Criticality Analysis for US-APWR New and Spent Fuel Storage Racks

Non-Proprietary Version

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List of Acronyms

ANS	American Nuclear Society
ASME	American Society of Mechanical Engineers
B-Al	Borated Aluminum
B-SS	Borated Stainless Steel
B&W	Babcock & Wilcox's Lynchburg Research Center, U.S.A.
COL	Combined License
DCD	Design Control Document
DFR	Damaged Fuel Rack
EALF	Energy of Average Lethargy Causing Fission
ENDF	Evaluated Nuclear Data Files
ft.	foot, feet
GDC	General Design Criteria
gpm	gallons per minute
ID	Inner Diameter
in.	inch, inches
keff	effective neutron multiplication factor
lb.	pound
MHI	Mitsubishi Heavy Industries, LTD.
NCS	Nuclear Criticality Safety
NFR	New Fuel Rack
NRC	U. S. Nuclear Regulatory Commission
NUREG	NRC Technical Report Designation (Nuclear Regulatory Commission)
OD	Outer Diameter
ORNL	Oak Ridge National Laboratory
ppm	parts per million
RWSP	Refueling Water Storage Pool
SFP	Spent Fuel Pit
SFPCS	Spent Fuel Pit Purification and Cooling System
SFR	Spent Fuel Rack
SRP	Standard Review Plan
SS	Stainless Steel
PWR	Pressurized Water Reactor
TD	Theoretical Density
US-APWR	United States - Advanced Pressurized Water Reactor
95/95	95 percent probability, 95 percent confidence level

1.0 Introduction

This technical report summarizes the criticality analysis for the New Fuel Rack (NFR) and the Spent Fuel Rack (SFR), which are the facilities of the US-APWR fuel storage system. The fuel assemblies stored in these racks are 17x17 fuel assemblies for the US-APWR (Reference [1]).

The design basis and evaluation of rack criticality safety are consistent with the contents described in US-APWR Design Control Document (DCD) " 9.1.1 Criticality Safety of New and Spent Fuel Storage" (Reference [2]), and criticality analyses are performed in accordance with the following acceptance criteria and relevant requirements: General Design Criterion (GDC) 62 (Reference [3]), 10 CFR 50.68 (Reference [4]), NRC guide (Reference [5]), ANSI/ANS-8.17-2004 (Reference [6]). Specifically,10 CFR 50.68 (b) item (2) and (3) for new fuel storage rack and item (4) for spent fuel storage rack are applied as the criticality safety design criteria, and the analysis results were evaluated referring to ANSI/ANS-8.17-2004.

The NFR of the US-APWR is made of stainless steel (SS) and it can store up to 180 fuel assemblies. The SFR uses the borated stainless steel (B-SS), which contains neutron absorber of about 1.0 wt% Boron (natural) and can store a maximum of 900 fuel assemblies. In addition, the Damaged Fuel Rack (DFR) made of stainless steel is provided which can store up to 12 Damaged Fuel Container.

Certain amount of the maximum of 5% reactivity margin allowed in 10CFR50.68 is taken as credit of boric acid in the spent fuel pool water or “Soluble Boron Credit”.

The results of criticality analysis for NFR and SFR are described in Chapter 2 and 3 respectively.

1.1 Analysis Code and Validation

For the criticality analyses of NFR and SFR, the continuous-energy Monte Carlo Code MCNP, version 5.1.40, (Reference [7]) and continuous-energy neutron cross section data ENDF/B-V are used. Code validation have been conducted analyzing 120 criticality experiments and drawn up in the report "Validation of MHI Criticality Safety Methodology (MUAP-07020)" (Reference [8]). Based on this validation, bias and uncertainty of MCNP Code to be taken into consideration for criticality analysis are 0.0029 and 0.0030 respectively. The One-sided tolerance limit factor to be multiplied by this uncertainty at a 95 percent probability, 95 percent confidence level is 1.899.

2.0 Criticality Analysis of New Fuel Rack

Chapter 2 contains the criticality analysis results for US-APWR 17x17 new fuel assemblies stored in NFR. It is shown that the maximum value of effective neutron multiplication factor (keff) at both flooded and optimum moderation conditions including biases and uncertainties, satisfies the design criteria and subcriticality is maintained.

2.1 Design Method

Design criteria, evaluation method and analysis code are described in the following subsections.

2.1.1 Design Criteria

The design criteria are pursuant to the 10 CFR 50.68 (b) item (2) and (3) for new fuel rack.

"For new fuel storage racks, the maximum keff value including all biases and uncertainties must be less than or equal to 0.95 for the flooded condition with unborated water, and less than or equal to 0.98 for optimum moderation, at a 95 percent probability, 95 percent confidence level (95/95). Rack cells are assumed to be loaded with fuel of the maximum fuel assembly reactivity."

As noted above, evaluations are conducted for the flooded and optimum moderation conditions.

2.1.2 Evaluation

Under the design criteria mentioned above, evaluations were conducted referring to the equation described in the most recent ANSI/ANS-8.17-2004. More specifically, Section 5 of ANSI/ANS-8.17-2004 states that the calculated multiplication factor k_p shall be equal to or less than an established allowable neutron multiplication factor; i.e.,

$$k_p \le k_c - \Delta k_p - \Delta k_c - \Delta k_m \qquad (1)$$

If the various uncertainties are independent,

$$k_p \le k_c - \left(\Delta k_p^2 + \Delta k_c^2\right)^{1/2} - \Delta k_m \qquad (2)$$

Where

k_p is the calculated keff
k_c is the mean keff derived from the code validation
Δk_p is the allowance for convergence*, tolerances, and modeling limitations
Δk_c is a bias uncertainty derived from the code validation
Δk_m is an arbitrary margin to ensure the subcriticality of k_p
(* The 2σ value of MCNP output is applied according to the 95/95 rule.)

In this evaluation, equation (2) is rearranged taking into consideration the following items:

- To compare with the design criteria of keff=1.0, 0.98, 0.95 stated in 10CFR50.68, which consider subcriticality margin, k_c is separated into critical condition keff=1.0 and analysis code bias, and (1-k_c) is moved to the left side of the equation as a symbol to denote a bias.
- The convolution term (root of sums of squares), denoting uncertainty of calculation,

tolerance and uncertainty term derived from code validation, are moved to the left side of the equation.

- Only the term (1.0-Δk_m) is left in the right side of the equation and keff=1.0, 0.98, 0.95 criteria are applied corresponding to the evaluation.

The rearranged equation becomes as follows.

$$k_p + (1 - k_c) + \left(\Delta k_p^2 + \Delta k_c^2\right)^{1/2} \le \left(1.0 - \Delta k_m\right) \qquad (3)$$

Additionally, using the analysis code bias of (1-k_c)=0.0029 and bias uncertainty Δk_c=0.0030 multiplied by benchmarking confidence coefficient of 1.899 at 95 percent probability, 95 percent confidence level as stated in Section 1.1, equation (3) becomes as follows.

$$k_p + 0.0029 + \left(\Delta k_p^2 + \left(1.899 \times 0.0030\right)^2\right)^{1/2} \le \left(1.0 - \Delta k_m\right) \qquad (4)$$

Consequently, the evaluation equations for NFR are as follows.

Fully flooded condition: $k_p + 0.0029 + \left(\Delta k_p^2 + \left(1.899 \times 0.0030\right)^2\right)^{1/2} \le 0.95$ (5)

Optimum moderation: $k_p + 0.0029 + \left(\Delta k_p^2 + \left(1.899 \times 0.0030\right)^2\right)^{1/2} \le 0.98$ (6)

2.1.2.1 Reactivity Uncertainty Due to Tolerances

The reactivity due independent tolerances may be statistically combined. Here, the components of the tolerance to be considered in the criticality analysis are the pellet diameter and density, the cladding inner and outer diameter, the fuel pin pitch, the rack cell board material and thickness, the rack cell inner wall to wall width, and the rack pitch between adjacent cells. The fuel position within rack cell is also considered. Each of these components of the tolerance is independent.

However, for this NFR analysis, each of the tolerances is modeled in the manner that maximizes reactivity, following method (1) of the “Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants”. U.S. NRC, February 1998. Excerpt of this guidance is as follows:

“Uncertainties should be determined for the proposed storage facilities and fuel assemblies to account for tolerances in the mechanical and material specifications. An acceptable method for determining the maximum reactivity may be either (1) a worst-case combination with mechanical and material conditions set to maximize keff or (2) a sensitivity study of the reactivity effects of tolerance variations. If used, a sensitivity study should include all possible significant variations (tolerances) in the material and mechanical specifications of the racks; the results may be combined statistically provided they are independent variations. Combinations of the two methods may also be used.”

2.1.3 Analysis Code

As stated in Section 1.1, criticality analysis uses the three-dimensional Monte Carlo code MCNP version 5.1.40 and the continuous-energy neutron data ENDF/B-V.

Additionally, for the S(α, β) thermal scattering data, “lwtr.01t” for hydrogen in light water is applied to water. Though the effect is small, scattering effect as reflector is applied to the hydrogen in floor and wall concretes.

Neutron generation histories in Monte Carlo calculation were set to four million as shown below. In this situation, 1σ is approximately 0.0004 and is sufficiently small.

- Number of neutron particles per generation : 2000
- Number of neutron generation : 2050
- Number of skipped generation : 50
- Number of total history : 4 million

2.2 Analysis

2.2.1 Analysis Conditions

Specifications of stored fuel and NFR together with conditions to be included in analysis model are described in this subsection.

2.2.1.1 Fuel Assembly Description

US-APWR 17x17 fuel assembly parameters used in the criticality analysis of NFR are listed in Table 2-1. Arrangement of fuel rods, control rod guide thimbles and an in-core instrumentation guide tube in the fuel assembly is shown in Figure 2-1. Fuel cladding is made of ZIRLO^{TM} which is a zirconium base alloy with a small amount of niobium (Nb) added for increasing corrosion resistance.

2.2.1.2 US-APWR New Fuel Rack Description

The NFR has a capacity to store a maximum of 180 new fuel assemblies. Rack configuration and design parameters are shown in Table 2-2 and Figure 2-2. As shown in Figure 2-2, the new fuel rack is composed of two modules of 13x7=91cells and 11x7+6x2=89cells. The rack pitch is 16.9 inch (43cm). The rack material is stainless steel-304 (SS304). SS supporting structures are installed to support rack modules, but are located locally and peripherally, so they do not affect the criticality analysis.

When the NFR is installed, the cells are placed a given distance from a baseline. The tolerance in this distance is given on Table 2-2. The worst case positioning of the cells would have the two cells placed where one cell is at the maximum distance from the baseline and the other cell is placed at the minimum distance from the baseline. This results in a worst case pitch of two cells to be twice the cell positioning tolerance.

Normally, new fuel assemblies are stored in racks in a dry condition. A drain system is provided for the New Fuel Storage Pit to preclude flooding. The rack structure and the fuel handling equipment are designed to preclude the fuel assembly misplacement and drop as the fuel handling accident. In addition, the rack is designed to have no significant deformation which affects criticality analysis. Incidentally, from the double contingency principle, a fuel handling accident condition with flooding condition does not need to be considered, as stated in Reference [4]. Therefore, the criticality analysis for NFR addresses the case of flooding with water.

2.2.1.3 Assumptions

Based on the fuel assembly and NFR parameters, criticality analyses are performed for the following conditions.

Assumptions on Fuel Assembly

- The fresh UO_2 fuel assembly without burnable absorber is assumed to have a maximum enrichment of five weight percent, which is pursuant to 10 CFR 50.68 (b) item (7).
- The fuel cladding is conservatively assumed to be 100% zirconium which has a smaller neutron absorption cross section compared with ZIRLO.
- The fuel rods, cladding and the control rod guide thimbles and the in-core instrumentation guide tube are modeled over the active fuel length of the fuel assembly. The grid spacers made of both Zircaloy-4 and Inconel 718 are conservatively neglected.
- Fuel assembly tolerances are treated to give conservative results (Worst Case Model).
- The structural material at both ends of fuel assembly have many holes to allow coolant flow so the effective contribution as neutron reflector is small, thus they can be replaced by water or concrete. At the flooded condition, a 30cm water layer and a 1m concrete layer have equivalent reflector effect and the thickness is sufficient to maximize the reflection effect. Then, 30cm water layer is placed on the top of the effective fuel length and a concrete layer of 1m thickness is placed on the underside. At a low water density condition, such as optimum moderation for NFR criticality evaluation, concrete floor is expected to have higher reflecting effect due to high energy neutron reflection, then the height between floor surface and the bottom of effective fuel is ignored and concrete is placed just beneath the effective fuel in the calculation.

Assumptions on NFR

- Calculations are performed simulating the actual NFR system. However, two modules are conservatively combined into one module by filling the two missing rack positions with normal rack. The resulting module is a 26x7 array of 182 cells with a rack pitch of 16.9inch (43cm).
- Water density of 62.43 lb/ft^3 ($1.0 g/cm^3$) is used to cover the maximum value and fractional densities are treated between 0 to 100 percent of full density so as to cover both flooded and optimum moderation.
- Minimum SS thickness is assumed to conservatively evaluate thermal neutron absorption effect.
- Other rack system tolerances and fuel positions are also treated to maximize keff (Worst Case Model), considering that water density is treated as a parameter and analysis is performed in a finite system.
- The concrete wall on the outside of the new fuel storage pit is modeled as 100 cm thick.
- Based on the double contingency principle, the simultaneous occurrence of an accident condition (ex. misloading, drop) with flooding condition need not be considered.

