Criticality Analysis for US-APWR Containment Racks

Non-Proprietary Version

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Revision History

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Abstract

This report summarizes the criticality analysis of the US-APWR Containment Racks, and provides a discussion of the design method, analysis, and results obtained to establish the margins of safety.

It is confirmed that the results of the analysis satisfied the fuel racks requirements of 10 CFR 50.68.

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List of Acronyms

ANS	American Nuclear Society
ANSI	American National Standards Institute
CFR	Code of Federal Regulations
CR	Containment Racks
GDC 62	General Design Criterion 62
ID	Inner Diameter
keff	effective neutron multiplication factor
MHI	Mitsubishi Heavy Industries, LTD.
NRC	U. S. Nuclear Regulatory Commission
OD	Outer Diameter
SFR	Spent Fuel Racks
SS	Stainless Steel
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 analyses for the Containment Racks (CR), which are the facilities of the US-APWR fuel temporary storage system. The fuel assemblies stored in these racks are 17x17 fuel assemblies for the US-APWR (Reference [1]).

Criticality analyses are performed in accordance with the following acceptance criteria and relevant requirements: General Design Criterion 62 (GDC 62) (Reference [2]), 10 CFR 50.68 (Reference [3]), NRC guidance (Reference [4]), and ANSI/ANS-8.17-2004 (Reference [5]). Specifically, 10 CFR 50.68 (b) item (4) for Spent Fuel Racks (SFR) is applied as the criticality safety design criteria for CR, and the results of the criticality analyses were evaluated referring to ANSI/ANS-8.17-2004.

The CR of the US-APWR are made of Stainless Steel (SS) boxes. The CR of the US-APWR are located in the refueling cavity area and can temporarily store up to 6 fuel assemblies.

The analyses are performed by Holtec International (Reference [6]) who has extensive licensing experience in the United States and abroad.

2.0 CRITICALITY ANALYSIS OF CONTAINMENT RACKS

Chapter 2 contains design method, analysis condition and results of the criticality analyses for US-APWR 17x17 new fuel assemblies temporarily stored in CR.

2.1 Design Method

The design criteria, evaluation and analysis code are described in the following subsections.

2.1.1 Design Criteria

CR are located in the refueling cavity area and filled with borated water along with SFR. Therefore, the same criteria with SFR are applied for CR. The design criteria are pursuant to the 10 CFR 50.68 (b) item (4) for SFR as follows: “If no credit for soluble boron is taken, the k-effective of the spent fuel storage racks loaded with fuel of the maximum fuel assembly reactivity must not exceed 0.95, at a 95 percent probability, 95 percent confidence level, if flooded with unborated water. If credit is taken for soluble boron, the k-effective of the spent fuel storage racks loaded with fuel of the maximum fuel assembly reactivity must not exceed 0.95, at a 95 percent probability, 95 percent confidence level, if flooded with borated water, and the k-effective must remain below 1.0 (subcritical), at a 95 percent probability, 95 percent confidence level, if flooded with unborated water.”

Therefore, an evaluation is performed to show that subcriticality is maintained if flooded with unborated water. If necessary, an additional evaluation is performed to determine the boron concentration to keep the effective neutron multiplication factor (keff) less than or equal to 0.95 at a 95 percent probability, 95 percent confidence level (95/95).

For accident conditions other than boron dilution, the highest boron concentration to offset the reactivity increase is determined to cover the most limiting accident as a single failure.

2.1.2 Evaluation

Under the design criteria mentioned above, evaluations were conducted referring to the equation described in 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.,

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

If the various uncertainties are independent,

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

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, 0.95 stated in 10 CFR 50.68 (b) item (4), 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, 0.95 criteria are applied corresponding to the evaluation.

The rearranged equation becomes as follows.

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

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 95/95, Equation (3) becomes as follows.

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

Consequently, the evaluation equations for CR are as follows.

