel Assembly Not Shown for Clarity)

A single model was created to address the off-center placement of fuel assemblies with the fuel compartments. For this model, each fuel assembly was placed in the corner of the fuel compartment closest to the center of the DPC. Figure 27 shows a cross section of this MCNP model.



Source: Original to this document.

Figure 27. Horizontal Cross Section of the BWR DPC MCNP Model Showing the Fuel Bunching Pattern Examined

6.1.5 PWR CSNF Staging Racks

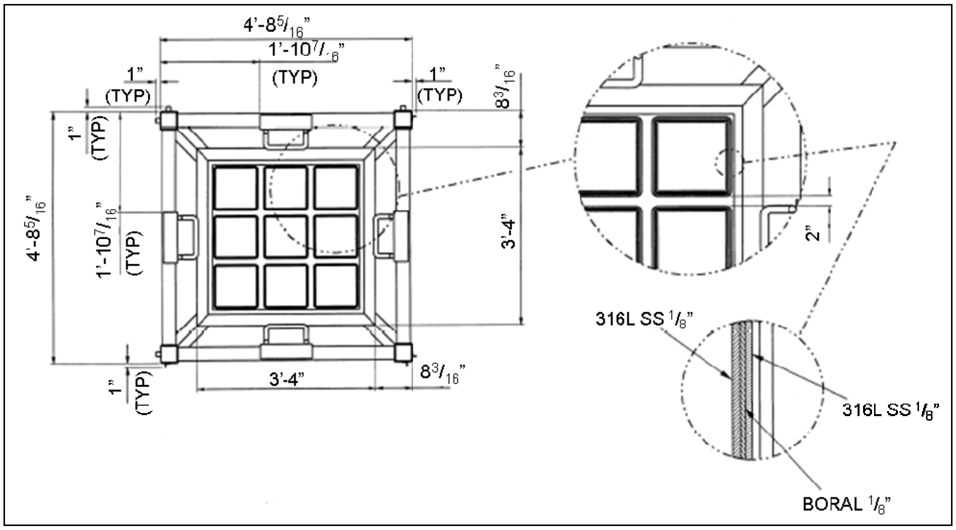
Nine PWR CSNF staging racks are located in the WHF pool (050-M90-HTF0-00102-000 Rev. 00A, *Wet Handling Facility SNF Staging Racks in Pool Mechanical Equipment Envelope* Ref. 2.2.9). The staging of the CSNF in the pool is needed in order to allow for the blending of fuel assemblies in the TAD canister to ensure that thermal and/or other requirements of the TAD canister are met. The basic design of the PWR CSNF staging racks is provided in 050-M90-HTF0-00101-000 Rev. 00A, *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope* (Ref. 2.2.10) and is shown in Figures 28 and 29.

The MCNP models used in this calculation simplified this structure such that only the Boral/steel fuel assembly compartments are modeled. The structural steel of the racks is ignored. The spacing between compartments is 2 inches but is varied in some of the models to either determine the minimum required separation or to evaluate other parameters or off-normal conditions. The steel of the compartments is modeled as continuous but the Boral is modeled as four separate plates, one on each side of the compartment. The Boral plates are $^{1}/_{8}$-inch thick with the steel cladding on both sides also $^{1}/_{8}$-inch thick. The interior compartment width is set at 9 inches. The overall width of the rack is maintained at 56 inches. The four vertical planes defining the outer rack width are modeled as reflective/mirror boundaries that result in the models effectively being an infinite square array of racks in the x-y plane. The racks are modeled with concrete reflection and water containing various levels of boron as both a moderator and top reflector.

The Boral plates are designed such that, at a minimum, the entire active fuel regions of the different fuel assemblies are covered. For the purpose of this calculation, the active fuel regions of the fuel assemblies are modeled as the total fuel assembly height. Therefore, the Boral plates and the fuel compartment steel are modeled as the height of the fuel assembly being modeled. Figures 30 through 32 are cross sections of the PWR CSNF staging rack MCNP model.

Two additional models were created to deal with specific off-normal conditions related to the PWR CSNF staging racks. The first model includes a fuel assembly lying horizontally on top of the staging rack. The model includes only a section of a fuel assembly with a length equal to the width of the staging rack (56 inches). However, because the model utilizes mirror boundary conditions on the sides of the rack, the fuel assembly on top of the rack is effectively modeled as an infinitely long fuel assembly. Figures 33 and 34 are cross sections of this MCNP model.

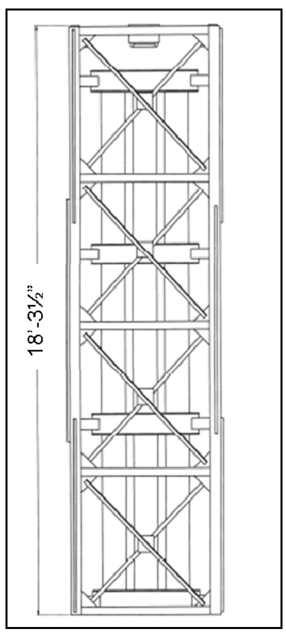
The second model involves positioning the fuel assemblies in off-center positions within the fuel compartment. This allows for fuel in adjacent compartments to be closer to one another and therefore may result in increases in the system reactivity. Figure 35 shows horizontal cross sections of the three fuel bunching patterns examined.



NOTE: ' = feet; " = inch; SS = stainless steel; TYP = typical

Source: *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope* (Ref. 2.2.10)

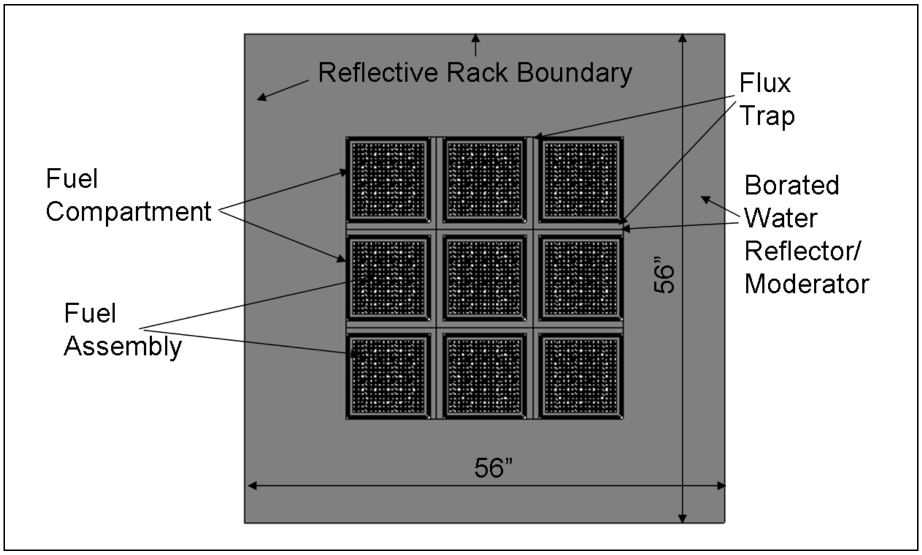
Figure 28. Plan View of PWR CSNF Staging Rack for WHF Pool



NOTE: ' = feet, " = inch

Source: *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope* (Ref. 2.2.10)

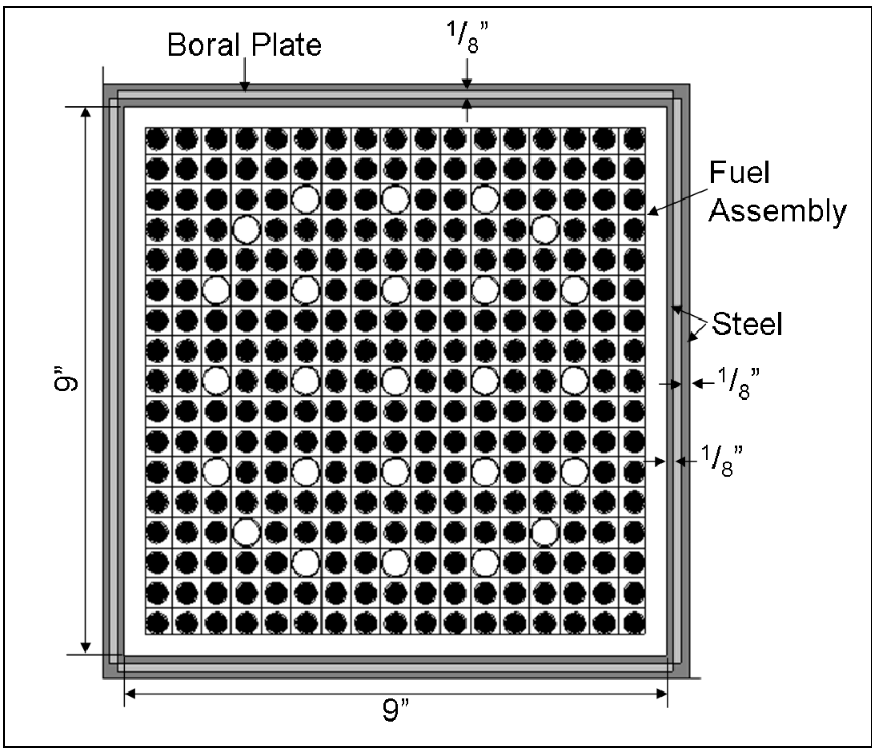
Figure 29. Elevation View of PWR CSNF Staging Rack for WHF Pool



NOTE: " = inch

Source: Original to this document.

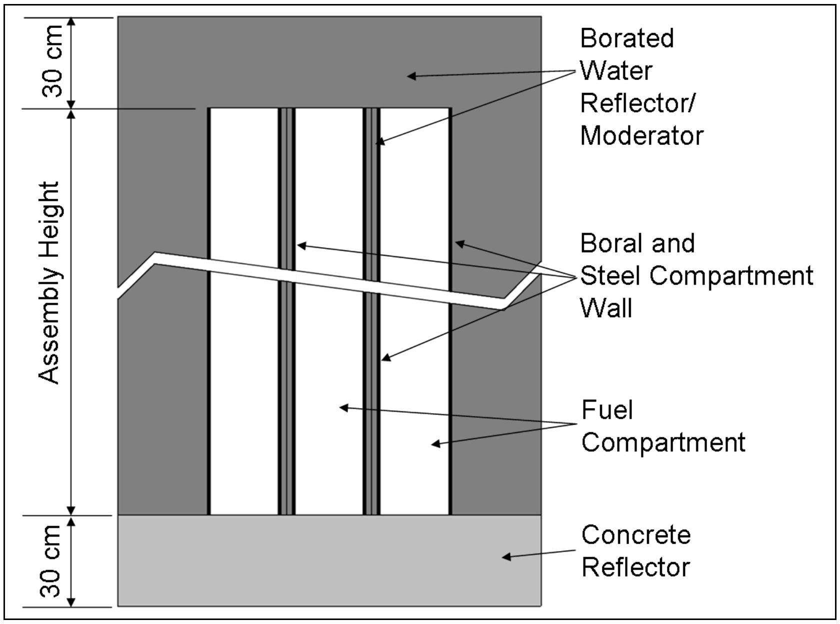
Figure 30. Horizontal Cross Section of the Basic PWR CSNF Storage Rack MCNP Model



NOTE: " = inch

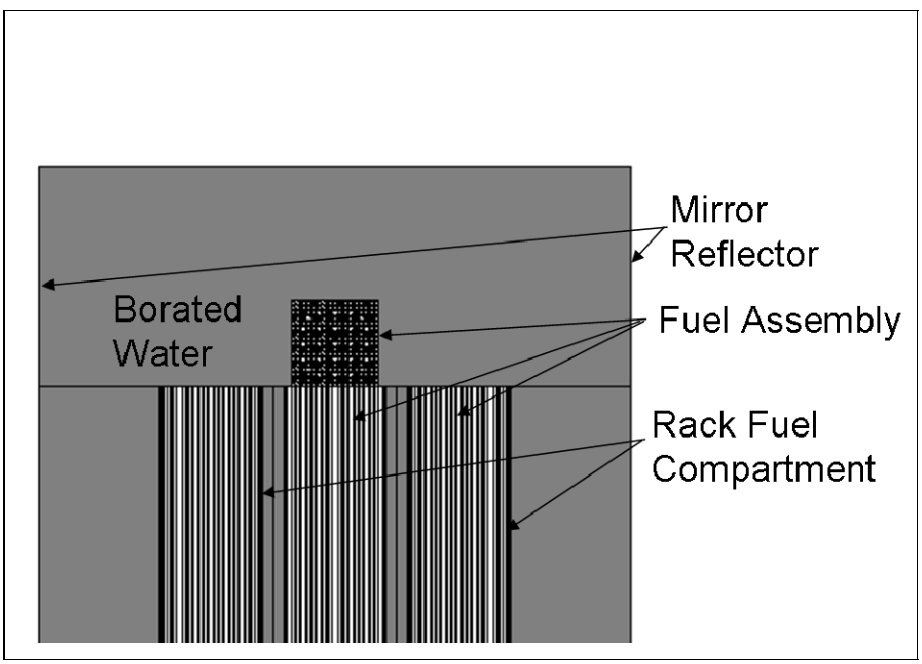
Source: Original to this document.

Figure 31. Horizontal Cross Section of the Basic PWR CSNF Storage Rack MCNP Model Showing a Single Storage Compartment



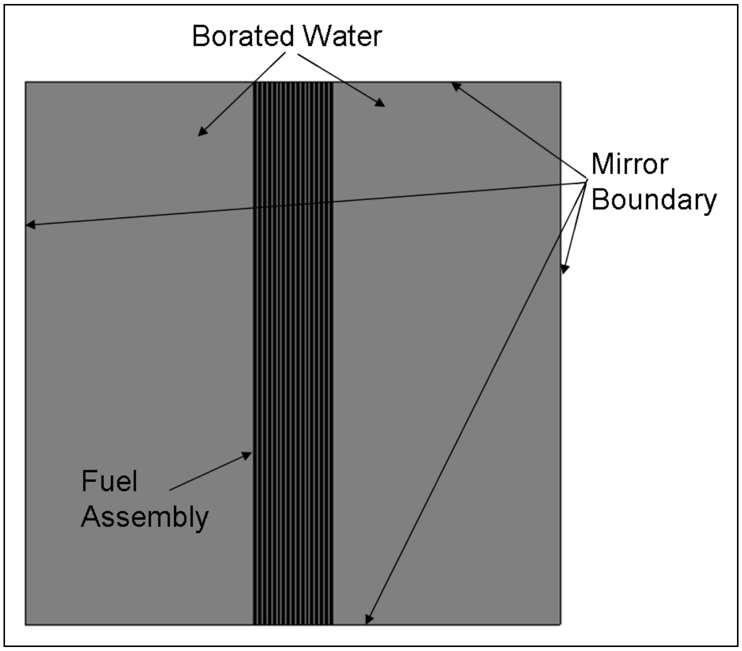
Source: Original to this document.

Figure 32. Vertical Cross Section of the PWR CSNF Staging Rack MCNP Model (Fuel Assemblies Not Shown for Clarity)



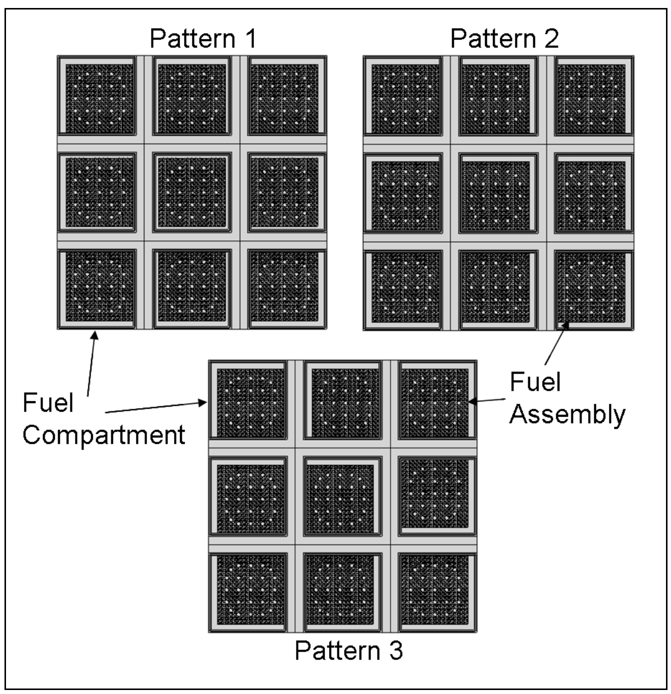
Source: Original to this document.

Figure 33. Vertical Cross Section of Upper Portion of PWR CSNF Staging Rack MCNP Model with Horizontal Fuel Assembly on Top of Staging Rack



Source: Original to this document.

Figure 34. Horizontal Cross Section of Upper Portion of PWR CSNF Staging Rack MCNP Model with Horizontal Fuel Assembly on Top of Staging Rack



Source: Original to this document.

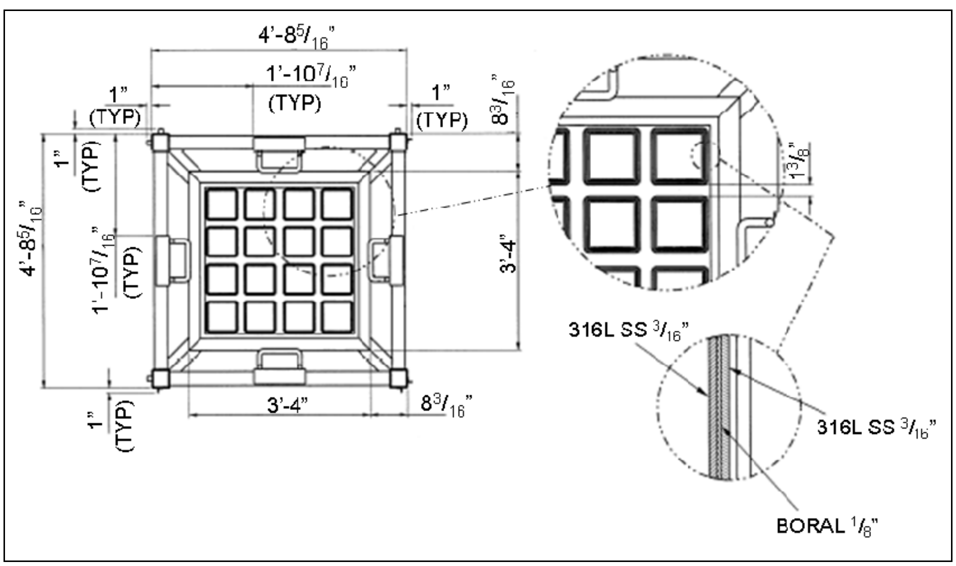
Figure 35. Horizontal Cross Sections of the PWR Staging Racks Fuel Bunching MCNP Models Showing the Three Fuel Bunching Patterns Examined

6.1.6 BWR CSNF Staging Racks

Eight BWR CSNF staging racks are located in the WHF pool (*Wet Handling Facility SNF Staging Racks in Pool Mechanical Equipment Envelope* Ref. 2.2.9). The staging of the CSNF in the pool is needed in order to allow for the mixing of fuel assemblies in the TAD canister to ensure that thermal and/or other requirements of the TAD canister are met. The basic design of the BWR CSNF staging racks is provided in *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope* (Ref. 2.2.10) and shown in Figure 36. The elevation is similar to that shown for the PWR CSNF staging rack in Figure 29 except that the overall height is 16 ft-4¼ in. (Ref. 2.2.10).

The MCNP models used in this calculation simplified this structure such that only the Boral/steel fuel assembly compartments are modeled. The structural steel of the racks is ignored. The overall width of the rack is maintained at 56 inches. The four vertical planes defining the outer rack width are modeled as reflective/mirror boundaries that result in the models effectively being an infinite square array of racks in the x-y plane. The racks are modeled with concrete reflection below the racks and water containing various levels of boron as both a moderator and top reflector.

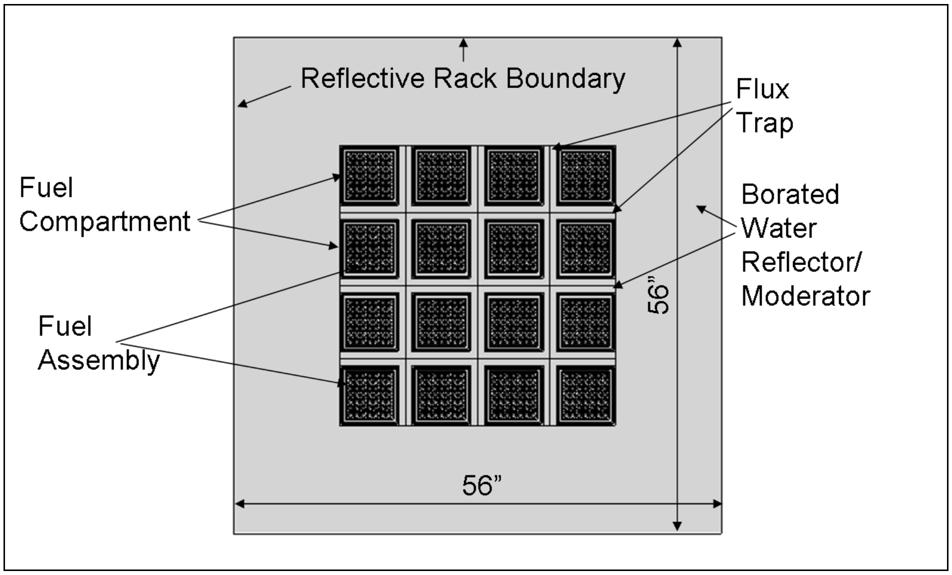
The steel of the compartments is modeled as continuous but the Boral is modeled as four separate plates, one on each side of the compartment. The Boral plates are 1/8-inch thick with the steel cladding on both sides also 1/8-inch thick. The fuel compartment interior width is set to 6 inches. The spacing between compartments is 13/8 inches but is varied in some of the models to either determine the minimum required separation or in evaluating other parameters or off-normal conditions. The height of the fuel compartments is modeled as the same height as the fuel assembly being modeled. Figures 37 through 39 are cross sections of the BWR CSNF staging rack MCNP model.



NOTE: ' = feet, " = inch; SS = stainless steel; TYP = typical

Source: Modified from *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope* (Ref. 2.2.10)

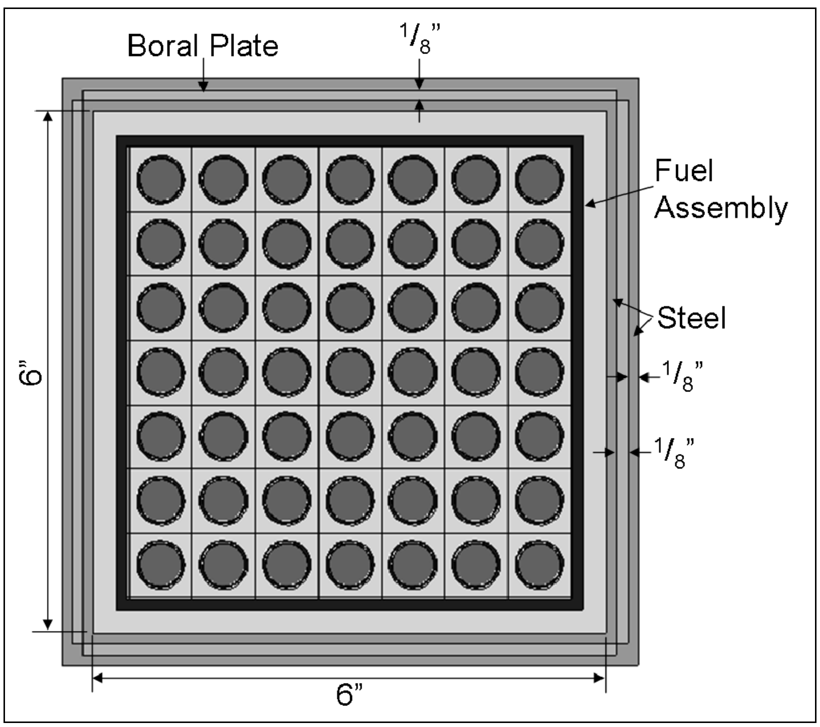
Figure 36. Plan View of BWR CSNF Staging Rack for WHF Pool



NOTES: “ = inch

Source: Original to this document.

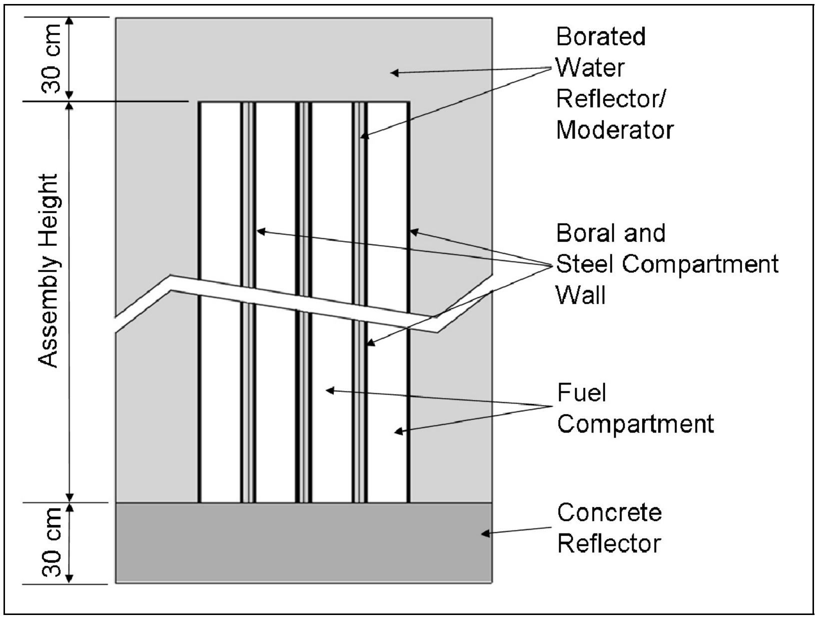
Figure 37. Horizontal Cross Section of the Basic BWR CSNF Staging Rack MCNP Model



NOTE: ‘ = inch

Source: Original to this document.

Figure 38. Horizontal Cross Section of the Basic BWR CSNF Staging Rack MCNP Model Showing a Single Storage Compartment



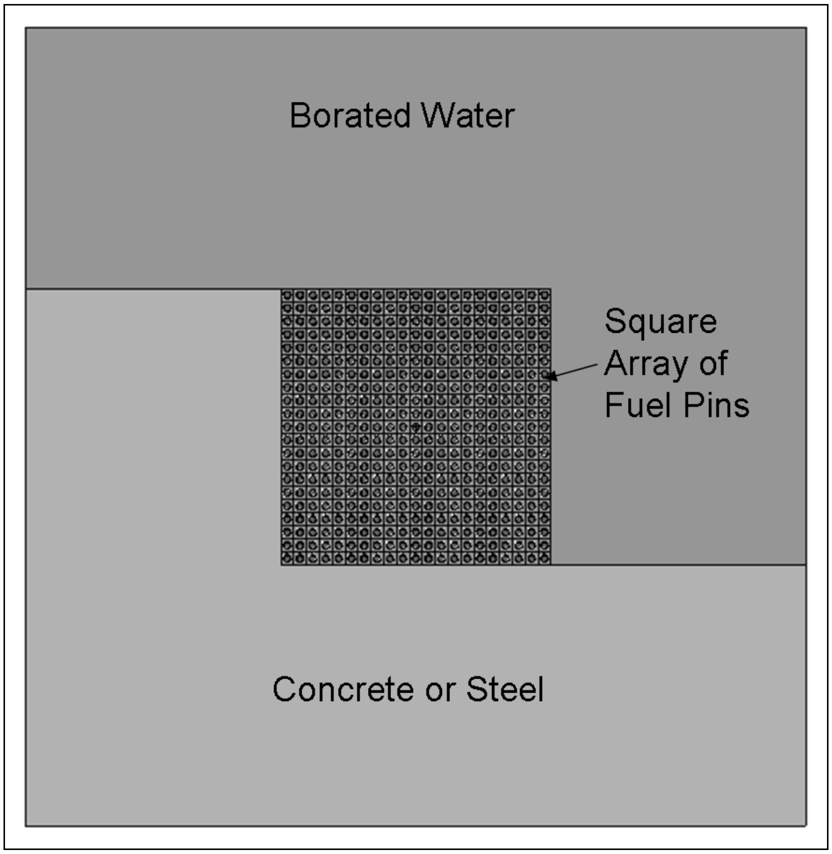
Source: Original to this document.

Figure 39. Vertical Cross Section of the Basic BWR CSNF Staging Rack MCNP Model (Fuel Assemblies Not Shown for Clarity)

6.1.7 Simple Geometry Models

Some event sequences and/or normal operations may not be explicitly covered by the MCNP models described in the Sections 6.1.1 through 6.1.6. These events could include large amounts of UO_2 (>> 1 kg) being released from fuel rods, severe crushing of the fuel assemblies, or other damage to all or part of a fuel assembly. In order to provide subcritical parameter limits for these generic conditions, a number of simple geometries are examined. These geometries involve heterogeneous and homogeneous mixtures of UO_2 and water/borated water in the shapes of reflected spheres, hemispheres, infinite slabs, and large arrays of fuel pins. Reflector materials are varied for the spheres and slabs and include water borated to the same level as in moderator, concrete, and Stainless Steel Type 304. For the hemispheres, the bottom is reflected by concrete and the top is reflected by borated water which is considered the most realistic condition for UO_2 that collects on the bottom of the pool.

The fuel pin array models consist of a simple square array of fuel pins moderated and reflected by borated water. Concrete or steel reflection is provided on three sides (two vertical sides and one of the axial ends). All reflectors are a minimum 30 cm thick. These models are meant to help evaluate and bound potential situations in which large arrays of fuel pins (> a single assembly's worth) are outside of their storage locations within the WHF pool. No instrument tubes, guide tubes, water channels, or other fuel assembly structures other than the fuel pins are modeled. An axial cross section of the basic model is given in Figure 40.



Source: Original to this document.

Figure 40. Horizontal Cross Section of the Simple Square Fuel Pin Array MCNP Model

6.2 MATERIALS

This section provides an overview of typical materials that are represented in the MCNP input files. The majority of the material specifications in the following sections are taken directly from *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8). For the remainder of this report, ZAID refers to the MCNP identifier of a data library for a specific element or isotope.

6.2.1 Isotopic Expansion of Elemental Weight Percents

The material specifications for borated water, borated stainless steel, and concrete utilized atomic weights, isotopic masses, and isotopic abundances in atom percent from *Nuclides and Isotopes* (Ref. 2.2.4) to expand the elemental weight percents into their constituent natural isotopic weight percents for use in MCNP. This expansion was performed by: (1) calculating a natural weight fraction of each isotope in the elemental state, and (2) multiplying the elemental weight percent in the material of interest by the natural weight fraction of the isotope in the elemental state to obtain the weight percent of the isotope in the material of interest. This process is described mathematically in Equations 1 and 2. When required, the derivations for the materials presented in this section are performed in Attachment 2, *Material Compositions.xls*, unless noted otherwise.

$$WF_i = \frac{A_i(At\%_i)}{\sum_{i=1}^{I} A_i\left(At\%_i\right)} \qquad \text{(Eq. 1)}$$

where

WF_i = the weight fraction of isotope i in the natural element

A_i = the atomic mass of isotope i

$At\%_i$ = the atom percent of isotope i in the natural element

I = the total number of isotopes in the natural element

$$Wt\%_i = WF_i(E_{wt\%}) \qquad \text{(Eq. 2)}$$

where

$Wt.\%_i$ = the weight percent of isotope i in the material composition

WF_i = the weight fraction of isotope i from Equation 1

$E_{wt.\%}$ = the referenced weight percent of the element in the material composition

The elements from material specifications that are split into their constituent isotopes are boron, chromium, iron, and nickel. In most cases these determinations were performed in documentation from which the material specification was taken. In a number of cases (e.g., borated stainless steel and concrete) this determination is performed here. In these cases, the atomic mass and isotopic abundance for the isotopes of each of these elements provided in Table 9 were used. These values were taken from *Nuclides and Isotopes* (Ref. 2.2.4). Included in Table 9 are the atomic masses for elements and isotopes used elsewhere for determining material specifications.