2.2.2 MCNP Model for NFR

As stated in 2.2.1.3, tolerances and off-center location of rack cells and fuel assemblies are considered as Worst Case Model, which maximize keff. More specifically,

- the maximum pellet diameter,

- the maximum pellet density,
- the minimum cladding outer diameter,
- the nominal cladding inner diameter because of negligible sensitivity in tolerance,
- the maximum pin pitch determined from the maximum fuel assembly width,
- the minimum rack pitch between a set of assemblies,
- the maximum inner rack cell dimension, and
- the minimum cell board thickness are used.

The values used in the model are found on Tables 2-1 and 2-2. Off-center locations of the racks and the fuel assemblies within tolerance are considered to maximize keff by uniformly moving each the rack cell and the fuel assembly to the direction of the center of the entire rack configuration. The analysis model is shown in Figure 2-3. Since the Worst Case Model is adopted, the only uncertainties considered in the calculated value of keff using equations (5) and (6) are the code bias and bias uncertainty from the criticality validation, and uncertainty in calculation.

2.2.3 Material Composition

The density, composition and atomic density for fuel, cladding, tube and thimble material used in the analysis are shown in Table 2-3. The same parameters for the SS rack, water between assemblies and as reflector material, and concrete are shown in Table 2-3. For each composition, MCNP ZAID library names are listed in Table 2-4. The temperature of the rack is near to the temperature where the built-in neutron cross section data in the MCNP library was prepared. Specifically, the temperature is 293.6K except for Zircaloy which is 300K.

2.3 Results

Analysis results of fully flooded and optimum moderation conditions are described.

2.3.1 Fully Flooded

As shown in Table 2-5, the analysis result is a keff of 0.91245 including uncertainty, which satisfies the design criteria of less than 0.95.

2.3.2 Optimum Moderation

Analysis results for various water densities from 0 to 100% are shown in Table 2-6 and in Figure 2-4. Optimum moderation occurs at 10% water density. Even at this condition keff is 0.93828 including uncertainty, and satisfies the design criteria of less than 0.98. Water density of ether mist or foam from fire sprinkler is known in practice to be less than 1%, and at this condition, the keff is less than 0.67, thus the system is enough sub-critical.

Table 2-1 MHI 17x17 Fuel Assembly Parameters of US-APWR for Criticality Analysis in NFR and SFR

Parameter	Design Parameters	MCNP Units
Fuel Rod Configuration	17x17 (Figure 2-1)	17x17 (Figure 2-1)
Rods per Assembly	264	264
Control Rod Guide Thimble / In-core Instrumentation Guide Tube per Assembly	24 / 1	24 / 1
Rod Pitch	0.496 inch	1.26 cm
Active Fuel Length	165.4 inch	420 cm
Pellet OD	0.322[ ] inch	0.819[ ] cm
Enrichment	5.0 wt%U-235	5.0 wt%U-235
UO_2 Density (% of Theoretical Density (TD))	97[ ] % of TD	97[ ] % of TD
[		
		]
Cladding OD	0.374[ ] inch	0.950[ ] cm
Cladding ID	0.329[ ] inch	0.836[ ] cm
Cladding Material	ZIRLO	Zr 100% (Comp.)
Control Rod Guide Thimble OD	0.482 inch	1.224 cm
Control Rod Guide Thimble ID	0.450 inch	1.143 cm
In-core Instrumentation Guide Tube OD	0.482 inch	1.224 cm
In-core Instrumentation Guide Tube ID	0.450 inch	1.143 cm
Control Rod Guide Thimble / In-core Instrumentation Guide Tube Material	Zircaloy-4	Zr 100% (Comp.)
[		]
Burnable Absorbers	—	None
Burn-up	—	0 MWd/t

Table 2-2 Design Parameters for New Fuel Rack

Parameter	Design Parameters	MCNP Units
Storage Cells	180	182 (for Analysis)
Cell Center-to-Center Pitch	16.9±0.4 inch	43.0±1.0 cm
Cell Positioning Tolerance	±0.2 inch	±0.5 cm
Cell Inner Dimension (Width)	8.98±0.08 inch	22.8±0.2 cm
Cell Wall Thickness	0.24 (-0.0) inch	0.6 cm (Min.)
Cell Wall Material	SS304	SS304

Table 2-3 (1/3) Materials and Compositions for NFR and SFR

(1) Fresh UO_2 Fuel Assembly (Enrichment = 5.0 wt%)

Material Condition (1)	**Isotope**	**Atom Density (atoms/barn-cm)**
a. For SFR Nominal Model Fractional TD = 97% (2)	^{235}U	
	^{238}U	
	O	
b. For NFR Worst Case Model and SFR Tolerance Sensitivity Analysis Fractional TD = [ ] (2)	^{235}U	
	^{238}U	
	O	
Zircaloy (6.55 g/cm^3) (3)	Zr	4.3239×10^{-2}

(1) UO_2 Pellet Density used is 10.96 g/cm^3 as 100% TD.
(2) The stack density is reduced to account for the pellet dishing and chamfering.
(3) Conservatively, ZIRLO cladding and Zircaloy were treated as 100 % Zr.

Table 2-3 (2/3) Materials and Compositions for NFR and SFR

(2) Structure Material

Material	Isotope	wt%	Atom Density (atoms/barn-cm)
SS304 (7.93 g/cm^3)	Ni	9.25	7.5246×10^{-3}
	Cr	19.0	1.7450×10^{-2}
	Fe	71.75	6.1329×10^{-2}
Borated Stainless Steel (B-SS) (7.75 g/cm^3) Boron=0.95 wt% Note Used in SFR except for DFR	^{10}B	0.174	8.1195×10^{-4}
	^{11}B	0.776	3.2888×10^{-3}
	Ni	9.25	7.3538×10^{-3}
	Cr	19.6	1.7593×10^{-2}
	Fe	70.2	5.8643×10^{-2}
Concrete (2.30 g/cm^3)	H	1.00	1.3742×10^{-2}
	O	53.00	4.5919×10^{-2}
	C	0.10	1.1532×10^{-4}
	Na	1.60	9.6395×10^{-4}
	Mg	0.22	1.2388×10^{-4}
	Al	3.39	1.7409×10^{-3}
	Si	33.67	1.6617×10^{-2}
	K	1.30	4.6052×10^{-4}
	Ca	4.34	1.5025×10^{-3}
	Fe	1.39	3.4492×10^{-4}

Table 2-3 (3/3) Materials and Compositions for NFR and SFR

(3) Between assemblies Water with or without boron and reflector water

Material	Water Density[(1)] (% of full density)	Isotope	Atom Density (atoms/barn-cm)
Water (Moderator)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}
	10	H	6.6854×10^{-3}
		O	3.3427×10^{-3}
Boric Acid Water (Boron conc. 100ppm)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}
		^{10}B	1.1028×10^{-6}
Boric Acid Water (Boron conc. 200ppm)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}
		^{10}B	2.2056×10^{-6}
Boric Acid Water (Boron conc. 300ppm)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}
		^{10}B	3.3084×10^{-6}
Water (Reflector)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}

(1) 100 % of full density: 62.43 lbm/ft^3 (1.0g/cm^3)

Table 2-4 MCNP ZAIDs Used for Each Nuclide

Nuclide	ENDF/B-V
H	1001.50c
^{10}B	5010.50c
^{11}B	5011.55c
C	6012.50c
N	7014.50c
O	8016.50c
Na	11023.51c
Mg	12000.50c
Al	13027.50c
Si	14000.51c
K	19000.51c
Ca	20000.51c
Cr	24000.50c
Fe	26000.55c
Ni	28000.50c
Zr	40000.56c
^{235}U	92235.50c
^{238}U	92238.50c

Table 2-5 NFR Analysis Result at Fully Flooded Condition

Item	Data
Keff ± 1σ	0.90380 ± 0.00039
Code Bias (1-k_c)	0.0029
Code Bias Uncertainty (Δk_c 95/95)	1.899 x 0.0030
Keff (incl. 95/95 uncertainties)	0.91245

Table 2-6 NFR Analysis Results on Surveying the Optimum Moderation Condition

Water Density (% of full density)	Calculated Keff	Keff (incl. 95/95 uncertainties)
0	0.58099 ± 0.00025	0.58961
1	0.65856 ± 0.00027	0.66718
3	0.79498 ± 0.00030	0.80361
5	0.87525 ± 0.00032	0.88388
7	0.91455 ± 0.00032	0.92318
8	0.92454 ± 0.00032	0.93317
9	0.92942 ± 0.00032	0.93805
10	0.92965 ± 0.00032	0.93828
11	0.92611 ± 0.00032	0.93474
20	0.84229 ± 0.00032	0.85092
30	0.75202 ± 0.00033	0.76066
50	0.71453 ± 0.00035	0.72317
100	0.90380 ± 0.00039	0.91245

Note. Same code bias and uncertainty are used at Table 2-5.