Unborated water: $$k_p + 0.0029 + \left(\Delta k_p^2 + \left(1.899 \times 0.0030\right)^2\right)^{1/2} < 1.0 \quad (5)$$

Borated water: $$k_p + 0.0029 + \left(\Delta k_p^2 + \left(1.899 \times 0.0030\right)^2\right)^{1/2} \le 0.95 \quad (6)$$

The reactivity due to independent tolerances may be statistically combined. Here, the components of the tolerance to be considered in the criticality analyses are those of the fuel, the rack cells, and the positioning of the fuel in the rack cells (see Table 2-5). Each of these components of the tolerance is independent.

2.1.3 Analysis Code

For the criticality analyses of CR, 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. The MHI code validation result was used because of a more conservative combination of a code bias of 0.0029 and bias uncertainty of ± 0.0030 (multiplied by the one-sided tolerance limit coefficient of 1.899 for 95/95) (Reference [8]).

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, the scattering effect as reflector is applied to the hydrogen in floor and wall concretes.

Neutron generation histories in the 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 temporary stored fuel and CR together with conditions to be included in the analysis model are described in the following subsections.

2.2.1.1 Fuel Assembly Description

US-APWR 17x17 fuel assembly parameters used in the criticality analyses 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 are shown in Figure 2-1. Fuel cladding is made of ZIRLO^{TM} which is a zirconium based alloy with a small amount of niobium (Nb) added for increasing corrosion resistance.

2.2.1.2 US-APWR Containment Racks Description

The CR have a capacity to temporarily store a maximum of 6 fuel assemblies. Rack configuration and design parameters are shown in Table 2-2 and Figure 2-2. As shown in Figure 2-2, the CR are composed of two modules of 3x1 = 3 cells each. The rack cell pitch is 16.9 inch (43 cm). The rack material is SS-304. SS supporting structures are installed to support rack cell modules, but are located locally and peripherally, so they do not affect the criticality analyses.

2.2.1.3 Assumptions

Using the fuel and CR parameters, analyses are performed with the following assumptions:

Assumptions on Fuel Assembly

- The fresh UO_2 fuel assembly without burnable absorber is assumed to have a maximum enrichment of five (5.0) 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^{TM}.
- 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 the fuel assembly has many holes to allow coolant flow so the effective contribution as neutron reflector is small, thus they can be replaced by water or concrete. A 30 cm water layer is placed on the top of the effective fuel length and a concrete layer of 1 m thickness is placed on the underside.

Assumptions on CR

- The nominal rack cell pitch is 16.9 inch (43 cm) in simulating the actual CR module, and the tolerances and biases are evaluated separately.
- Water density of 62.43 lb/ft^3(1.0 g/cm^3) is used to cover the maximum value.

2.2.2 MCNP Model for CR

2.2.2.1 Nominal Model

As stated in Subsection 2.2.1.3, the evaluations are carried out using a complete model of the CR including only one individual module of 3 cells. The analysis model is shown in Figure 2-3.

2.2.2.2 Uncertainty Analysis Models for Tolerances

Sensitivity analyses for independent tolerances are carried out individually utilizing the finite model by changing the dimensions of the respective parameter. The values used in the model are shown in Tables 2-1 and 2-2. Additionally, fuel displacement within cells of CR is considered in a way that maximizes keff by two eccentric positioning cases. Eccentric positioning case 1 has the center fuel assembly centered in the rack cell and the outer assemblies shifted towards the center. Eccentric positioning case 2 models the center and left assembly shifted towards the right cell and the right cell shifted toward left. The analysis models are shown in Figure 2-4.

2.2.3 Material Composition

For fuel, cladding and thimble materials, the density, composition and atomic density used in the analyses are shown in Table 2-3. The corresponding parameters for the SS rack, water between assemblies and as reflector material, and concrete are also shown in Table 2-3. For each composition, MCNP ZAID library names are listed in Table 2-4.

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(1.0 g/cm^3) is taken for the condition that maximizes the reactivity.