Table 9. Isotopic Abundances and Atomic Masses

Element/ Isotope	Natural Isotopic Abundance (atom %)	Atomic Mass (g/mol)
H	--	1.00794
B	--	10.811
^{10}B	19.9	10.012937
^{11}B	80.1	11.0093005
O	--	15.9994
Cr	--	51.9961
^{50}Cr	4.345	49.946050
^{52}Cr	83.789	51.940512
^{53}Cr	9.501	52.940654
^{54}Cr	2.365	53.938885
Fe	--	55.845
^{54}Fe	5.845	53.939615
^{56}Fe	91.754	55.934942
^{57}Fe	2.119	56.935399
^{58}Fe	0.282	57.933280
Ni	--	58.6934
^{58}Ni	68.0769	57.935348
^{60}Ni	26.2231	59.930791
^{61}Ni	1.1399	60.931060
^{62}Ni	3.6345	61.928349
^{64}Ni	0.9256	63.927970
^{235}U	0.72	235.043923
^{238}U	99.2745	238.050783

Source: *Nuclides and Isotopes* (Ref. 2.2.4).

6.2.2 Fuel Assembly Materials

The fuel material for all of these fuel assemblies is taken as UO_2 at 98% of theoretical density (Assumption 3.2.1) and having a uranium enrichment of 5 wt.% ^{235}U with the balance of the uranium being ^{238}U. The theoretical density of UO_2 is 10.97 g/cm^3 (*CRC Handbook of Chemistry and Physics*, Ref. 2.2.18, p. 4-97). The UO_2 density utilized in this calculation is therefore 10.751 g/cm^3. Only ^{235}U, ^{238}U, and O are considered when determining the fuel composition. No burnable poisons, fission products, or other actinides are modeled as part of the fuel. This specified fuel material, when used for criticality safety analyses, is bounding of the actual CSNF fuel material to be handled in the WHF. The weight percent determinations for each of the fuel components are shown below.

The atomic weights utilized in the following determinations were taken from *Nuclides and Isotopes* (Ref. 2.2.4). The molecular weight of UO_2 is determined as:

$$
\begin{aligned}
AM_{5\%U} &= \frac{1}{\dfrac{wf_{^{235}U}}{MW_{^{235}U}} + \dfrac{wf_{^{238}U}}{MW_{^{238}U}}} \\
&= \frac{1}{\dfrac{0.05}{235.043923} + \dfrac{0.95}{238.050783}} \\
&= 237.8986 \\
MW_{UO_2} &= AM_{5\%U} + (2 \times AM_O) \\
&= 237.8986 + (2 \times 15.9994) \\
&= 269.8974 \frac{g}{mol}
\end{aligned}
$$

where

$AM_{5\%U}$ = atomic mass of uranium enriched to 5 wt.% ^{235}U

MW_{UO_2} = molecular weight UO_2

$wf_{^{235}U}$ = isotopic weight fraction of ^{235}U in U

$AM_{^{235}U}$ = atomic mass of ^{235}U

$wf_{^{238}U}$ = isotopic weight fraction of ^{238}U in U

$AM_{^{238}U}$ = atomic mass of ^{238}U

AM_O = atomic mass of oxygen

The weight percents of the various fuel components are:

$$
\begin{aligned}
Wt\%_{^{235}U} &= \frac{wf_{^{235}U} \times AM_{5\%U}}{MW_{UO_2}} \times 100 \\
&= \frac{0.05 \times 237.8986}{269.8974} \times 100 \\
&= 4.4072
\end{aligned}
$$

$$
\begin{aligned}
Wt\%_{^{238}U} &= \frac{wf_{^{238}U} \times AM_{5\%U}}{MW_{UO_2}} \times 100 \\
&= \frac{0.95 \times 237.8986}{269.8974} \times 100 \\
&= 83.7369
\end{aligned}
$$

$$
\begin{aligned}
Wt\%_{O} &= \frac{2 \times AM_{O}}{MW_{UO_2}} \times 100 \\
&= \frac{2 \times 15.9994}{269.8974} \times 100 \\
&= 11.8559
\end{aligned}
$$

As discussed in Sections 6.1.1 and 6.1.2, the fuel cladding, guide tubes, instrument tube, and/or water tube materials are Zircaloy-2 or Zircaloy-4 for BWR or PWR, respectively. The material specifications for the Zircaloy and fuel materials used as part of the fuel assembly models are provided in the following tables.

Table 10. Material Specification for Zircaloy-2

Element/Isotope	ZAID	Wt.%	Element/Isotope	ZAID	Wt.%
^{50}Cr	24050.60c	0.0042	^{58}Ni	28058.60c	0.0370
^{52}Cr	24052.60c	0.0837	^{60}Ni	28060.60c	0.0147
^{53}Cr	24053.60c	0.0097	^{61}Ni	28061.60c	0.0007
^{54}Cr	24054.60c	0.0024	^{62}Ni	28062.60c	0.0021
^{54}Fe	26054.60c	0.0076	^{64}Ni	28064.60c	0.0006
^{56}Fe	26056.60c	0.1241	^{16}O	8016.50c	0.1250
^{57}Fe	26057.60c	0.0029	Zr-nat	40000.60c	98.1350
^{58}Fe	26058.60c	0.0004	Sn-nat	50000.35c	1.4500
Density = 6.55 g/cm^3					

NOTE: nat = natural

Source: *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8, Table 11)

Table 11. Material Specification for Zircaloy-4

Element/Isotope	ZAID	Wt.%	Element/Isotope	ZAID	Wt.%
^{50}Cr	24050.60c	0.0042	^{57}Fe	26057.60c	0.0045
^{52}Cr	24052.60c	0.0837	^{58}Fe	26058.60c	0.0006
^{53}Cr	24053.60c	0.0097	^{16}O	8016.50c	0.1250
^{54}Cr	24054.60c	0.0024	Zr-nat	40000.60c	98.1150
^{54}Fe	26054.60c	0.0119	Sn-nat	50000.35c	1.4500
^{56}Fe	26056.60c	0.1930	Density = 6.56 g/cm3		

NOTE: nat = natural

Source*: Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8, Table 10)

Table 12. Material Specification for UO_2 (5 wt.% ^{235}U Enriched U)

Isotope	ZAID	Wt.%
^{235}U	92235.50c	4.4072
^{238}U	92238.50c	83.737
^{16}O	8016.50c	11.8558
Density = 10.751 g/cm^3 per discussion above and Section 3.2.1.		

Source: Original to this document.

6.2.3 External Reflectors

The following materials may be used as a reflector in the WHF criticality safety models. These external reflector materials, if used, are on the outside of the main geometry which contains the fissile material (single fuel assembly, waste package, storage rack, etc.).

6.2.3.1 Water

Water is modeled simply as H_2O in the MCNP models using the atomic fraction variation for material input. The density is modeled as 0.99821 g/cm^3 based on water at 20 ˚C (*CRC Handbook of Chemistry and Physics,* Ref. 2.2.18, p. 6-2). The specification for water is provided in Table 13.

Table 13. Water Material Specification

Element/ Isotope	ZAID	Atoms per Molecule
^{1}H	1001.50c	2
^{16}O	8016.50c	1
Density: 0.99821 g/cm^3		

Source: *CRC Handbook of Chemistry and Physics* (Ref. 2.2.18)

6.2.3.2 Borated Water

The water in the WHF pool is expected to contain boron to act as a neutron poison. This borated water is modeled as a simple combination of water and boric acid. The specification for water is given in Section 6.2.3.1. Boric acid is H_3BO_3 with a density of 1.5 g/cm^3 (*CRC Handbook of Chemistry and Physics,* Ref. 2.2.18, p. 4-53).

The determination of weight fractions of the various elements is based upon a simple volume displacement model. The mass of boric acid added to the water displaces an equal volume of water. The following determinations and equations are used to determine the final weight fractions.

$$MW_{H_3BO_3} = (3 \times AM_H) + (AM_B) + (3 \times AM_{O`})$$
$$= 3 \times 1.00794 + 10.811 + (3 \times 15.9994)$$
$$= 61.83302 \frac{g}{mol}$$

where

$MW_{H_3BO_3}$ = molecular weight of H_3BO_3

AM_H = atomic mass hydrogen

AM_B = atomic mass of boron

AM_O = atomic mass of oxygen

$$MW_{H_2O} = (2 \times AM_H) + (AM_O)$$
$$= 2 \times 1.00794 + 15.9994$$
$$= 18.01528 \frac{g}{mol}$$

where

MW_{H_2O} = molecular weight of H_2O

Given the molecular weights determined above, the weight fractions for each element in boric acid and water are determined as follows:

Boric Acid:

$$wf_{H\text{ in }H_3BO_3} = \frac{3 \times AM_H}{MW_{H_3BO_3}} = \frac{3 \times 1.00794}{61.83302} = 0.048903$$

$$wf_{B\text{ in }H_3BO_3} = \frac{AM_B}{MW_{H_3BO_3}} = \frac{10.811}{61.83302} = 0.174842$$

$$wf_{O\text{ in }H_3BO_3} = \frac{3 \times AM_O}{MW_{H_3BO_3}} = \frac{3 \times 15.9994}{61.83302} = 0.776255$$

Water:

$$wf_{H\text{ in }H_2O} = \frac{2 \times AM_H}{MW_{H_2O}} = \frac{2 \times 1.00794}{18.01528} = 0.111898$$

$$wf_{O\text{ in }H_2O} = \frac{AM_O}{MW_{H_2O}} = \frac{15.9994}{18.01528} = 0.888102$$

Given a desired boron content in the water, the concentration of boric acid may be determined as follows:

$$C_{H_3BO_3} = \frac{C_B}{wf_{B\,in\,H_3BO_3}}$$

where

$C_{H_3BO_3}$ = concentration of boric acid in borated water

C_B = concentration of boron in borated water

The concentration of the water in the borated water mixture can be determined by:

$$C_{H_2O} = \left[1 - \frac{C_{H_3BO_3}}{\rho_{H_3BO_3}}\right] \times \rho_{H_2O}$$

where

C_{H_2O} = concentration of water in borated water

$\rho_{H_3BO_3}$ = density of boric acid

ρ_{H_2O} = density of water

The overall density of the borated water is:

$$\rho_{BW} = C_{H_3BO_3} + C_{H_2O}$$

The overall weight fractions hydrogen, boron, and oxygen in the borated water are:

$$wf_H = \frac{\left(C_{H_3BO_3} \times wf_{H\,in\,H_3BO_3}\right) + \left(C_{H_2O} \times wf_{H\,in\,H_2O}\right)}{\rho_{BW}}$$

$$wf_O = \frac{\left(C_{H_3BO_3} \times wf_{O\,in\,H_3BO_3}\right) + \left(C_{H_2O} \times wf_{O\,in\,H_2O}\right)}{\rho_{BW}}$$

$$wf_B = \frac{C_{H_3BO_3} \times wf_{B\,in\,H_3BO_3}}{\rho_{BW}}$$

The above borated water density and individual weight fractions are determined for a given boron concentration. The boron weight fraction is split into weight fractions for the ^{10}B and ^{11}B boron isotopes based upon their natural abundances from Table 9. Table 14 provides the borated water material specifications used in this calculation for the most common of the boron concentrations evaluated herein.

Table 14. Borated Water Weight Fractions and Densities used in MCNP Models

Element/Isotope (MCNP ZAID)	Boron Concentrations (mg/L)				
	500	1000	1500	2000	2500
H (1001.50c)	1.1171×10^{-01}	1.1153×10^{-01}	1.1135×10^{-01}	1.1117×10^{-01}	1.1100×10^{-01}
O (8016.50c)	8.8779×10^{-01}	8.8747×10^{-01}	8.8715×10^{-01}	8.8683×10^{-01}	8.8651×10^{-01}
^{10}B (5010.50c)	9.2232×10^{-05}	1.8429×10^{-04}	2.7617×10^{-04}	3.6787×10^{-04}	4.5940×10^{-04}
^{11}B (5011.50c)	4.0819×10^{-04}	8.1559×10^{-04}	1.2222×10^{-03}	1.6281×10^{-03}	2.0331×10^{-03}
Density (g/cm^3)	0.99917	1.00012	1.00108	1.00204	1.00299

Source: Original to document. Values determined based on equations given in Section 6.2.1 and Equations 1 and 2.

For some of the simple geometry cases boron enriched in ^{10}B is utilized. This allows for greater neutron poison capabilities while maintaining the same overall boron concentration. The enriched borated water material specifications are determined in the same way as the natural boron specifications described above except that a new boron atomic weight is determined based upon the atom percents of the boron isotopes (^{10}B and ^{11}B) in the enriched boron. The boron concentration for all of the enriched borated water materials is maintained at 2500 mg/L. The enriched borated water weight fractions and densities used in the MCNP models are shown in Table 15.

Table 15. Enriched Borated Water Weight Fractions and Densities used in MCNP Models

Element/Isotope (MCNP ZAID)	Boron Enrichment (^{10}B atom %)			
	40	60	80	90
H (1001.50c)	1.1099×10^{-01}	1.1098×10^{-01}	1.1096×10^{-01}	1.1096×10^{-01}
O (8016.50c)	8.8652×10^{-01}	8.8653×10^{-01}	8.8654×10^{-01}	8.8655×10^{-01}
^{10}B (5010.50c)	9.4080×10^{-04}	1.4381×10^{-03}	1.9549×10^{-03}	2.2208×10^{-03}
^{11}B (5011.50c)	1.5516×10^{-03}	1.0542×10^{-03}	5.3735×10^{-04}	2.7131×10^{-04}
Density (g/cm^3)	1.00304	1.00308	1.00313	1.00315

Source: Original to document. Values determined based on equations given in Section 6.2.1 and Equations 1 and 2.

6.2.3.3 Concrete

Concrete reflection is considered for certain configurations since it is the primary composition of the overpack and the floors and walls of the WHF. There are numerous concrete compositions available and some of the most common were evaluated in *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8). The results (Ref. 2.2.8, Table 57) demonstrate that the values of k_{eff} for each concrete type are within 2σ of each other. Therefore, the use of different concrete material specifications may be considered statistically indistinguishable from one another. For this calculation, the concrete composition designated as SAR concrete composition given in Ref. 2.2.8 is used in this analysis. Note that 'SAR' is not defined as an acronym in Ref. 2.2.8 and is used here simply as an identifier to the specific concrete composition used in this calculation. The specification for the SAR concrete from Ref. 2.2.8 did not include the isotopic breakdown for iron. This breakdown was performed using Equations 1 and 2 and the information presented in Table 9. The SAR concrete material specification is provided in Table 16.

Table 16. Material Specifications for SAR Concrete

Element/ Isotope	ZAID	Wt.%	Element/ Isotope	ZAID	Wt.%
^{1}H	1001.50c	0.6	Fe-nat	N/A	1.2
^{16}O	8016.50c	50.0	^{54}Fe	26054.60c	0.0677
^{23}Na	11023.50c	1.7	^{56}Fe	26056.60c	1.1028
^{27}Al	13027.50c	0.480	^{57}Fe	26057.60c	0.0259
Si-nat	14000.50c	31.5	^{58}Fe	26058.60c	0.0035
K-nat	19000.50c	1.90	Density = 2.35 g/cm^3		
Ca-nat	20000.50c	8.30			

NOTE: nat = natural

Source: *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8, Table 56)

6.2.3.4 Steel

Steel, as a separate external reflector, is modeled as Stainless Steel Type 304. The specification for Stainless Steel Type 304 is taken from *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8) where it is designated as SA-240 S30400. The steel specification is given in Table 17.

Table 17. Material Specification for Stainless Steel Type 304

Element/Isotope	ZAID	Wt.%	Element/Isotope	ZAID	Wt.%
C-nat	6000.50c	0.0800	^{54}Fe	26054.60c	3.8844
^{14}N	7014.50c	0.1000	^{56}Fe	26056.60c	63.1751
Si-nat	14000.50c	0.7500	^{57}Fe	26057.60c	1.4859
^{31}P	15031.50c	0.0450	^{58}Fe	26058.60c	0.1997
S-nat	16032.50c	0.0300	^{58}Ni	28058.60c	6.2161
^{50}Cr	24050.60c	0.7939	^{60}Ni	28060.60c	2.4765
^{52}Cr	24052.60c	15.9031	^{61}Ni	28061.60c	0.1095
^{53}Cr	24053.60c	1.8378	^{62}Ni	28062.60c	0.3543
^{54}Cr	24054.60c	0.4652	^{64}Ni	28064.60c	0.0937
^{55}Mn	25055.50c	2.0000	Density = 7.94 g/cm^3		

NOTE: nat = natural

Source: *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8, Table 12)

6.2.3.5 Depleted Uranium

Depleted uranium may be present in the WHF as a shielding material. In regards to criticality, this material acts as a potential neutron reflector. The form of the uranium is metal which has a density of 18.95 g/cm^3 per *Nuclides and Isotopes* (Ref. 2.2.4). Per Assumption 3.2.3, the depleted uranium is conservatively assumed to be naturally enriched uranium with a ^{235}U content of 0.72 atom percent (Assumption 3.2.3). The balance of the uranium (99.28 atom percent) is ^{238}U. The material specification for the uranium shield material is given in Table 18. The depleted uranium is referred to as natural uranium throughout the rest of this document.

Table 18. Natural Uranium Metal Material Specification

Element/ Isotope	ZAID	Atom Weight Fraction
^{235}U	92235.50c	0.0072
^{238}U	92238.50c	0.9928
Density: 18.95 g/cm^3		

Source: *Nuclides and Isotopes* (Ref. 2.2.4) and Section 3.2.3

6.2.3.6 Lead

Lead is used as a shielding material for the CSNF in various packages and acts as an external reflector. Lead is modeled as 100% lead metal with a density of 11.35 g/cm^3 per Ref. 2.2.4. The natural lead cross section, ZAID 82000.50c, is used to model lead in the MCNP criticality safety models.

6.2.4 TAD Canister Materials

The TAD canister is in the WHF to package CSNF for disposal. The *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14) requires the use of Type 300-series stainless steel for the construction of the TAD canister. For the purpose of this analysis, Stainless Steel Type 316 (UNS S31600) is used as the material of construction of the TAD canister when stainless steel is called for (See Assumption 3.1.2). The specification further requires the use Borated Stainless Steel Type 304B4 UNS S30464 for use as neutron absorber plates.

The specification for Stainless Steel Type 316 provided in Table 19 is taken directly from *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8).

Table 19. Material Specification for Stainless Steel Type 316

Element/Isotope	ZAID	Wt.%	Element/Isotope	ZAID	Wt.%
C-nat	6000.50c	0.0800	^{54}Fe	26054.60c	3.7007
^{14}N	7014.50c	0.1000	^{56}Fe	26056.60c	60.1884
Si-nat	14000.50c	0.7500	^{57}Fe	26057.60c	1.4156
^{31}P	15031.50c	0.0450	^{58}Fe	26058.60c	0.1902
^{32}S	16032.50c	0.0300	^{58}Ni	28058.60c	8.0641
^{50}Cr	24050.60c	0.7103	^{60}Ni	28060.60c	3.2127
^{52}Cr	24052.60c	14.2291	^{61}Ni	28061.60c	0.1420
^{53}Cr	24053.60c	1.6443	^{62}Ni	28062.60c	0.4596
^{54}Cr	24054.60c	0.4162	^{64}Ni	28064.60c	0.1216
^{55}Mn	25055.50c	2.0000	Mo-nat	42000.50c	2.5000
Density = 7.98 g/cm^3					

NOTE: nat = natural

Source: *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.8, Table 5)

The specification for the Borated Stainless Steel Type 304B4 UNS S30464 comes from Table 1 of *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application* (Ref. 2.2.2). The weight percents for chromium and nickel were set to the mid-point of the given ranges and the value for nitrogen was set to the maximum. Per *Transportation, Aging and Disposal Canister System Performance Specification* (Ref. 2.2.14), the boron content of the borated steel is 1.1 – 1.2 weight percent. The lower limit of this range is conservatively used in determining the final material specification for the borated stainless steel. This value is further reduced by 25% to 0.825 weight percent per the recommendation from NUREG-1567, *Standard Review Plan for Spent Fuel Dry Storage Facilities* (Ref. 2.2.19) to take no more than 75% credit for fixed neutron absorbers.

In determining the density, the borated stainless steel is taken as a mixture of boron (2.35 g/cm^3 per *Nuclides and Isotopes,* Ref. 2.2.4), Stainless Steel Type 304 (7.94 g/cm^3 from Table 17) (Assumption 3.2.2), and void (to account for the 25% reduction in boron). Given this and the above information, the density of the borated steel with a 25% reduction in the boron is determined as follows:

$$\rho_{BSS} = \frac{\left(\frac{g_B}{g_{BSS}} \times 0.75\right) + \left(\frac{g_{304}}{g_{BSS}}\right)}{\left(\frac{g_B}{g_{BSS}} \div \rho_B\right) + \left(\frac{g_{304}}{g_{BSS}} \div \rho_{304}\right)}$$

$$= \frac{(0.011 \times 0.75)\frac{g_B}{g_{BSS}} + (1 - 0.011)\frac{g_{304}}{g_{BSS}}}{\left(\frac{0.011\frac{g_B}{g_{BSS}}}{2.35\frac{g_B}{cm^3}}\right) + \left(\frac{(1 - 0.011)\frac{g_{304}}{g_{BSS}}}{7.94\frac{g_{304}}{cm^3}}\right)}$$

$$= 7.716\frac{g}{cm^3}$$

where

ρ_{BSS} = the determined density for borated stainless steel

g_B = grams boron

g_{BSS} = grams borated stainless steel

g_{304} = grams Stainless Steel Type 304

ρ_B = the density of boron

ρ_{304} = the density for Stainless Steel Type 304

For boron, chromium, iron, and nickel the isotopic cross sections versus a combined elemental cross section are utilized. The material specification for borated stainless steel from *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application* (Ref. 2.2.2) provides only elemental weight percents. The weight percents for the isotopes of boron, chromium, iron, and nickel were determined based upon the information given in Table 9 and Equations 1 and 2. The final specification for borated stainless steel to be used in this calculation is provided in Table 20.

Table 20. Material Specification for Borated Stainless Steel

Element/Isotope	ZAID	Wt.%	Element/Isotope	ZAID	Wt.%
B	N/A	0.825	^{55}Mn	25055.50c	2.0000
^{10}B	5010.50c	0.1521	Fe	N/A	62.675
^{11}B	5011.50c	0.6729	^{54}Fe	26054.60c	3.5384
C-nat	6000.50c	0.0800	^{56}Fe	26056.60c	57.5994
^{14}N	7014.50c	0.1000	^{57}Fe	26057.60c	1.3540
Si-nat	14000.50c	0.7500	^{58}Fe	26058.60c	0.1834
^{31}P	15031.50c	0.0450	Ni	N/A	13.5
^{32}S	16032.50c	0.0300	^{58}Ni	28058.60c	9.0717
Cr	N/A	19.0	^{60}Ni	28060.60c	3.6148
^{50}Cr	24050.60c	0.7930	^{61}Ni	28061.60c	0.1598
^{52}Cr	24052.60c	15.9029	^{62}Ni	28062.60c	0.5177
^{53}Cr	24053.60c	1.8380	^{64}Ni	28064.60c	0.1361
^{54}Cr	24054.60c	0.4661	Density = 7.716 g/cm^3		

NOTE: The total wt.% is 99.725 versus 100% due to reduced boron content. This maintains the correct relative amounts. MCNP automatically re-ratios these values to total 100%.

nat = natural ; N/A = not applicable

Source: *Standard Specification for Borated Stainless Steel Plate, Sheet, and Strip for Nuclear Application* (Ref. 2.2.2, Table 1) except for the determined/modified values as discussed above.

6.2.5 DPCs

The materials of construction for both the PWR and BWR DPCs are the same. The main structural components (DPC and fuel baskets) are constructed of "Alloy X" which, per *Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261* (Ref. 2.2.16, Section 1.4, Drawings 3923, 3926, and 3928) can be Stainless Steel Type 316, 316LN, 304, or 304LN. For the purpose of this calculation, the structural components of the DPC and fuel basket are modeled as Stainless Steel Type 316 as given in Table 19.

The Boral material used in the models of the PWR DPC is based on the 0.0279 g ^{10}B/cm^2 plate Boral specification from Table 5-21 of *CSNF Assembly Type Sensitivity Evaluation for Pre- and Postclosure Criticality Analysis* (Ref. 2.2.7). The original boron content is reduced by 25% per the recommendation from NUREG-1567, *Standard Review Plan for Spent Fuel Dry Storage Facilities* (Ref. 2.2.19) to take no more than 75% credit for fixed neutron absorbers. The density is reduced from the given 2.660 g/cm^3 to 2.476 g/cm^3 to account for the reduced boron concentration. This was determined as follows:

$$\rho_{Reduced} = \rho_{Boral} - \left[\left(\frac{wf_{^{10}B} + wf_{^{11}B}}{wf_{total}}\right) \times \rho_{Boral} \times 0.25\right]$$

$$= 2.660 - \left[\left(\frac{0.05089 + 0.22570}{1.0004}\right) \times 2.660 \times 0.25\right]$$

$$= 2.476 \frac{g}{cm^3}$$

where

$\rho_{Reduced}$ = reduced Boral density due to reduced boron content

ρ_{Boral} = unreduced Boral density

$wf_{^{10}B}$ = unreduced ^{10}B weight fraction in Boral

$wf_{^{11}B}$ = unreduced ^{11}B weight fraction in Boral

wf_{total} = total of all given weight fractions for Boral

NOTE: given weight fractions total to slightly more than 1

The reworked specification is shown in Table 21.

Table 21. Material Specification for Boral

Element/ Isotope	ZAID	Original Wt.%	Reduced Boron Wt.%
^{10}B	5010.50c	5.089	3.81675
^{11}B	5011.50c	22.570	16.9275
C-nat	6000.50c	7.675	7.675
^{27}Al	13027.50c	64.670	64.670
Total		100.04	93.08925 (1)
Density = 2.476 g/cm^3			

NOTE: (1) The total wt.% is 93.08925 versus 100% due to reduced boron content. This maintains the correct relative amounts. MCNP automatically re-ratios these values to total 100% and is therefore not corrected here.

nat = natural

Source: *CSNF Assembly Type Sensitivity Evaluation for Pre- and Postclosure Criticality Analysis* (Ref .2.2.7, Table 5-21) except for the determined/modified values as discussed above.

The MPC-24 (*Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report*, Ref. 2.2.16, Section 1.4, Drawing 3926) and MPC-68 (Ref. 2.2.16, Section 1.4, Drawing 3928) on which the DPC fuel basket models are based, require a minimum ^{10}B content of 0.0267 g/cm^2 and 0.0372 g/cm^2, respectively. In order to ensure the use of the specification from Table 21 is conservative, the unreduced boron specification is used to determine the minimum ^{10}B content of the PWR and BWR Boral plates and compared to the minimum requirements as described above.

Given the nominal Boral plate thicknesses (0.075 inches (PWR DPC per Section 6.1.4.1) and 0.101 inches (BWR DPC per Section 6.1.4.2) and the unreduced Boral density and ^{10}B content, the ^{10}B content for BWR and PWR DPC Boral plates can be determined as follows:

$$
\begin{aligned}
{}^{10}B_{PWR}\ \text{content} &= \rho_{Boral} \times wf_{^{10}B} \times T_{Boral-PWR} \\
&= 2.660 \times 0.05089 \times (0.075 \times 2.54) \\
&= 0.0258 \frac{g}{cm^2} \\
{}^{10}B_{BWR}\ \text{content} &= \rho_{Boral} \times wf_{^{10}B} \times T_{Boral-BWR} \\
&= 2.660 \times 0.05089 \times (0.101 \times 2.54) \\
&= 0.0347 \frac{g}{cm^2}
\end{aligned}
$$

where

$^{10}B_{PWR}$ content = the determined ^{10}B content for the Boral plates in the PWR fuel basket

$^{10}B_{BWR}$ content = the determined ^{10}B content for the Boral plates in the BWR fuel basket

ρ_{Boral} = Boral density with unreduced boron content

$wf_{^{10}B}$ = unreduced ^{10}B weight fraction in Boral

$T_{Boral-PWR}$ = modeled Boral plate thickness in the PWR fuel basket

$T_{Boral-BWR}$ = modeled Boral plate thickness in the BWR fuel basket

The above determinations show that the use of Boral specification as given in Table 21 is conservative in regards to the modeled ^{10}B content of the Boral over what is expected in actual Boral plates of the PWR and BWR DPC Boral plates. Additional conservatism is added by using the boron reduced specification from Table 21.

6.2.6 CSNF Staging Racks

CSNF staging racks for CSNF are provided in the pool of the WHF to allow for creating the proper mix of CSNF in the TAD canisters. The staging racks are constructed primarily of Stainless Steel Type 316L and Boral per *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope* (Ref. 2.2.10). The material specification for Stainless Steel Type 316L is provided in Table 22 and based on the specification in ASTM A 240/A 240M-06c (*Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications*, Ref. 2.2.1, Table 1). The density for 316L is 7.98 g/cm^3 per ASTM G1-03 (*Standard Practice for Preparing, Cleaning, and Evaluating*

Corrosion Test Specimens, Ref. 2.2.3, Table X1.1). The values for chromium, nickel, and molybdenum are specified as ranges in *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications* (Ref. 2.2.1). The values used for these elements in Table 22 are within these given ranges. The iron content is not explicitly given in *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications* (Ref. 2.2.1), but is the value needed to achieve 100 wt.% when all the elemental weight percents are summed.

For boron, chromium, iron, and nickel the isotopic cross sections versus a combined elemental cross section are utilized. The material specification for Stainless Steel Type 316L from *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications* (Ref. 2.2.1) provides only elemental weight percents. The weight percents for the isotopes of chromium, iron, and nickel were determined based upon the information given in Table 9 and Equations 1 and 2. The final specification for Stainless Steel Type 316L to be used in this calculation is provided in Table 22.

Table 22. Material Specification for Stainless Steel Type 316L

Element/Isotope	ZAID	Wt.%	Element/Isotope	ZAID	Wt.%
C-nat	6000.50c	0.0300	Fe	--	66.045
^{14}N	7014.50c	0.1000	^{54}Fe	26054.60c	3.7286
Si-nat	14000.50c	0.7500	^{56}Fe	26056.60c	60.6965
^{31}P	15031.50c	0.0450	^{57}Fe	26057.60c	1.4268
^{32}S	16032.50c	0.0300	^{58}Fe	26058.60c	0.1932
Cr	--	17.0	Ni	--	11.5
^{50}Cr	24050.60c	0.7095	^{58}Ni	28058.60c	7.7277
^{52}Cr	24052.60c	14.2289	^{60}Ni	28060.60c	3.0792
^{53}Cr	24053.60c	1.6445	^{61}Ni	28061.60c	0.1361
^{54}Cr	24054.60c	0.4171	^{62}Ni	28062.60c	0.4410
^{55}Mn	25055.50c	2.0000	^{64}Ni	28064.60c	0.1159
			Mo-nat	42000.50c	2.5000
Density = 7.98 g/cm^3					

NOTE: nat = natural

Source: *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications* (Ref. 2.2.1, Table 1) except for the determined/modified values as discussed above.

The Boral material used in the models of the CSNF staging racks is based upon the material specification given in Table 21.

6.3 MCNP MODEL CALCULATION RESULTS

The following sections present the results of the MCNP models described in Section 6.1. The models are varied on a number of parameters that are pertinent to determining optimum conditions (e.g., fuel pin pitch), determining subcritical values for a control parameter (e.g., boron concentration), and/or understanding neutronic behavior of the system (e.g., voiding out of neutron absorbing materials).

In determining the value of a control parameter that must be maintained in order to ensure the reactivity of the system remains below the 0.92 USL (Assumption 3.1.1), interpolation of the results on the USL was performed. This was done by fitting a series of results to a third order polynomial utilizing the LINEST spreadsheet function in Excel (Section 4.2.2). The polynomials are only used to perform interpolation of data. Extrapolation of data was not done. The fitting parameters may be found in the Excel spreadsheets in Attachment 2.

For some of the results reported in Section 6.3.5 the boron enrichment in the isotope ^{10}B is varied. These include the results presented in Figures 109 through 117. Unless otherwise noted the results in the following sections are based upon natural boron (19.9 atom% ^{10}B). The presence of enriched boron is specifically noted in the results when applicable.

6.3.1 Single CSNF Assembly Results

This section presents the MCNP k_{eff} results for single CSNF assemblies under a variety of conditions. These conditions all involved a fuel assembly in the WHF pool and outside of any container (e.g., fuel rack, DPC, TAD canister). The single fuel assembly MCNP models are described in Sections 6.1.1 and 6.1.2.