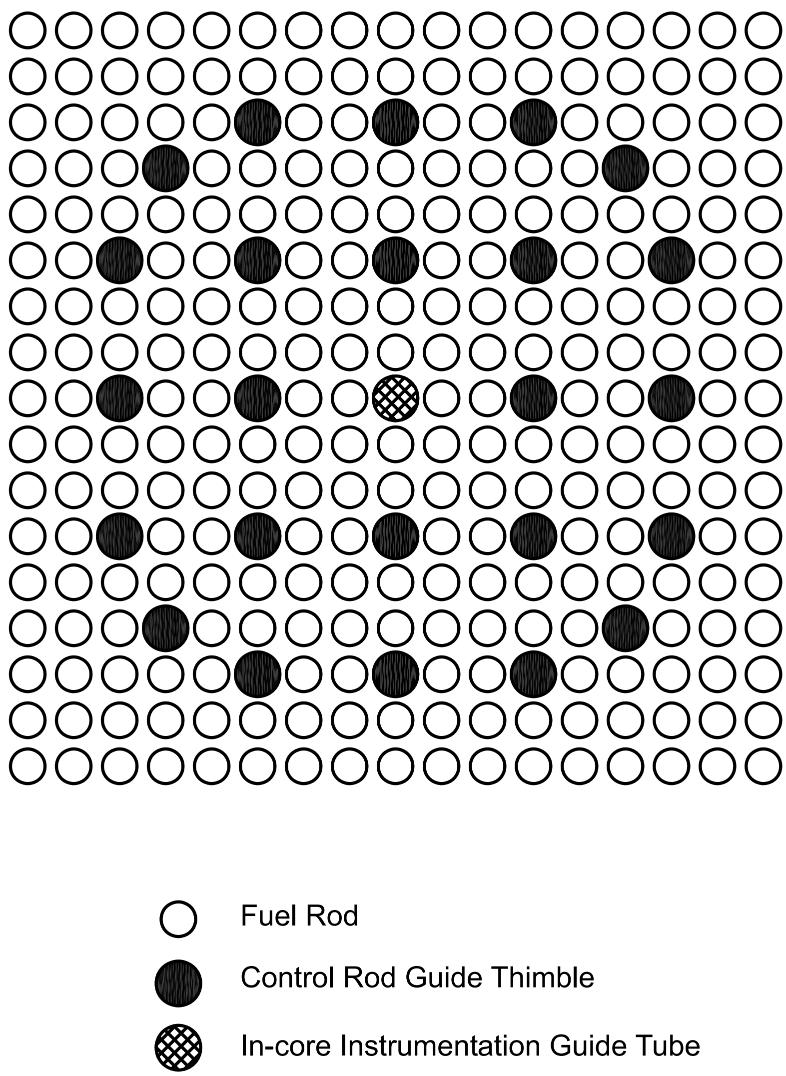
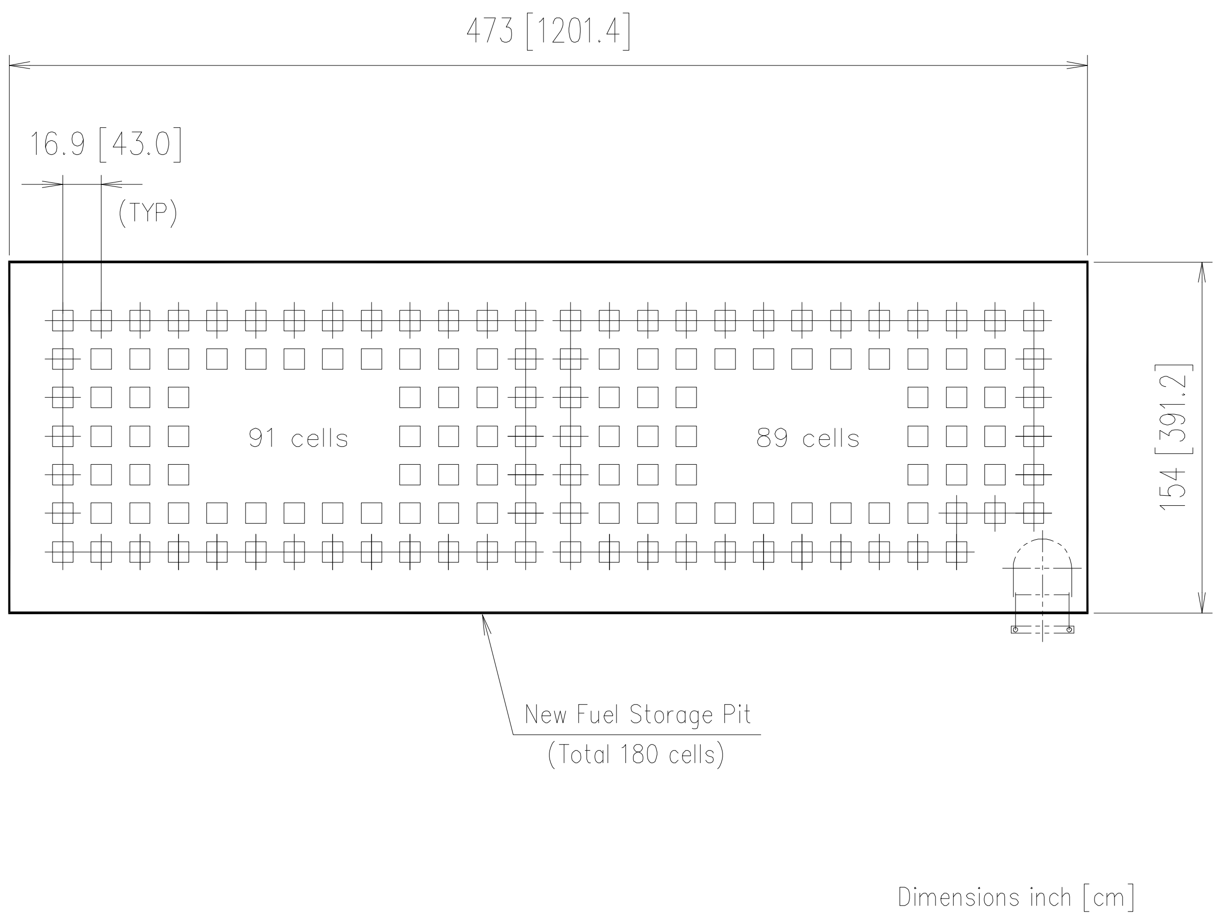
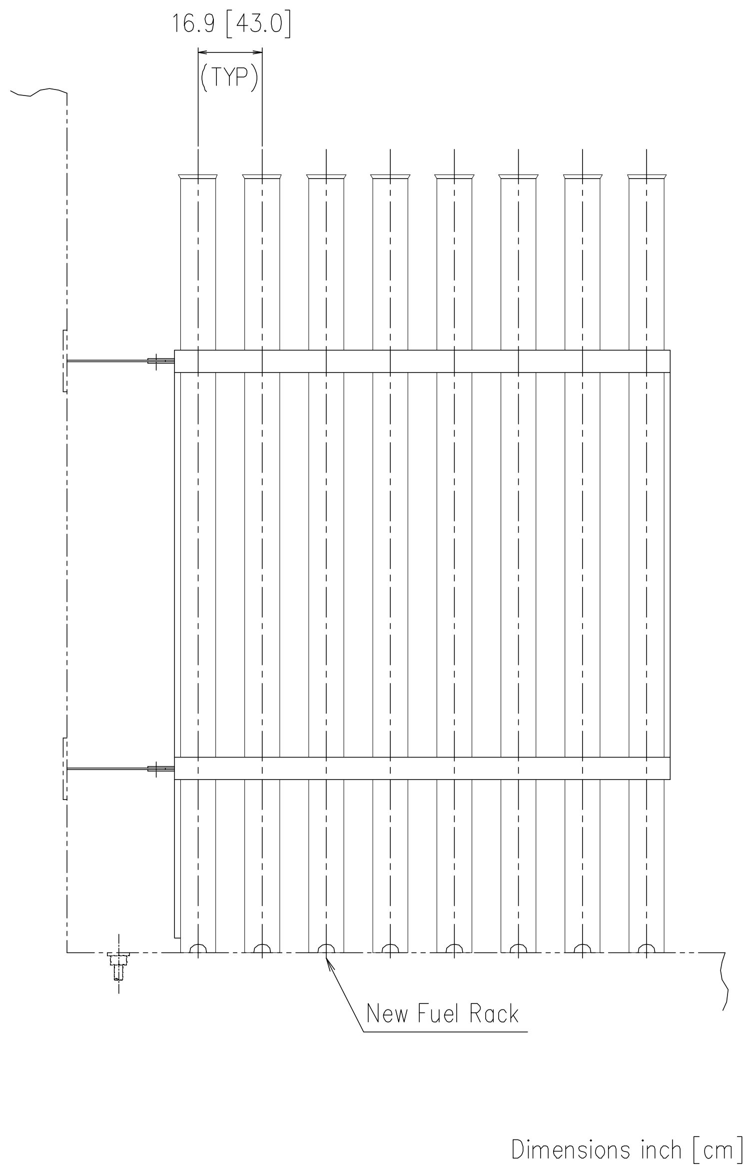


Figure 2-1 MHI US-APWR 17x17 Fuel Assembly Cross Section



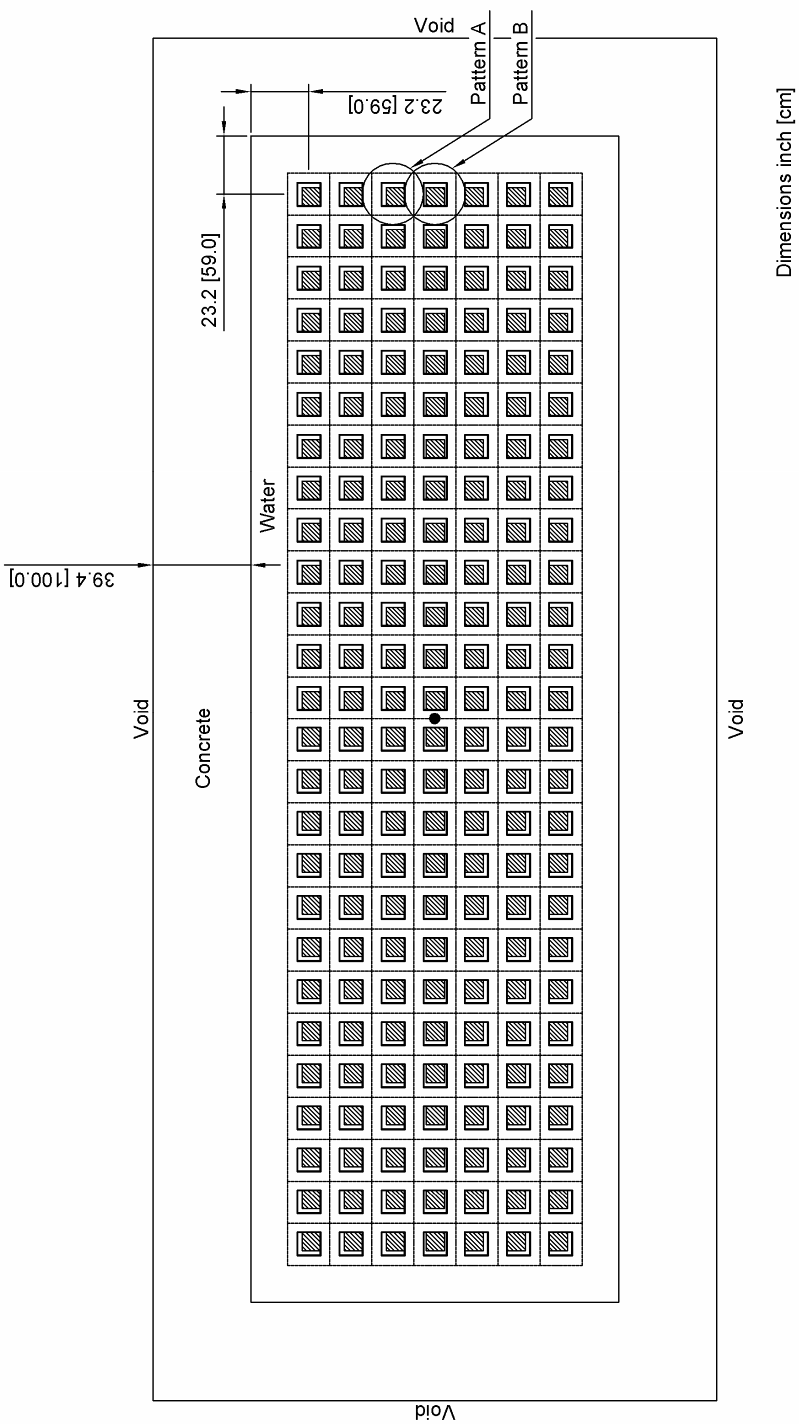
Plan

Figure 2-2 (1/2) Configuration of New Fuel Rack



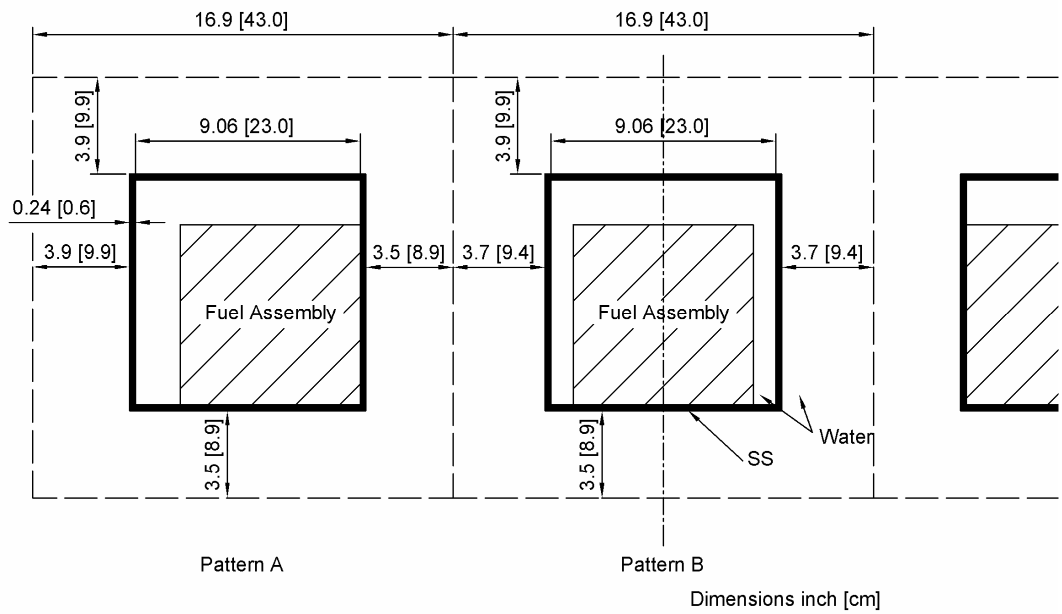
Elevation

Figure 2-2 (2/2) Configuration of New Fuel Rack



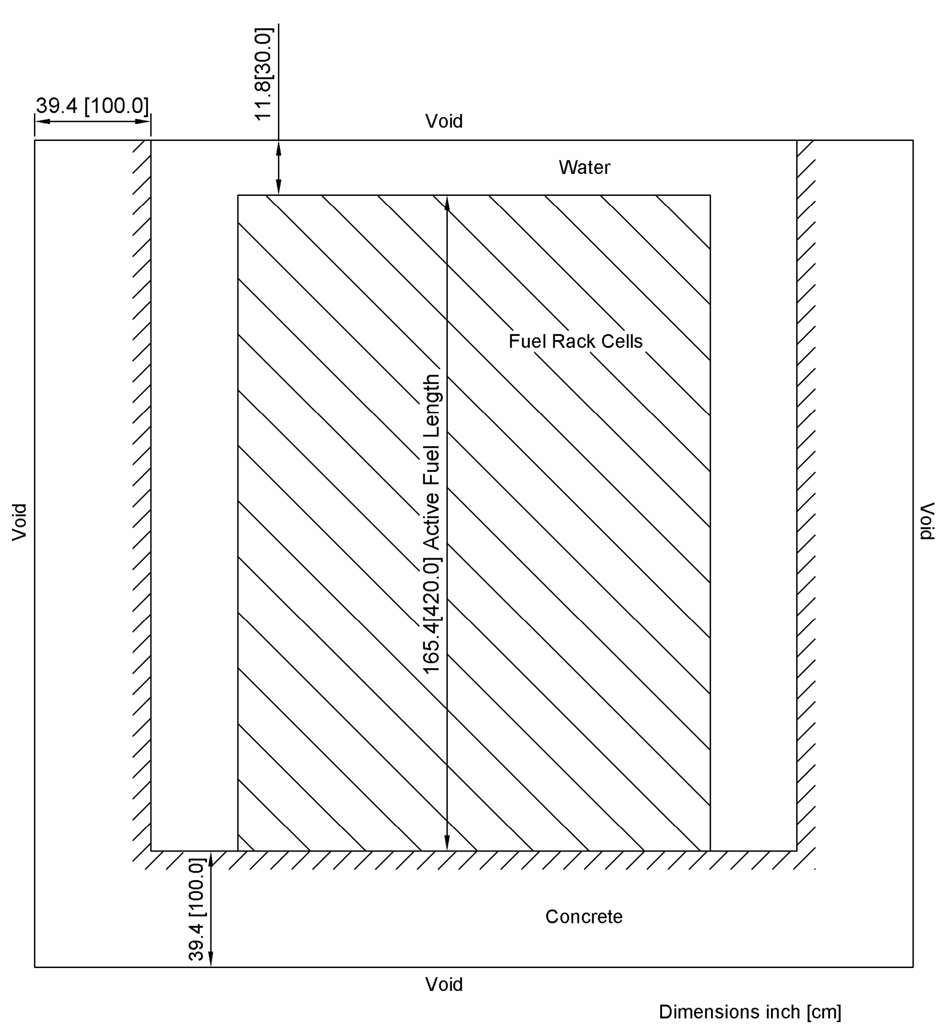
Plan for Whole
(Dotted circle means the direction of off-center arrangement of racks and fuel assemblies.)