2.3 Results

As shown in Tables 2-5 and 2-6, the final keff value is 0.8991 without applying credit for soluble boron, including uncertainties. This value is well below both design criteria of less than or equal to 0.95 and less than 1.0. Therefore, calculations with credit for soluble boron are not required. Uncertainty of individual tolerances are obtained by differing two keffs calculated by Monte Carlo for two points, and adding the root of sum of squares of uncertainties (2σ) as probability error.

Namely,

$$\Delta keff_i = \left| keff_i - keff_0 \right| + \sqrt{\left(2 \times \sigma_0\right)^2 + \left(2 \times \sigma_i\right)^2} \quad (7)$$

$keff_0$ = keff for normal condition
$keff_i$ = keff for model considering tolerance i
σ_0: 1σ for nominal model

σ_i: 1σ for model considering tolerance i

2.3.1 Abnormal and Accident Conditions

The effects on reactivity of the credible abnormal and accident conditions are examined in this section. This section identifies which if any of the credible abnormal or accident conditions would result in exceeding the limiting reactivity (keff < 0.95). The double contingency principal (Reference [4]) specifies that it shall require at least two unlikely, independent and concurrent events to produce a criticality accident. This principle precludes the necessity of considering the simultaneous occurrence of multiple accident conditions.

2.3.1.1 Dropped Assembly – Horizontal

For the case in which a fuel assembly is assumed to be dropped on top of CR, the fuel assembly will come to rest horizontally on top of the rack with a minimum separation distance from the active fuel region of more than 17 inches, which is sufficient to preclude neutron coupling (i.e., an effectively infinite separation). Consequently, the horizontal fuel assembly drop accident will not result in an increase in reactivity and no separate calculation is performed for the drop accident.

2.3.1.2 Dropped Assembly – Vertical

It is also possible to vertically drop an assembly into a location that might be occupied by another assembly or that might be empty. The mechanical implications of such a drop been evaluated (Reference [9]). The result is shown in a loss of the top of the rack cells of 4 inches due to the vertical drop accident. However, CR are made of SS and do not contain fixed neutron absorber, thus the influence of the damage is of no concern to the criticality analyses.

2.3.1.3 Abnormal Location of a Fuel Assembly

2.3.1.3.1 Misloaded Fresh Fuel Assembly

Since CR are qualified for temporary storage of fresh fuel with the highest anticipated reactivity, the misloading of a fresh fuel assembly is of no concern.

2.3.1.3.2 Mislocated Fresh Fuel Assembly

The mislocation of a fresh fuel assembly could, in the absence of soluble neutron absorber, result in exceeding the regulatory limit (keff < 0.95). This could possibly occur if a fresh fuel assembly of the maximum enrichment of five weight percent were to be accidentally mislocated outside of CR adjacent to other fuel assemblies. The CR could potentially have a fuel assembly mislocated outside its location and calculations were also performed for this case and the results were presented in Table 2-7. The amount of soluble boron needed to meet regulatory requirements was also determined by running the given accident case with 800 ppm soluble boron. This is far less than the boron concentration in the CR in the refueling cavity which is filled with borated water that has the refueling water storage pit boron concentration.

2.3.1.4 Rack Movement

The CR are fixed to the refueling cavity wall and are designed to withstand the seismic force. Then the distance between two containment rack cells is not change after the seismic event.

Table 2-1 US-APWR 17x17 Fuel Assembly Parameters used in the Criticality Analysis

Parameter	Design Parameters
Fuel Rod Configuration	17x17 (Figure 2-1)
Rods per Assembly	264
Control Rod Guide Thimble / In-core Instrumentation Guide Tube per Assembly	24 / 1
Rod Pitch (i)	0.496 [ ] inch
Active Fuel Length	165.4 inch
Pellet Outer Diameter (OD)	0.322 [ ] inch
Enrichment	5.0 wt% U-235
UO_2 Density (% of Theoretical Density (TD))	97 [ ] % of TD
Cladding OD	0.374 [ ] inch
Cladding Inner Diameter (ID)	0.329 [ ] inch
Cladding Material	ZIRLO™ (modeled as 100% Zr)
Control Rod Guide Thimble OD	0.482 inch
Control Rod Guide Thimble ID	0.450 inch
In-core Instrumentation Guide Tube OD	0.482 inch
In-core Instrumentation Guide Tube ID	0.450 inch
Control Rod Guide Thimble / In-core Instrumentation Guide Tube Material	Zircaloy-4 (modeled as 100% Zr)