As discussed in Sections 6.1.1 and 6.1.2, two PWR and two BWR CSNF assembly types are examined. The MCNP models varied a number of parameters in a matrix fashion. These parameters are shown in Table 23.

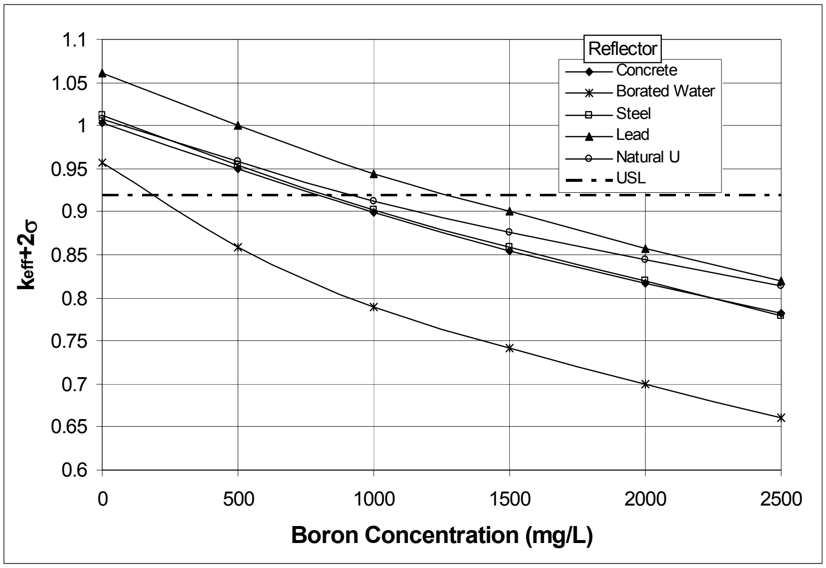
Table 23. Parameter Variations Examined for Single CSNF Assemblies

Parameter	Range/Values Examined
Pin pitch - 17x17 OFA (cm)	1.2598 (normal/undamaged) – 3.0
Pin pitch - B&W 15x15 (cm)	1.4427 (normal/undamaged) – 3.0
Pin pitch - 9x9 (cm)	1.43 (normal/undamaged) – 1.51[(1)]
Pin pitch - 7x7 (cm)	1.8745 (normal/undamaged) – 1.968[(1)]
Boron content in water moderator (mg/L)	0 – 2500
Reflector material (surrounds all six sides of fuel assembly)	Borated water[(2)], water[(3)], concrete, steel, lead, natural U
Reflector thickness (cm) • Performed for the undamaged 17x17 OFA and 7x7 assemblies only • Boron contents examined: 0 and 2500 mg/L boron only • Boron ^{10}B enrichments of 19.9 (natural) and 90 atom percent for the 2500 mg/L boron cases.	10 - 100

NOTES: (1) Maximum pitch restricted by presence of fuel channel.
(2) This water has the same boron content as the water moderator.
(3) Water reflection is denoted as borated water with zero boron content in the figures of this section.

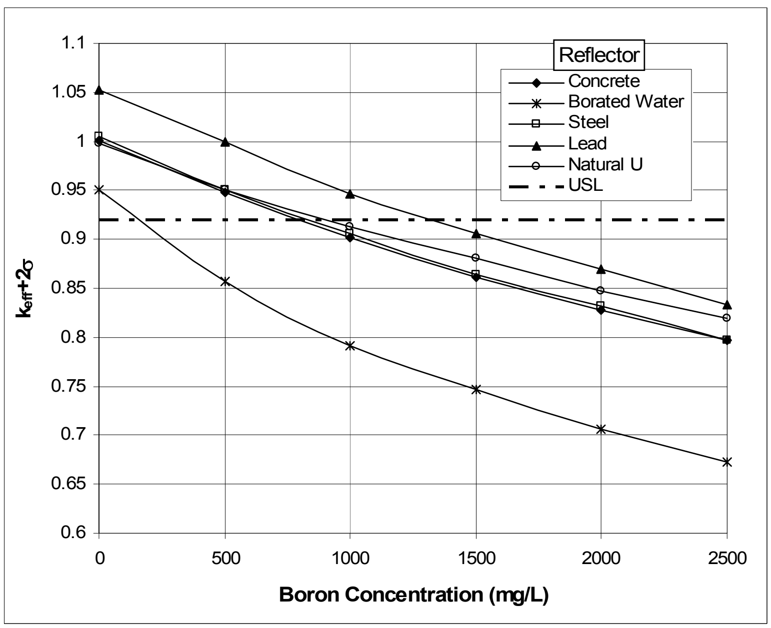
Source: Original to this document.

Figures 41 and 42 show the results for the undamaged PWR fuel assemblies. These and similar sets of results are then interpolated to the 0.92 USL (Assumption 3.1.1) to give the minimum boron concentration needed to ensure the single fuel assembly remains safely subcritical. All the results may be found in Attachment 2 (*Single Assembly Results.xls*).



Source: Original to this document.

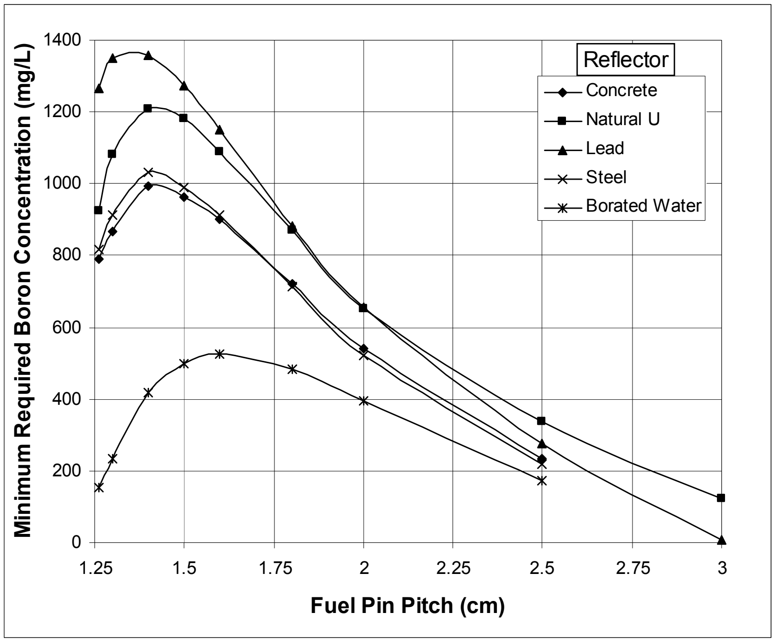
Figure 41. Results for a Single Undamaged 17x17 OFA



Source: Original to this document.

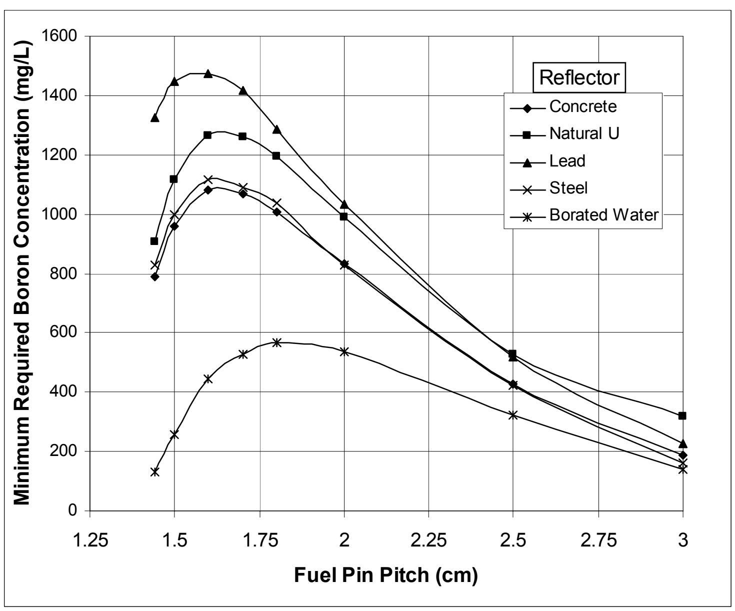
Figure 42. Results for a Single Undamaged B&W 15x15 Fuel Assembly

Figures 43 and 44 show the minimum required boron concentration in water needed to meet the USL of 0.92 (Assumption 3.1.1) for varying pin pitch and reflector materials for the two PWR fuel assemblies examined. The data presented in these figures demonstrate that under the given conditions, lead is the most effective reflector and that the B&W 15x15 is slightly more reactive than the Westinghouse 17x17 OFA. Table 24 gives the determined minimum boron concentration for each reflector type for each PWR fuel assembly type based on the optimized pin pitch.



Source: Original to this document.

Figure 43. Minimum Required Boron Concentration for a Single 17x17 OFA



Source: Original to this document.

Figure 44. Minimum Required Boron Concentration for a Single B&W 15x15 Fuel Assembly

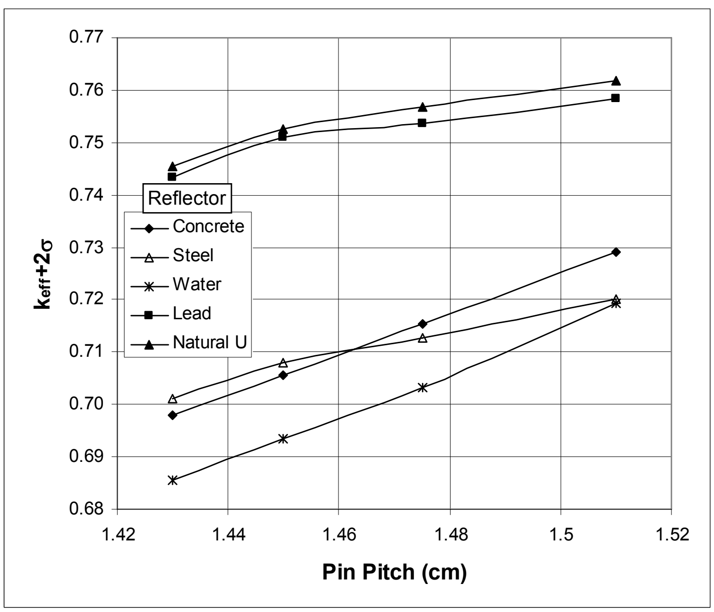
Table 24. Minimum Boron Concentration in Water Needed for a Single PWR Fuel Assembly with Optimum Fuel Pin Pitch

Reflector	Minimum Boron Concentration Needed to Meet the 0.92 USL (mg/L)
17x17 OFA	
Borated water(1)	527
Concrete	988
Steel	1029
B&W 15x15	
Borated water(1)	561
Concrete	1074
Steel	1124

NOTE: (1)The boron content of the water reflector is the same as for the water moderator modeled.

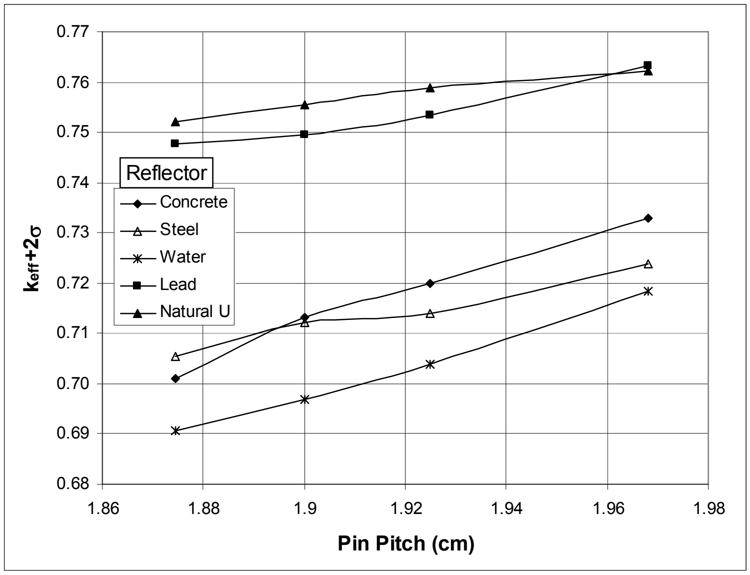
Source: Original to this document.

Figures 45 and 46 show the system reactivity versus pin pitch for the two BWR fuel assembly types with no boron in the water. These results demonstrate that boron in the WHF pool water is not required for a single BWR fuel assembly under normal handling conditions or upset conditions that involve changes in pin pitch within the confines of the fuel channel.



Source: Original to this document.

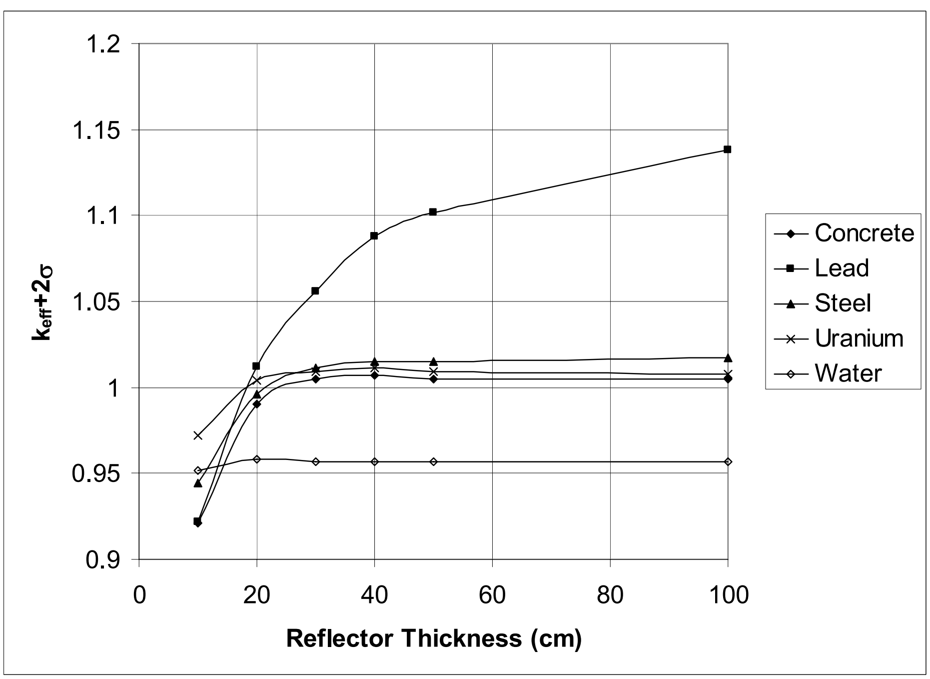
Figure 45. Results for a Single BWR 9x9 Fuel Assembly with Water Moderation and No Boron



Source: Original to this document.

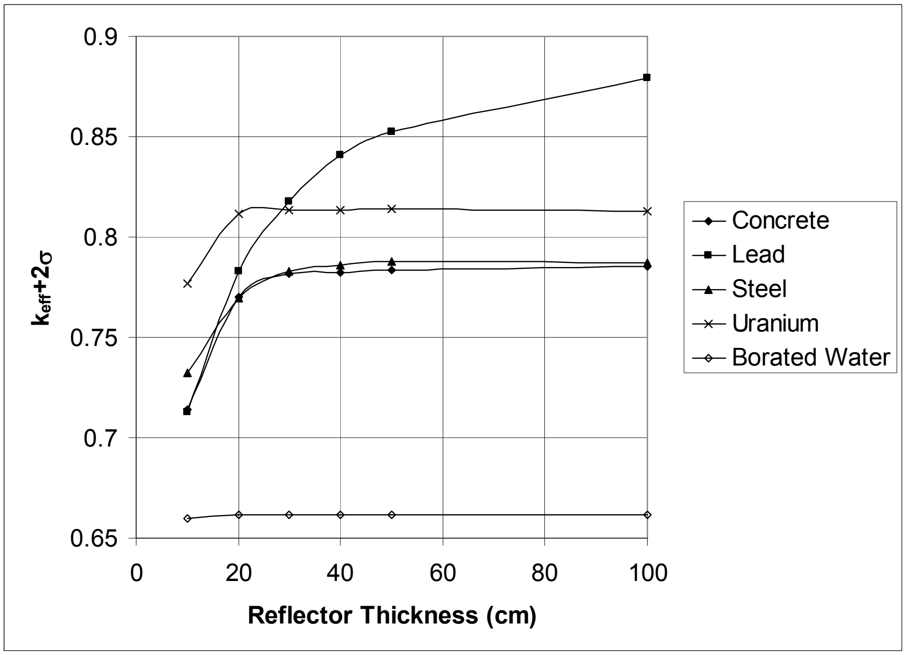
Figure 46. Results for a Single BWR 7x7 Fuel Assembly with Water Moderation and No Boron

Figures 47 through 52 show the effect of varying reflector thickness on system reactivity for the undamaged 17x17 OFA and BWR 7x7 assemblies. These figures demonstrate that the reactivity worth of reflector material beyond 30 cm is negligible with the exception of lead reflection.



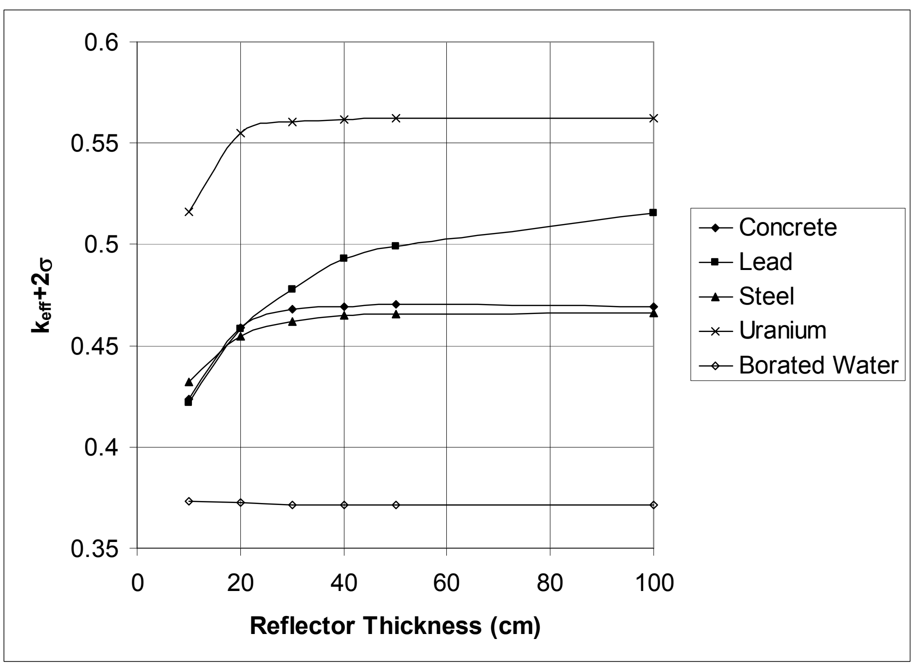
Source: Original to this document.

Figure 47. Reactivity versus Reflector Thickness for a Single 17x17 OFA with no Boron in the Water



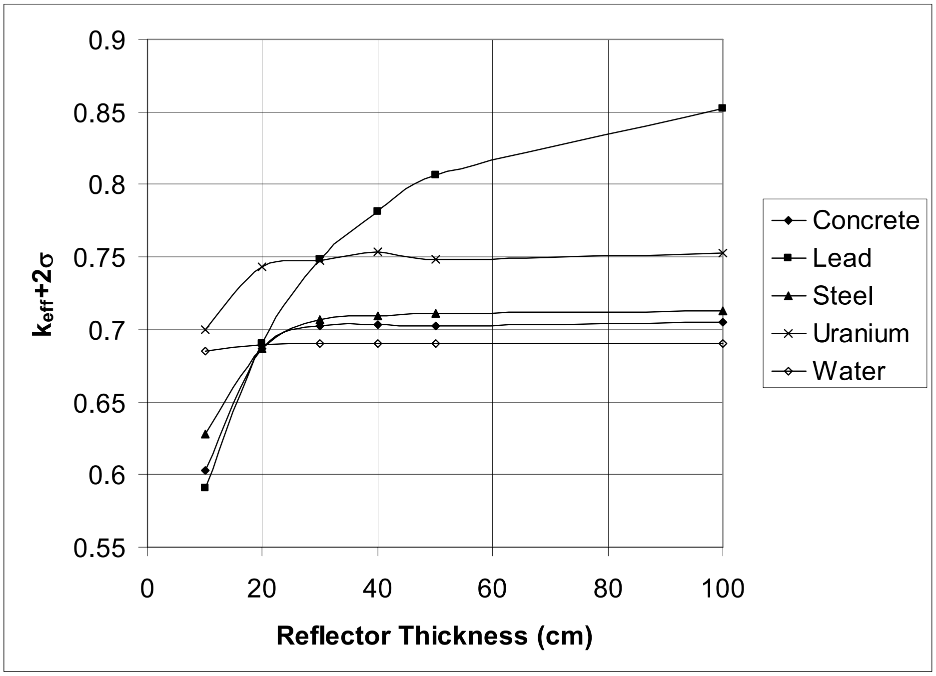
Source: Original to this document.

Figure 48. Reactivity versus Reflector Thickness for 17x17 OFA with 2500 mg/L of Natural Boron in the Water



Source: Original to this document.

Figure 49. Reactivity versus Reflector Thickness for 17x17 OFA with 2500 mg/L of 90 atom% ^{10}B Boron in the Water



Source: Original to this document.

Figure 50. Reactivity versus Reflector Thickness for BWR 7x7 with no Boron in the Water

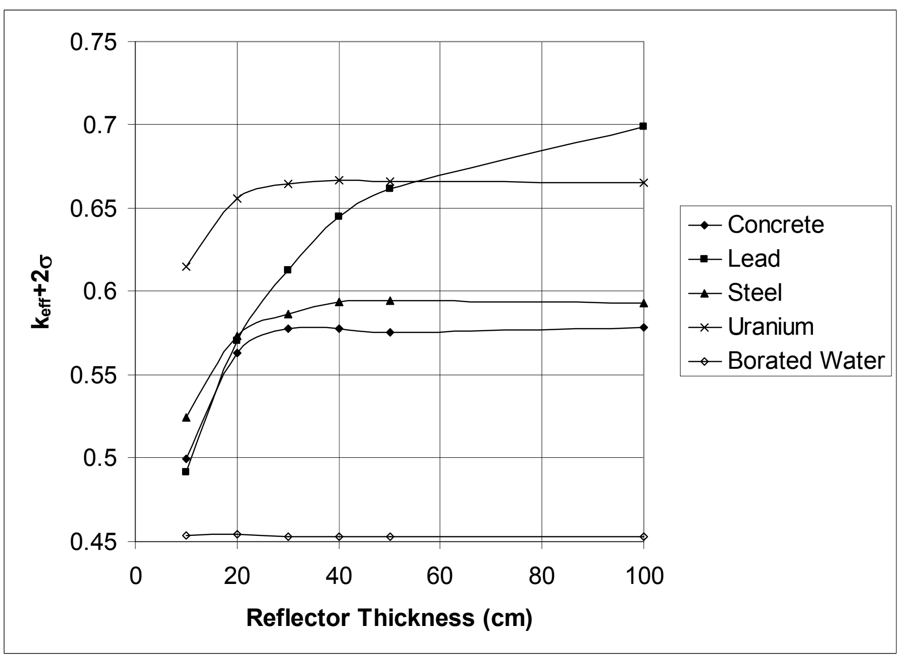


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Figure 51. Reactivity versus Reflector Thickness for BWR 7x7 with 2500 mg/L of Natural Boron in the Water

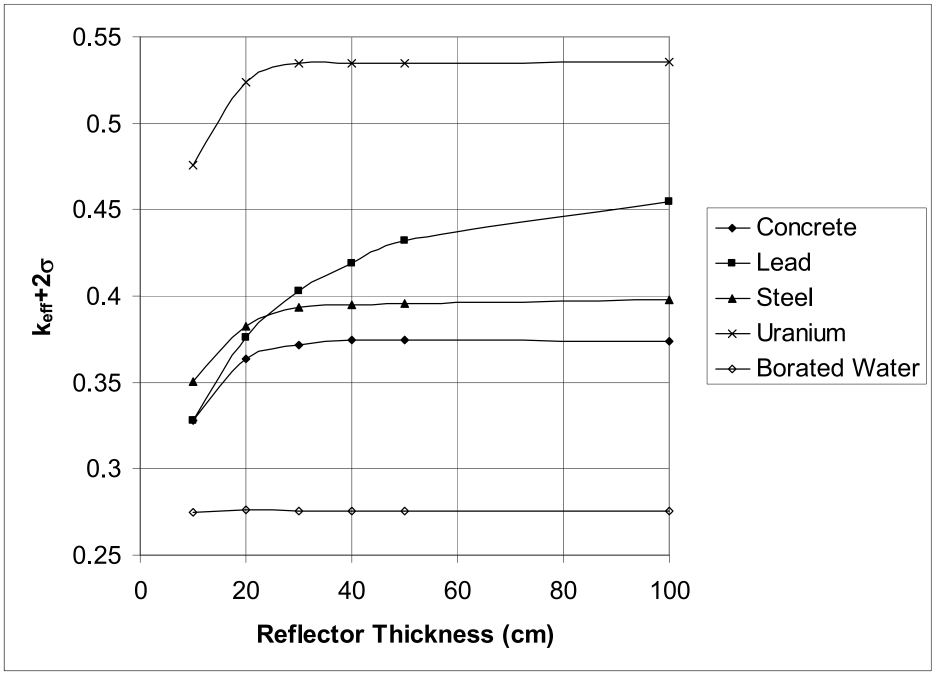

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Figure 52. Reactivity versus Reflector Thickness for BWR 7x7 with 2500 mg/L of 90 atom% ^{10}B Boron in the Water

6.3.2 TAD Canister Results

This section presents the MCNP k_{eff} results for the PWR and BWR fuel in the TAD canister under a variety of conditions. These conditions involved variations in parameters such as flux trap size, boron concentration, and pin pitch and were chosen to cover normal/undamaged conditions and upset conditions. The TAD canister models are described in Section 6.1.3. As described in Section 6.1.3, the TAD canister is effectively modeled as an infinite hexagonal planar array of canisters by imposing mirror reflection conditions on the vertical surfaces of the hexagonal prism surrounding the canister. The parameter variations examined are given in Table 25.

Table 25. Parameter Variations Examined for the TAD Canister MCNP Models

Parameter	Range/Values Examined
Pin pitch – 17x17 OFA (cm)	1.2598 (normal/undamaged) – 1.371[1]
Pin pitch – B&W 15x15 (cm)	1.44272 (normal/undamaged) – 1.5541[1]
Pin pitch – 9x9 (cm)	1.43 (normal/undamaged) – 1.5138 [2]
Pin pitch – 7x7 (cm)	1.8745 (normal/undamaged) – 1.9677[2]
Boron content in the water moderator (mg/L)	0 – 2500
PWR basket flux trap between adjacent fuel compartments (cm)	0.00212 – 2.32433 (normal/undamaged)
BWR basket flux trap between adjacent fuel compartments (cm)	0.0001 – 1.4752 (normal/undamaged)
Presence of borated stainless steel panels	Present (normal/undamaged) Replaced with Stainless Steel Type 304
Axial end reflector (PWR)	Concrete Borated water Steel Lead Natural U
Axial end reflector (BWR)	Concrete below and borated water on top

NOTES: [1] Maximum pitch restricted by fuel compartment size.
[2] Maximum pitch restricted by presence of fuel channel.

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Figures 53 and 54 present the MCNP k_{eff} results for the undamaged PWR basket in a TAD canister with undamaged fuel assemblies. The data presented in Figures 53 and 54 shows little variation in system reactivity due to different axial reflector materials. Further examination of the raw results (See Attachment 2) demonstrates that no single reflector material resulted in the maximum system reactivity over the range of parameters examined. Given this, the rest of the results presented here are based upon the maximum reactivity regardless of axial reflector material. Also, the BWR analysis only examines the normal expected reflection condition with concrete below and borated water above.

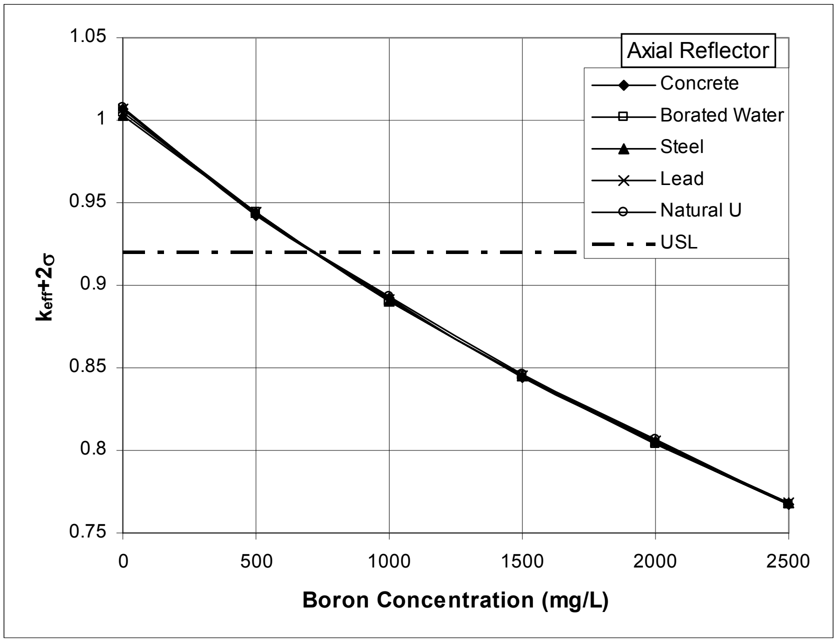

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Figure 53. Results for the PWR TAD Canister with Undamaged Basket and 17x17 OFAs

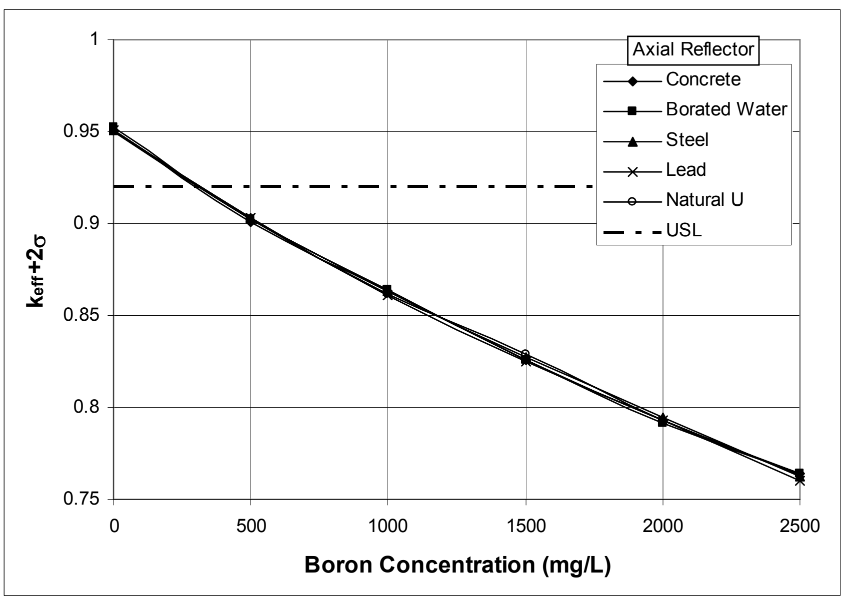

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Figure 54. Results for the PWR TAD Canister with Undamaged Basket and B&W 15x15 Fuel Assemblies

Figures 55 through 58 show the maximum $k_{eff}+2\sigma$ results for all examined pin pitches and axial reflectors. The results presented in Figures 57 and 58 are for those models with the borated steel of the neutron absorber panels replaced by Stainless Steel Type 304. The data presented in Figures 55 through 58 was interpolated to determine the minimum boron concentration needed in the pool for a given flux trap. The interpolated values are presented in Figures 59 and 60 and Table 26.