Figure 2-3 (1/3) MCNP Model of New Fuel Rack



Plan of detailed rack model

Figure 2-3 (2/3) MCNP Model of New Fuel Rack



Elevation

Figure 2-3 (3/3) MCNP Model of New Fuel Rack

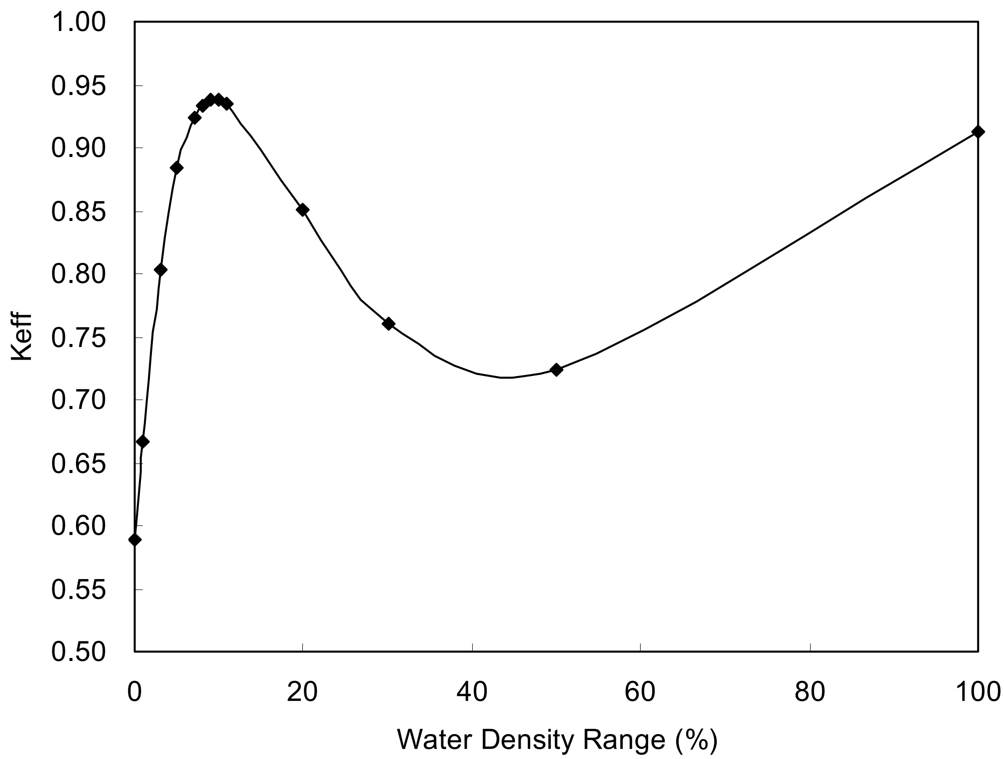


Figure 2-4 Results of Keff vs Various Water Density of New Fuel Rack

3.0 Criticality Analysis of Spent Fuel Rack

Chapter 3 describes the criticality analysis results for US-APWR 17×17 fuel assemblies stored in SFR. It is shown that the maximum value of keff at pure water flooded condition is less than 1.0, and when applying soluble boron credit, keff is less than or equal to 0.95, therefore the design criteria is satisfied and subcriticality is maintained.

3.1 Design Method

Design criteria, evaluation results and analysis code are described in the following subsections.

3.1.1 Design Criteria

The design criteria are pursuant to the 10 CFR 50.68 (b) item (4) for spent fuel rack as follows: "For spent fuel storage racks, the maximum keff value, including all biases and uncertainties, must be less than or equal to 0.95 with partial credit for soluble boron credit and less than 1.0 with full density unborated water, at a 95 percent probability, 95 percent confidence level. Rack cells are assumed to be loaded with fuel of the maximum fuel assembly reactivity."

Therefore, an evaluation is performed to show that subcriticality is maintained at the pure water flooded condition followed by an evaluation to determine the boron concentration to keep keff less than or equal to 0.95.

In the boron dilution event described in Section 3.4, this boron concentration is considered as the limiting boron concentration and the time and volume of water needed to meet this limiting boron concentration is calculated and it is shown to be no matter.

Although not used in the dilution evaluation from the double contingency principle, if accident conditions other than boron dilution are postulated, the highest boron concentration to offset the reactivity increase is added to the above limiting concentration to cover the most limiting accident as a single failure.

3.1.2 Evaluation

Based on the design criteria in the previous section and equation (4) in section 2.1.2 of NFR, the evaluation equations for SFR are expressed as follows.

Pure water :
$$k_p + 0.0029 + \left(\Delta k_p^2 + (1.899 \times 0.0030)^2\right)^{1/2} < 1.0 \qquad (7)$$

Borated water :
$$k_p + 0.0029 + \left(\Delta k_p^2 + (1.899 \times 0.0030)^2\right)^{1/2} \leq 0.95 \qquad (8)$$

3.1.2.1 Reactivity Uncertainty Due to Tolerances

Statistical combination of the reactivity effect of independent tolerances is performed for this SFR analysis. The tolerances of the fuel assembly, the rack cell, rack cell installation, and fuel positioning in the rack cell are evaluated individually. These are described more in 2.1.2.1.

As for the neutron absorption materials, minimum amounts are conservatively considered. Therefore, B-SS plate thickness and its boron concentration added for SFR are set at the minimum value.

3.1.3 Analysis Code

As stated in Section 1.1 the criticality safety analysis uses the three-dimensional Monte Carlo code MCNP version 5.1.40 and the continuous-energy neutron data ENDF/B-V.
Additionally, for the S(α, β) thermal scattering data, "lwtr.01t" for hydrogen in light water is applied to water. Though the scattering effect as reflector is small, it is applied to the hydrogen in floor and wall concretes.

Neutron generation histories in Monte Carlo calculation were set to four million as shown below. In this condition, 1σ is approximately 0.0004 and is sufficiently small.

- Number of neutron particles per generation: 2000
- Number of neutron generation: 2050
- Number of skipped generation: 50
- Number of total history: 4 million

3.2 Analysis

3.2.1 Analysis Conditions

Specifications of stored fuel and SFR together with conditions to be used in analysis model are described in this subsection.

3.2.1.1 Fuel Assembly Description

US-APWR 17x17 fuel assembly parameters used in the criticality analysis of NFR are listed in Table 2-1. Arrangement of fuel rods, control rod guide thimbles and an in-core instrumentation guide tube in the fuel assembly is shown in Figure 2-1. Fuel cladding is made of ZIRLO which is a zirconium base alloy with a small amount of niobium (Nb) added for increasing corrosion resistance.

3.2.1.2 US-APWR Spent Fuel Rack Description

The SFR have a capacity to store a maximum of 900 fuel assemblies. Rack configuration and design parameters are shown in Table 3-1 and Figure 3-1. As shown in Figure 3-1, the SFR is composed of four modules of 11.1 inch (28.2 cm) rack pitch. They are two modules of 18×12=216cells and two modules of 18x13=234cells. The rack material is Borated stainless steel (B-SS), which contains approximately 1.0 weight percent boron. When the SFR is installed, the cells are placed a given distance from a baseline. The tolerance in this distance is given on Table 3-1. SS supporting structures are installed to support B-SS rack modules, but are located locally and peripherally, so they do not affect the criticality analysis.

In addition, the Damaged Fuel Rack which can store 12 Damaged Fuel Container in a row are provided in vicinity to the B-SS racks. Damaged fuel is inserted into Damaged Fuel Container and stored in annular Damaged Fuel Rack. The rack material is stainless steel, the rack pitch is 24 inch (60.9 cm), and it is 21.7 inch (55 cm) apart from the B-SS rack. Rack configuration and design parameters of Damaged Fuel Rack are shown in Table 3-2 and Figure 3-1.

The rack structure and the fuel handling equipment are designed to preclude the fuel assembly misplacement and drop as the fuel handling accident. In addition, the rack is designed to have no significant deformation in fuel assembly drop accident which may affect criticality analysis. If a fuel assembly can be placed either horizontally on the top of the racks or just outside of the racks, the resulting keff is anticipated sufficiently less than the criticality safety design criteria because of the existence of boric acid water at 4000 ppm boron. And under the double contingency principle, the dilution event needs not to be considered concurrently with the other accident conditions.

3.2.1.3 Assumptions

Using the fuel and SFR parameters, analyses are performed for the following conditions

Assumptions on Fuel Assembly

- The fresh UO_2 fuel assembly without burnable absorber is assumed to have a maximum enrichment of five weight percent which is pursuant to 10 CFR 50.68 (b) item (7).
- The fuel cladding is conservatively assumed to be 100% zirconium which has a smaller neutron absorption cross section compared with ZIRLO.
- The fuel rods, cladding and the control rod guide thimbles and the in-core instrumentation guide tube are modeled over the active fuel length of the fuel assembly. The grid spacers made of both Zircaloy-4 and Inconel 718 are conservatively neglected.
- The structural material at both ends of fuel assembly have many holes to allow coolant flow so the effective contribution as neutron reflector is small, thus they can be replaced by water or concrete. At the flooded condition, a 30cm water layer and a 1m concrete layer have equivalent reflector effect and the thickness is sufficient to maximize the reflection effect. Then, 30cm water layer is placed on the top of the effective fuel length and a concrete layer of 1m thickness is placed on the underside.

Assumptions on Spent Fuel Rack

- B-SS rack calculations at nominal conditions are conducted for rack cells of 11.1 inch (28.2cm) in an infinitely repeated array system, and the tolerances and biases are evaluated separately.
- For the uncertainties in the fuel rack pitch and the uncertainties in the fuel assembly placement in each cell, analysis are carried out for centrally off-centered 4, 16, 36 fuel assembly configuration given reflective boundary condition. The maximum saturated reactivity increase among them is selected as the reactivity uncertainty.
- For B-SS rack plate, minimum thickness and minimum boron contents are used.
- Water density of 62.43 lb/ft^3 ($1.0 g/cm^3$) is used to cover the maximum value.

Assumptions on Damaged Fuel Rack

- The 12 DFR made of SS are sufficiently isolated each other and also from the B-SS racks from the neutron interaction viewpoint. However the Damaged Fuel Container made of SS inserted into the DFR is conservatively neglected to reduce the rack pitches by the degree of rack ID minus fuel assembly width. Therefore only the fuel assemblies and the annular DFR are considered.

Relating the assumption mentioned above;

- Since there is no axial variation in the rack B-SS materials, there is no fuel assembly drop that could change the amount of neutron absorbers covering the active fuel.
- Since there is considerable boric acid water between the top of the active fuel and the top of the fuel racks, a dropped assembly that would lie horizontally on the top of the racks has no impact on reactivity.
- There are no areas in the SFR where a fuel assembly can be placed effectively just outside of the racks. And if this event is hypothetically occurred, the resulting keff is sufficiently less than 0.95 because of the highly concentrated boric acid water at 4000 ppm boron.
- Evaluation of dilution event is conducted in Chapter 3.4.

3.2.2 MCNP Model for SFR

3.2.2.1 Model for Flooded without Boron

3.2.2.1.1 Nominal Model

As stated in Subsection 3.2.1.3, the evaluations are carried out in basic system of an infinitely repeating array of nominal rack pitch. Analysis model is shown in Figure 3-2.

3.2.2.1.2 Uncertainty Analysis Models for Tolerances

Sensitivity analyses for independent tolerances are carried out individually utilizing the above nominal model by changing the dimension of the objective parameter. However, for the rack pitch and fuel placement cases stated in assumptions in 3.2.1.3, simulations by this model are impracticable. The analysis models for these cases are shown in Figure 3-3 and Figure 3-4.

3.2.2.2 Soluble Boron Credit

Analyses are carried out for an infinitely repeating array of nominal models with boron concentrations as parameter.

Tolerance uncertainties evaluated in pure water are equally applied to these cases. The reason of this treatment is that the inhomogeneity of thermal neutron flux distribution in pool water is higher for no boron existing case, for example thermal neutron flux gradient near fuel assembly is larger for 0 ppm boron. So, the total uncertainty at 0 ppm boron is thought to be nearly equal or slightly conservative.

3.2.2.3 Damaged Fuel Rack

As stated in assumptions in 3.2.1.3, only the fuel assemblies and the SS annular racks are considered and others are omitted to reduce the rack pitches by the degree of rack ID minus fuel assembly width. The analysis information and model are shown in Table 3-2 and Figure 3-5. The total 936 B-SS rack cells in a 26x36 array with the same rack pitch as the actual one are placed adjacent to the Damaged Fuel Rack. And the worst case model is considered for tolerances and location of fuel assemblies and racks.

Sensitivity evaluation is carried out by comparing the analyses with and without Damaged Fuel Rack. This evaluation is performed for pure water model where neutron interaction is thought to be nearly equal or slightly strong.

3.2.3 Material Composition

For fuel, cladding and thimble materials, the density, composition and atomic density used in the analysis are shown in Table 2-3. The rack B-SS, water, and concrete material compositions are shown in Table 2-3. For each composition, MCNP ZAID library names are listed in Table 2-4.