(i) [ ]

Table 2-2 Design Parameters for CR

Parameter	Design Parameter
Storage Cells	6
Cell Center-to-Center Pitch	16.9 [ ] inch
Cell Inner Dimension (Width)	8.8 [ ] inch
Cell Wall Thickness	0.209 [ ] inch
Cell Wall Material	SS

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

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

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

(i) UO_2 Pellet Density is 10.96 g/cm^3 as 100% TD.
(ii) Conservatively, ZIRLO™ cladding and Zircaloy were treated as 100% Zr.

Table 2-3 (2/3) Materials and Compositions for CR

(2) Structure Material

Material	Isotope	Atom Density (atoms/barn-cm)
SS-304 (7.84 g/cm^3)	Ni	8.047×10^{-3}
	Cr	1.720×10^{-2}
	Fe	5.838×10^{-2}
	Mn	1.720×10^{-3}
Concrete (2.35 g/cm^3)	H	8.806×10^{-3}
	O	4.623×10^{-2}
	Na	1.094×10^{-3}
	Al	2.629×10^{-4}
	Si	1.659×10^{-2}
	K	7.184×10^{-4}
	Ca	3.063×10^{-3}
	Fe	3.176×10^{-4}

Table 2-3 (3/3) Materials and Compositions for CR

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

Material	Water Density (i) (% of full density)	Isotope	Atom Density (atoms/barn-cm)
Water (Moderator)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}
Boric Acid Water (Boron conc. 800 ppm)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}
		^{10}B	8.8225×10^{-6}
Water (Reflector)	100	H	6.6854×10^{-2}
		O	3.3427×10^{-2}

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

Table 2-4 MCNP ZAIDs Used for Each Nuclide

Nuclide	ENDF/B-V
H	1001.50c
^{10}B	5010.50c
O	8016.50c
Na	11023.51c
Al	13027.50c
Si	14000.51c
K	19000.51c
Ca	20000.51c
Cr	24000.50c
Mn	25055.50c
Fe	26000.55c
Ni	28000.50c
Zr	40000.56c
^{235}U	92235.50c
^{238}U	92238.50c

Table 2-5 Results of the CR Tolerance Calculations

Calculation Description	keff	σ	Delta-keff
Reference keff	0.8888	0.0004	n/a
Pellet Density max			
Pellet OD max			
Pin Pitch max			
Pin Pitch min			
Clad OD max			
Clad OD min			
Clad ID max			
Clad ID min			
Cell ID max			
Cell ID min			
Cell Wall Thickness max			
Cell Wall Thickness min			
Cell Pitch max			
Cell Pitch min			
Eccentric Positioning Case 1	0.8881	0.0004	0.0004
Eccentric Positioning Case 2	0.8891	0.0004	0.0014
Calculated Tolerances Square Root Sum of the Squares (positive results) (i)			0.0046
Calculation Statistics 2 Sigma (max of all cases)		0.0008	

(i) The maximum positive result for each case was used.

Table 2-6 Results of the CR Calculations

Parameter	Value
Uncertainties:	
Bias Uncertainty 1.899 x 0.003 (95/95)	0.0057
Calculation Statistics (95/95, 2σ)	0.0008
Calculated Tolerances	0.0046
Statistical Combination of Uncertainties	0.0074
Calculated MCNP5 keff (no soluble boron)	0.8888
Calculation Bias	0.0029
Maximum keff	0.8991
Regulatory Limit	0.9500

Table 2-7 Summary of CR Accident Case Calculations

CR Mislocated Fuel Assembly Calculation	
Parameter	**keff**
Calculated MCNP5 keff (0 ppm soluble boron)	1.0349
Maximum keff (0 ppm soluble boron)	1.0452
Calculated MCNP5 keff (800 ppm soluble boron)	0.9166
Maximum keff (800 ppm soluble boron)	0.9269

