Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

NEDO-33326
Revision 0
Class I
eDRF-0000-0067-3427
July 2007

Licensing Topical Report

GE14E FOR ESBWR INITIAL CORE NUCLEAR DESIGN REPORT

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Abstract

The purpose of this report is to document the steady state nuclear characteristics of the ESBWR initial core consistent with those reported in NEDC-33239P (Reference 1) for the analysis basis equilibrium core and to demonstrate conformance with nuclear design requirements. An ESBWR reference initial core has been designed to achieve an eighteen month operating cycle utilizing the GE14E bundle. The bundle designs and core design are evaluated based on the nuclear physics methods previously described in Reference 1. Section 1 of this report summarizes the design bases that were established to develop effective designs for the ESBWR Cycle 1 bundles and core. Discussion is included on nuclear dynamic parameters, shutdown margin, overpower bases, standby liquid control system and stability bases. Section 2 presents the GE14E bundles that were designed specifically for the ESBWR initial core to achieve adequate performance. Illustrations of each bundle are provided that shows the pin-by-pin enrichment of each lattice and the axial location of each lattice within each bundle design. Reactivity and local peaking characteristics are discussed relative to core performance. Finally, the detailed core performance results are presented in Section 3. Results include hot excess reactivity, cold shutdown margin, standby liquid control system margin, a rodded depletion scenario throughout the cycle and other analysis results that describe Cycle 1 performance. This report illustrates that all nuclear design requirements as stipulated in Section 1 have been met.

ACRONYMS AND ABBREVIATIONS

Acronym	***Description***
APLHGR	Average Planar Linear Heat Generation Rate
AOO	Anticipated Operational Occurrences
ARI	All Rods In
BOC	Beginning of Operating Cycle
BOL	Beginning of Life
BWR	Boiling Water Reactor
CBH	Control Blade History
CCC	Control Cell Core
CPR	Critical Power Ratio
ECCS	Emergency Core Cooling System
EFPD	Effective Full Power Days
EOC	End of Operating Cycle
ESBWR	Economic Simplified Boiling Water Reactor
GDC	General Design Criteria
HCU	Hydraulic Control Unit
HOTUNC	Hot Uncontrolled K-infinities
HOTUNCD	Hot Uncontrolled K-infinities - Doppler
LCO	Limiting Condition of Operation
LHGR	Linear Heat Generation Rate
MAPLHGR	Maximum Average Planar Linear Heat Generation Rate
MAPRAT	Ratio of APLHGR to MAPLHGR
MFLCPR	Maximum Fraction of Limiting Critical Power Ratio
MFLPD	Maximum Fraction of Limiting Power Density
MLHGR	Maximum Linear Heat Generation Rate
MOC	Middle of Operating Cycle
OLMCPR	Operating Limit Minimum Critical Power Ratio
OLTP	Operating Licensed Thermal Power
SDM	Shutdown Margin
SLCS	Standby Liquid Control System
SRO	Strongest Rod Out

1. NUCLEAR DESIGN BASIS

The design bases are those that are required for the plant to operate, meeting all safety requirements. The safety design bases that are required fall into two categories:

- The reactivity basis, which prevents an uncontrolled positive reactivity excursion.
- The overpower bases for the control of power distribution, which prevent the core from operating beyond the fuel integrity limits.

This report describes how the ESBWR initial core and GE14E bundle designs conform to these design bases. The applicable General Design Criteria (GDC) as described in Appendix A of 10 CFR 50, "General Design Criteria for Nuclear Power Plants," have been identified below and are the same as those applied to the ESBWR equilibrium core design in Reference 1. All evaluation results presented herein are based on the nuclear methods that have been described in detail in Reference 1.

1.1 Negative Reactivity Feedback Bases

Reactivity coefficients, the differential changes in reactivity produced by differential changes in core conditions, are useful in calculating stability and evaluating the response of the core to external disturbances. The base initial condition of the system and the postulated initiating event determine which of the several defined coefficients are significant in evaluating the response of the reactor. The coefficients of interest are the Doppler coefficient, the moderator void reactivity coefficient and the moderator temperature coefficient. Also associated with the BWR is a power reactivity coefficient. The power coefficient is a combination of the Doppler and void reactivity coefficients in the power operating range; this is not explicitly evaluated. The Doppler coefficient, the moderator void reactivity coefficient and the moderator temperature coefficient of reactivity shall be negative for power operating conditions, thereby providing negative reactivity feedback characteristics. The above design basis meets GDC 11.

The Doppler coefficient, relative to the bundle nuclear design, is discussed in more detail in Section 2. The moderator temperature and void coefficients are discussed in more detail in Section 3.

1.2 Control Requirements (Shutdown Margins)

The core must be capable of being made sub-critical, with margin, in the most reactive condition throughout the operating cycle with the highest worth control rod, or rod pair, stuck in the full-out position and all other rods fully inserted. This design basis satisfies GDC 26. Shutdown margin (SDM) evaluation results for the ESBWR initial core design are presented in Section 3.

1.3 Control Requirements (Overpower Bases)

The nuclear design basis for control requirements is that the Maximum Linear Heat Generation Rate (MLHGR) and the Minimum Critical Power Ratio (MCPR) constraints shall be met during operation. The MCPR and MLHGR are determined such that, with 95% confidence, the fuel does not exceed required licensing limits during abnormal operational occurrences (AOO). This design basis satisfies GDC 10.