Pool water temperature in SFR is the maximum 120 °F (48.9°C) at normal operation condition, the maximum 140 °F (60°C) at single failure condition, and the maximum operation temperature defined in the system design is 200 °F (93.3°C). Considering dependency of water density to temperature, the use of the library made at ambient temperature is conservative and the value of water density 62.43 lb/ft^3 (1.0g/cm^3) is taken for the condition that the maximizes reactivity.

3.3 Results

3.3.1 No Soluble Boron Calculation Results

As shown in Table 3-3, the final keff value is 0.96025 including uncertainties. This value is well below the design criteria of less than or equal to 1.0.

Uncertainty of individual tolerances are obtained by differing two effective multiplication factors calculated by Monte Carlo for two points, and adding the root of sum of squares of uncertainties (2σ) as probability error.

Namely,

$$\Delta keff_i = \left| keff_i - keff_0 \right| + \sqrt{(2 \times \sigma_0)^2 + (2 \times \sigma_i)^2} \tag{9}$$

$keff_0$ = effective multiplication factor for normal condition
$keff_i$ = effective multiplication factor for model considering tolerance i
σ_0 : 1σ for nominal model
σ_i : 1σ for model considering tolerance i

3.3.2 Soluble Boron Credit Requirement

The minimum soluble boron requirement as a partial credit for soluble boron was evaluated. The normal operating soluble boron concentration is 4000 ppm. However, as can be observed from Table 3-4 and Figure 3-6, only 100 ppm is required to reduce the keff to be less than 0.95 design criteria. Since the boron requirement is so low, it was decided to raise the minimum boron requirement to 200 ppm so the boron dilution analysis would not have to be redone if design changed were made. Therefore 200 ppm, which indicates 0.93779 in the keff including uncertainties, is selected for the requirement of soluble boron credit.

3.3.3 Sensitivity of Damaged Fuel Rack

Sensitivity analysis results are shown in Table 3-5. The difference between the keff with and without the Damaged Fuel Rack is within the uncertainties of the analysis. Therefore it is concluded that the soluble boron credit of 200 ppm is also acceptable.

Table 3-1 Design Parameters for Spent Fuel Rack

Parameter	Design Parameters	MCNP Units
Storage Cells	900	(Infinite)
Cell Center-to-Center Pitch	11.1±0.4 inch	28.2±1.0 cm
Cell Positioning Tolerance	±0.2 inch	±0.5 cm
Cell Inner Dimension (Width)	8.98±0.08 inch	22.8±0.2 cm
Cell Wall Thickness	0.16 (-0.0) inch	0.4 cm (Min.)
Cell Wall Material (Neutron Absorber)	B-SS (Borated SS)	B-SS (Borated SS)
Boron Content (Natural Boron)	0.95 to 1.05 wt% Range	0.95 wt% (Min.)

Table 3-2 Design Parameters for Damaged Fuel Rack

Parameter	Design Parameters	MCNP Units
Annular Storage Cells	12	12
Cell Center-to-Center Pitch (1)	24±0.7 inch	60.9±1.8 cm
Cell Positioning Tolerance	±0.35 inch	±0.9 cm
Center-to-Center Pitch to near B-SS Cell (1)	21.7±0.7 inch	55.0±1.8 cm
Cell Inner Diameter	14.6±0.4 inch	37.2±1.1 cm
Cell Wall Thickness	0.2±0.08 inch	0.5±0.195 cm
Cell Wall Material	SS304	SS304

(1) Conservatively, as the Damaged Fuel Container itself is omitted to reduce the rack pitch by the degree of rack ID minus fuel assembly width (8.43 cm both sides of fuel assembly), shown in Figure 3-5.

Table 3-3 Analysis Results of Fully Flooded without Boron for SFR

Case Description		Calculated Keff	ΔKeff
Nominal Case		0.94359 ± 0.00040	N/A
Asymmetric Cell Positioning (36 Cells gives max. Keff.)	4 Cells	0.94873 ± 0.00040	-
	16 Cells	0.94815 ± 0.00040	-
	36 Cells	0.94902 ± 0.00041	0.00658
Increase in Cell ID (+0.08 in.)		0.95132 ± 0.00041	0.00888
Asymmetric Fuel Positioning (4 Cells gives max. Keff.)	4 Cells	0.94412 ± 0.00041	0.00168
	16 Cells	0.94370 ± 0.00041	-
	36 Cells	0.94402 ± 0.00040	-
Increase in Pellet OD ([ ] in.)		0.94475 ± 0.00041	0.00231
Increase in Pellet Density ([ ])		0.94496 ± 0.00041	0.00252
Decrease in Cladding ID ([ ] in.)		0.94389 ± 0.00040	0.00143
Decrease in Cladding OD ([ ] in.)		0.94590 ± 0.00040	0.00344
Increase in Assembly Pitch ([ ] in.)		0.94491 ± 0.00040	0.00245
Code Bias (k_c)			0.0029
Code Uncertainty (Δk_c)			0.0030
95/95 Confidence coefficient			1.899
Sum of 95/95 Uncertainties and Biases			**0.01666**
Keff (incl. 95/95 uncertainty)		**0.96025**	

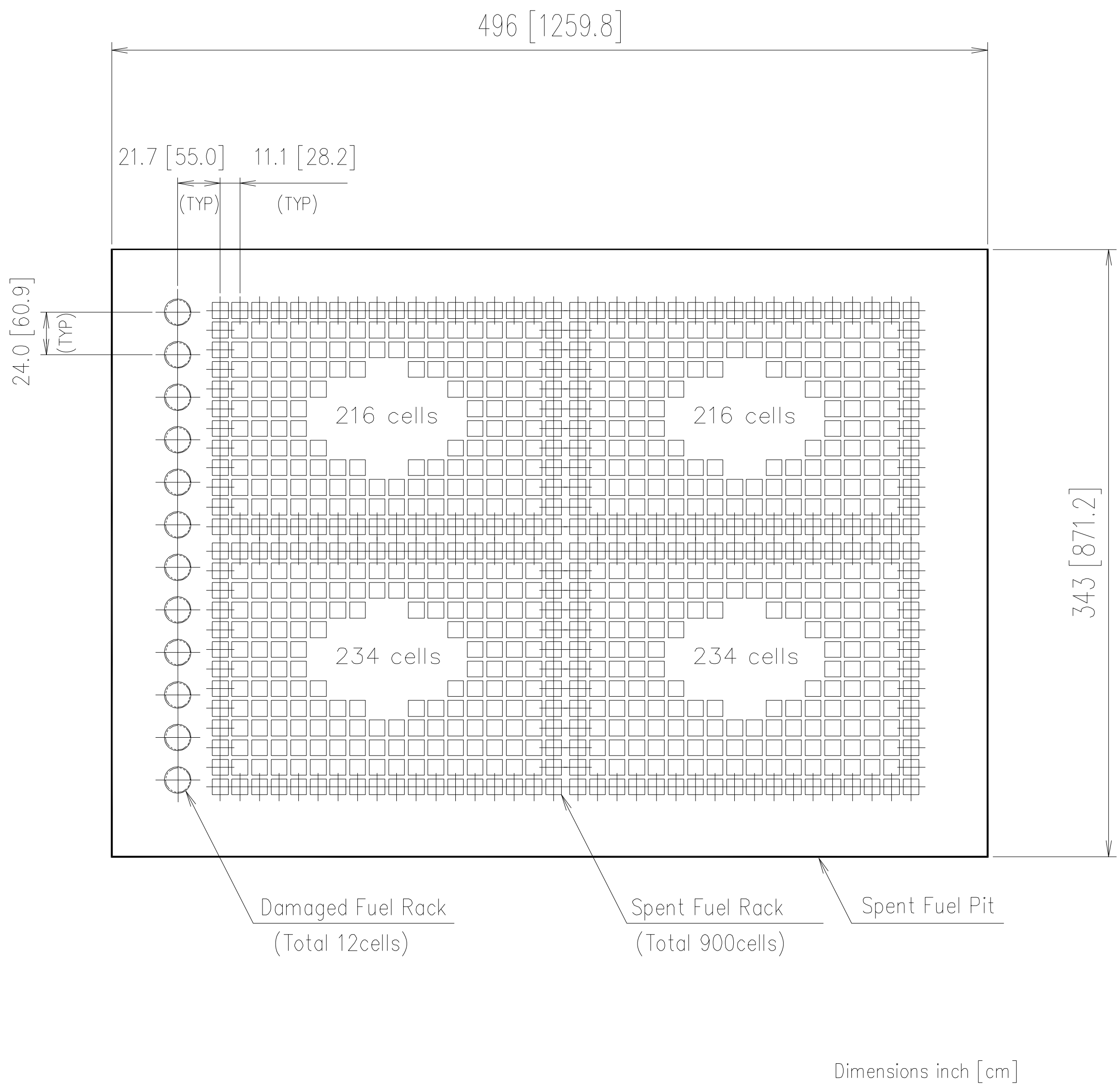
Table 3-4 Analysis Results of Fully Flooded with Boron for SFR

Soluble Boron Concentration	Calculated Keff	Keff (incl. uncertainty)(1)
0 ppm	0.94359 ± 0.00040	0.96025
100 ppm	0.93259 ± 0.00040	0.94925
200 ppm	0.92113 ± 0.00041	0.93779
300 ppm	0.91037 ± 0.00039	0.92703

(1) The results included a total uncertainty of（0.01666）for 0ppm

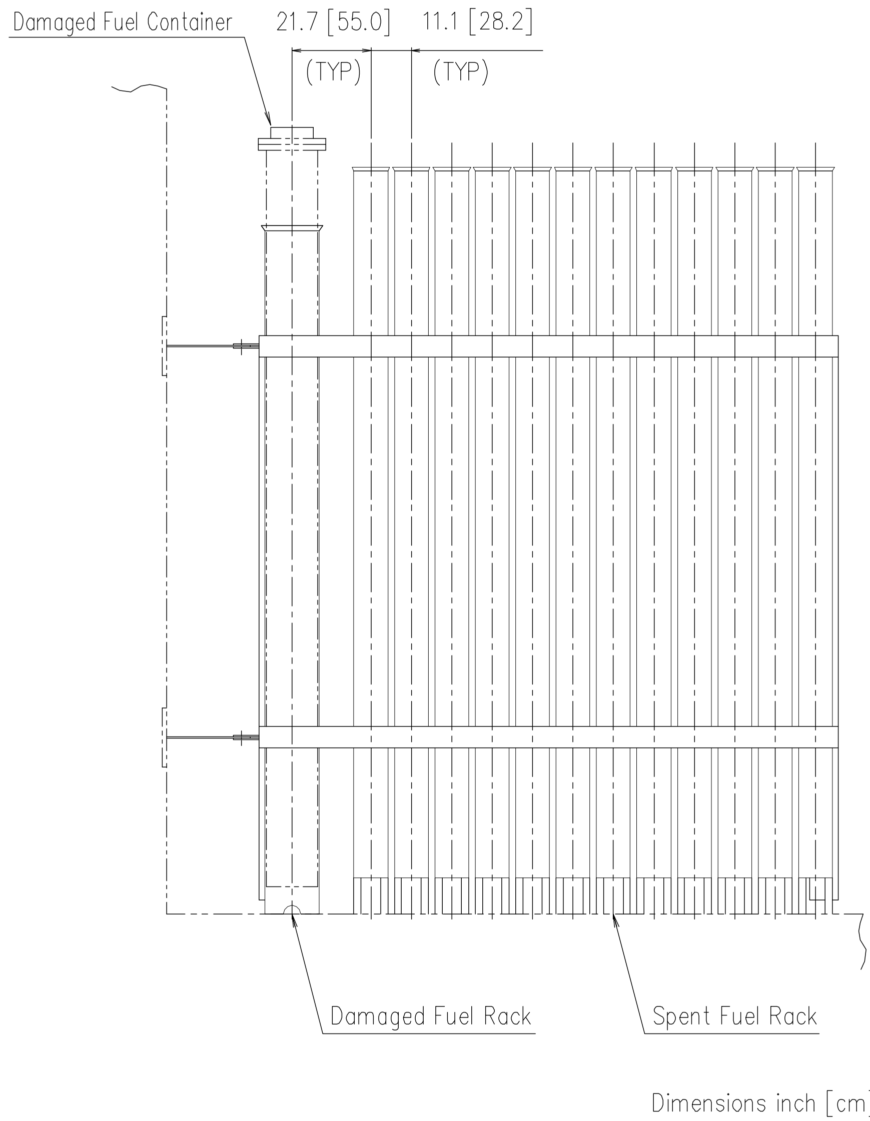
Table 3-5 SFR Analysis Results with and without Damaged Fuel Rack

Case	Calculated Keff
B-SS Rack Cells only	0.95844 ± 0.00040
With Damaged Fuel Racks	0.95870 ± 0.00040