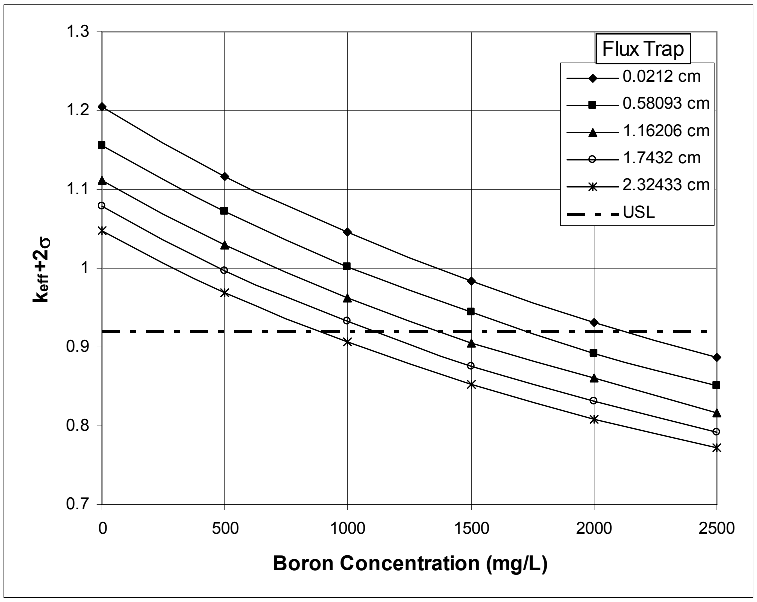

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Figure 55. Maximum $k_{eff}+2\sigma$ results for the PWR TAD Canister with 17x17 OFAs

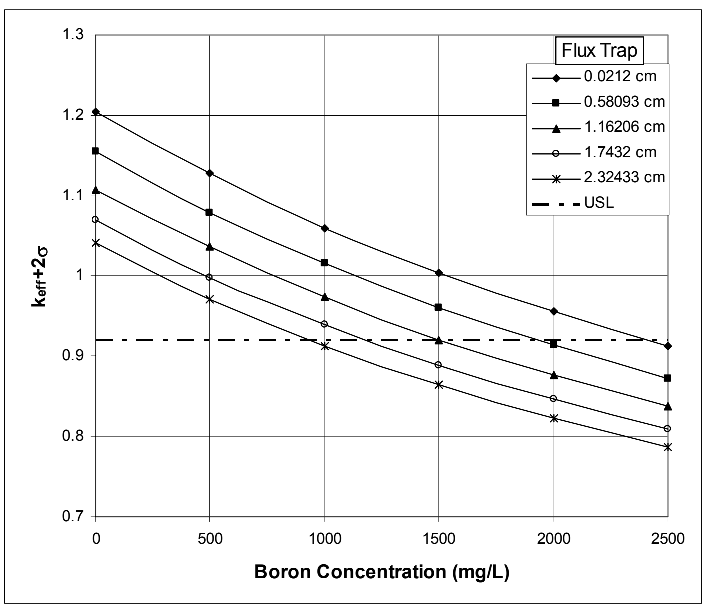

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Figure 56. Maximum $k_{eff}+2\sigma$ results for the PWR TAD Canister with B&W 15x15 Fuel Assemblies

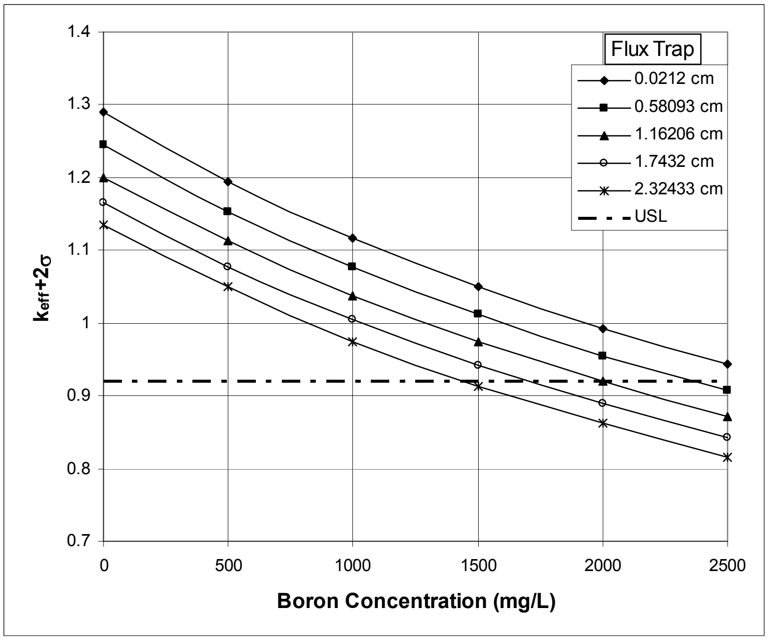

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Figure 57. Maximum k_{eff}+2σ results for the PWR TAD Canister with 17x17 OFAs and Absorber Panels of Stainless Steel Type 304

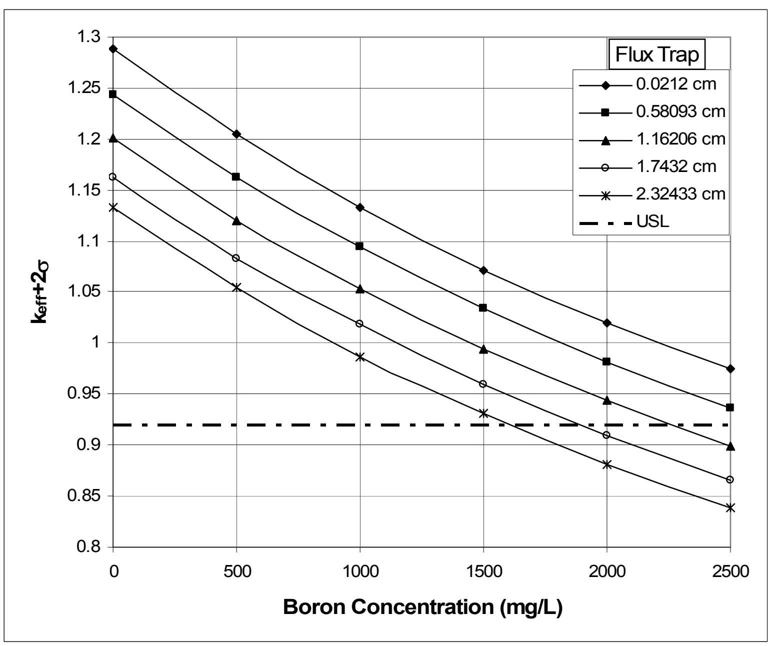

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Figure 58. Maximum k_{eff}+2σ results for the PWR TAD Canister with B&W 15x15 Fuel Assemblies and Absorber Panels of Stainless Steel Type 304

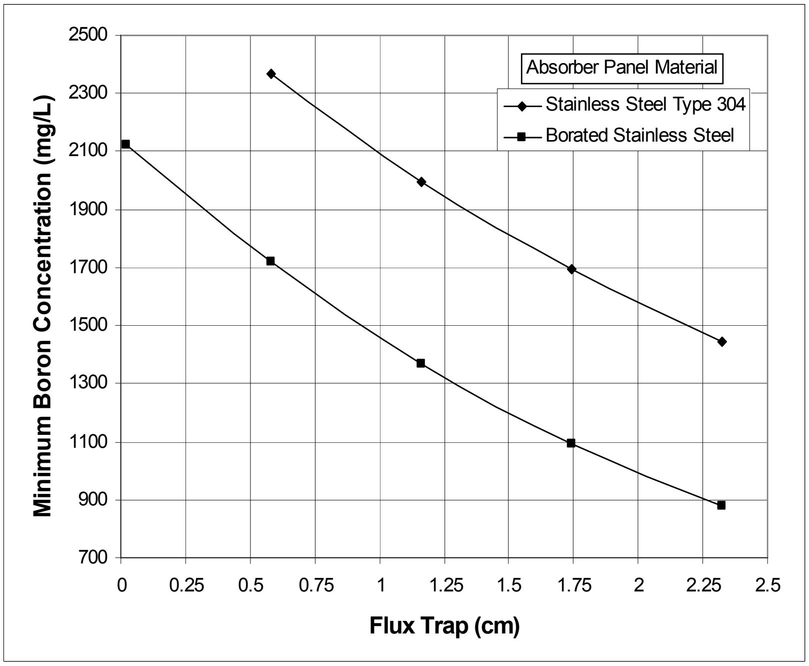

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Figure 59. Minimum Boron Concentration for the TAD Canister with 17x17 OFAs

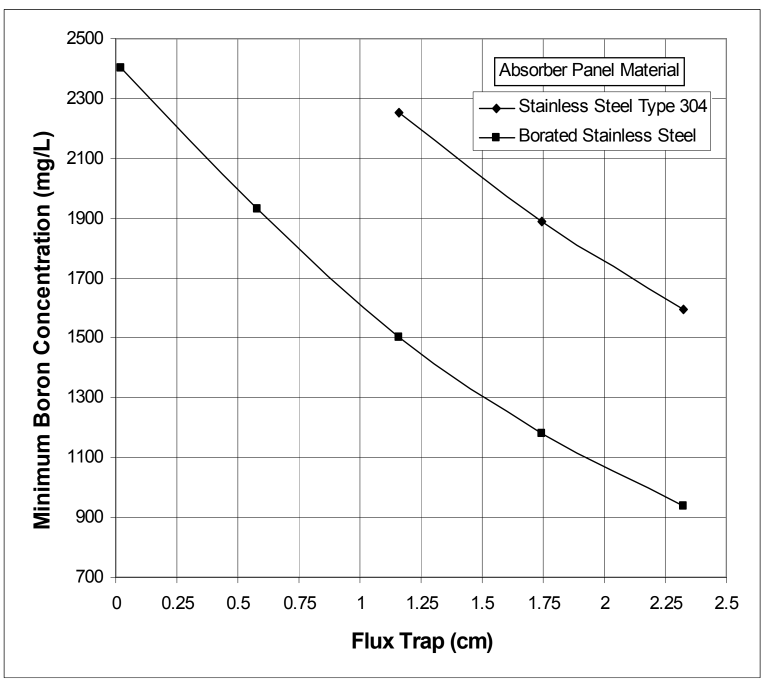

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Figure 60. Minimum Boron Concentration for the TAD Canister with B&W 15x15 Fuel Assemblies

Table 26. Minimum Boron Concentrations for the PWR TAD Canister

Flux Trap (cm)	Minimum Required Boron Concentration to Meet 0.92 USL (mg/L)	
	Basket Modeled with Borated Stainless Steel Absorber Panels	Basket Modeled with Stainless Steel Type 304 Absorber Panels
17x17 OFA		
0.0212	2122	> 2500
0.58093	1720	2370
1.16206	1370	1996
1.7432	1093	1697
2.32433	880	1444
B&W 15x15		
0.0212	2401	> 2500
0.58093	1931	> 2500
1.16206	1503	2255
1.7432	1182	1889
2.32433	937	1597

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Figure 61 presents the $k_{eff}+2\sigma$ results for the TAD canister with undamaged BWR basket and fuel assemblies. Figures 61 through 65 show the maximum $k_{eff}+2\sigma$ results for all examined pin pitches. The results presented in Figures 64 and 65 are for those models with the borated steel of the neutron absorber panels replaced by Stainless Steel Type 304. The data presented in Figures 61 through 65 was interpolated to determine the minimum boron concentration needed in the pool for a given flux trap. The interpolated values for the cases in which the borated stainless steel is replaced by Stainless Steel Type 304 are presented in Figure 66. The interpolated minimum boron concentrations are presented in Table 27. For flux traps of 0.5 cm or greater, the $k_{eff}+2\sigma$ values for the cases that include the borated stainless steel panels do not exceed the 0.92 USL (Assumption 3.1.1) with no boron in the water moderator/reflector.

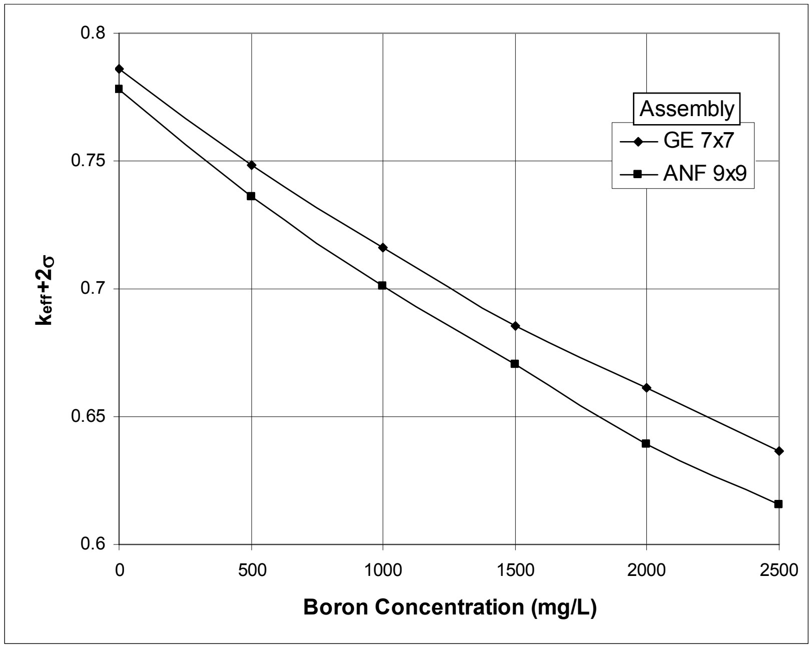

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Figure 61. Results for TAD Canister with Undamaged BWR Basket and Fuel Assemblies

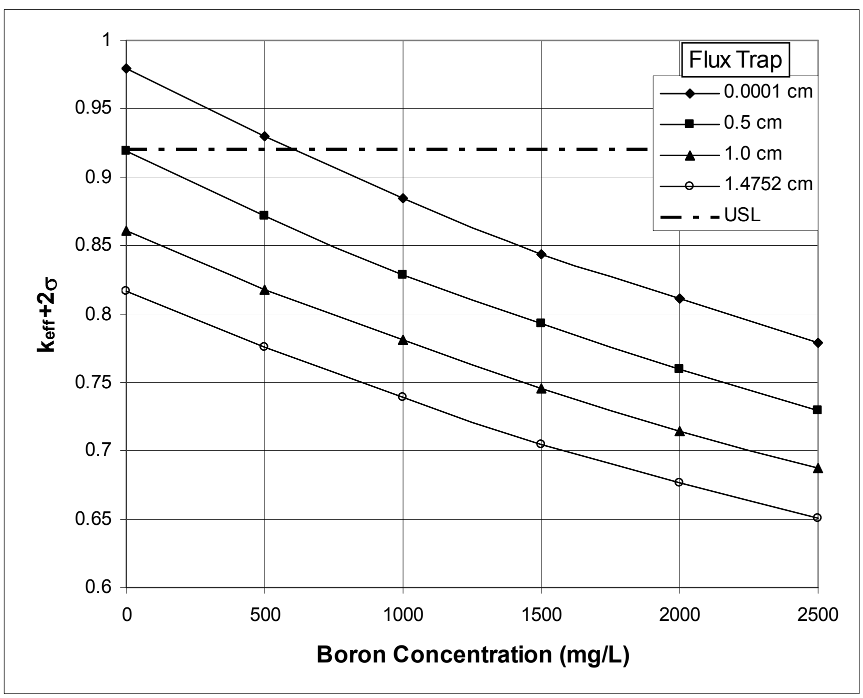

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Figure 62. Maximum $k_{eff}+2\sigma$ Results for the BWR TAD Canister with 7x7 Fuel Assemblies

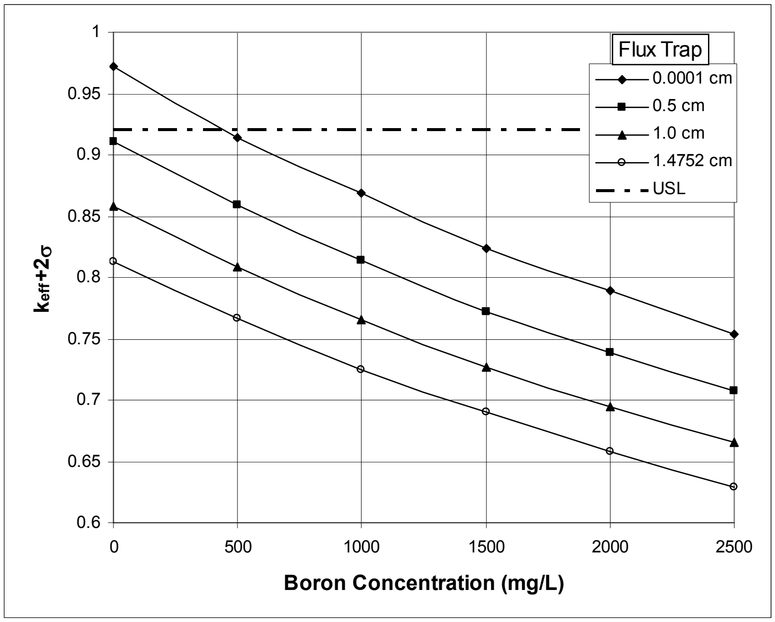

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Figure 63. Maximum k_{eff}+2σ Results for the BWR TAD Canister with 9x9 Fuel Assemblies

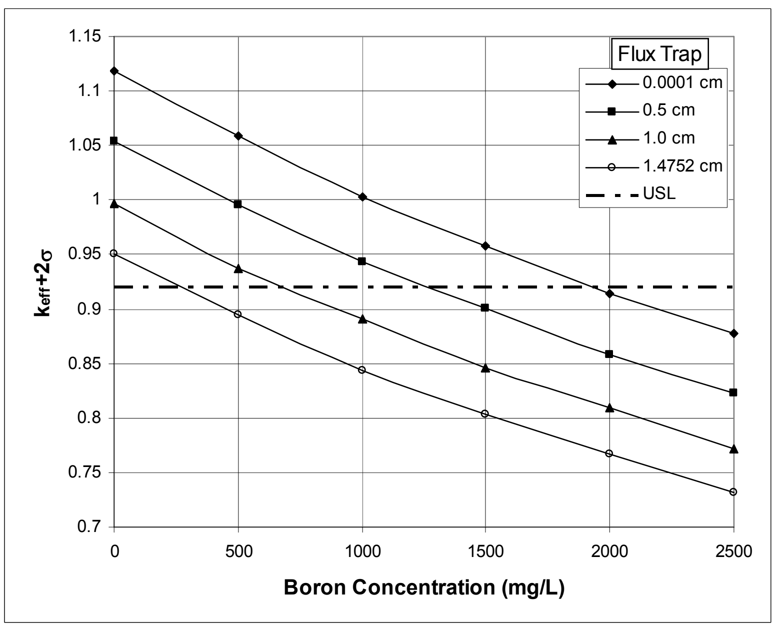

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Figure 64. Maximum k_{eff}+2σ Results for the BWR TAD Canister with 7x7 Fuel Assemblies and Stainless Steel Type 304 Absorber Panels

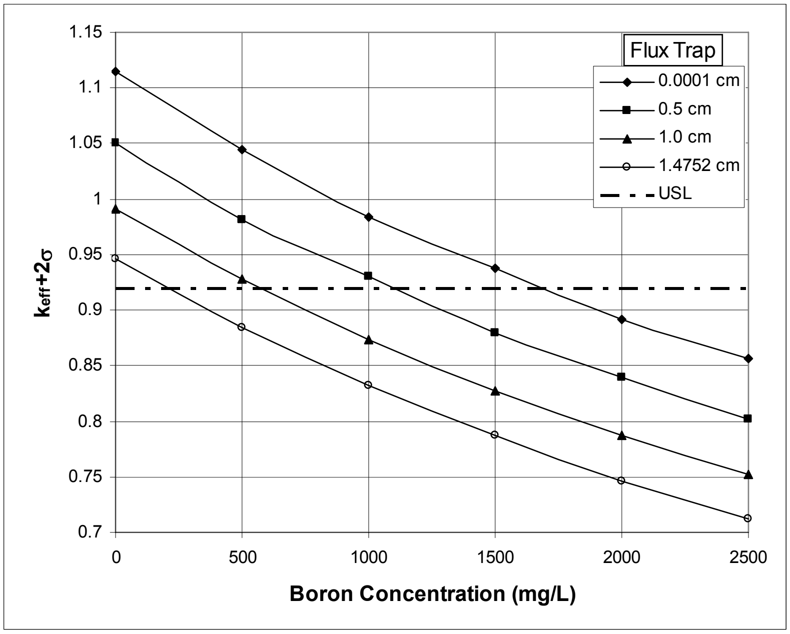

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Figure 65. Maximum k_{eff}+2σ Results for the BWR TAD Canister with 9x9 Fuel Assemblies and Stainless Steel Type 304 Absorber Panels

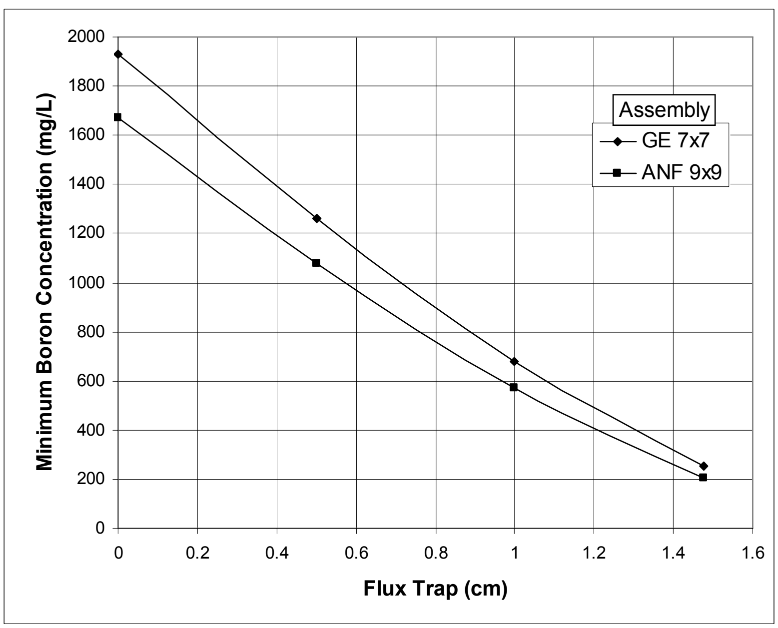

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Figure 66. Minimum Boron Concentration for the BWR TAD Canister with Stainless Steel Type 304 Absorber Panels

Table 27. Minimum Boron Concentrations for the BWR TAD Canister

Flux Trap (cm)	Minimum Boron Concentration to Meet 0.92 USL (mg/L)	
	Basket Modeled with Borated Stainless Steel Absorber Panels	**Basket Modeled with Stainless Steel Type 304 Absorber Panels**
GE 7x7		
0.0001	599	1930
0.5	0	1264
1	0	678
1.4752	0	256
ANF 9x9		
0.0001	453	1671
0.5	0	1080
1	0	571
1.4752	0	206

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6.3.3 DPC Results

The section presents the MCNP k_{eff} results for the PWR and BWR fuel in the DPC under a variety of conditions. These conditions involved variations in parameters such as flux trap size, boron concentration, and pin pitch and were chosen to cover normal/undamaged conditions and upset conditions. The DPC models are described in Section 6.1.4. As described in Section 6.1.4, the DPC is effectively modeled as an infinite hexagonal planar array of canisters by imposing mirror reflection conditions on the vertical surfaces of the hexagonal prism surrounding the canister.

The parameter variations examined are given in Table 28. These models included water in the gap between the fuel and clad only. The only reflection conditions evaluated for the fully flooded PWR DPCs is having borated water above and concrete below, which is the anticipated normal reflection condition of the DPCs in the WHF pool. This is based upon the results in Figure 53 for the PWR TAD canister which shows no significant variation in reactivity with changing axial reflector types. The PWR TAD canister is considered to be sufficiently similar in design to the PWR DPC that its reactivity characteristics related to changes in axial reflection conditions would be similar. The BWR DPC is evaluated as the BWR TAD Canister with only water (with or without boron) on top and concrete on the bottom.

Examination of the results in Attachment 2 demonstrated that there was no significant variation in reactivity due to variations in the space between the bottom of the fuel assemblies and the inside bottom of the DPC. In all cases the variation in k_{eff} was observed to be less than 1% and generally less than 0.5%. As a result, these results are not presented further here. Further, as indicated in Table 28 the PWR fuel bunching models and PWR dry models were performed with a fixed spacing as indicated.

Table 28. Parameter Variations Examined for the DPC MCNP Models

Parameter/Condition	Range/Value Examined
Pin pitch – 17x17 OFA (cm)	1.2598 (normal/undamaged) – 1.3583[(1)]
Pin pitch – B&W 15x15 (cm)	1.371 – 1.5396[(1)] 1.4427 (normal/undamaged)
Pin pitch – 9x9 (cm)	1.43 (normal/undamaged) – 1.5138[(2)]
Pin pitch – 7x7 (cm)	1.8745 (normal/undamaged) – 1.9677[(2)]
Boron content in the water moderator (mg/L)	0 – 2500
Axial reflectors	Water (with or without boron) on top Concrete on bottom
Bottom Space between Bottom of Fuel Assembly and Inside Bottom of DPC (cm)	
17x17 OFA	0.001 – 47.11[(3)]
B&W 15x15	0.001 – 32.225[(3)]
9x9	0.001 – 5.7254[(3)]
7x7	0.001 – 5.8727[(3)]
PWR basket flux trap between adjacent fuel compartments (cm)	0.001 – 2.7686
PWR fuel bunching – 17x17 OFA undamaged (normal pin pitch)	Patterns 1 and 2 from Figure 23 Flux trap 0.001 cm and 2.7686 cm Bottom space between fuel assembly and inside bottom of DPC: 15.24 cm
BWR fuel bunching – 9x9 undamaged fuel assemblies	Pattern as given in Figure 27
Presence of Boral panels – PWR basket	Present (normal/undamaged) Replaced with void
[(4)]Boral panels replaced by void in central area of BWR basket for borated water concentrations of 1000 – 1500 mg/L and the nominal fuel pin pitch. Bottom space between fuel assembly and inside bottom of DPC: 2.54 cm	0 (normal/undamaged) – 32
[(4)]Reduced Boral density of Boral plates in BWR basket for borated water boron concentrations of 1000 – 2000 mg/L for BWR basket and the nominal fuel pin pitch. Bottom space between fuel assembly and inside bottom of DPC: 2.54 cm	0.247 – 2.476 (normal/undamaged)g/cm^3
[(4)]Void fraction in water/borated water of PWR DPC with B&W 15x15 fuel assemblies and nominal fuel pin pitch for boron concentrations 0 – 2500 mg/L. Bottom space between fuel assembly and inside bottom of DPC: 2.54 cm	0 – 0.995
[(5)]PWR DPC dry and undamaged with undamaged/normal fuel. Only variation performed is changing axial reflectors for both PWR fuel types. Bottom space between fuel assembly and Inside bottom of DPC: 15.24 cm	Reflectors: concrete, water, steel, lead, and natural U.
[(5)]BWR DPC dry and undamaged with undamaged/normal fuel. Only variation performed is changing axial reflectors for both BWR fuel types. Bottom space between fuel assembly and inside bottom of DPC: 2.54 cm	Reflectors: concrete, water, steel, lead, and natural U.

NOTES: [(1)] Maximum pitch restricted by fuel compartment size.
[(2)] Maximum pitch restricted by presence of fuel channel.
[(3)] Maximum bottom space examined based on overall fuel assembly height and interior height of DPC.
[(4)] These parameter variations were examined separately from the other parameter variations.
[(5)] No moderation in DPC. Water is modeled in the fuel/clad gap.

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Figure 67 presents the $k_{eff}+2\sigma$ results for an undamaged DPC loaded with undamaged PWR fuel assemblies. The results are maximized over the range of bottom space values examined as given in Table 28. Figures 68 through 71 show the maximum $k_{eff}+2\sigma$ results for all examined pin pitches. The results presented in Figures 70 and 71 are for those models with the Boral plates modeled as void. The data presented in Figures 68 through 71 was interpolated to determine the minimum boron concentration needed in the pool for a given flux trap. The interpolated values for the cases in which the Boral plates are present are presented in Figure 72. The interpolated minimum boron concentrations are presented in Table 29. For flux traps of ≤0.635 cm (17x17 OFA) or ≤1.27 cm (B&W 15x15) and the Boral plates modeled as void the $k_{eff}+2\sigma$ values exceed the 0.92 USL (Assumption 3.1.1) at the largest boron concentration examined (2500 mg/L). These are noted as >2500 in Table 29.

Table 30 presents the $k_{eff}+2\sigma$ results for an undamaged/dry DPC loaded with undamaged PWR fuel assemblies.

The $k_{eff}+2\sigma$ results of the MCNP models examining fuel bunching in the PWR DPC are presented in Table 31. These results show there is little change in the reactivity of the system due to changes in fuel assembly placement within the fuel compartments of the PWR DPC.

A single MCNP model examined the effect of placing a fuel assembly horizontally across a PWR DPC. All the fuel assemblies involved were 17x17 OFAs. The boron concentration of the water is 1500 mg/L. The physical description of the model can be found in Section 6.1.4. The fuel assemblies are modeled elevated above the bottom of the DPC to bring them in close proximity to the fuel assembly on top of the DPC. The fuel assemblies and DPC basket are undamaged and the fuel is centered in the fuel compartments. This model resulted in a $k_{eff}+2\sigma$ of 0.81943 (DPC_17OFA_Assembly_on_topo in MCNP Files.zip from Attachment 2). The normal case without the fuel assembly on top results in a $k_{eff}+2\sigma$ of 0.82081 (DPC_17OFA_B_2.7686_1.2598_47.11_1500_ino in MCNP Files.zip from Attachment 2). These results show that there is no significant change in reactivity due to a single fuel assembly lying across the top of the DPC.

A set of MCNP models examined the effect of increasing the void fraction in the water/borated water for the PWR DPC loaded with B&W 15x15 fuel assemblies. The void fraction was simply factored into the modeled density of the water/borated water by multiplying the water density (Section 6.2.3.1) or borated water density (Section 6.2.3.2) by a factor of 1 – void fraction. Figure 73 presents the results which clearly show a trend of decreasing reactivity with increased void fraction modeled in the water/borated water of the moderator and top axial reflector.