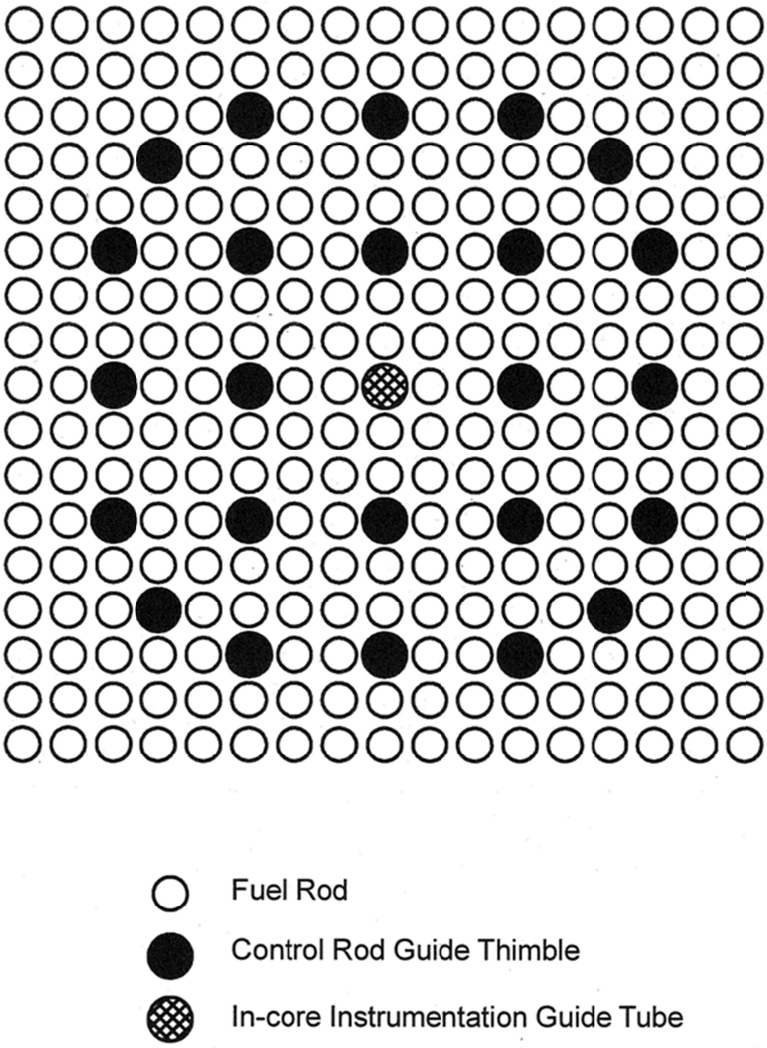


Figure 2-1 US-APWR 17x17 Fuel