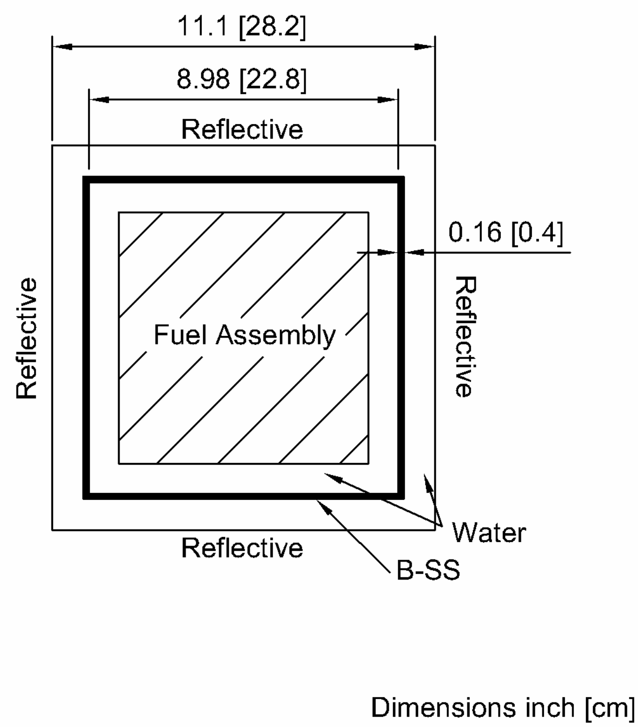
Plan

Figure 3-1 (1/2) Configuration of Spent Fuel Rack



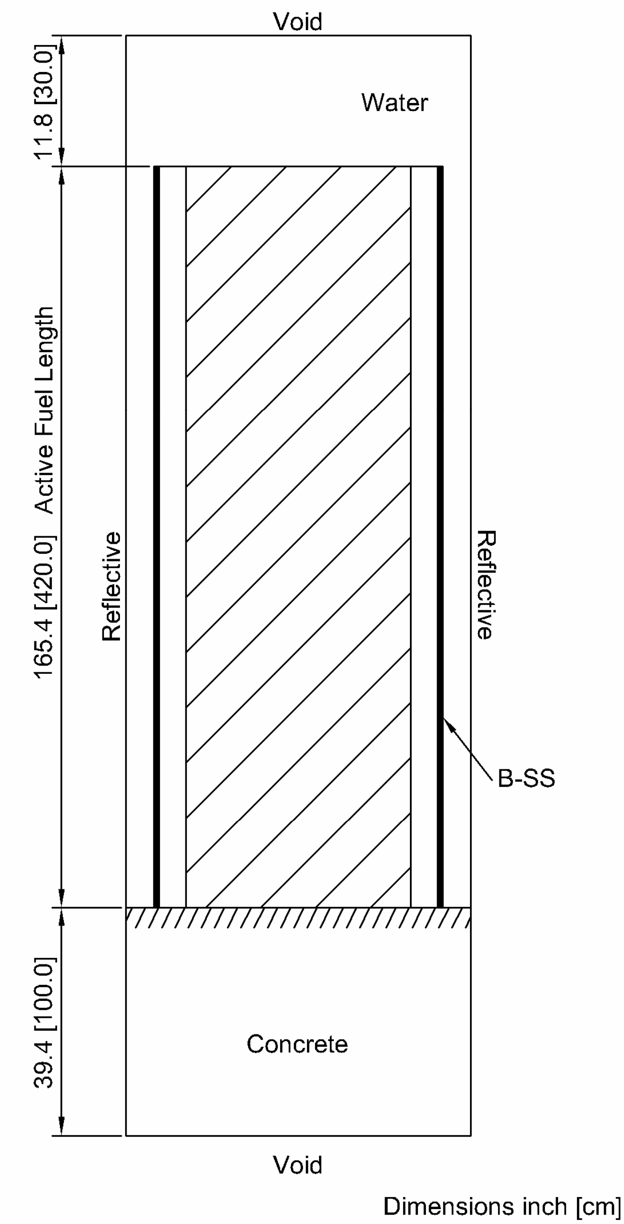
Elevation

Figure 3-1 (2/2) Configuration of Spent Fuel Rack



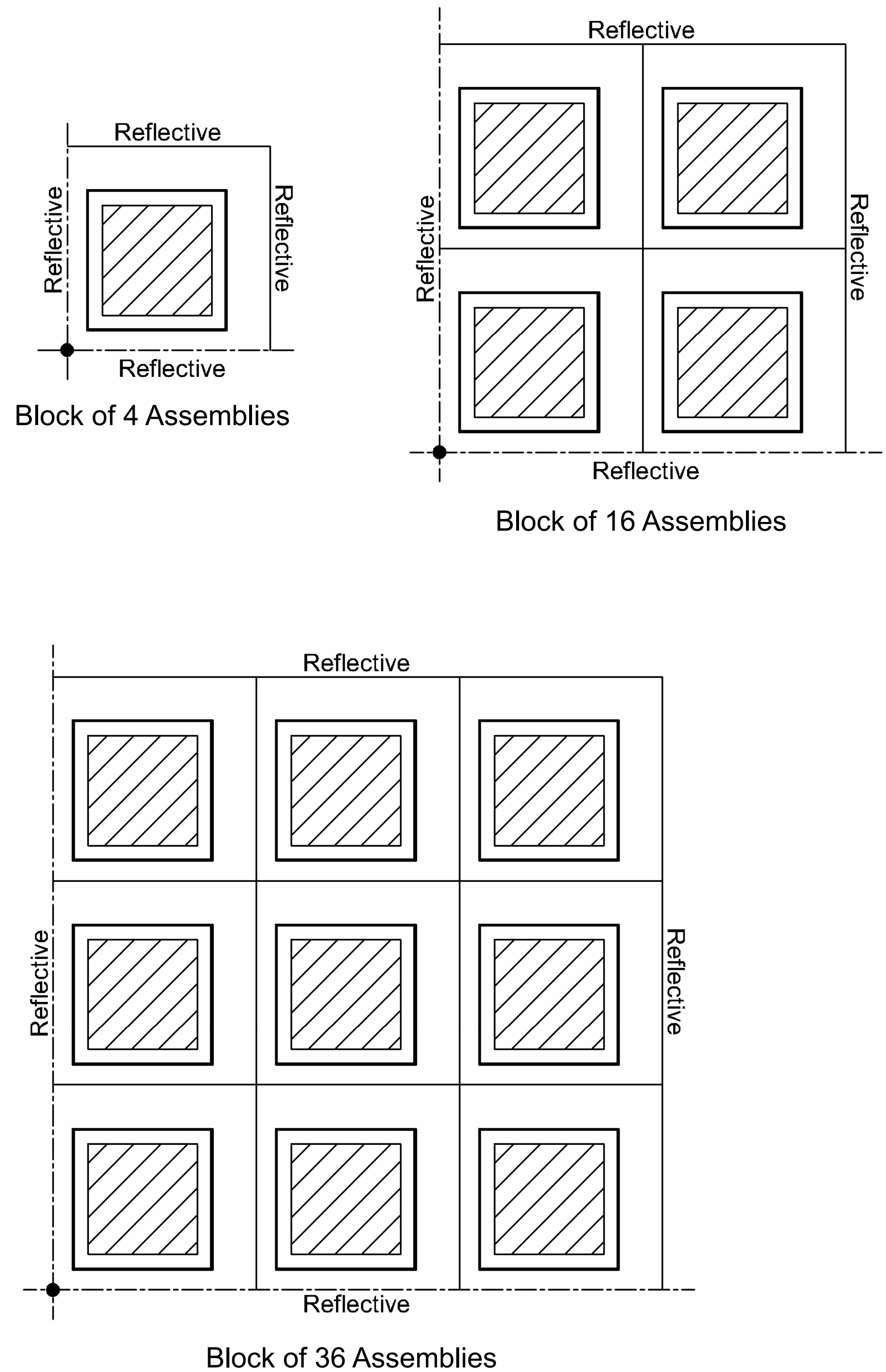
Plan

Figure 3-2 (1/2) Nominal MCNP Model of Spent Fuel Rack



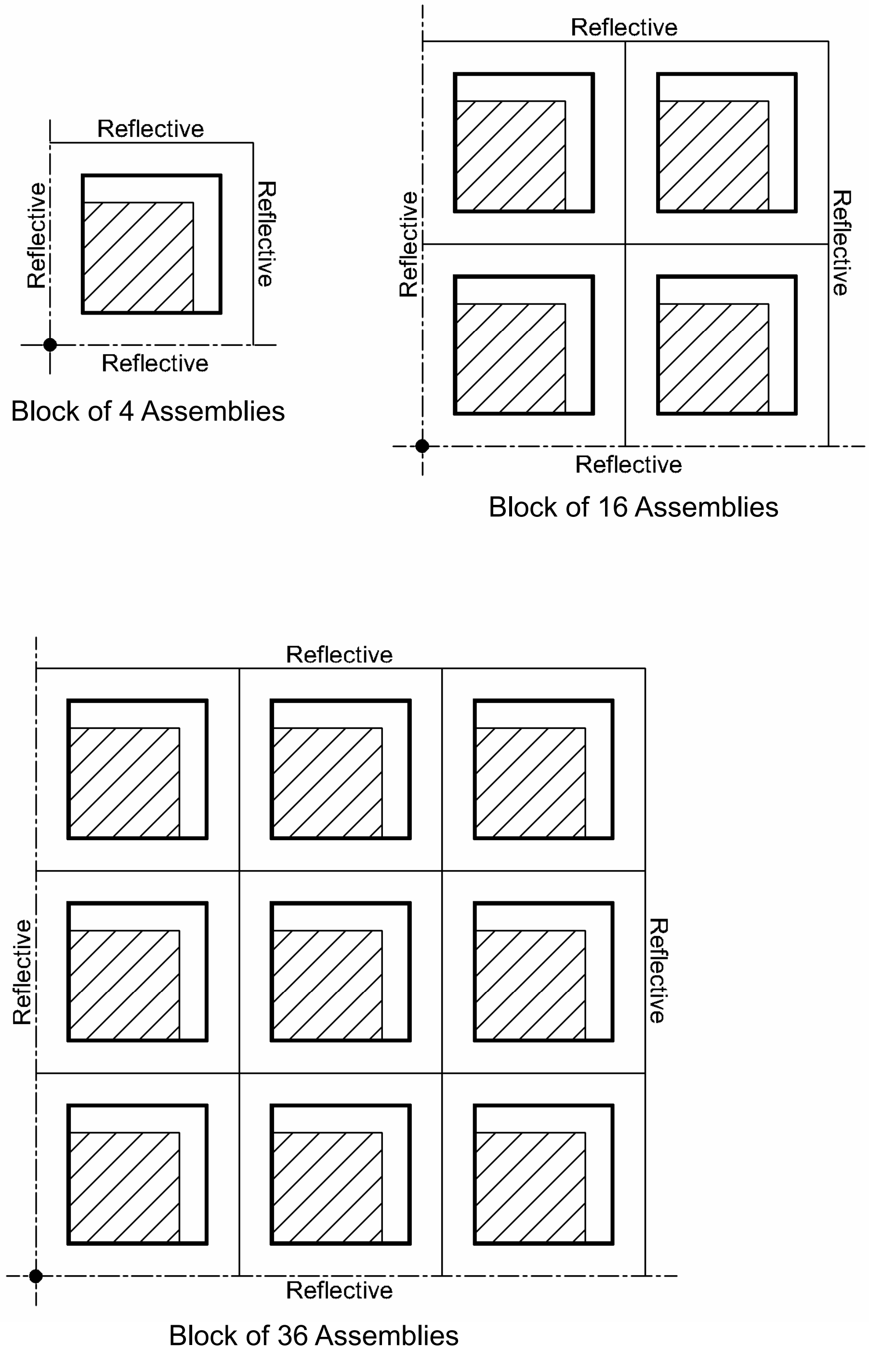
Elevation

Figure 3-2 (2/2) Nominal MCNP Model of Spent Fuel Rack



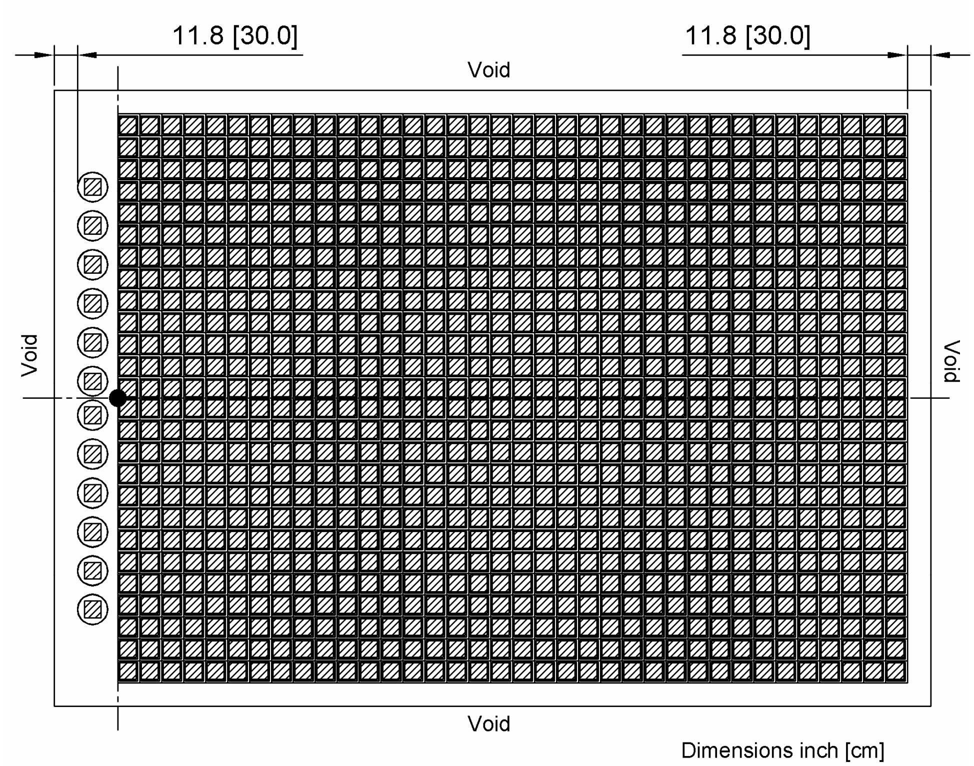
Plan
(Dotted circle means the direction of off-center arrangement of racks.)