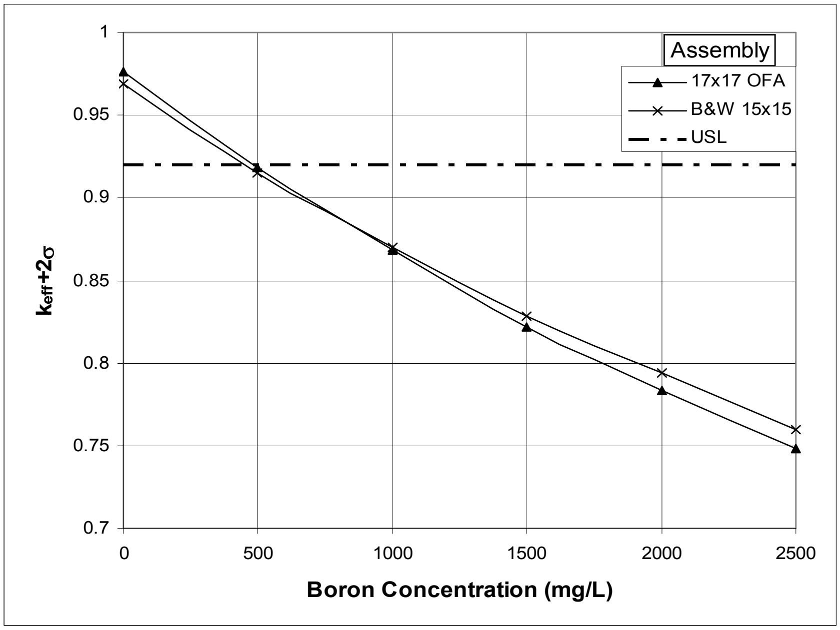

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Figure 67. Results for the PWR DPC with Undamaged Fuel Basket and Fuel Assemblies

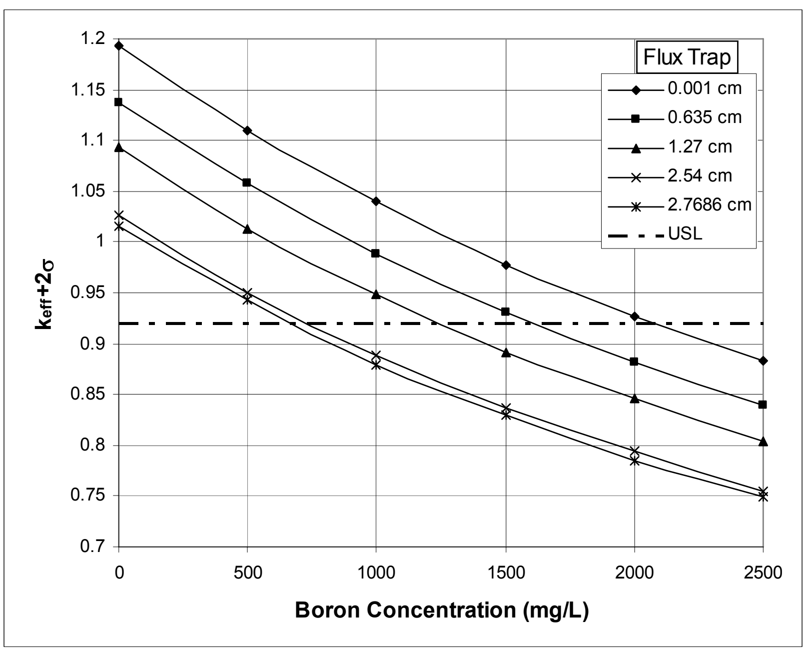

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Figure 68. Maximum k_{eff}+2σ Results for the PWR DPC with 17x17 OFAs

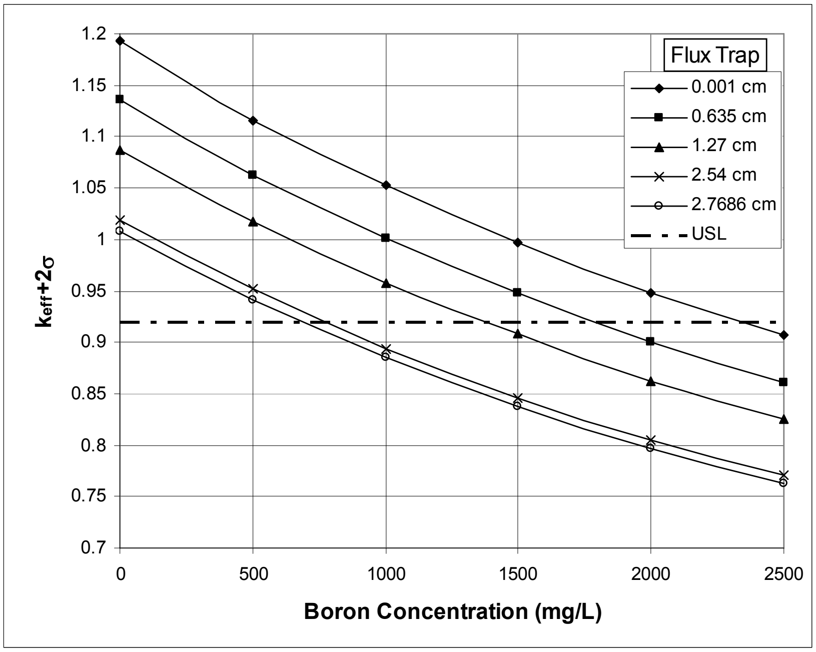

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Figure 69. Maximum k_{eff}+2σ Results for the PWR DPC with B&W 15x15 Fuel Assemblies

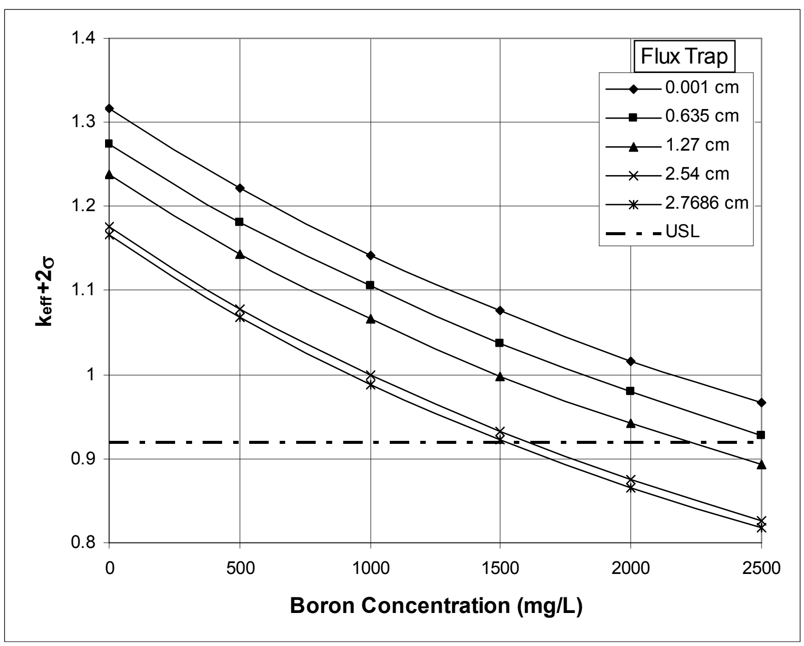

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Figure 70. Maximum k_{eff}+2σ Results for the PWR DPC with 17x17 OFAs and Boral Plates Modeled as Void

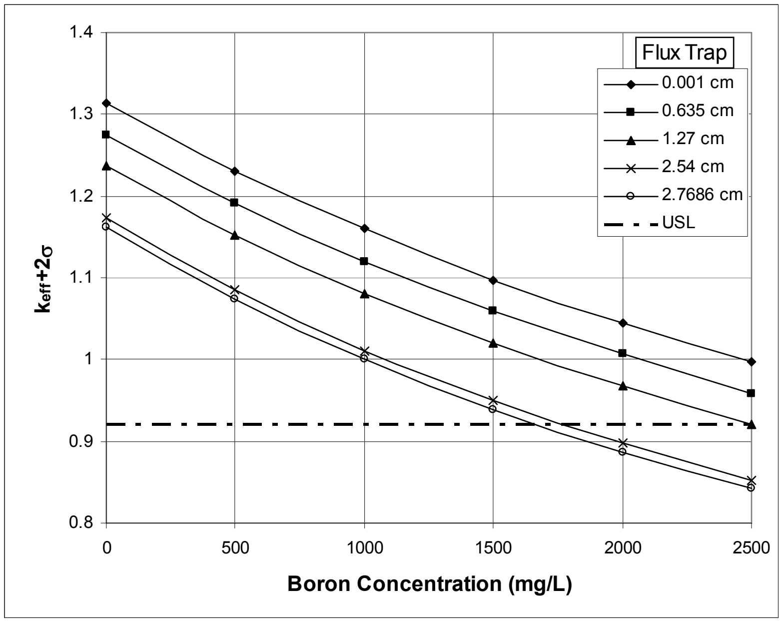

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Figure 71. Maximum k_{eff}+2σ Results for the PWR DPC with B&W 15x15 Fuel Assemblies and Boral Plates Modeled as Void

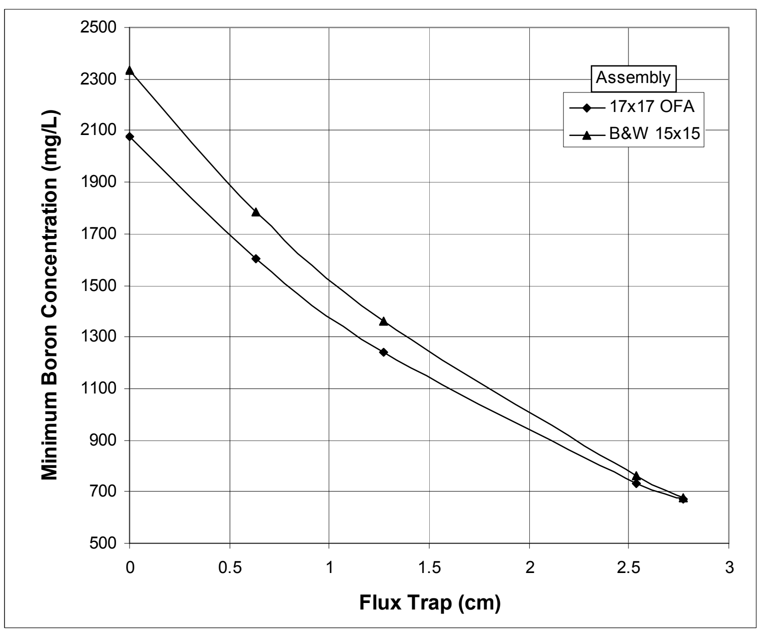

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Figure 72. Minimum Boron Concentration for the PWR DPC with the Boral Plates Present

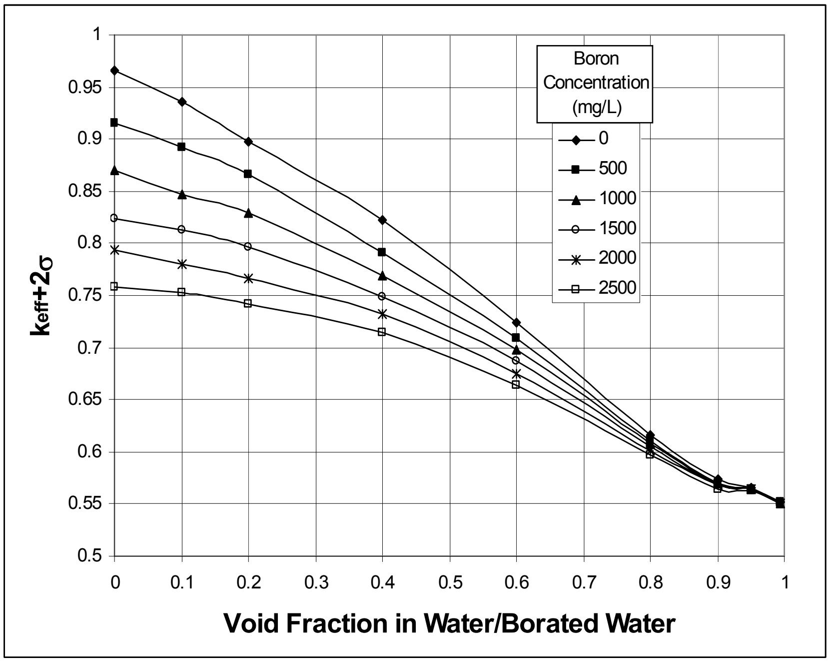

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Figure 73. $k_{eff}+2\sigma$ Results for the PWR DPC with B&W 15x15 Fuel Assemblies with Varying Void Fraction in Water/Borated Water

Table 29. Determined Minimum Boron Concentrations for the PWR DPC

Flux Trap (cm)	Minimum Required Boron Concentration to Meet 0.92 USL (mg/L)	
	Boral Plates Present	**Boral Plates Modeled as Void**
17x17 OFA		
0.001	2076	> 2500
0.635	1603	> 2500
1.27	1243	2216
2.54	731	1604
2.7686	670	1516
B&W 15x15		
0.001	2333	> 2500
0.635	1786	> 2500
1.27	1364	> 2500
2.54	764	1778
2.7686	678	1671

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Table 30. k_{eff}+2σ Results for Dry Undamaged PWR DPCs

Axial Reflector	k_{eff}+2σ for 17x17 OFAs	k_{eff}+2σ for B&W 15x15 Fuel Assemblies
Concrete	0.54762	0.57393
Water	0.54571	0.57255
Steel	0.55031	0.57601
Lead	0.55288	0.57947
Natural U	0.55023	0.57699

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Table 31. k_{eff}+2σ Due to Bunching of Fuel in a PWR DPC with 17x17 OFAs

Fuel Position/Pattern	Flux Trap (cm)	k_{eff}+2σ
Centered	0.001	0.96369
Pattern 1	0.001	0.96642
Pattern 2	0.001	0.94676
Centered	2.7686	0.82180
Pattern 1	2.7686	0.81962
Pattern 2	2.7686	0.80899

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Figure 74 presents the k_{eff}+2σ results for the BWR DPC as described in Section 6.1.4.2 with undamaged fuel assemblies. Figure 75 presents the maximum k_{eff}+2 σ results for the BWR DPC over the range of model variations given in Table 28. The data presented in Figure 75 are interpolated to determine the minimum required boron concentration needed to meet the 0.92 USL (Assumption 3.1.1). The results of the interpolations are presented in Table 32.

Three additional models were created for the DPC with the BWR basket to address variations due to off-normal conditions. These involved reducing the Boral density, missing Boral plates, and bunching of fuel assemblies. The variations for the Boral density and the missing Boral plates are described in Table 28.

Figures 76 through 79 present the results of reducing the Boral density and removing Boral plates from the central region of the BWR basket. The results show that with a boron concentration of 1500 mg/L in the water, the Boral density reduced to 20% (0.494 g/cm^3) of its original value would not result in the reactivity of the system exceeding the 0.92 USL (Assumption 3.1.1). The results also show that with a boron concentration of 1500 mg/L more than 16 of the Boral panels must be missing from the center fuel compartments before the 0.92 USL can be exceeded.

The fuel bunching variation examined is described in Section 6.1.4.2 and depicted in Figure 27. This single model was run with the DPC loaded with undamaged 7x7 fuel assemblies, a boron concentration of 1500 mg/L, and a space between the bottom of the fuel and the inside bottom of the DPC of 2.54 cm. The results of this model and the fuel centered model are presented in Table 33. This shows that the off-centered fuel loading can raise the reactivity of the system by approximately 1%; however, given a nominal 1500 mg/L of Boron in the WHF pool water, the reactivity remains well below the 0.92 USL.

A set of MCNP models examined the effect of increasing the void fraction in the water/borated water for the BWR DPC loaded with 7x7 fuel assemblies. The void fraction was simply factored into the modeled density of the water/borated water by multiplying the water density (Section 6.2.3.1) or borated water density (Section 6.2.3.2) by a factor of 1 – void fraction. Figure 80 presents the results which clearly show a trend of decreasing reactivity with increased void fraction modeled in the water/borated water of the moderator and top axial reflector.

Table 34 presents the k_{eff}+2σ results for an undamaged/dry DPC loaded with undamaged BWR fuel assemblies.

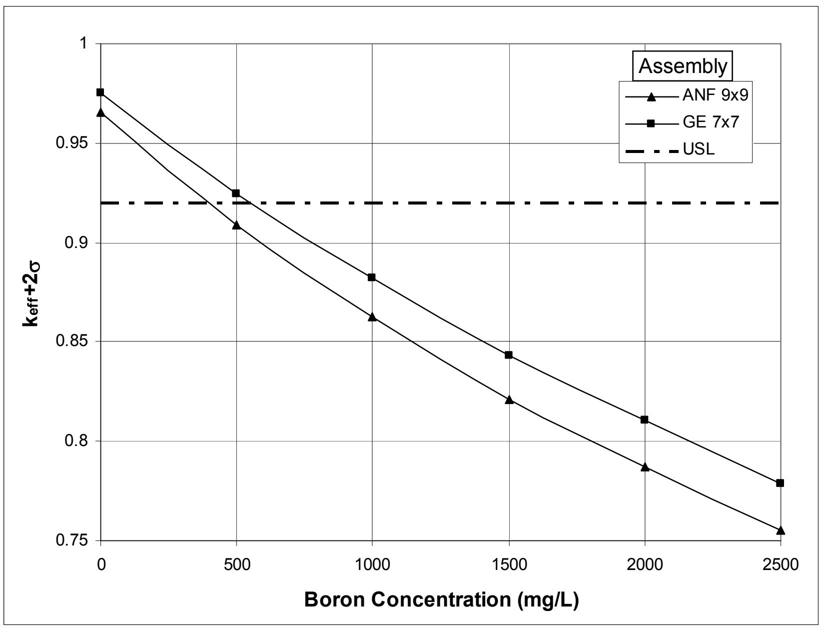

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Figure 74. k_{eff}+2σ Results for the BWR DPC with Undamaged Fuel Assemblies

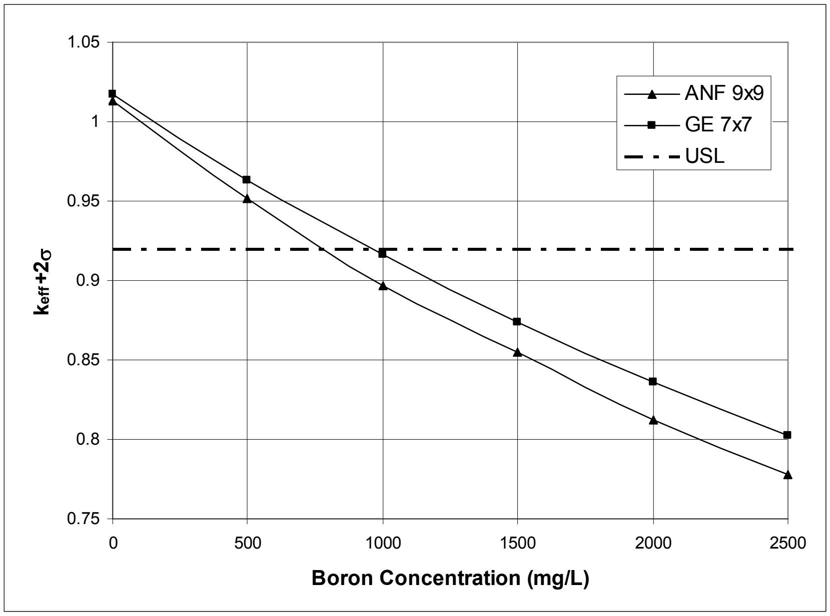

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Figure 75. Maximum k_{eff}+2σ Results for the BWR DPC

Table 32. Minimum Boron Concentrations for the BWR DPC

Fuel	Minimum Required Boron Concentration to Meet 0.92 USL (mg/L)
GE 7x7	953
ANF 9x9	784

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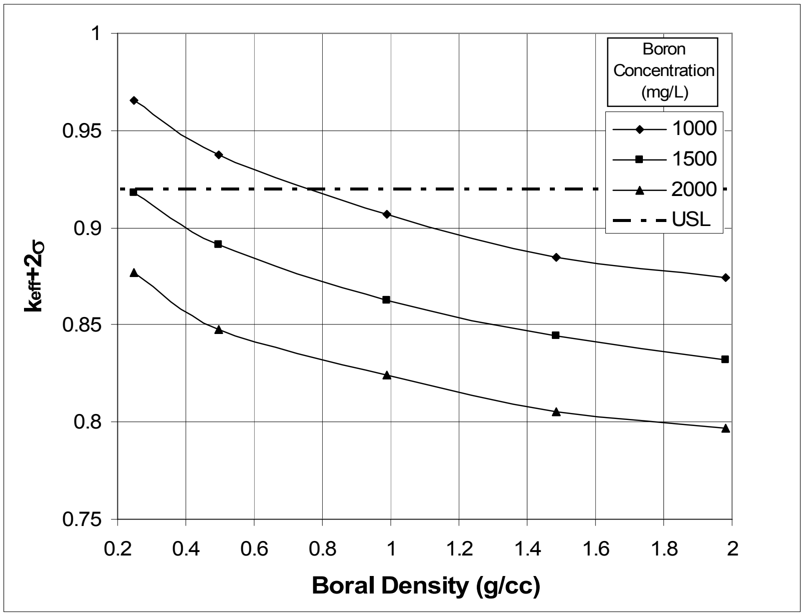

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Figure 76. Effect of Boral Plate Density on k_{eff}+2σ for the BWR DPC with 9x9 Fuel Assemblies

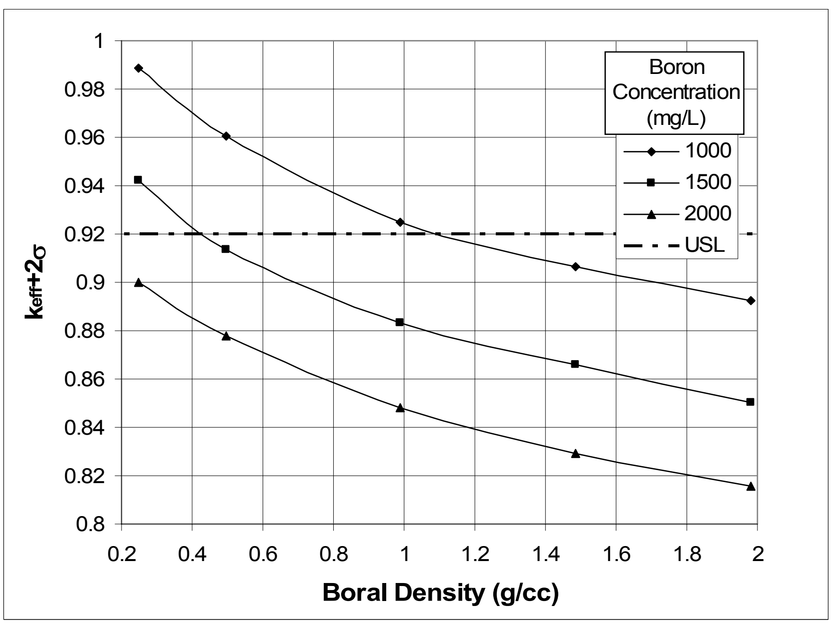

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Figure 77. Effect of Boral Plate Density on k_{eff}+2σ for the BWR DPC with 7x7 Fuel Assemblies

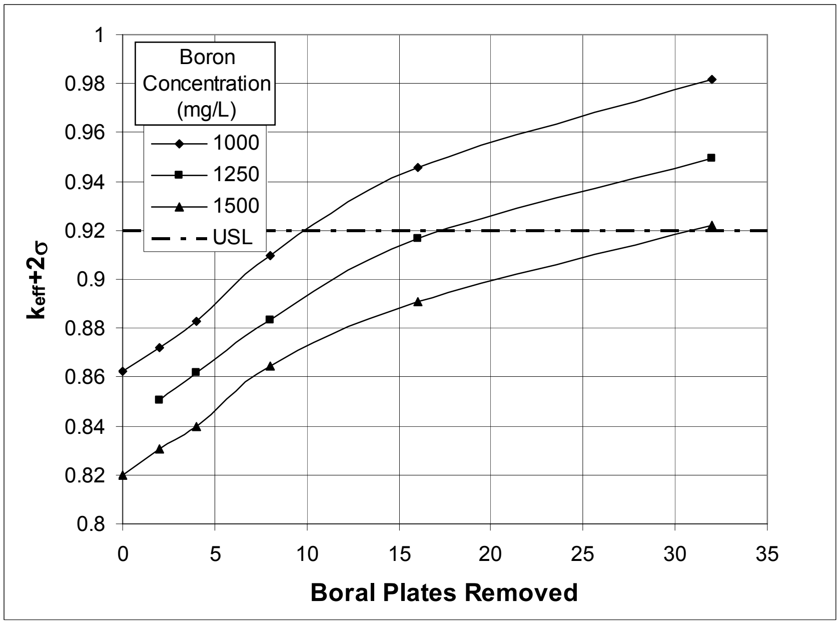

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Figure 78. Effect of Removing Boral Plates on keff+2σ for the BWR DPC with 9x9 Fuel Assemblies

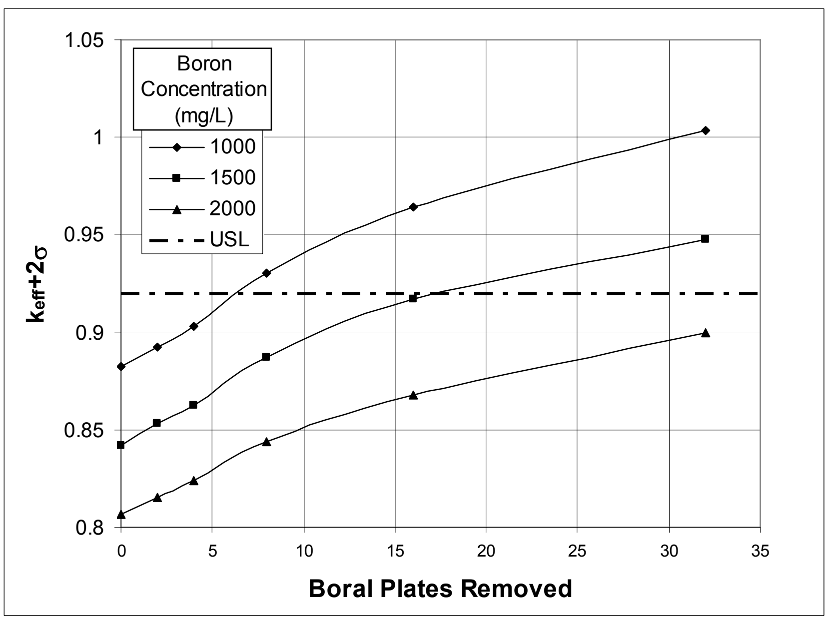

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Figure 79. Effect of Removing Boral Plates on k_{eff}+2σ for the BWR DPC with 7x7 Fuel Assemblies

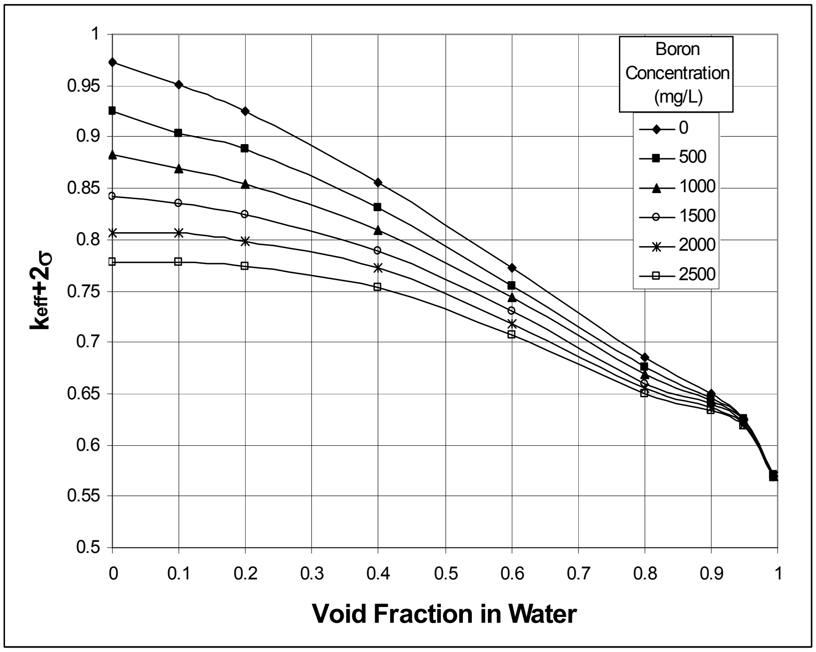

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Figure 80. k_{eff}+2σ Results for the BWR DPC with 7x7 Fuel Assemblies with Varying Void Fraction in Water/Borated Water

Table 33. k_{eff}+2σ Results for the DPC with BWR Fuel Basket Loaded with 7x7 Fuel Assemblies and Fuel Assemblies Loaded Off-Center within the Fuel Compartments

Pattern	Boron Concentration (mg/L)	Pin Pitch (cm)	Bottom Space (cm)	k_{eff}+2σ
Centered	1500	1.8745	2.54	0.84188
Off-center per Figure 27	1500	1.8745	2.54	0.85109

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Table 34. k_{eff}+2σ Results for Dry Undamaged BWR DPCs

Axial Reflector	k_{eff}+2σ for 7x7 Fuel Assemblies	k_{eff}+2σ for 9x9 Fuel Assemblies
Concrete	0.58843	0.56345
Water	0.58631	0.56245
Steel	0.59008	0.56581
Lead	0.59180	0.56690
Natural U	0.59001	0.56611

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6.3.4 WHF Pool Staging Rack Results

This section presents the MCNP k_{eff} results for the PWR and BWR fuel WHF pool staging racks under a variety of conditions. The variations in these conditions are designed, initially, to cover normal conditions, some basic upset conditions (e.g., changes in fuel pin pitch), and to help understand and identify parameters important to ensuring the staging racks remain subcritical (e.g., minimum boron concentration). Additional models are developed based upon the results of these initial runs, as needed, to further evaluate parameters that may be important to potential upset conditions (e.g., fuel assembly bunching) or in furthering the understanding of the reactivity of the system.

The MCNP models utilized for the staging racks are discussed in detail in Sections 6.1.5 and 6.1.6. Four different fuel assemblies were examined (2 PWR and 2 BWR). For each fuel assembly type a number of parameters were varied in a matrix fashion. The initial parameters varied and the ranges/values examined are shown in Table 35.

Table 35. Parameter Variations Examined for the WHF CSNF Staging Racks

Parameter	Range/Value Examined
Pin pitch – 17x17 OFA (cm)	1.2598 (normal/undamaged) – 1.37[(1)]
Pin pitch – B&W 15x15 (cm)	1.4427 (normal/undamaged) – 1.55[(1)]
Pin pitch – 9x9 (cm)	1.43 (normal/undamaged) – 1.51[(2)]
Pin pitch – 7x7 (cm)	1.8745 (normal/undamaged) – 1.968[(2)]
Boron content in the water moderator (mg/L)	0 – 2500
Flux trap between adjacent fuel compartments (cm)	1.27 – 7.62 PWR (normal/undamaged): 3.81 BWR (normal/undamaged): 3.4925
Presence of Boral panels	Present (normal/undamaged) Replaced with void
Fuel bunching – 17x17 OFAs	Off centered according to patterns given in Figure 35
Fuel assembly on top of PWR CSNF Staging Rack – 17x17 OFAs	As described in Section 6.1.5 and depicted in Figure 33 and Figure 34

NOTES: [(1)] Maximum pitch restricted by fuel compartment size.
[(2)] Maximum pitch restricted by presence of fuel channel.

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Figure 81 presents the $k_{eff}+2\sigma$ results for the undamaged PWR staging racks with undamaged fuel assemblies. Figures 82 through 85 present the maximum $k_{eff}+2\sigma$ results for the PWR staging racks for all examined pin pitches. Figures 84 and 85 present results for the PWR staging racks with the Boral plates modeled as void. For data sets with at least one $k_{eff}+2\sigma$ value greater than the 0.92 USL (Assumption 3.1.1), the data is interpolated to provide a minimum required boron concentration. The minimum required boron concentrations for the WHF PWR CSNF staging racks are presented in Figures 86 and 87 and in Table 36.

Two variations of the undamaged PWR staging racks were examined using undamaged 17x17 OFAs. These were a fuel assembly lying horizontally across the top of the rack and the fuel assemblies placed in off-centered positions within the fuel compartments. Each of these models is discussed in Section 6.1.5. In each case, the boron content in the water is assumed to be either 1000 or 1500 mg/L. The flux trap is taken as the minimum needed such that the reactivity of the system does not exceed the 0.92 USL with no boron in the pool water. From Figure 82 this would be 2 inches (5.08 cm). The results of these variations are presented in Tables 37 and 38.