Assembly Cross Section

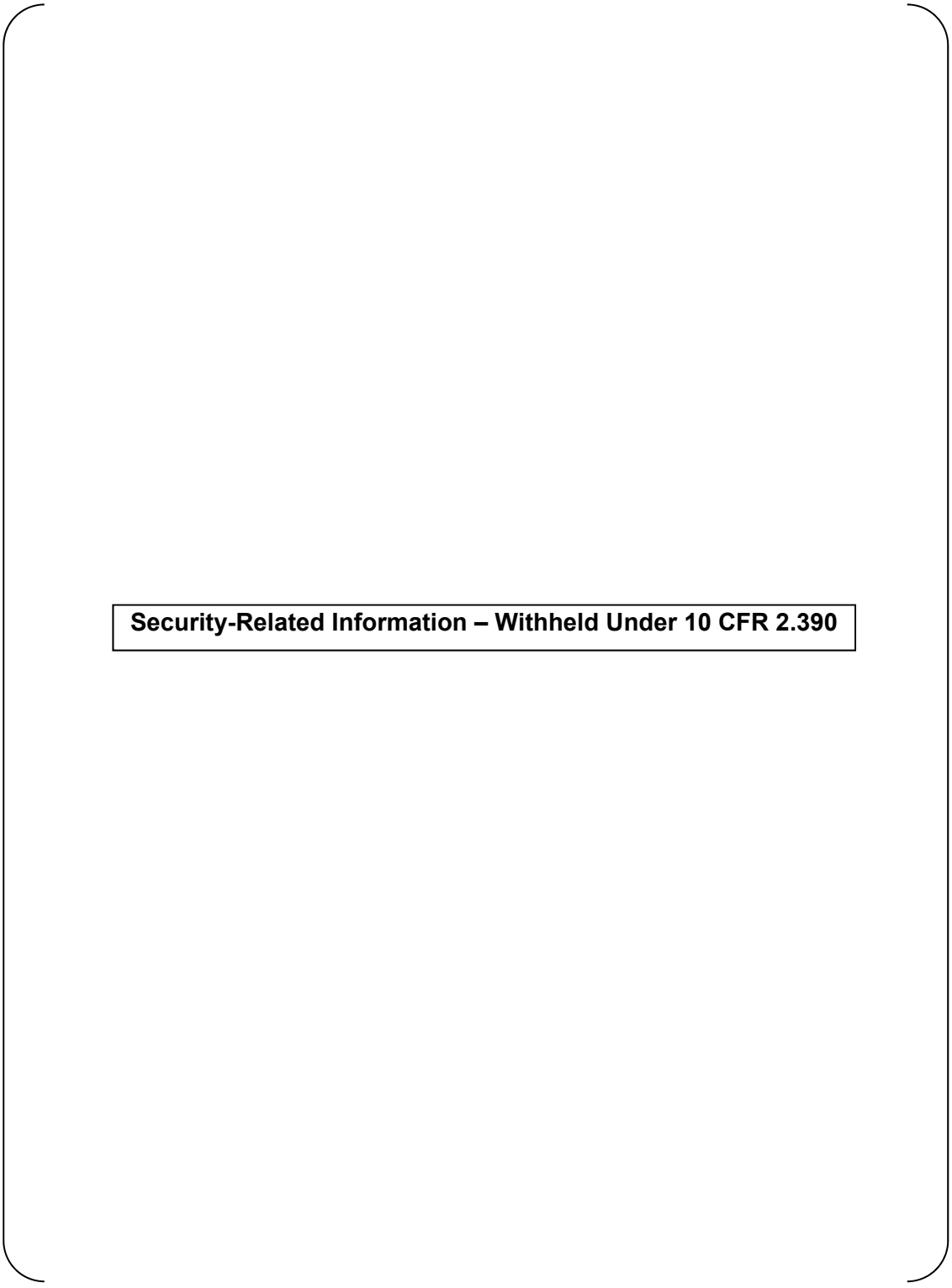