Figure 3-3 MCNP Model for Rack Pitch Displacement of Spent Fuel Rack



Plan
(Dotted circle means the direction of off-center arrangement of fuel assemblies.)

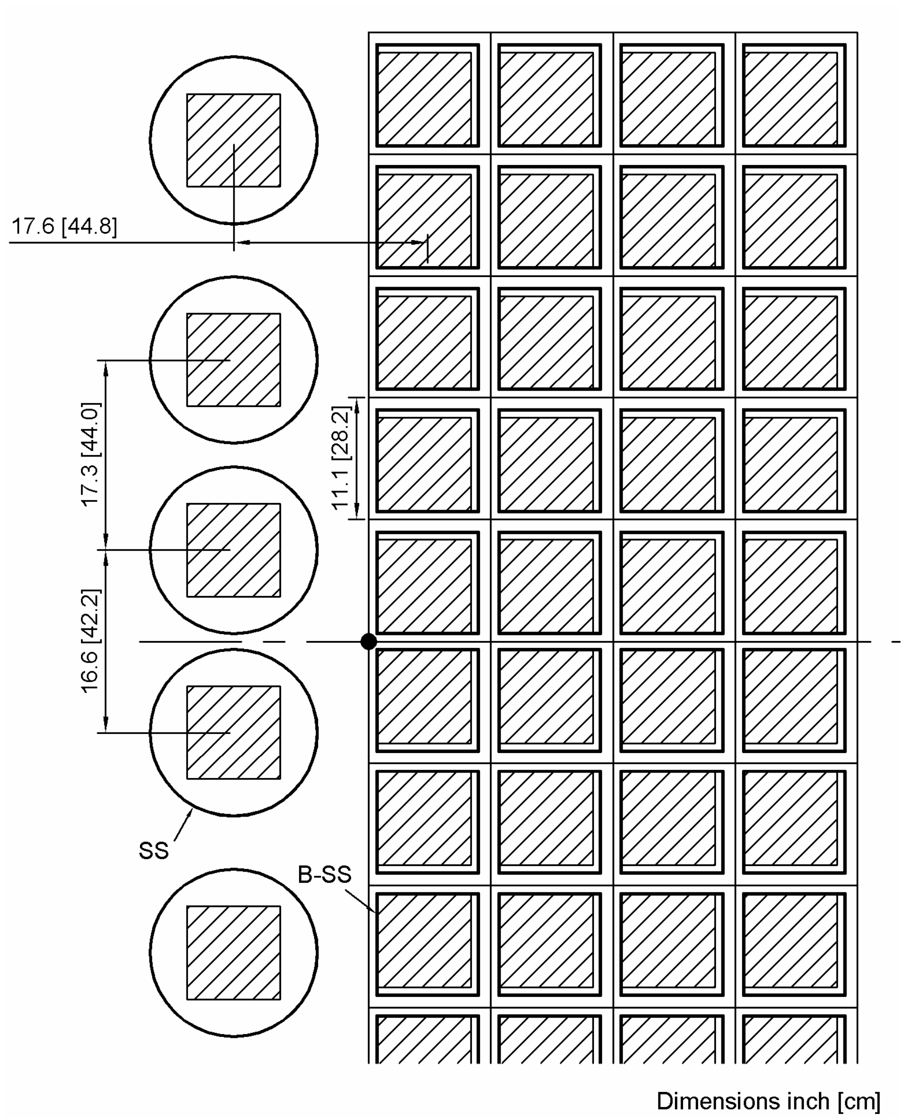
Figure 3-4 MCNP Model for Fuel Displacement within Cells of Spent Fuel Rack



Plan

(Dotted circle means the direction of off-center arrangement of racks and fuel assemblies.)

Figure 3-5 (1/4) MCNP Model for Entire Spent Fuel Rack with Damaged Fuel Rack



Plan

(Dotted circle means the direction of off-center arrangement of racks and fuel assemblies.)

Figure 3-5 (2/4) MCNP Model for Entire Spent Fuel Rack with Damaged Fuel Rack

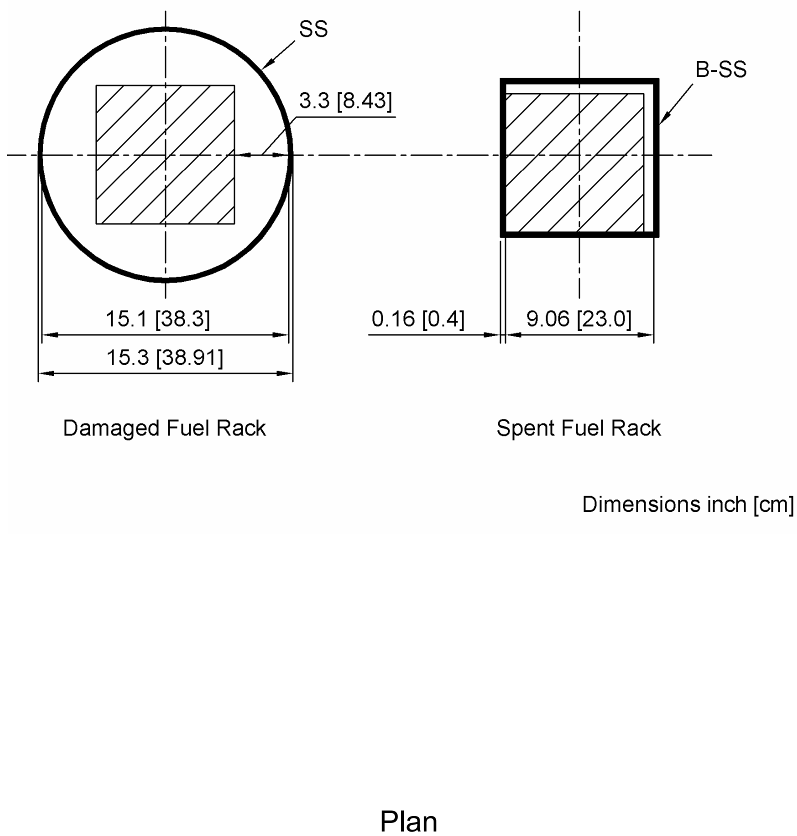
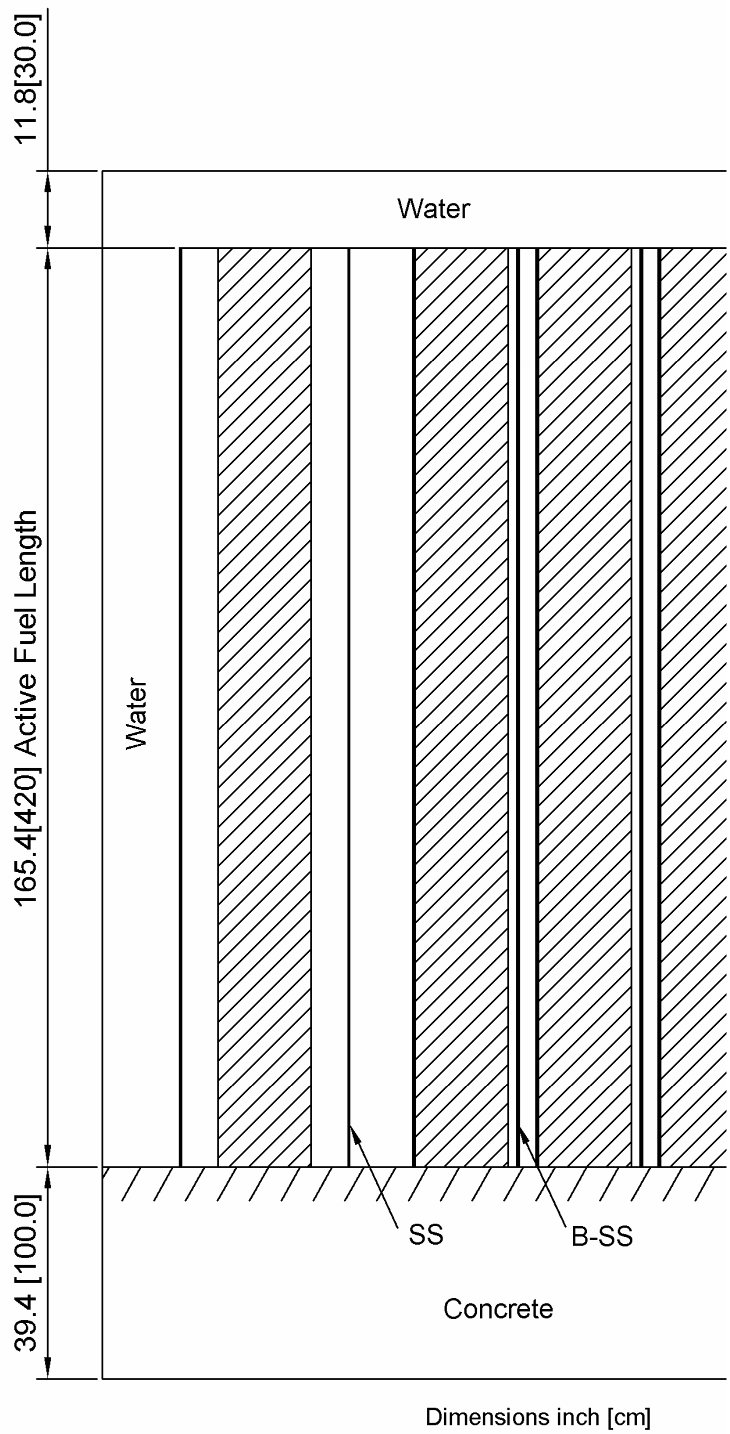


Figure 3-5 (3/4) MCNP Model for Entire Spent Fuel Rack with Damaged Fuel Rack



Elevation

Figure 3-5 (4/4) MCNP Model for Entire Spent Fuel Rack with Damaged Fuel Rack

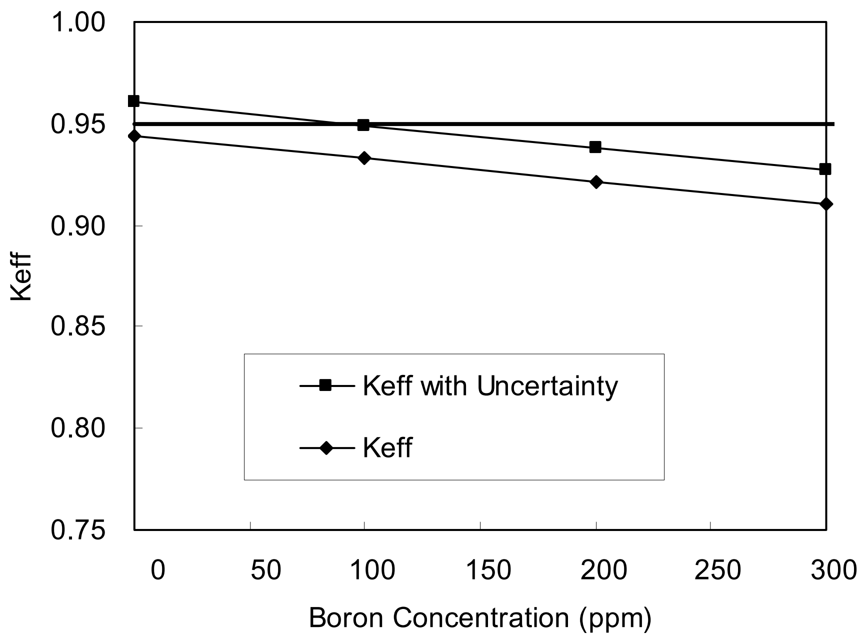


Figure 3-6 Results of Keff vs Soluble Boron Concentration of Spent Fuel Rack

3.4 Spent Fuel Pit Boron Dilution Evaluation

3.4.1 Background

Boron in acid form is utilized to control the reactivity of spent fuel in the spent fuel pit (SFP). In normal conditions, the boric acid water concentration is maintained at 4000 ppm which is the same as that of the refueling water storage pit (RWSP). A 7-day periodic surveillance of the pit water is conducted to ascertain that the boron concentration is within the specified limit (Refer to DCD Chapter 16.3.7.13).

On the other hand, the minimum boron concentration to keep the spent fuel in subcritical conditions is calculated to be 200 ppm. This value has been determined in anticipation of inadvertent boron dilution events that might occur through the various systems that are connected to the SFP. Component failures within such systems will alter normal SFP conditions and are likely causes for boron dilution. For example, a broken pipe in the fuel handling area inside the reactor building (R/B) may cause unborated water to flow into the SFP. Operator failures may also account for these events, such as unintentional flushing of unborated water from a non-borated water source and demineralized water into the SFP supply line in situations where the spent fuel pit cooling and purification system (SFPCS) lost its cooling capacity.

This section presents an analysis to provide assurance that even if such events occur, the minimum boron concentration requirement in the SFP is met so subcriticality is assured.