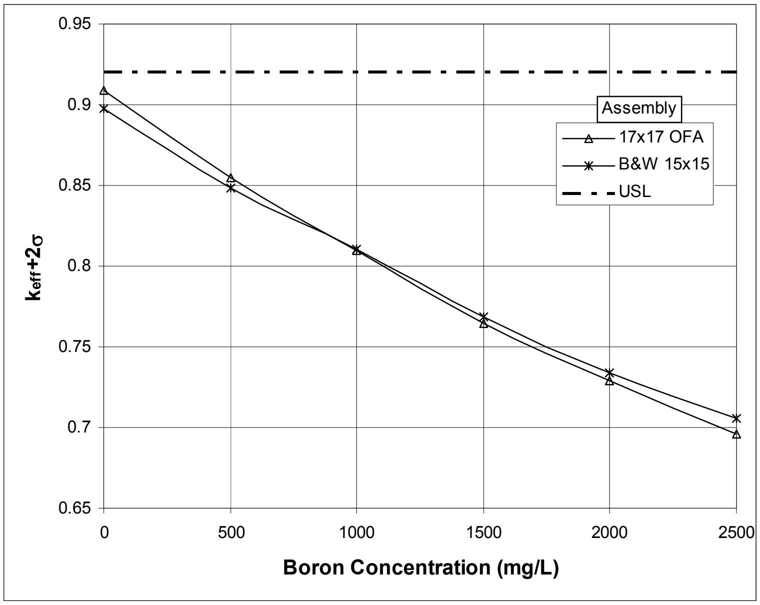

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Figure 81. k_{eff}+2σ Results for the Undamaged PWR Staging Rack with Undamaged Fuel Assemblies

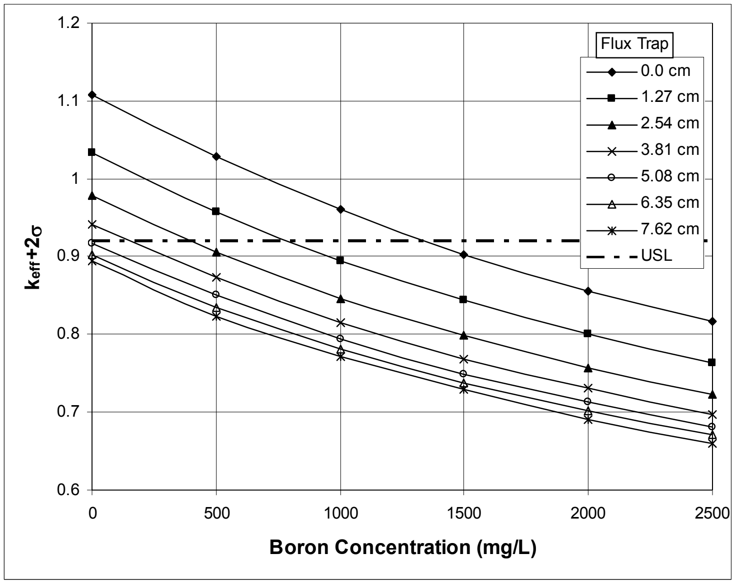

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Figure 82. Maximum k_{eff}+2σ Results for the PWR Staging Rack with 17x17 OFAs

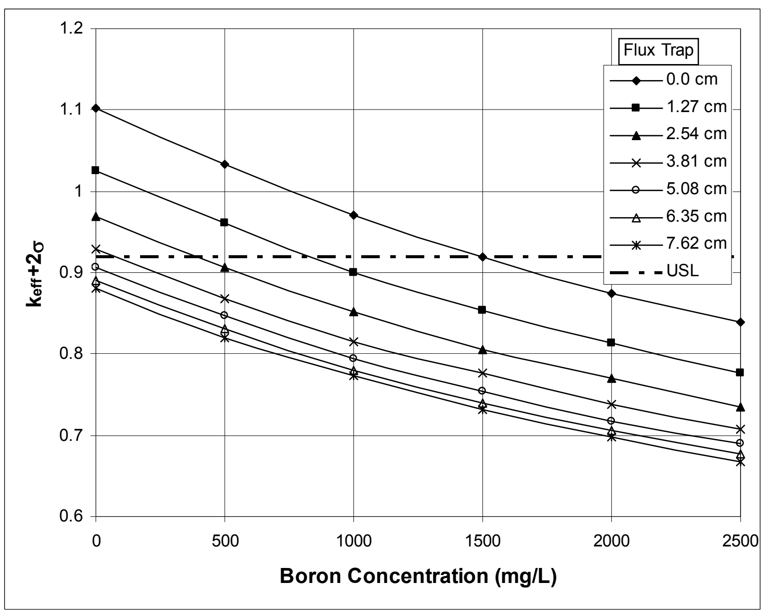

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Figure 83. Maximum k_{eff}+2σ Results for the PWR Staging Rack with B&W 15x15 Fuel Assemblies

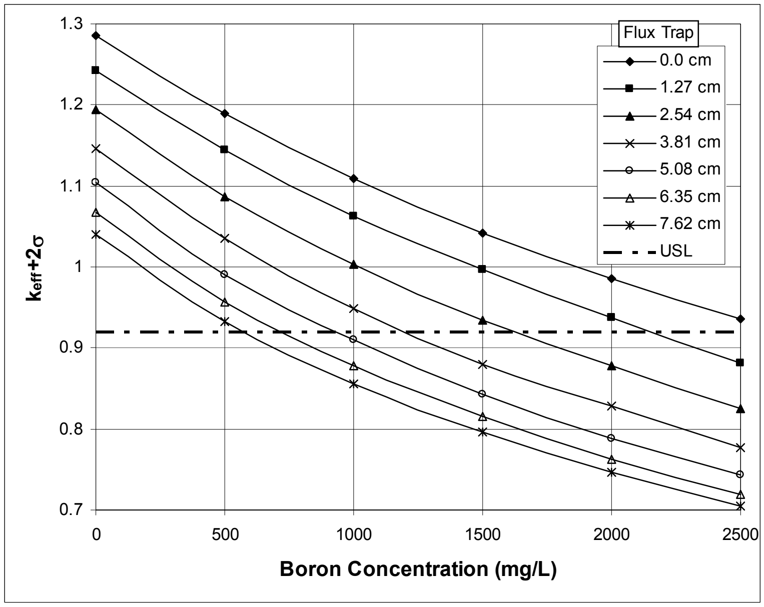

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Figure 84. Maximum k_{eff}+2σ Results for the PWR Staging Rack with the Boral Plates Modeled as Void and 17x17 OFAs

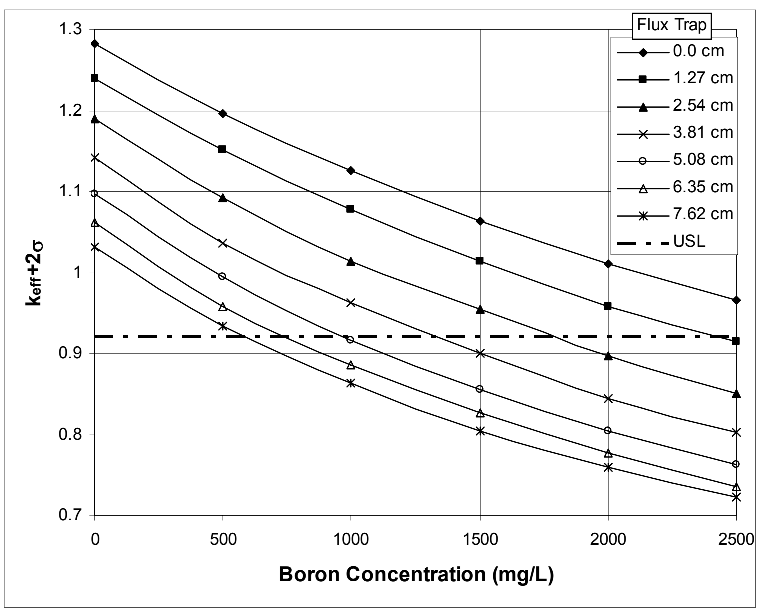

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Figure 85. Maximum k_{eff}+2σ Results for the PWR Staging Rack with the Boral Plates Modeled as Void and B&W 15x15 Fuel Assemblies

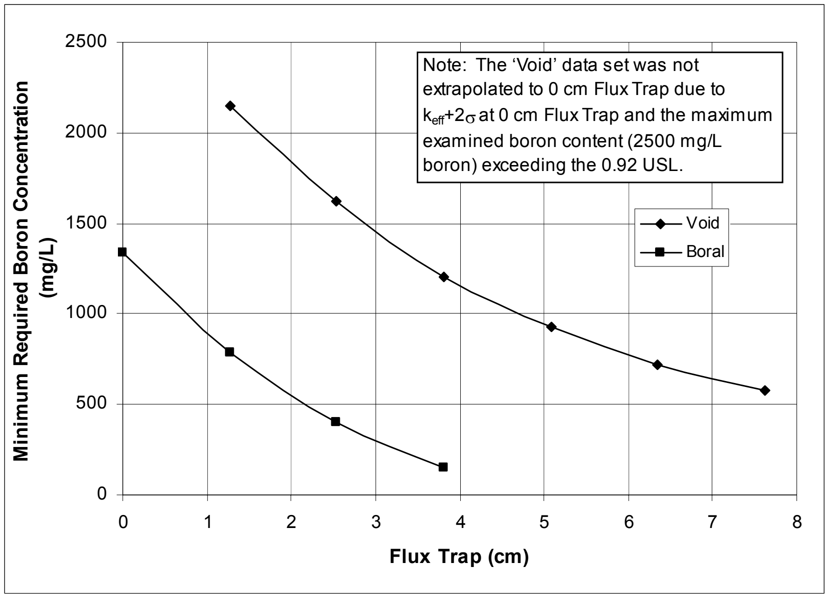

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Figure 86. Minimum Required Boron Concentration for the PWR Staging Racks with 17x17 OFAs

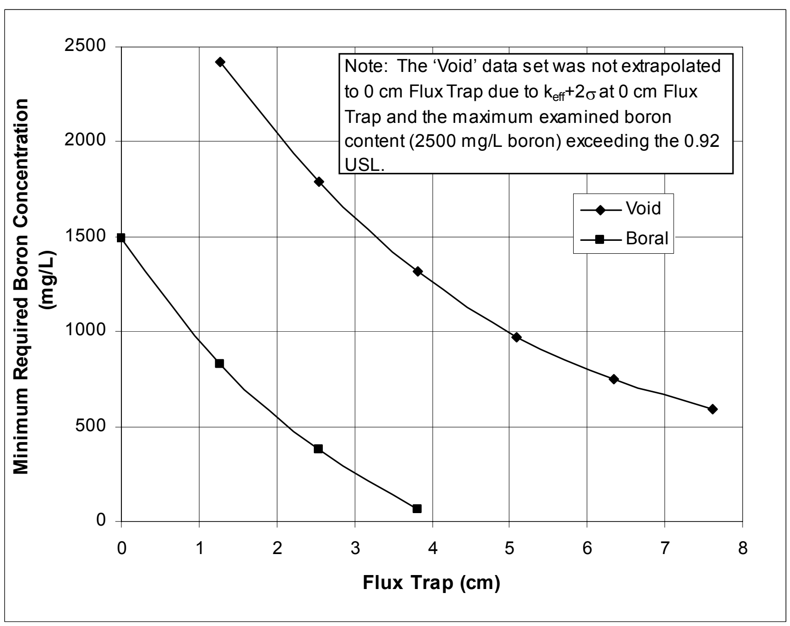

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Figure 87. Minimum Required Boron Concentration for the PWR Staging Racks with B&W 15x15 Fuel Assemblies

Table 36. Determined Minimum Boron Concentrations for the WHF Staging Racks

Flux Trap (cm)	Minimum Required Boron Concentration to Meet 0.92 USL (mg/L)	
	Boral Plates Present	**Boral Plates Modeled as Void**
17x17 OFA		
0	1341	>2500 (Beyond evaluated range)
1.27	790	2147
2.54	398	1624
3.81	152	1203
5.08	0	925
6.35	0	719
7.62	0	574
B&W 15x15		
0	1490	>2500 (Beyond evaluated range)
1.27	831	2421
2.54	375	1792
3.81	64	1316
5.08	0	967
6.35	0	746
7.62	0	594
ANF 9x9		
0	0	1518
1.27	0	576
2.54	0	35
3.81	0	0
5.08	0	0
6.35	0	0
7.62	0	0
GE 7x7		
0	0	1735
1.27	0	678
2.54	0	60
3.81	0	0
5.08	0	0
6.35	0	0
7.62	0	0

Source: Original to this document.

Two additional models were run utilizing the PWR staging rack model loaded with 17x17 OFAs. The first of these models examined the effect on the system reactivity due to a fuel assembly lying horizontal on top of the rack. The second examined the effect on the system reactivity due to the fuel assemblies being in an off-centered location in the fuel compartment. In both cases the fuel pin pitch is maintained at the nominal value (1.25984 cm per Table 5) and the Boral plates are assumed to be present. The results and additional model parameters are provided in Table 37 and include normal condition results.

Table 37. $k_{eff}+2\sigma$ Results for Additional Off-Normal Conditions for the WHF PWR Fuel Staging Racks Loaded with 17x17 OFAs

Fuel Assembly on Top	Pin Pitch (cm)	Flux Trap (cm)	Borated Water Boron Concentration (mg/L)	$k_{eff}+2\sigma$
	Fuel Assembly on Top of Rack Variations			
No	1.25984	5.08	1500	0.74646
Yes	1.25984	5.08	1500	0.78760
Fuel Assembly Pattern	Fuel Assembly Loading Variations			
Centered	1.25984	0	1500	0.89374
1 (See Figure 35)	1.25984	0.001	1500	0.90578
2 (See Figure 35)	1.25984	0.001	1500	0.90324
3 (See Figure 35)	1.25984	0.001	1500	0.90274
Centered	1.25984	5.08	1500	0.74646
1 (See Figure 35)	1.25984	5.08	1500	0.74911
2 (See Figure 35	1.25984	5.08	1500	0.74488
3 (See Figure 35)	1.25984	5.08	1500	0.74392

Source: Original to this document.

The results presented in Table 37 demonstrate that a boron concentration of at least 1500 mg/L in the WHF pool water is sufficient to ensure that the system reactivity remains below the 0.92 USL (Assumption 3.1.1) for the examined off-normal conditions. The results also show a significant increase in reactivity due to the proximity of the additional fuel assembly on top of the rack, although not sufficient to exceed the 0.92 USL. All of the results associated with varied fuel assembly bunching patterns are given in Table 38.

Table 38. k_{eff}+2σ Results for PWR Staging Rack with Varied Fuel Assembly Placement Patterns

Pattern	Flux Trap (cm)	Boron Concentration (mg/L)	k_{eff}+2σ
Centered	0.001	1000	0.94331
1 from Figure 35	0.001	1000	0.95568
2 from Figure 35	0.001	1000	0.94836
3 from Figure 35	0.001	1000	0.95025
Centered	5.08	1000	0.78786
1 from Figure 35	5.08	1000	0.78722
2 from Figure 35	5.08	1000	0.78438
3 from Figure 35	5.08	1000	0.78405
Centered	0.001	1500	0.89374
1 from Figure 35	0.001	1500	0.90578
2 from Figure 35	0.001	1500	0.90324
3 from Figure 35	0.001	1500	0.90274
Centered	5.08	1500	0.74646
1 from Figure 35	5.08	1500	0.74911
2 from Figure 35	5.08	1500	0.74488
3 from Figure 35	5.08	1500	0.74392

Source: Original to this document.

Figure 88 presents the k_{eff}+2σ results for the undamaged BWR staging racks with undamaged fuel assemblies. The values presented in Figure 88 are interpolated values since the 3.4925 cm flux trap was not specifically modeled. Figures 89 through 92 present the maximum k_{eff}+2σ results for all examined pin pitches for the BWR staging racks. Figures 91 and 92 present results for the BWR staging racks with the Boral plates modeled as void. For data sets with at least one k_{eff}+2σ value greater than the 0.92 USL (Assumption 3.1.1), the data is interpolated to provide a minimum required boron concentration. Only a small number of data sets had values that exceeded the 0.92 USL and the interpolated values are presented in Table 36.

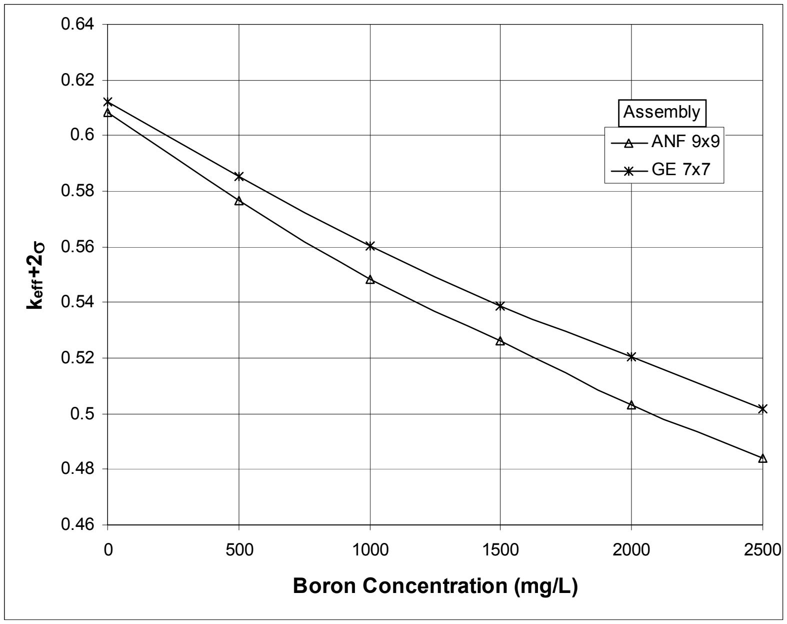

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Figure 88. Interpolated k_{eff}+2σ Results for the Undamaged BWR Staging Rack with Undamaged Fuel Assemblies

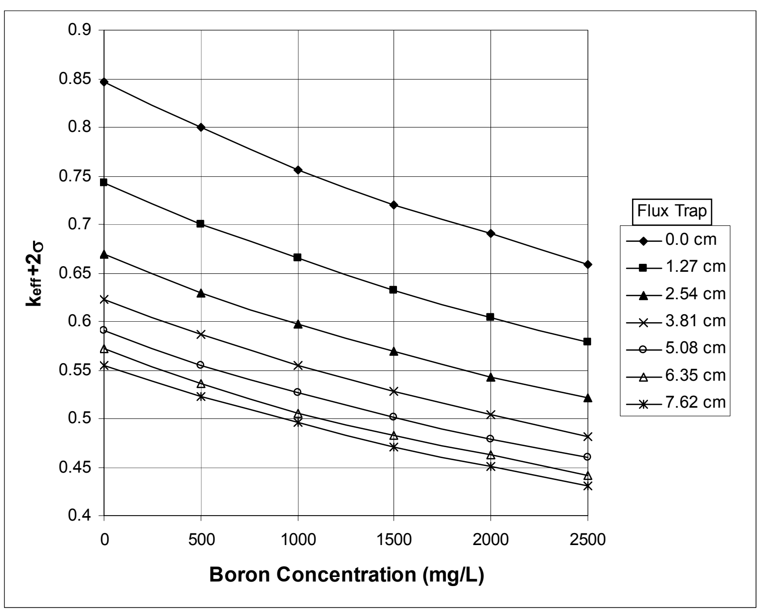

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Figure 89. Maximum k_{eff}+2σ Results for the BWR Staging Rack with 9x9 Fuel Assemblies

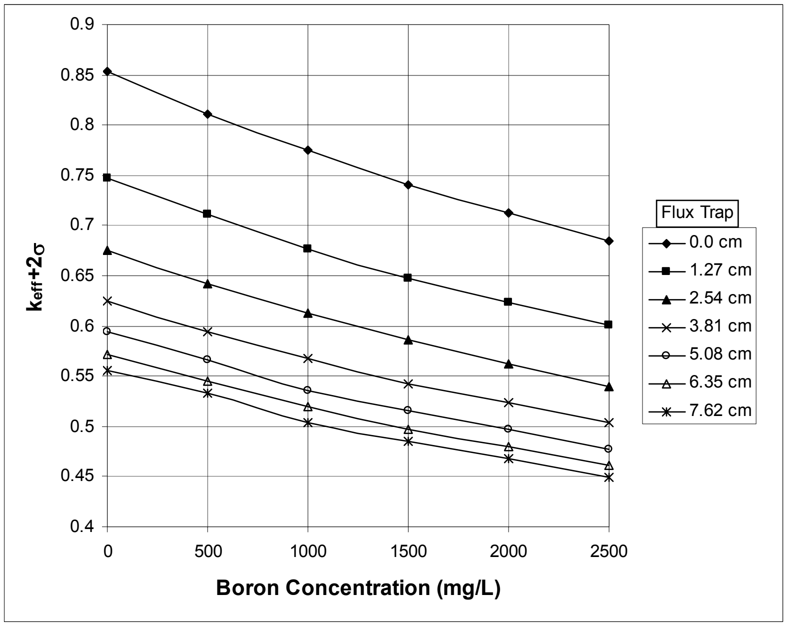

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Figure 90. Maximum k_{eff}+2σ Results for the BWR Staging Rack with 7x7 Fuel Assemblies

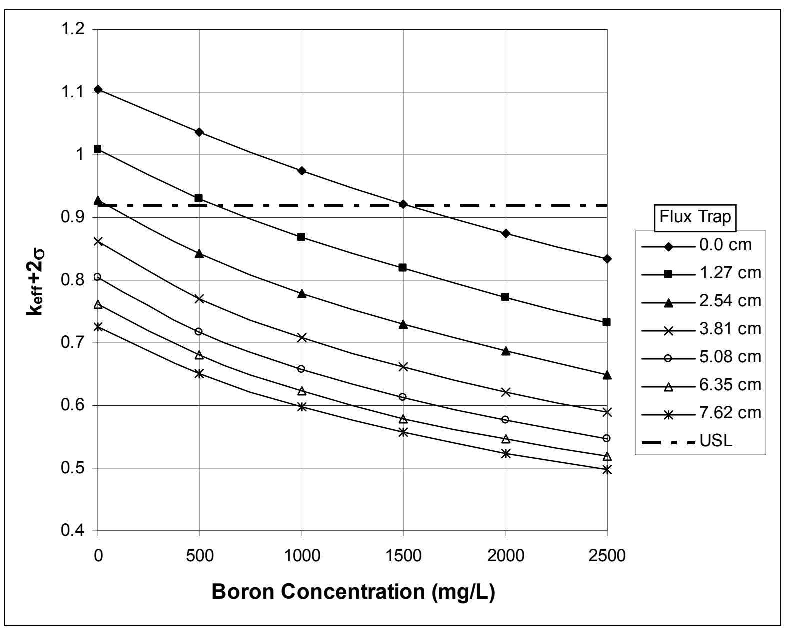

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Figure 91. Maximum k_{eff}+2σ Results for the BWR Staging Rack with 9x9 Fuel Assemblies and Boral Plates Modeled as Void

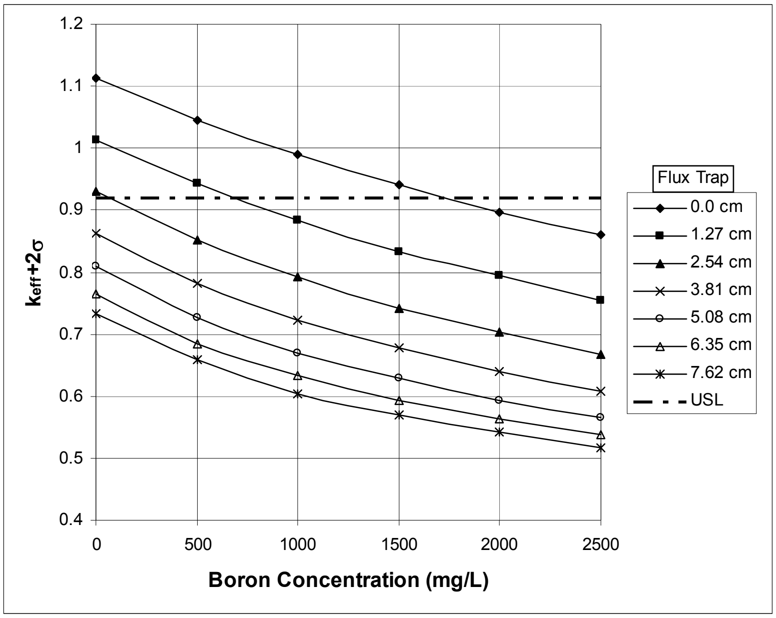

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Figure 92. Maximum k_{eff}+2σ Results for the BWR Staging Rack with 7x7 Fuel Assemblies and Boral Plates Modeled as Void

6.3.5 Simple Geometry Results

This section presents the MCNP determined k_{eff} values for simple spherical, hemispherical, infinite slab, and simple fuel pin array geometries as described in Section 6.1.7. In all cases the fuel is moderated by borated water. The model variations examined are presented in Table 39. Unless specifically stated all boron concentrations given in this section are for natural boron (19.9 atom% ^{10}B).

Table 39. Parameter Variations Examined for Simple Geometries

Parameter	Range/Values Examined
UO_2 particle size (sphere, hemisphere, and slab)	Homogeneous, 0.2 – 0.6 cm
UO_2 Fuel Pin Geometries (fuel pin arrays)	B&W 15x15 per Section 6.1.1 and Table 5 Westinghouse 17x17 OFA per Section 6.1.1 and Table 5 7x7 per 6.1.2 and Table 6 9x9 per 6.1.2 and Table 6
$H/^{235}U$ (Sphere, Hemisphere, and Infinite Slab Models)	75 – 400 1 – 400 (Homogeneous borated water reflected)
$H/^{235}U$ (fuel pin arrays)	20 - 300 (B&W 15x15) 20 – 150 (Westinghouse 17x17 OFA, 7x7, and 9x9)
Pin Pitch (fuel pin arrays)	1.1309 – 2.4631 cm (B&W 15x15) 0.9468 – 1.5667 cm (Westinghouse 17x17) 1.1651 – 1.9279 cm (9x9) 1.4807 – 2.4501 cm (7x7)
Sphere UO_2 mass (kg)	30 – 200
Hemisphere UO_2 mass (kg)	100 – 500
Slab thickness (cm)	5 – 30
Boron content (mg/L)	500 – 2500 (sphere, hemisphere, and slab) 2500 (fuel pin array)
Boron Enrichment (^{10}B atom%)	19.9 (sphere, hemisphere, and slab) 19.9 – 90.0 (fuel pin array)
Number of Fuel Pins	121 – 5041 (B&W 15x15) 121 – 6561 (Westinghouse 17x17 OFA) 121 – 5625 (7x7 and 9x9)
Reflector	Borated water, concrete, and steel (slab and sphere) Concrete on bottom and borated water above (hemisphere) Concrete or steel on three sides and borated water elsewhere (fuel pin arrays)

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Figure 93 presents the $k_{eff}+2\sigma$ for a homogeneous 20 cm thick slab of UO_2 moderated by borated water with borated water reflection. This data shows that the optimum $H/^{235}U$ ranges between 75 and 150 depending upon the boron concentration in the water. Figure 94 shows a relatively flat trend (in comparison to the $H/^{235}U$ trends in Figure 93) in reactivity with changes in particle radius. The trend may continue but would not be expected to increase dramatically from that depicted in the figure. Further, the maximum 0.6 cm radius would cover all but one of the BWR fuel pellet diameters examined (1.43 cm for 7x7 per Table 6).

Figures 95 through 97 present the maximum $k_{eff}+2\sigma$ results for the reflected slab geometry over the particle sizes and $H/^{235}U$ values examined as given in Table 39. The results in these figures were interpolated to give the maximum safely subcritical slab thickness for each reflector at a given boron concentration. These results are presented in Figure 98 and in Table 40.

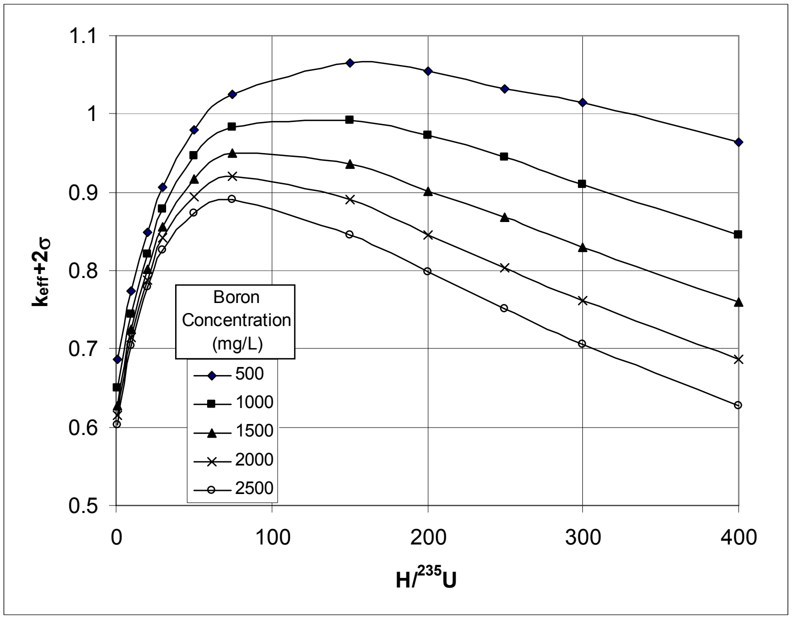

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Figure 93. k_{eff}+2σ Results for a 20 cm Thick Slab of Homogeneous Mixture of UO_2 and Borated Water with Borated Water Reflection

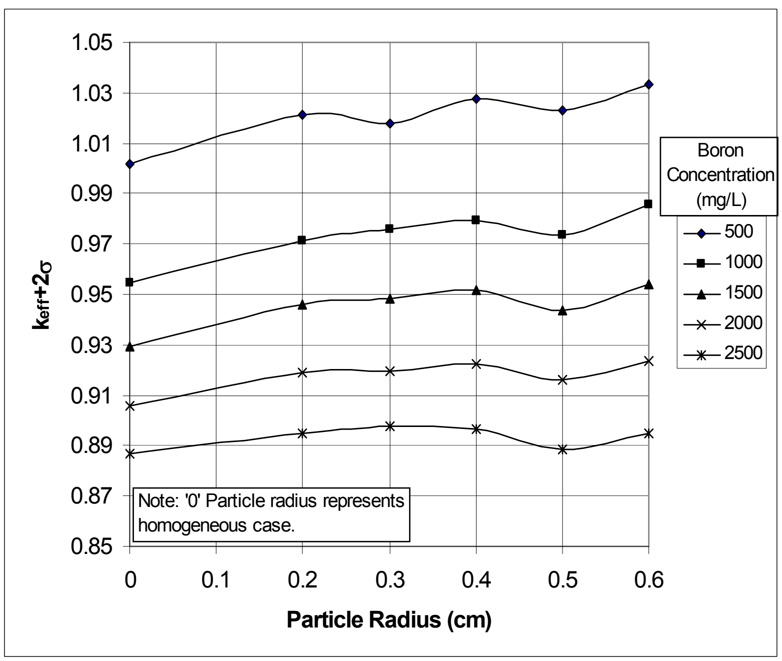

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Figure 94. Maximum k_{eff}+2σ Results over Examined $H/^{235}U$ Ratios for a 10 cm Thick Slab of UO_2 with Concrete Reflection

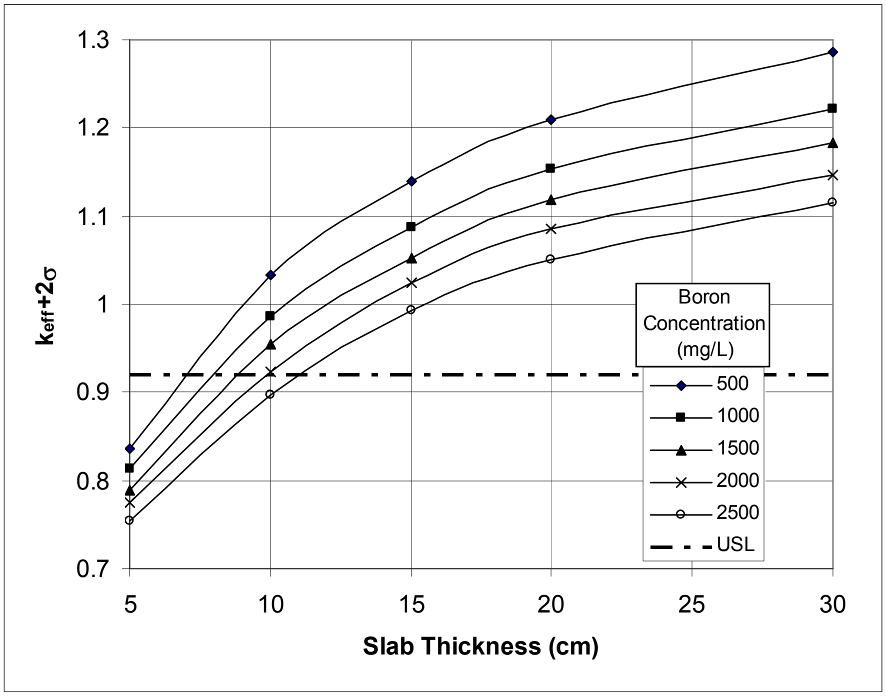

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Figure 95. Maximum k_{eff}+2σ Results for Concrete Reflected Slab