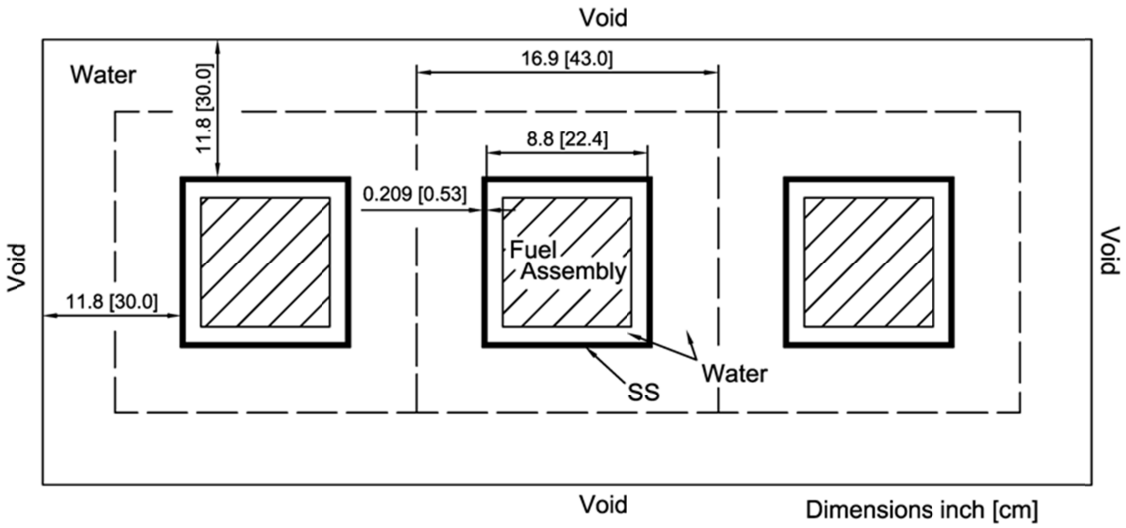
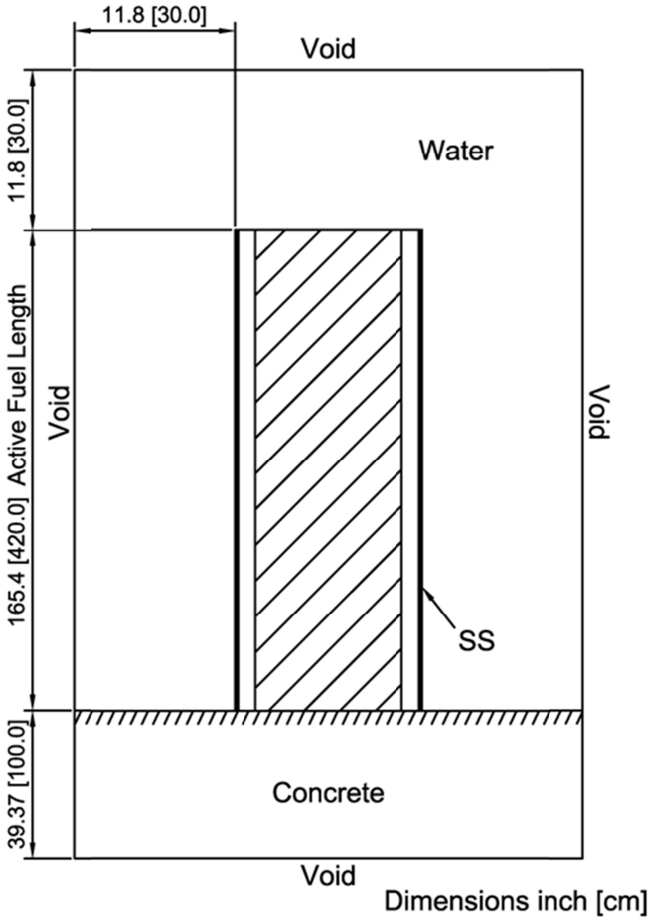