3.4.2 Description of SFP and Related Systems

The SFP is part of the SFPCS which provides continuous cooling of stored spent fuel assemblies and purification of the pit water and water in other connected systems, such as the RWSP, refueling cavity, and the refueling water storage auxiliary tank (RWSAT). The cooling portion is located in the R/B while the purification side is in the auxiliary building (A/B). There are two SFPCS trains, and each is composed of an SFP pump, a heat exchanger, a filter, and a demineralizer. The cooling portion of the system is classified to Equipment Class 3 and designed according to the ASME Boiler and Pressure Vessel Code Section III, Class 3 (Reference [9]) and Seismic Category I requirements (Reference [10]) that require the SSCs to maintain their structural integrity in the event of natural phenomena such as SSEs, winds, tornadoes, and floods.

The SFP boric acid water volume at normal levels, without considering the space occupied by the irradiated fuel assemblies and spent fuel racks, is 400,000 gallons and is constantly cooled by continuous circulation through the heat exchangers in order to effectively remove decay heat coming from the spent fuel. The non-seismic purification portion of the system, i.e., composed of the demineralizer and filter, removes impurities and dissolved solids from the SFP and from other systems mentioned above.

The primary SFP water source is the refueling water storage pit (RWSP) which is Seismic Category I and stores boric acid water at 4000 ppm. Other interconnections of the SFP to various systems provide supplementary support mechanisms for an uninterrupted operation. Loss of SFP water due to natural evaporation or boiling is compensated through a non-seismic demineralized water source and makeup line from the demineralized water system (DWS). In the event that the SFPCS lost its cooling capacity, water is supplied from the RWSP or the Seismic Category I emergency feedwater (EFW) pit with a non-Seismic Category I backup line to the SFP to remove the spent fuel heat load. Since some of these structures are not categorized to Seismic Category I requirements, component failures such as pipe breaks, valve failures, and so on are inevitable during SSEs. The likelihood of these conditions can be assumed to effect abnormal SFP water levels and boron dilution events.

Another possible contributor to dilution of boron in the SFP is the non-borated water supply line to the SFP demineralizer. Resin transfer operations in the demineralizer involve a repetitive backwashing of the resin prior to transfer for treatment at the solid waste management system and piping flushing in preparation for new resin filling. Non-borated water from the primary makeup water system (PMWS) is supplied to accomplish this step.

3.4.3 Boron Dilution Scenarios

Careful considerations are given to the design of the plant as a whole and each system and subsystems to mitigate and preclude accidents and AOOs that may cause boron dilution events.

- As already mentioned, monitoring of the boron concentration in the SFP is performed every 7 days to ensure conformance to the specified limit.
- The R/B, which includes the cooling portion of the SFPCS and the SFP, is designed to Seismic Category I requirements so that it can withstand the effects of seismic and natural phenomena events, thereby precluding floods and other accidents that lead to inadvertent dilution of borated water in the SFP.
- Non-seismic components of the SFPCS in the R/B which might fail during SSEs, such as pipes, have countermeasure provisions against failures that are detrimental to related systems. For example, piping is arranged in a manner that will cause the least possible damage to the connecting or adjacent systems.
- Operator error is prevented by the locked closed position of the flow control valves that have limit switches that indicate an open valve in the MCR.
- Alarm annunciation systems are provided to monitor SFP water levels and notice abnormalities brought about by external and accidental unborated water flushing.
- Volumes of possible dilution sources are not large enough to bring the boron concentration lower than the calculated minimum of 200 ppm.
- Dilution times are long enough to allow for corrective actions to be taken even when the possible dilution source volumes are larger than that which is necessary to dilute the SFP water.

To demonstrate that the proposed system has the capacity and design to mitigate the effects of, or preclude and avoid dilution of the boric acid water concentration in the SFP, different possible scenarios are postulated below:

1. Leakage due to pipe breaks in the fire protection system
2. Leakage of unborated water due to SSE-related pipe breaks in the DWS and emergency feedwater system (EFWS)
3. Inadvertent water injection due to an open valve in the makeup line from the DWS and EFWS
4. Inadvertent water injection due to an open valve during backwashing of the SFP demineralizer

3.4.3.1 Leakage due to pipe breaks in the fire protection system

There is a possibility of pipe breaks in the non-seismic portion of the fire protection system that would cause leakage in the fuel handling area. Dilution brought about by this scenario has little possibility since the pipes are laid out below the floor level of the fuel handling area. Thus, no water coming from the broken pipes will enter the SFP surface but will be collected into the floor drains then to the sump. Enclosures are also provided to prevent unborated water to flow into the SFP.

3.4.3.2 Leakage due to SSE-related pipe breaks in the DWS and EFWS

Pipe breaks due to SSEs of the non-seismic piping in the DWS and EFWS are possible to occur. However, the piping is arranged considerably far away from the SFP with the inlets of both systems to the SFP connected to the main pipe (located below the SFP datum level) of the SFP cooler discharge so that there is no overhead leakage from the pipes to the SFP. The systems are also properly isolated with enclosures to contain leaks within the system and into the R/B sump tank through the floor drains. Assuming that the pipes are laid out in the open space above the SFP, the enclosures are enough barriers for water entry.

3.4.3.3 Inadvertent water injection due to an open valve in the makeup line from the DWS and EFWS

Occurrence of this scenario is almost unlikely as the valves are in a locked closed condition at all times, except during SFP water makeup operations due to evaporative losses where there is a need for either or both systems to be activated. The valves also have limit switches for the operator to take notice of an open valve in the non-borated water source line through indications in the MCR. However, assuming that by poor judgment the operator mistakenly opens the valve, purified water flowing from the DWS or EFWS will cause an unmonitored dilution of the boron content and increase in the SFP water level but upon reaching a critical level, alarms will be annunciated to the MCR. Cases like these only occur when the SFP water level alarms remain undetected or are ignored, albeit, events like these are extremely rare. Calculations related to this case are presented in subsection 3.4.4.

3.4.3.4 Inadvertent water injection due to an open valve during resin transfer operations in the SFP demineralizer

During demineralizer resin transfer operations, the normally closed valve downstream of the PMWS and the demineralizer inlet valve are opened to supply non-borated water for backwashing. Another normally closed valve downstream of the PMWS and located above the demineralizer is opened for resin fluidization. These are repeated until the resin is ready for transport to the resin storage or disposal facilities. Two normally open valves between the demineralizer and the SFP are installed. These valves are securely closed to keep the transfer water within the system before discarding for treatment.

This scenario can only occur if there is deliberate intention to dilute the borated water in the SFP. The redundancy of the valves also assures that no backwashing water flushes through the SFP during this period. Limit switches in the valves between the PMWS and SFP demineralizer inform the operator of valve openings through MCR annunciations. Therefore, the possibility of the valves to remain open is very remote. SFP water level alarms are also annunciated to indicate high water levels. If, by any chance, all these indications remain undetected by the operator, there is still ample time before the criticality limit, i.e., below 200 ppm boron, is reached. During that time, it is assumed that some other personnel have already taken notice of such situations. Calculations related to this case are presented in subsection 3.4.4.

3.4.4 Dilution Rates, Volumes, and Time

Based on the discussions in the previous section, the most probable cause for the dilution of boron in the SFP is the inadvertent opening of valves during the backwashing of the demineralizer tanks and activation of the DWS and EFWS for SFP water makeup purposes. The rates, volumes, and time of dilution are treated in the following subsections.

3.4.4.1 Dilution Rates

Sufficient makeup water from the EFWS is required to remove the SFP heat load caused by loss of water through evaporation. The piping between the EFW pit to the SFP is designed to gravitationally transport water into the SFP at the minimum rate of 100 gpm at minimum pit water levels. At full open valve positions and sufficient EFW water levels, the rate of flow will be normally greater than the minimum. The line is laid out to produce pipe resistances that would limit the rate of transport to a maximum of 200 gpm at full open valve positions and full EFW pit water conditions. This value is used as a basis for the boron dilution evaluation through the EFW.

The maximum flow rate, i.e. at full open valve position, of makeup water from the DW tank is limited to 150 gpm, and is the value used in the probable dilution of the SFP water.

The unborated transfer water from the SFP demineralizer is from the PMW tank which supplies at a rate between 50~100 gpm. The maximum value, i.e. at full open valve position, of 100 gpm is used in the dilution evaluation.

3.4.4.2 Dilution Volumes and Time

The length of time elapsed before detection of the dilution event is as crucial as the time it takes for the boron concentration to reach the 200 ppm limit. Ample time is therefore needed to execute remedial actions to prevent dilution from reaching beyond the 200 ppm limit. A differential equation that relates dilution rate and time in a perfectly stirred tank of a constant volume has the form,

$$\frac{d}{dt}VC(t) = QC(t_0) - QC(t) \tag{1}$$

where $C(t_0)$ is the initial boron concentration in the SFP; $C(t)$, the concentration after time t; Q, the dilution rate of pure water; and V, the SFP volume. Since the volume introduced into the tank is pure water, the solution to the equation is easily found to be

$$C(t) = C(t_0)e^{-(Q/V)t} \tag{2}$$

Rearranging the equation gives the dilution time as follows:

$$t = -\frac{V}{Q} ln \frac{C(t)}{C(t_0)} \tag{3}$$

Taking into account the volume occupied by the spent fuel racks and spent fuel assemblies, and providing enough margin for design safety, the effective SFP water volume to cool these structures reduces to 80% of the volume at normal SFP level.

Dilution times are calculated at different dilution rates ranging from a minimum of 100 gpm which is equivalent to the maximum rate of transfer water from the SFP demineralizer. Calculations are based on the assumption that equal volumes of unborated water and SFP water enter and leave the SFP, respectively, and the water level remaining constant.

For the control values of 100 gpm, 150 gpm, and 200 gpm corresponding to the maximum flow rates of water from the dilution sources, the dilution times as shown in Table 3-6 are long enough for dilution events to be taken notice of and for corrective actions to be initiated to control further dilution. Level alarms that annunciate at the MCR are also provided to allow immediate operator action in cases where SFP water levels reach the maximum, thus prolonged periods of undetected dilution are precluded.

The sum of the volumes of the possible dilution water sources is about 89% of the volume needed to bring the boron concentration to 200 ppm at the higher limit of 200 gpm; refer to Table 3-7. The difference between these volumes implies that all the dilution water sources have already been depleted before reaching the 200 ppm limit; during that time, the lowest possible boron concentration will be in the vicinity of 279 ppm. Hence, there is assurance that the spent fuel will remain subcritical in this extreme case of inadvertent dilution.

Furthermore, since there is a constant SFP volume throughout the plant operation where the SFP water that has been pumped out for cooling is being returned, accidental input from unborated water sources will cause a significant change in the SFP water volume. Higher rates shorten the water level alarm intervals, thus there is no possibility of a prolonged unawareness of boron dilution.

3.4.5 Conclusions

The R/B, which includes the cooling portion of the SFPCS, is designed to Seismic Category I requirements and can withstand the effects of natural phenomena, thereby, preventing SFP water dilution brought about by these events. The favorable piping arrangement of the makeup line of the DWS, EFWS, and fire protection system prevents leakage seeping into the SFP during failures of non-seismic piping brought about by SSEs. Thus, no credit is taken for boron dilution from these events.

The only credible factor for dilution events in the SFP would be human-induced factors which are either deliberate or unintentional opening of flow control valves. From the assumptions made, the calculated dilution times are long enough to allow corrective actions to be made and disrupt the dilution event. The total volumes of dilution water are less than those required to bring the boron concentration to the limit values, therefore, subciriticality is being maintained. According to the actual conditions of the SFP, there is but a short period before high water level annunciations are initiated and hence, prolonged and unmonitored dilution events are precluded.

Table 3-6 Boron Dilution Rates, Volumes, and Time

Boron concentration (ppm)	Dilution Water Volume (gal)	Dilution Time to Reach 200 ppm (hrs)					
		Dilution Rate					
		100 gpm	150 gpm	200 gpm	300 gpm	400 gpm	500 gpm
4000	0	0	0	0	0	0	0
3500	36000	7	4	3	2	1	1
3000	84000	15	10	7	5	3	3
2500	144000	25	16	12	8	6	5
2000	216000	36	24	18	12	9	7
1500	312000	52	34	26	17	13	10
1000	432000	73	49	36	24	18	14
750	528000	89	59	44	29	22	17
500	660000	110	73	55	36	27	22
300	828000	138	92	69	46	34	27
250	876000	147	98	73	49	36	29
200	948000	159	106	79	53	39	31

Table 3-7 Maximum Volumes of Unborated Water Sources

Unborated Water Source	Volume (gal)
EFW pit	204,850
DW storage tank	500,000
PMW tank for resin transfer	140,000

4.0 Conclusions

From the evaluation results of NFR described in Chapter 2 and SFR in Chapter 3, it is confirmed that the design criteria 10CFR50.68 are met and that subcriticality is maintained.

For the SFR, the requirement of minimum soluble boron concentration to assure the keff is less than 0.95 was set to 200 ppm. This is far less than the normal operating conditions of 4000 ppm. In the case of a boron dilution event, the dilution is detectable and enough time is available to terminate the event.

5.0 References

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[5] Kopp, L. Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants. U.S. Nuclear Regulatory Commission, Washington, DC, February 1998.

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[8] Validation of the MHI Criticality Safety Methodology, MUAP-07020, Dec. 2007.

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[10] Seismic Design Qualification, U.S. Nuclear Regulatory Commission (US-NRC), Regulatory Guide 1.29, Rev. 4, March 2007.