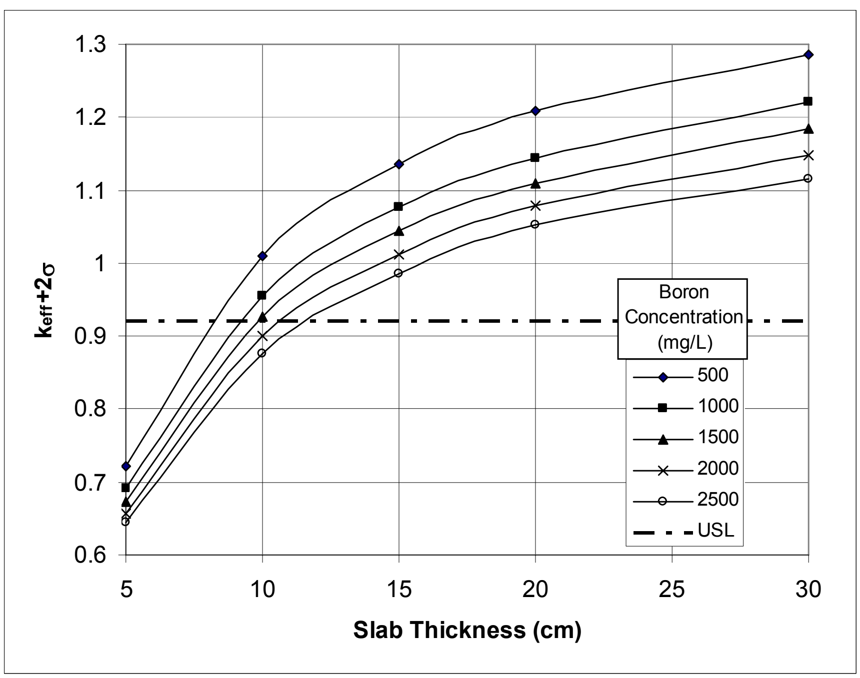

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Figure 96. Maximum k_{eff}+2σ Results for Steel Reflected Slab

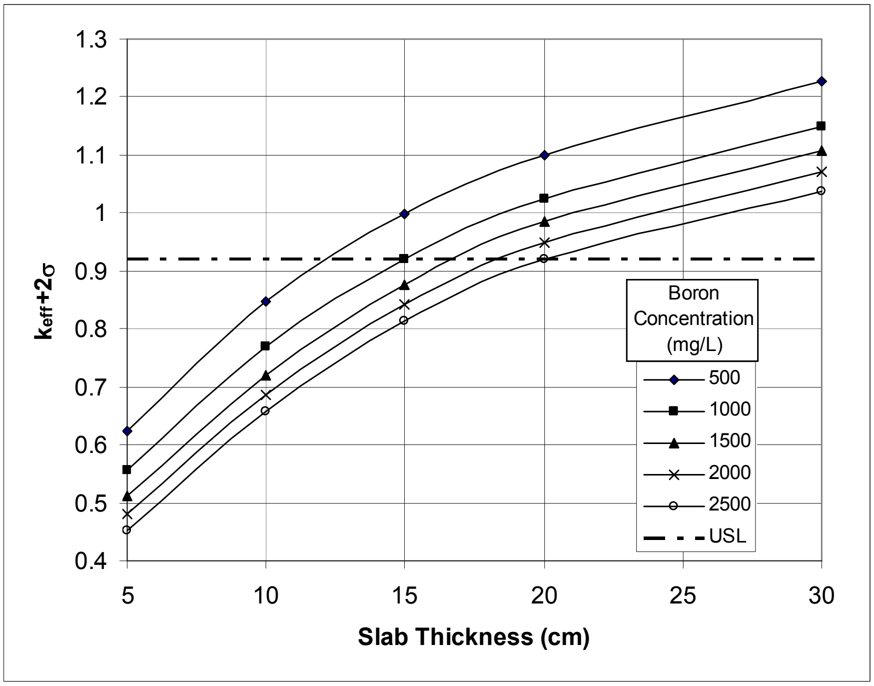

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Figure 97. Maximum k_{eff}+2σ Results for Borated Water Reflected Slab

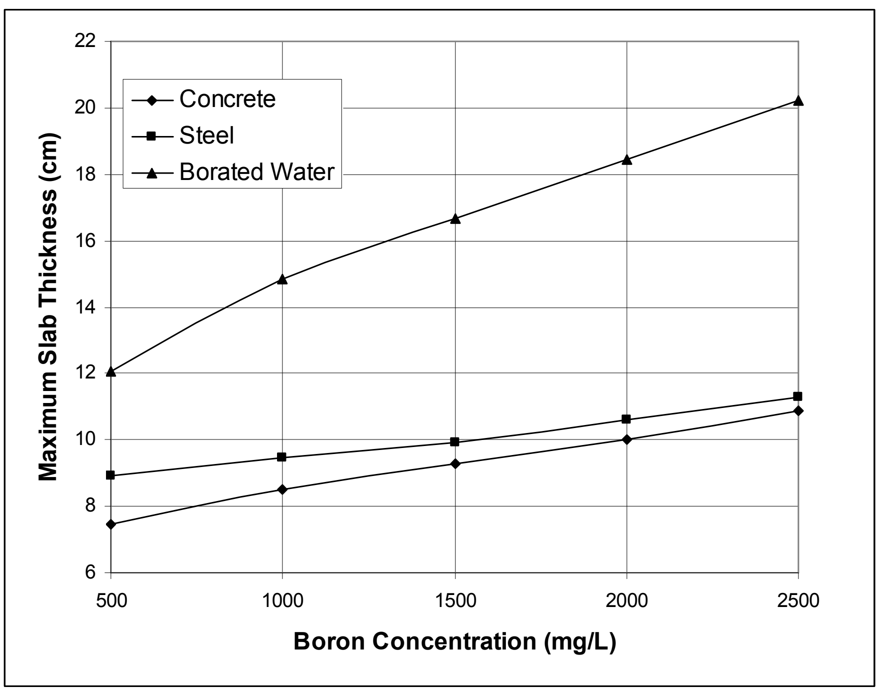

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Figure 98. Maximum Safely Subcritical Slab Thickness for a UO_2/Borated Water Moderated Slab

Table 40. Determined Maximum Safely Subcritical Slab Thicknesses for UO_2/Borated Water Mixtures

Boron Concentration (mg/L)	Maximum Safely Subcritical Slab Thickness (cm)
Concrete Reflection	
500	7.5
1000	8.5
1500	9.3
2000	10.0
2500	10.9
Steel Reflection	
500	8.93
1000	9.46
1500	9.92
2000	10.58
2500	11.29
Borated Water Reflection (Boron Concentration Same as Moderator)	
500	12.06
1000	14.83
1500	16.67
2000	18.46
2500	20.24

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Figure 99 presents the k_{eff}+2σ for a sphere of homogeneous UO_2/borated water mixture with borated water reflection. This data shows that the optimum $H/^{235}U$ ranges between 150 and 250 depending upon the boron concentration in the water. Figure 100 shows the trend for system reactivity versus UO_2 particle size. This figure shows that these trends are essentially flat with the optimum UO_2 particle radius appearing to be between 0.2 and 0.4 cm. The particle size, however, does not appear to be as significant to system reactivity as $H/^{235}U$ ratios as is seen in Figure 99. Figures 101 through 103 present the maximum k_{eff}+2σ results for the reflected sphere geometry over the particle sizes and $H/^{235}U$ values examined as given in Table 39. The results in these figures were interpolated to give the maximum safely subcritical UO_2 mass for each reflector at a given boron concentration. These results are presented in Figure 104 and in Table 41.

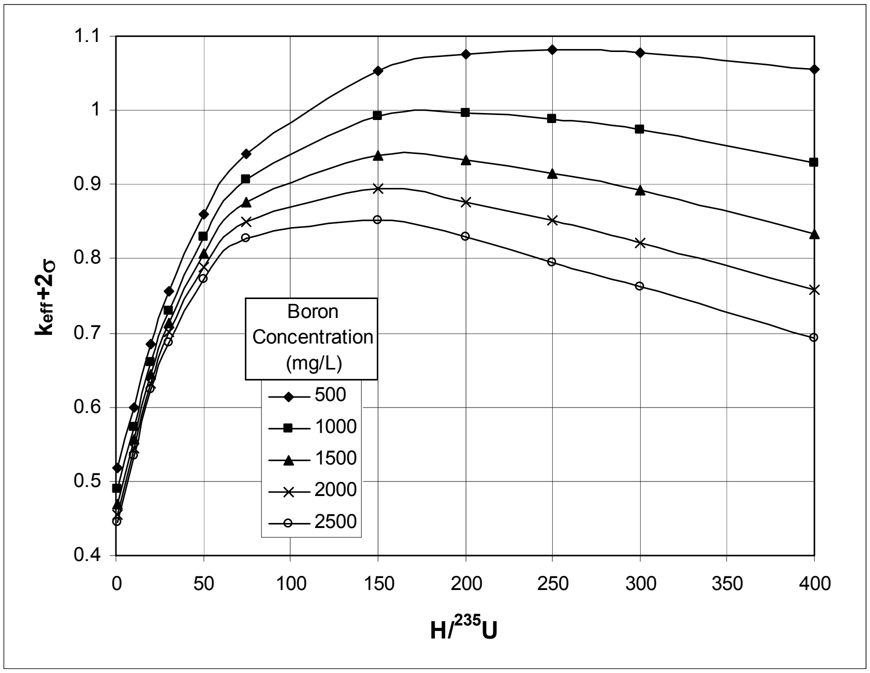

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Figure 99. k_{eff} + 2σ Results for a Sphere of a Homogeneous Mixture of 200 kg UO_2 and Borated Water Reflected by Borated Water

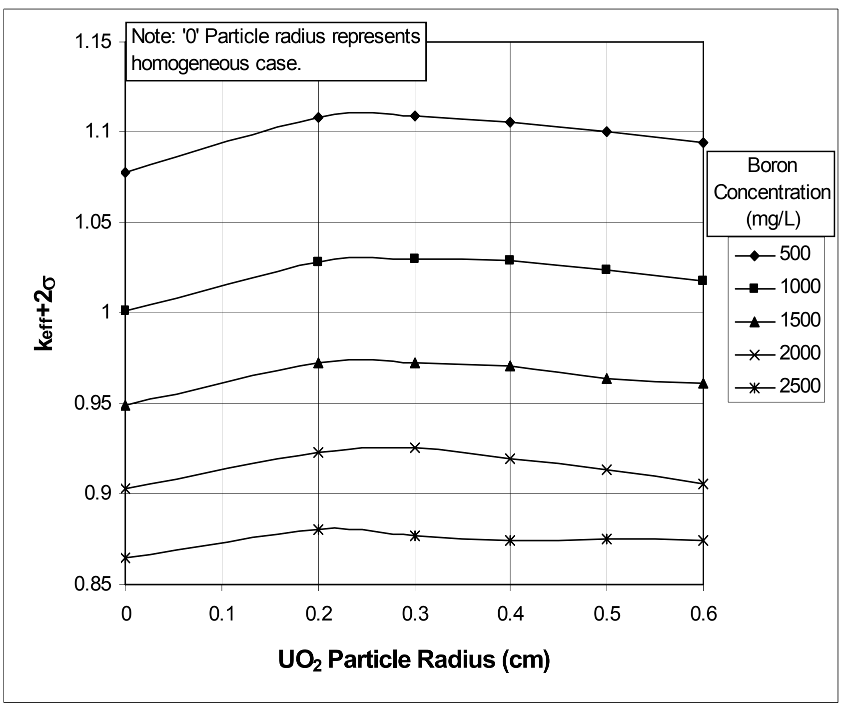

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Figure 100. Maximum k_{eff}+2σ Results for 150 kg UO_2 Over All $H/^{235}U$ Values Examined in a Borated Water Sphere with Concrete Reflection

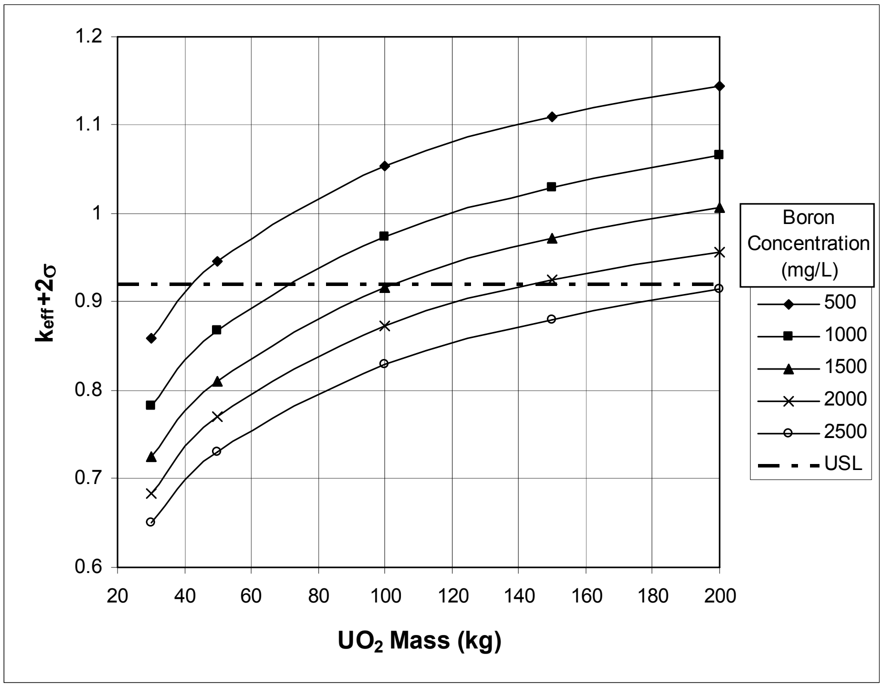

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Figure 101. Maximum k_{eff}+2σ Results for Concrete Reflected Sphere

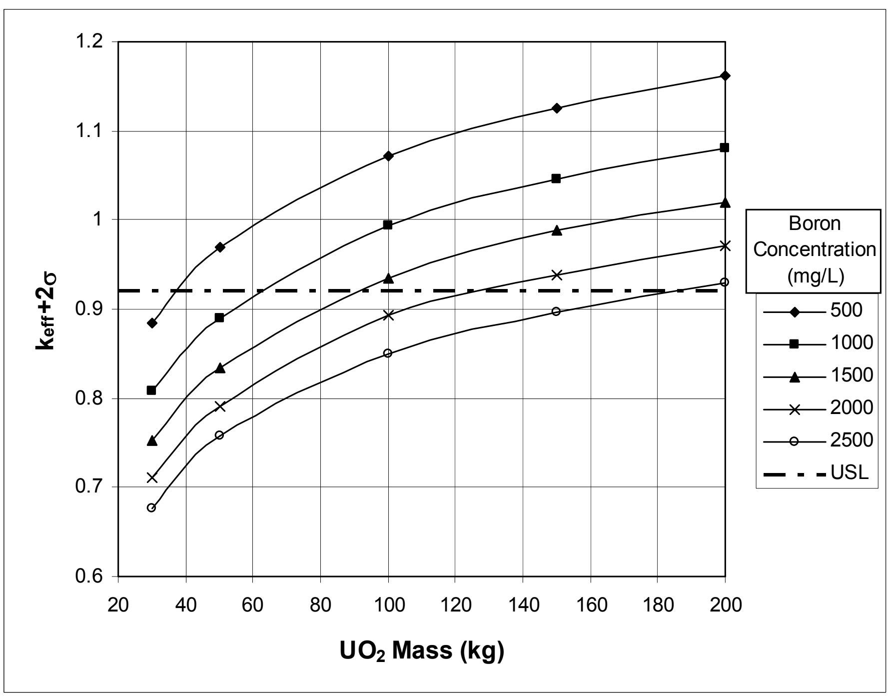

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Figure 102. Maximum k_{eff}+2σ Results for Steel Reflected Sphere

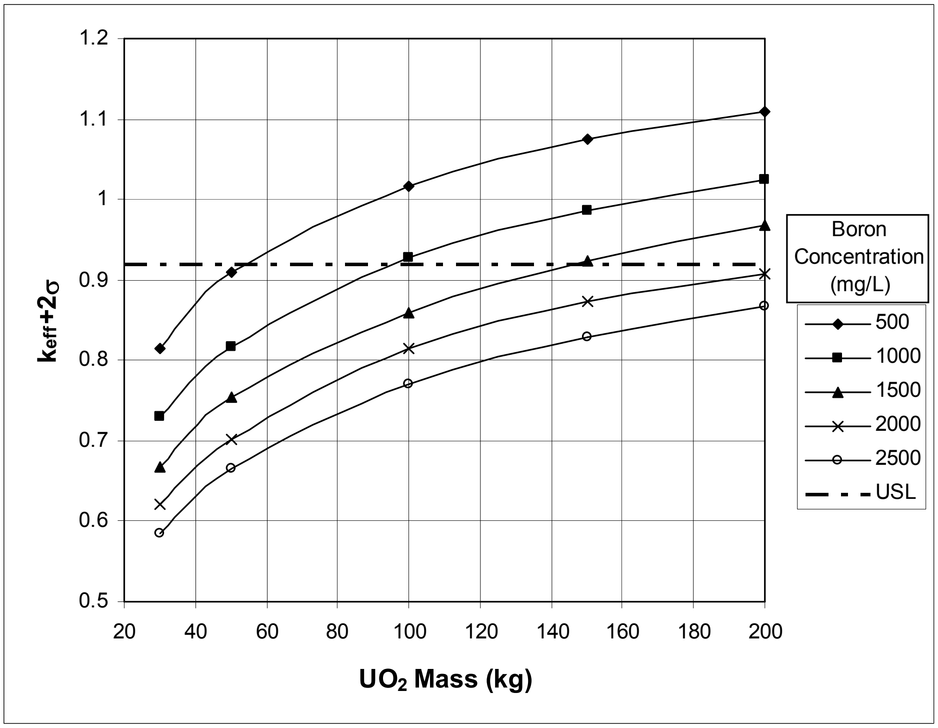

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Figure 103. Maximum $k_{eff}+2\sigma$ Results for Borated Water Reflected Sphere

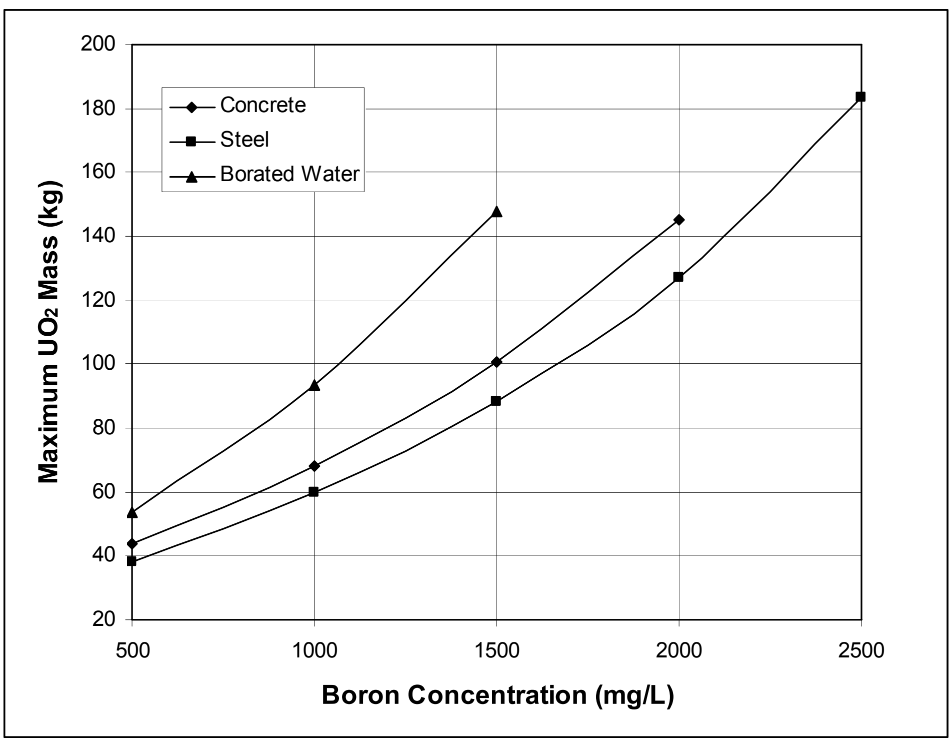

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Figure 104. Maximum Safely Subcritical UO_2 Mass for a UO_2/Borated Water Moderated Sphere

Table 41. Determined Maximum UO_2 Mass for Spheres of UO_2/Borated Water Mixtures

Natural Boron Concentration (mg/L)	Maximum Safely Subcritical UO_2 Mass (kg)
Concrete Reflection	
500	44.0
1000	68.3
1500	100.8
2000	145.3
2500	>200$^{(1)}$
Steel Reflection	
500	38.2
1000	59.7
1500	88.1
2000	127.2
2500	183.6
Borated Water Reflection (Boron Concentration Same as Moderator)	
500	53.7
1000	93.7
1500	147.8
2000	>200$^{(1)}$
2500	>200$^{(1)}$

NOTE: $^{(1)}$ $k_{eff}+2\sigma$ values are all less than 0.92 USL over the examined range. The safely subcritical mass limit is therefore greater than the largest value examined (200kg).

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Figure 105 presents the $k_{eff}+2\sigma$ for a hemisphere of homogeneous UO_2/borated water mixture with concrete (below) and borated water (above) reflection. This data shows that the optimum $H/^{235}U$ ranges between 150 and 250, depending upon the boron concentration in the water. Figure 106 shows trend in reactivity due to changing particle size. The figure shows only a slight trend with changing particle size with the optimum being between 0.2 and 0.4 cm. Figure 107 presents the maximum $k_{eff}+2\sigma$ results for the reflected hemisphere geometry over the particle sizes and $H/^{235}U$ values examined as given in Table 39. The results in this figure were interpolated to give the maximum safely subcritical UO_2 mass at a given boron concentration. These results are presented in Figure 108 and in Table 42.

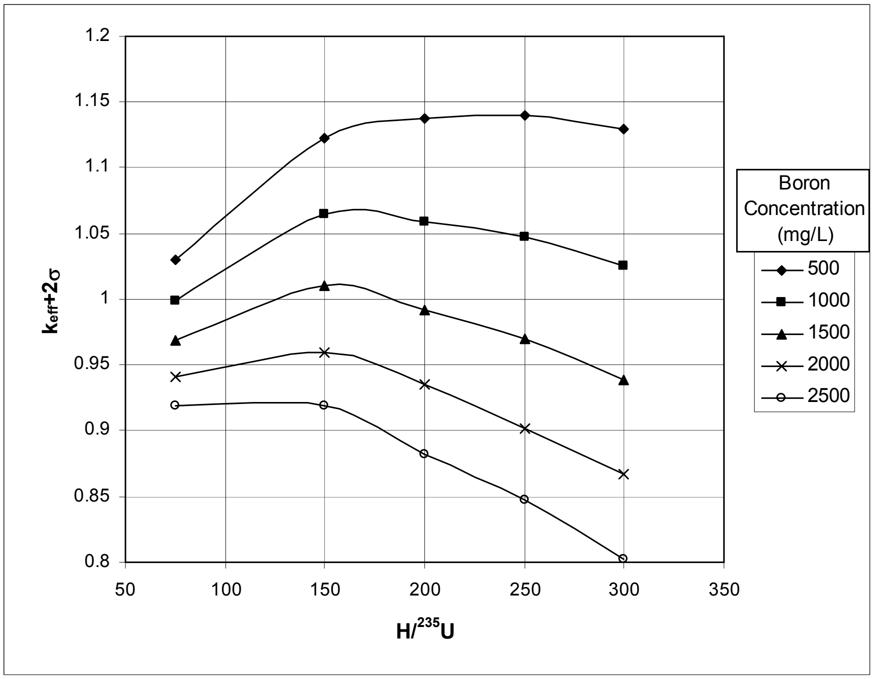

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Figure 105. Homogeneous Mixture of 400 kg UO_2 k_{eff}+2σ Results in a Borated Water Reflected Hemisphere

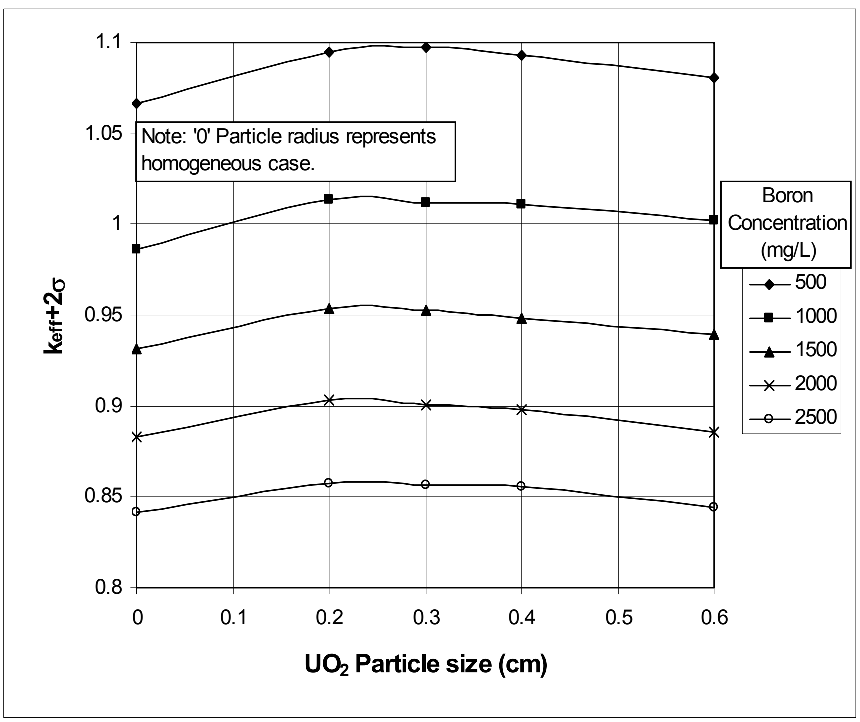

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Figure 106. Maximum k_{eff}+2σ Results for 200 kg UO_2 over all $H/^{235}U$ Values Examined in a Borated Water Hemisphere

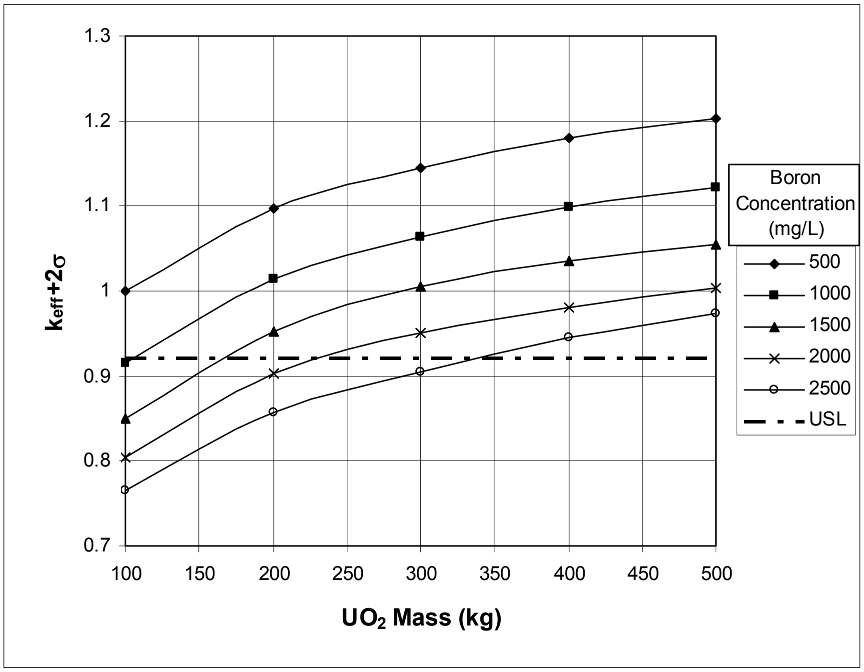

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Figure 107. Maximum k_{eff}+2σ Results for a Concrete/Borated Water Reflected Hemisphere

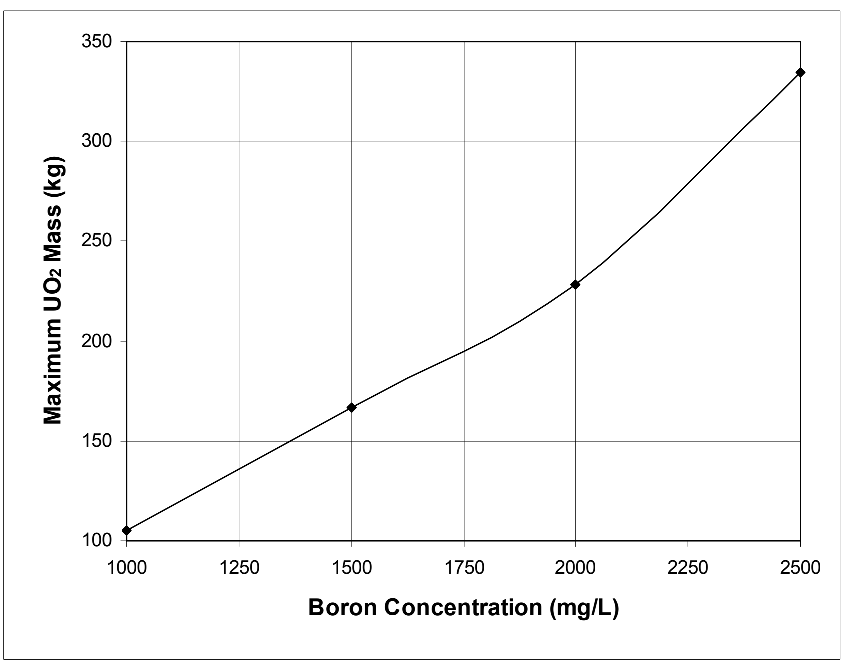

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Figure 108. Maximum Safely Subcritical UO_2 Mass for a UO_2/Borated Water Moderated Hemisphere

Table 42. Determined Maximum Safely Subcritical UO_2 Mass for Hemispheres of UO_2/Borated Water Mixtures

Natural Boron Concentration (mg/L)	Maximum Safely Subcritical UO_2 Mass (kg)
1000	105
1500	167
2000	228
2500	334

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Figure 109 presents the results for a square pitched array of 3,721 B&W 15x15 fuel pins with varying $H/^{235}U$, boron enrichments (given in atom % ^{10}B), a fixed boron concentration of 2500 mg/L, and concrete reflection on three sides. The results demonstrate the typical trends seen in the other related series of models.

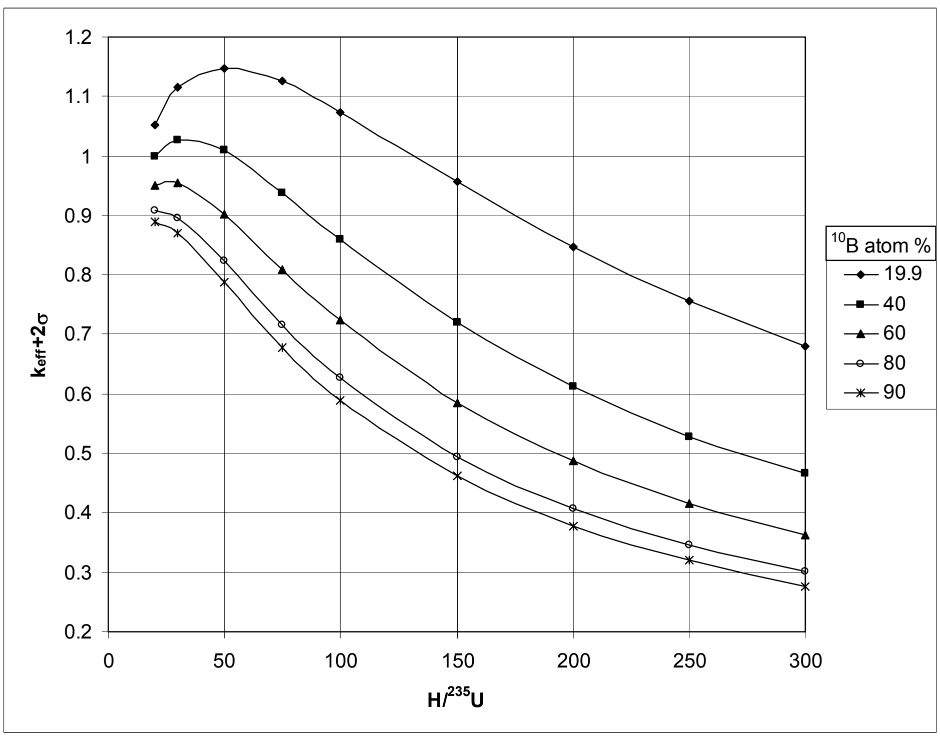

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Figure 109. $k_{eff}+2\sigma$ Results for a Concrete and Borated Water Reflected Square Pitched Array of 3,721 B&W 15x15 Fuel Pins with 2500 mg/L Boron

Figures 110 through 117 present the maximum reactivity over all $H/^{235}U$ values examined versus total number of fuel pins in the array for the four fuel pin types modeled with either concrete/borated water or steel/borated water reflection. The boron concentration remains fixed at 2500 mg/L.