Figure 2-2 Configuration of CR



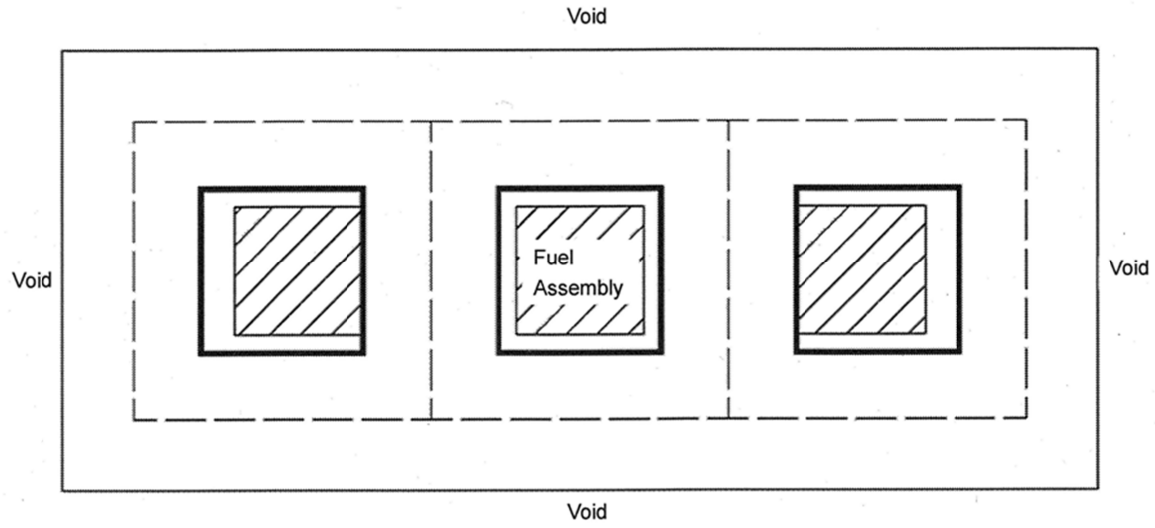
Plan

Figure 2-3 (1/2) Nominal MCNP Model of CR

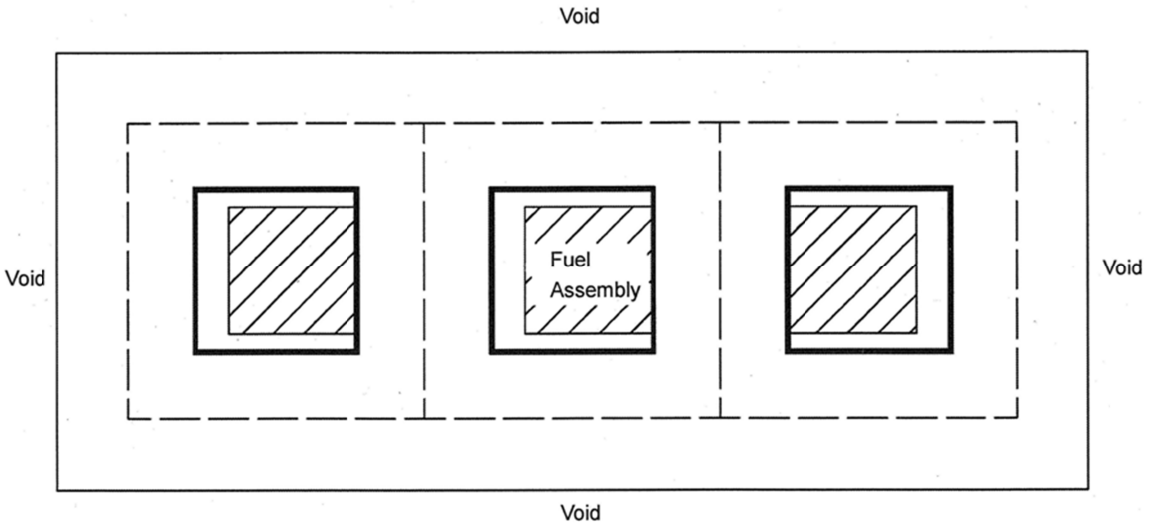


Elevation

Figure 2-3 (2/2) Nominal MCNP Model of CR



Eccentric Positioning Case 1



Eccentric Positioning Case 2

Figure 2-4 MCNP Model for Fuel Displacement within Cells of CR

3.0 CONCLUSIONS

The criticality analyses for CR are performed in accordance with the following acceptance criteria and relevant requirements: GDC 62 (Reference [2]), 10 CFR 50.68 (Reference [3]), NRC guidance (Reference [4]), and ANSI/ANS-8.17-2004 (Reference [5]). Specifically, 10 CFR 50.68 (b) item (4) for SFR is applied as the criticality safety design criteria for CR, and the analyses results were evaluated referring to ANSI/ANS-8.17-2004.

For nominal condition, the final keff value is 0.8991 without applying credit for soluble boron, including all uncertainties, and it is well below design criteria.

For accident conditions, the requirement of minimum soluble boron concentration to assure the keff less than 0.95 was set to 800 ppm, which is lower than the boron concentration in CR.
.

4.0 REFERENCES

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