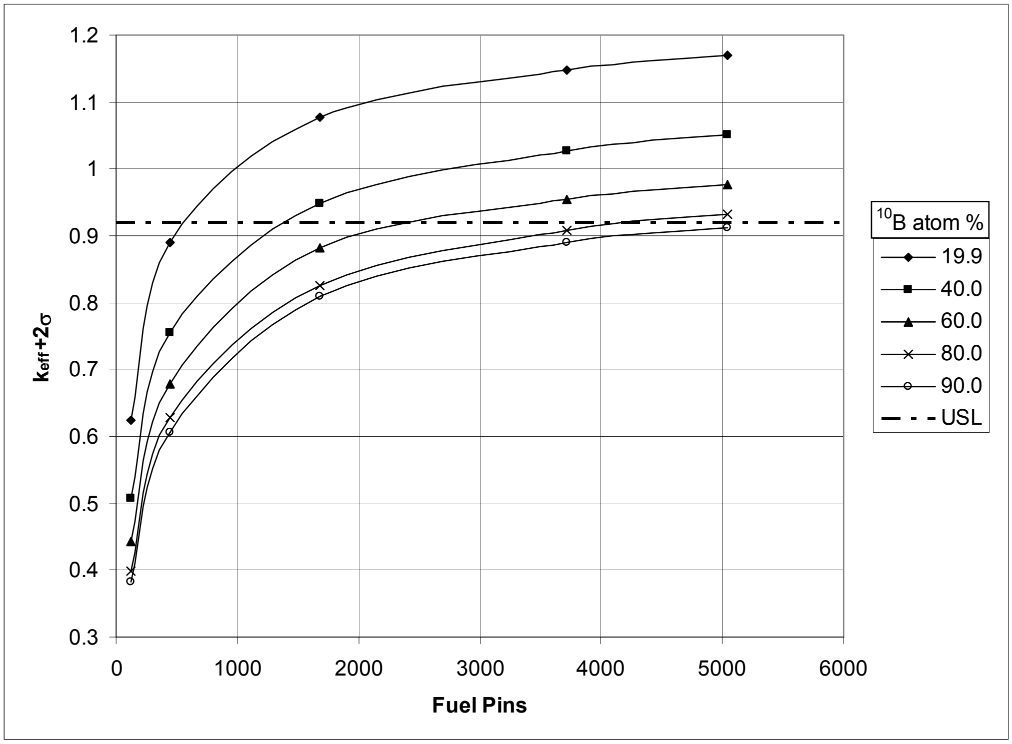

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Figure 110. Maximum Reactivity versus Number of B&W 15x15 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Concrete and Borated Water Reflection

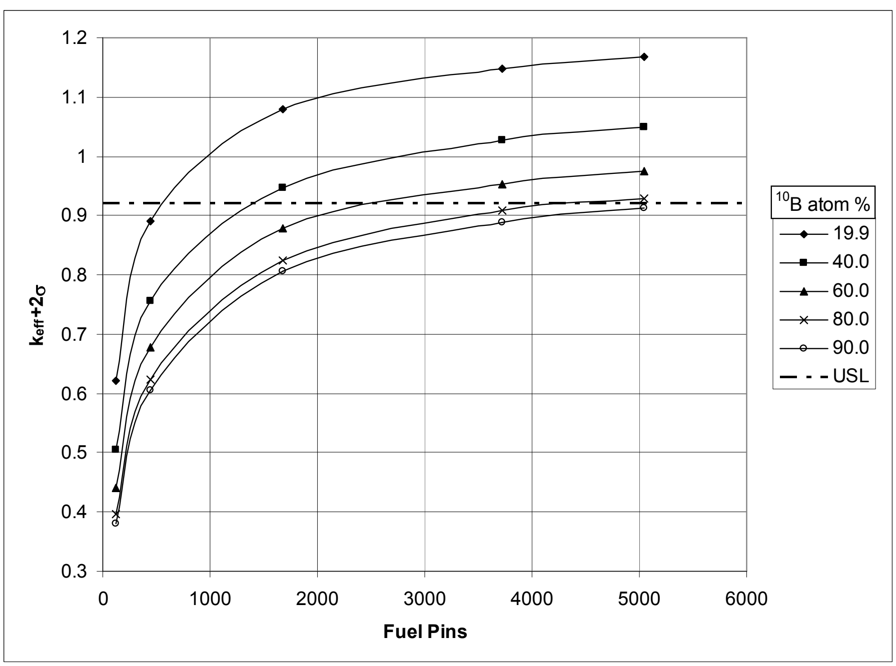

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Figure 111. Maximum Reactivity versus Number of B&W 15x15 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection

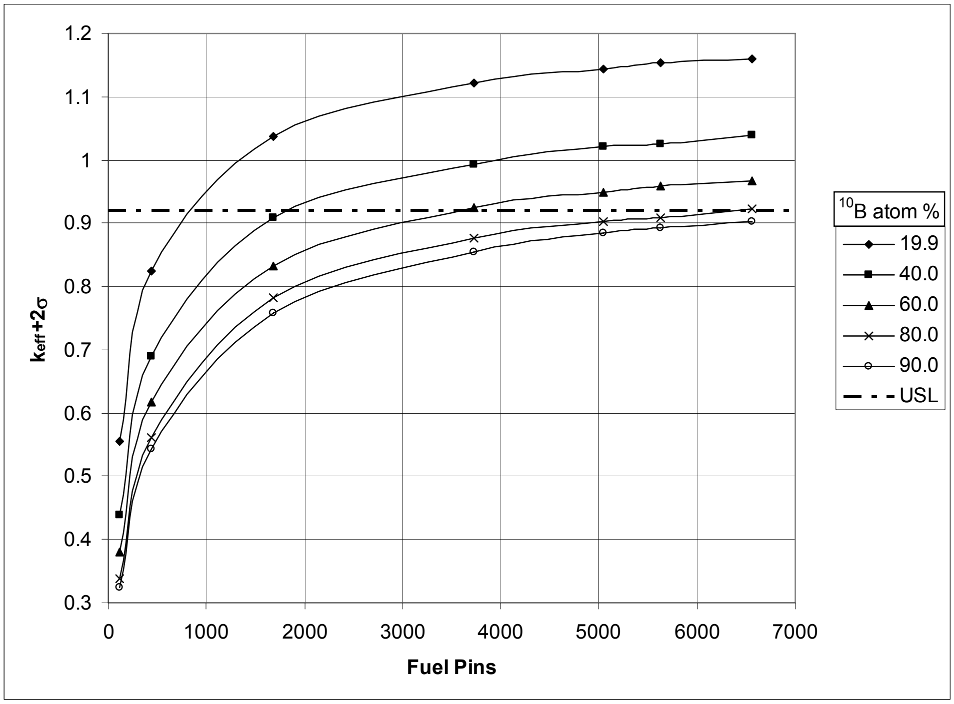

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Figure 112. Maximum Reactivity versus Number of Westinghouse 17x17 OFA Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Concrete and Borated Water Reflection

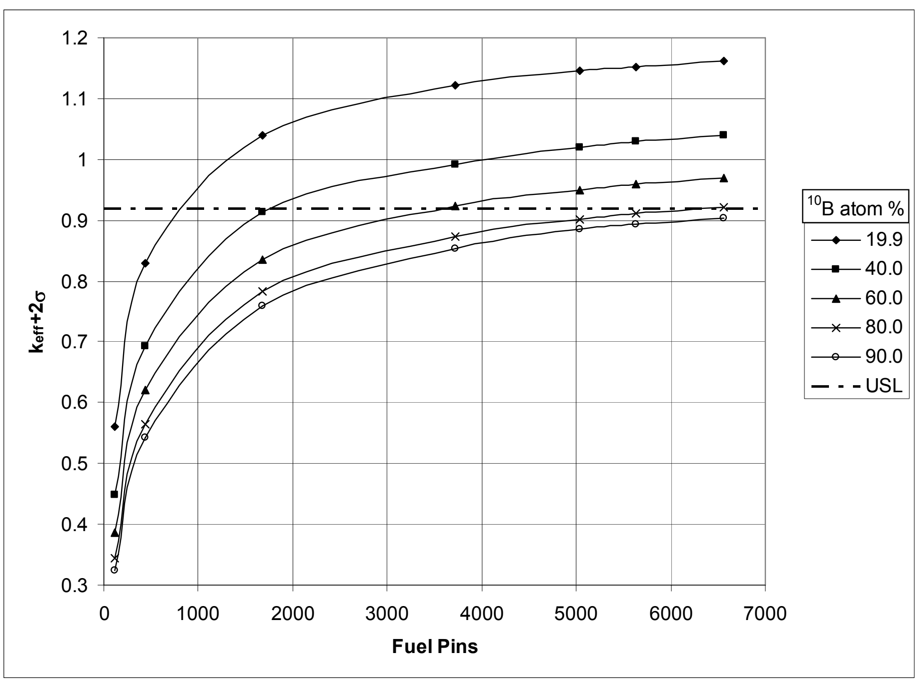

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Figure 113. Maximum Reactivity versus Number of Westinghouse 17x17 OFA Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection

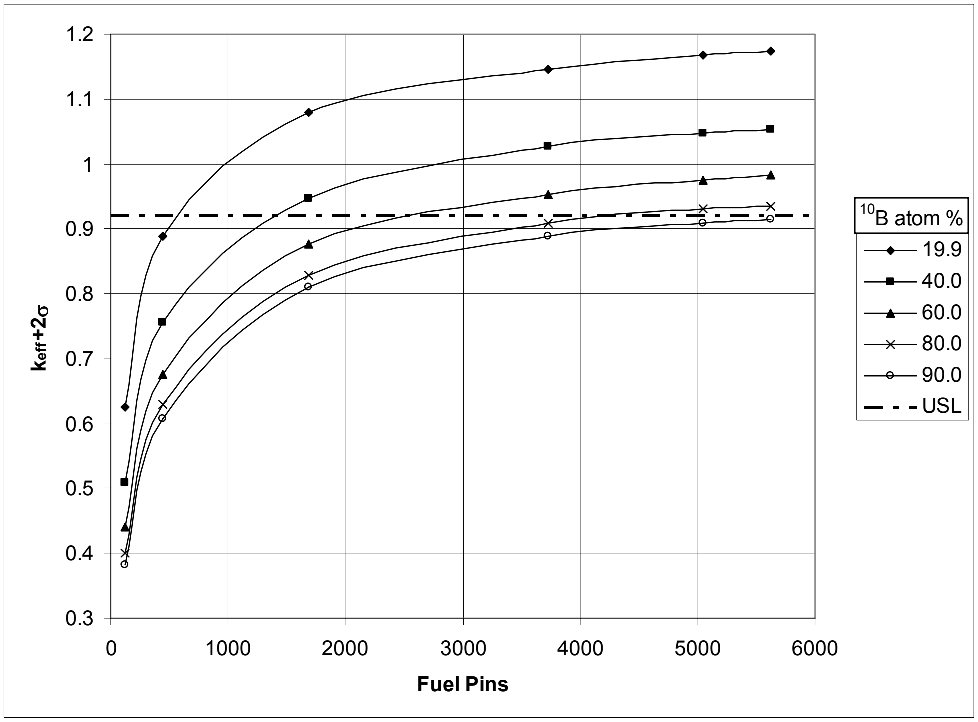

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Figure 114. Maximum Reactivity versus Number of 9x9 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Concrete and Borated Water Reflection

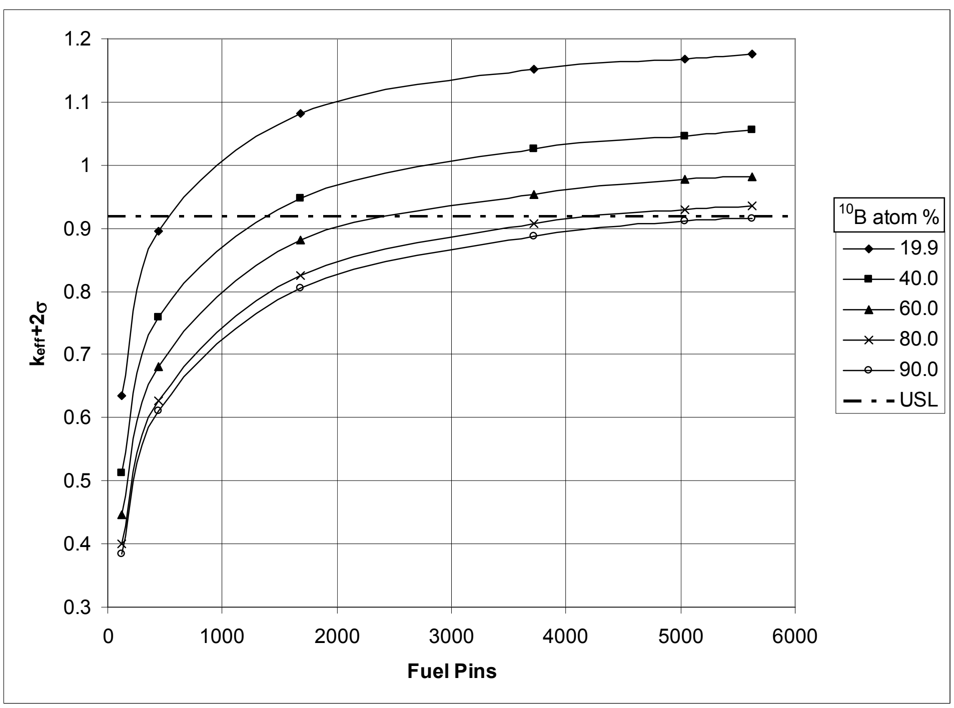

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Figure 115. Maximum Reactivity versus Number of 9x9 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection

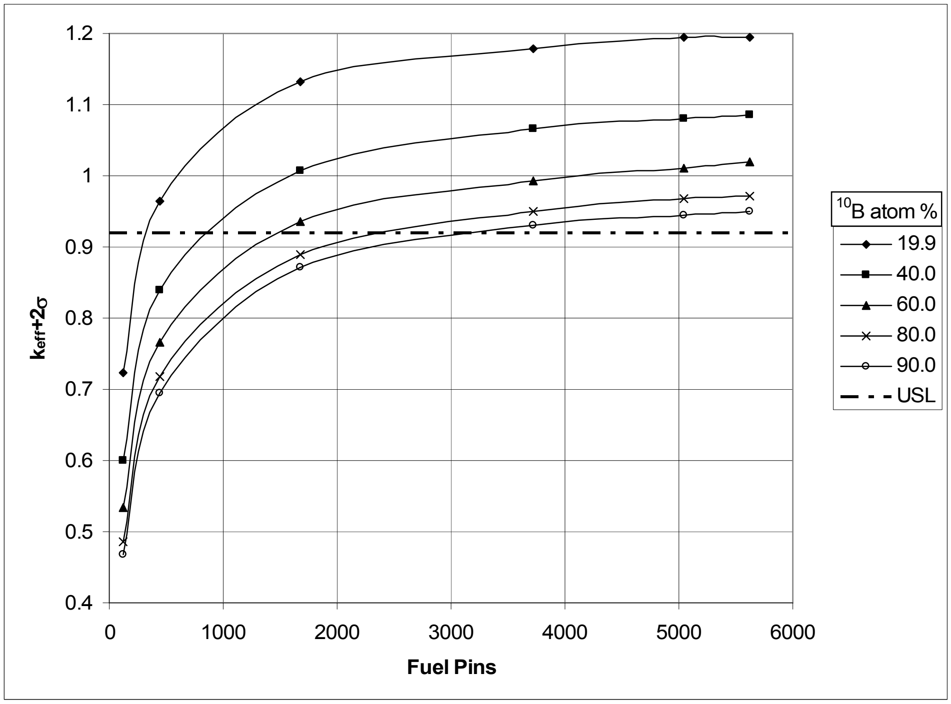

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Figure 116. Maximum Reactivity versus Number of 7x7 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Concrete and Borated Water Reflection

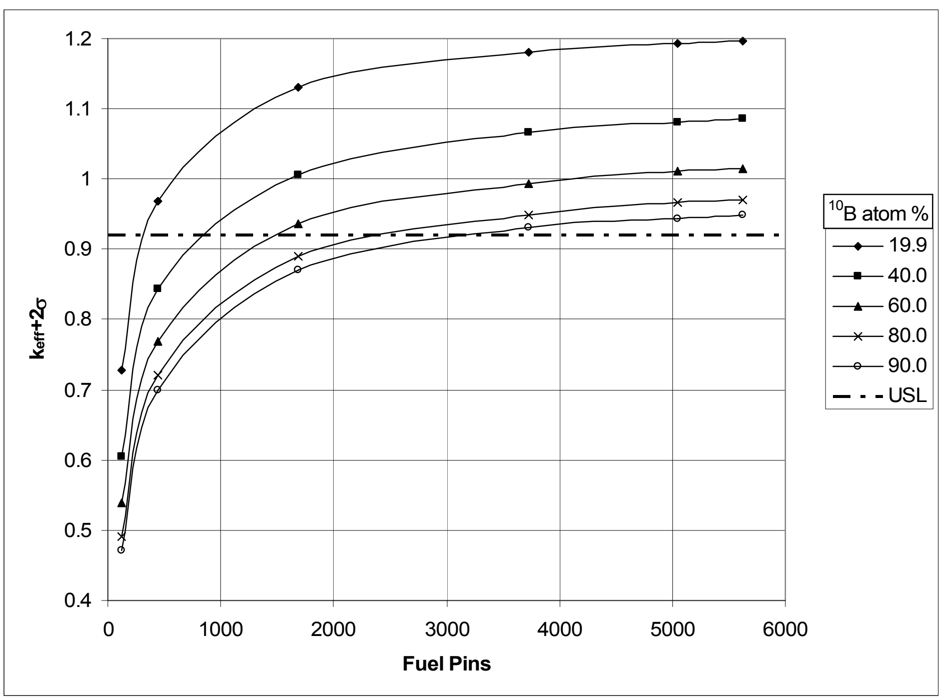

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Figure 117. Maximum Reactivity versus Number of 7x7 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection

7. RESULTS AND CONCLUSIONS

The results presented in Section 6.3 cover a variety of normal and potential off-normal conditions applicable to WHF CSNF operations as described in Section 1.1.2. Many of the configurations evaluated herein resulted in k_{eff} values that exceed the established upper subcritical limit of 0.92 (Assumption 3.1.1). In these cases, limits on appropriate parameters were developed that, if maintained, would ensure that the examined configuration remains safely subcritical. The following sections summarize these basic limits and discuss those parameters important to criticality safety specifically applicable to the WHF CSNF operations.

7.1 SUMMARY OF RESULTS AND CONCLUSIONS

Ensuring that the WHF operations remain safely subcritical is dependent upon a number of parameters. These parameters are interdependent. Further, setting all but one or two of these parameters to their most reactive condition results in boron concentration and/or enrichment requirements that are considered excessive (>2500 mg/L or >19.9 atom% ^{10}B). Therefore, more than one limit may exist for the parameters important to criticality safety. For the WHF, those operations that require the fuel assemblies to be partly or fully submerged in water are of primary concern for criticality safety.

The results of this calculation demonstrate that placing a single undamaged PWR fuel assembly in unborated water results in exceeding the upper subcritical limit of 0.92. Further, putting unborated water into an undamaged PWR TAD canister or DPC (PWR or BWR) results in exceeding the upper subcritical limit of 0.92. The required natural boron concentration needed to ensure these normal operations remain safely subcritical was found to range from approximately 500 to 800 mg/L of boron depending on the exact normal configuration examined.

Table 43 presents the limits on various parameters important to the criticality safety of the WHF given an assumed natural boron concentration control limit. Pin pitch, reflection, and interaction have either been optimized or bounded in conjunction with the other parameter limits (exception for the simple geometries is noted in the table). The limits on the other parameters are based upon the assumption that these parameters are affected independently of the others. For example, the flux trap limits assume that the normal condition neutron absorbers are present. Other limitations are noted in Table 43.

Table 44 presents the approximate maximum safe number of fuel pins in borated water with varying levels of boron enrichment. These limits are based upon a simple square pitched array of fuel pins with no other assembly structure.

Table 45 presents minimum soluble natural boron concentrations for a variety of normal and off-normal configurations.

Table 43. Parameter Requirements for Various Soluble Natural Boron Concentrations

Parameter	Natural Boron (19.9 atom % ^{10}B) Concentration (mg/L)			
	1000	1500	2000	2500
Geometry – minimum required flux trap	PWR TAD canister – 2.32433 cm BWR TAD canister – 0 PWR DPC – 2.54 cm BWR DPC – N/A PWR staging rack – 1.27 cm BWR staging rack – 1.27 cm	PWR TAD canister – 1.25 cm BWR TAD canister – 0 PWR DPC – 1.27 cm BWR DPC – N/A PWR staging rack – 0 BWR staging rack – 0	PWR TAD canister – 0.58 cm BWR TAD canister – 0 PWR DPC – 0.635 cm BWR DPC – N/A PWR staging rack – 0 BWR staging rack – 0	PWR TAD canister – 0 BWR TAD canister – 0 PWR DPC – 0 BWR DPC – N/A PWR staging rack – 0 BWR staging rack – 0
Geometry – pin pitch	The pin pitch upon which the other values in this table are based is the most reactive given the constraints of the geometry being examined. These constraints are: PWR single fuel assemblies –None, optimum pin pitch utilized PWR TAD canisters, DPCs, and staging racks: Inner width of storage location. BWR – All models: Inner width of fuel channel.			
Geometry – slab thickness	8.5 cm	9.3 cm	10.0 cm	10.9 cm
Fixed neutron absorbers – presence of absorber	Fixed neutron absorbers are present in the TAD canister, DPC, and staging rack designs evaluated in this calculation. In most cases, these absorbers were modeled as either being present or not. For each given level of boron concentration control, the presence of these fixed neutron absorbers is determined as either being required or not.			
	PWR TAD canister, DPC, and staging rack: Presence required. BWR TAD canister and staging rack: Presence not required.	PWR TAD canister: Presence required PWR DPC and staging rack : Presence not required BWR TAD canister and staging rack: Presence not required.	TAD canister, staging rack, and PWR DPC: Presence not required	TAD canister, staging rack, and PWR DPC: Presence not required
Fixed neutron absorbers – Boral density for BWR DPC	Given the high reactivity of the modeled BWR DPC, the Boral density was systematically reduced versus being simply eliminated. The normal density is 2.47 g/ cm^3. 0.247 g/ cm^3 was the lowest Boral density examined hence the 0.247 g/ cm^3 value for both 2000 and 2500 mg/L boron concentration levels.			
	1.2 g/ cm^3	0.5 g/ cm^3	0.247 g/ cm^3	0.247 g/ cm^3
Reflection	The range of materials used as reflectors in this calculation includes all those which may reasonably be expected in the WHF. Therefore the reflection conditions used herein are considered to be bounding of those expected in the WHF.			
Interaction	Single fuel assemblies: Only one fuel assembly is allowed outside of its storage position (DPC, TAD canister, or staging rack) in the WHF pool at any one time. DPCs, TAD canisters, and staging racks: The models examined herein assumed infinite planar arrays of the units being modeled. This effectively bounds any credible interaction between units in the WHF. Simple geometries (spheres, hemispheres, slabs): Interaction with these configurations is not expected in the WHF and is not evaluated in this calculation. Therefore, interaction between these geometries and other fissile material due to a credible off-normal condition would need to be controlled/prevented.			
Fissile material mass	Sphere: 59.7 kg Hemisphere: 105 kg	Sphere: 88.1 kg Hemisphere: 167 kg	Sphere: 127.2 kg Hemisphere: 228 kg	Sphere: 183.6 kg Hemisphere: 334 kg

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Table 44. Approximate Maximum Safe Number of Pins in An Optimized Square Pitch Array with Varying Boron Enrichment and overall Boron Concentration of 2500 mg/L

Fuel Pin Type	Boron Enrichment (^{10}B atom %)				
	19.9	40.0	60.0	80.0	90.0
B&W 15x15 (based on Figure 110)	600	1500	2700	4800	5041(1)
Westinghouse 17x17 OFA (based on Figure 112)	900	2000	3700	6561(1)	6561(1)
9x9 (based on Figure 114)	600	1500	2700	4600	5625(1)
7x7 (based on Figure 116)	350	1000	1600	2500	3500

Notes: (1) In these cases the maximum number of pins evaluated remained below the USL. The maximum number of pins is therefore listed here.

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Table 45. Minimum Soluble Natural Boron Requirements for Various Conditions

Condition	Control Parameter	Requirement	Source/Basis
PWR Single Fuel Assembly in Pool			
Normal/optimized pin pitch	Soluble natural boron concentration	≥ 1124 mg/L	Table 24 – Steel reflected B&W 15x15
BWR Single Fuel Assembly in Pool			
Normal/optimized pin pitch within constraints of fuel assembly channel	Soluble natural boron concentration	0 mg/L (no soluble boron required)	Figures 51 and 52
PWR TAD Canister in Pool			
Normal/optimized pin pitch within constraints of fuel compartment	Soluble natural boron concentration	≥ 937 mg/L	Table 26 – B&W 15x15 and 2.32433 cm flux trap
Flux trap collapse between all compartments	Soluble natural boron concentration	≥ 2401 mg/L	Table 26 – B&W 15x15 and 0.0212 cm flux trap
Replacement of all borated stainless steel panels with regular Stainless Steel Type 304	Soluble natural boron concentration	≥ 1597 mg/L	Table 26 – B&W 15x15 and 2.32433 cm flux trap
BWR TAD Canister in Pool			
Normal/optimized pin pitch within constraints of fuel compartment	Soluble natural boron concentration	0 mg/L (no soluble boron required)	Table 27 – 1.4752 cm flux trap
Flux trap collapse between all compartments	Soluble natural boron concentration	≥ 599 mg/L	Table 27 – 7x7 and 0.0001 cm flux trap
Replacement of all borated stainless steel panels with regular Stainless Steel Type 304	Soluble natural boron concentration	≥ 256 mg/L	Table 27 – 7x7 and 1.4752 cm flux trap
PWR DPC in Pool			
Normal/optimized pin pitch within constraints of fuel compartment	Soluble natural boron concentration	≥ 678 mg/L	Table 29 – B&W 15x15 and 2.7686 cm flux trap
Flux trap collapse between all compartments	Soluble natural boron concentration	≥ 2333 mg/L	Table 29 – B&W 15x15 and 0.001 cm flux trap
Replacement of all Boral plates with	Soluble natural boron	≥ 1671 mg/L	Table 29 – B&W 15x15 and

Condition	Control Parameter	Requirement	Source/Basis
void	concentration		2.7686 cm flux trap
BWR DPC in Pool			
Normal/optimized pin pitch within constraints of fuel compartment	Soluble natural boron concentration	≥ 953 mg/L	Table 32
Boron concentration in Boral plates reduced to 10% of nominal	Soluble natural boron concentration	≥ 2000 mg/L	Figures 76 and 77
Up to 16 Boral plates replaced by void	Soluble natural boron concentration	≥ 1250 mg/L	Figures 78 and 79
PWR Fuel Staging Racks in Pool			
Normal/optimized pin pitch within constraints of fuel compartment	Soluble natural boron concentration	≥ 152 mg/L	Table 36 – 17x17 OFA with 3.81 cm flux trap
Flux trap collapse between all compartments	Soluble natural boron concentration	≥ 1490 mg/L	Table 36 – B&W 15x15 with 0 cm Flux Trap
Replacement of all Boral plates with void	Soluble natural boron concentration	≥ 1316 mg/L	Table 36 – B&W 15x15 with 3.81 cm flux trap
BWR Fuel Staging Racks in Pool			
Normal/optimized pin pitch within constraints of fuel compartment	Soluble natural boron concentration	0 mg/L (no soluble boron required)	Table 36
Flux trap collapse between all compartments	Soluble natural boron concentration	0 mg/L (no soluble boron required)	Table 36
Replacement of all Boral plates with void	Soluble natural boron concentration	≥ 60 mg/L	Table 36 – 7x7 with 2.54 cm flux trap (as designed is 3.4925 cm)

NOTE: Results presented are not all inclusive and are not necessarily bounding of combinations of upset conditions. See Section 6.3 for complete results.

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7.2 CRITICALITY CONTROL PARAMETERS

The following sub-sections identify the physical parameters that are important to the criticality safety of WHF pool operations and their limitations as applicable.

7.2.1 SNF Parameters

This nuclear criticality calculation evaluated four sets of fuel assembly parameters (2 PWR and 2 BWR) as discussed in Sections 6.1.1, 6.1.2, and 6.2.2. The fuel was conservatively modeled as fresh fuel with a bounding 5% enrichment and high fuel density. While these fuel assemblies are conservatively modeled, they are not necessarily bounding of all CSNF assembly types/designs. The results can, however, be expected to be similar for other CSNF in regards to reactivity trends, parameters requiring controls, and control limits.

7.2.2 Geometry

Many aspects of the geometry are varied to either their most reactive or physically limiting state. These include pin pitch and flux trap size. The need to control and/or limit these parameters is dependent upon the control of other parameters, most notably boron concentration. This is demonstrated in the summary results presented in Tables 43 and 44. Table 43 demonstrates that the various geometry parameters examined in the analysis do not need to be limited/controlled if the natural boron concentration is 2500 mg/L or more.

7.2.3 Fixed Neutron Absorbers

The fixed neutron absorbers that are part of the TAD canister, DPC, and staging rack designs are modeled as either being present, some or all replaced by void, replaced by unborated stainless steel (TAD canister), or modeled with a reduced boron density (BWR DPC). As with many of the important geometry parameters, the need for control of the fixed neutron absorber parameters is dependent upon the control of other parameters, most notably boron concentration.

7.2.4 Soluble Neutron Absorbers

The results of this calculation have demonstrated that under normal conditions, some amount of soluble neutron absorber is required to be present in the water of the pool and that used to fill the DPCs prior to placing them in the pool. The exact amount required is dependent upon the limiting conditions and/or control of the other parameters important to criticality safety.

7.2.5 Moderation

The only moderator examined in this analysis is water. The results demonstrate that unborated water must not be allowed as a moderator for many of the fuel type/storage type combinations examined.

7.2.6 Interaction

The models for the TAD canisters, DPCs, and staging racks all consisted of infinite hexagonal planar arrays of close fitting units. This modeling assumption is conservative and effectively bounds the interaction of units. The interaction between single fuel assemblies is not evaluated because the operations involving the removal of fuel assemblies from a storage location (TAD canister, DPC, or Staging Rack) are to be restricted to the movement of one fuel assembly at a time. Interaction between units does not need to be further restricted and is considered bounded.

7.2.7 Reflection

All criticality calculations are performed with close fitting full thickness reflection with a comprehensive range of reflector materials. Consequently, the reflection conditions accounted for in the criticality calculations are considered bounding to any potential reflection conditions that could be expected as a result of WHF operations. Therefore, reflection control is not important to ensuring the subcriticality of CSNF in the WHF.

ATTACHMENT 1
LIST OF FILES ON THE ATTACHMENT 2 DVD

This attachment contains a listing and description of the files contained on the attachment DVD of this report (Attachment 2). The DVD was written using Sonic Digital Media Plus v7 installed on DOE M&O Property tag number YMP003943 central processing unit, and can be viewed on most standard DVD-ROM drives. The zip archive was created using WINZIP 9.0 SR-1. The file attributes on the DVD are as follows:

Filename	File Size (KB)	File Date	File Time	Description
MCNP Files.zip	1,965,032	11/27/2007	3:23p	Archive containing MCNP files
DPC Results.xls	1,131	11/27/2007	12:32p	Excel spreadsheet containing results of the DPC models and subsequent manipulations
List of all MCNP Results.xls	2,359	11/27/2007	1:49p	Excel spreadsheet containing a list of all MCNP output files and their results
Material Compositions.xls	163	11/27/2007	1:14p	Excel spreadsheet containing the material specifications and related calculations
Rack Results.xls	742	6/13/2007	11:09a	Excel spreadsheet containing results of the staging rack models
Simple Geometry Results.xls	2,200	11/27/2007	12:32p	Excel spreadsheet containing results of the simple geometry models
Single Assembly Results.xls	431	11/26/2007	11:24a	Excel spreadsheet containing results of the single fuel assembly models
TAD Results.xls	1,220	8/29/2007	12:34p	Excel spreadsheet containing results of the TAD canister models
UO2 Material Specification.ReadMe	1	8/6/2007	3:42p	Provides information on minor material specification error

The archive file (*MCNP Files.zip*) contains a total of 34,001 files (not including folders) contained in a unique directory structure. Files ending with an “in” are input files, and files ending with an "ino" are output files.