MLHGR and MCPR are defined as follows:

1.3.1 Maximum Linear Heat Generation Rate

The MLHGR is the maximum linear heat generation for the fuel rod with the highest linear power density at a given nodal plane in the bundle. The MLHGR operating limit is bundle type dependent. The MLHGR can be monitored to assure that all thermal-mechanical design requirements are met. The fuel will not be operated at MLHGR values greater than those found to be acceptable within the body of the safety analysis under normal operating conditions. Under abnormal conditions, including the maximum overpower condition, the MLHGR will not cause fuel melting or cause the stress and strain limits to be exceeded.

1.3.2 Minimum Critical Power Ratio

The MCPR is the minimum CPR allowed for a given bundle type to avoid boiling transition. The CPR is a function of several parameters; the most important of which are bundle power, bundle flow, the local power distribution and specific features of the bundle mechanical design. The plant Operating Limit MCPR (OLMCPR) is established by considering the limiting AOO for each operating cycle. The OLMCPR is determined such that 99.9% of the rods avoid boiling transition during the transient of the limiting analyzed AOO.

Detailed evaluation results including MLHGR and MCPR throughout the cycle, based on a rodded depletion scenario, are presented in Section 3.

1.4 Control Requirements (Standby Liquid Control System)

GDC 27 requires that the reactivity control systems have a combined capability, in conjunction with poison addition by the emergency core cooling system (ECCS), of reliably controlling reactivity changes under postulated accident conditions, with appropriate margin for stuck rods. The nuclear design basis is that, assuming a stuck rod, or rod pair, the standby liquid control system (SLCS) provides sufficient liquid poison into the system so that sufficient shutdown margin is achieved.

SLCS evaluation results for the ESBWR initial core design are presented in Section 3.

1.5 Stability Bases

The licensing basis for stability must comply with the requirements of GDC 10 and 12.

GDC 10 (Reactor Design) requires that:

> "The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences."

GDC 12 (Suppression of Reactor Power Oscillations) requires that:

> "The reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillations which can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed."

Xenon stability performance is discussed in Section 3.

2. BUNDLE DESIGN EVALUATION

2.1 Introduction

Bundle and lattice designs have been developed using the methodology and codes described in Reference 1. This section presents several GE14E bundles that have been designed for initial core operation. Given that core operation begins from zero exposure conditions, multiple designs are needed to achieve the desired distribution of power in both radial and axial directions, thereby meeting the key design bases discussed in Section 1.

2.2 Bundle and Lattice Designs

A total of six unique GE14E bundle designs have been developed for the ESBWR reference initial core. Each bundle design is comprised of three to six unique lattice configurations as shown in the table below. The bundle designs are described in Figures 2-1 through 2-24. These figures include the 2-D pin-by-pin enrichment array for each lattice, axial profiles for each unique rod type, the axial location of each lattice within the bundle and the splits and weights for each bundle.

Bundle Number	Bundle Name	Number of Lattices	Lattice Numbers
2990	[[		
2991			
2992			
2993			
2994			
2995			]]

Many factors are considered in the development of these bundle designs in addition to overall cycle energy requirements and operating strategy. Perhaps the key considerations are given to achieving the desired reactivity and local peaking behavior required for an initial core application. Acceptability of the designs can be confirmed when the overall performance is assessed by 3-D simulator evaluations using the methodology and codes discussed in Reference 1. Lattice reactivity characteristics can be judged by the core hot excess reactivity and cold shutdown margin behavior. Lattice k-infinities versus burn-up for the hot uncontrolled condition at three void fractions have been provided in Tables 2-1 through 2-29 and in Figures 2-25 through 2-53 for each lattice design. Similarly, lattice local peaking characteristics can be judged by the thermal margin performance as determined by 3-D simulator calculations. The maximum lattice local peaking versus burn-up for the hot uncontrolled condition at the same void fractions are provided in Tables 2-30 through 2-58 and in Figures 2-54 through 2-82 for each lattice design. Core reactivity and thermal margin performance results based on these six bundle designs will be presented in Section 3. Acceptable core performance is strongly dependent on the k-infinity and local peaking characteristics at the bundle and lattice design level.

2.2.1 GE14E Bundle Design Features for Initial Core

As previously mentioned, each GE14E bundle designed for this initial core application consists of three to six unique lattice configurations. The top and bottom lattice of each bundle consists of a six inch blanket of natural uranium. The first enriched lattice above the bottom natural uranium zone is referred to as the "dominant" zone. This lattice represents the largest zone within the bundle and establishes the overall reactivity characteristics. For reload applications, the GE14E design typically includes a shorter power shaping zone as the first enriched zone at the bottom. However, for an initial core application in which all bundles have zero burn-up history, such a zone is not necessary. The remaining lattices above the dominant zone correctly model the axially varying geometry (i.e., plenums and vanishing rods) that is associated with the part length rod feature of the GE14E design.

2.2.2 Bundle Local Peaking

One of the important parameters affecting linear heat generation rate (LHGR) performance of a bundle is the local peaking value. Figures 2-83 through 2-88 provide the 2-D pin-by-pin lattice local peaking values for each dominant lattice of all six bundle designs at 40% void and beginning of life (BOL) conditions. This is in addition to the maximum lattice local peaking versus burn-up data previously provided. The resulting core LHGR performance based on a rodded depletion scenario is described in Section 3.

2.2.3 Bundle R-Factor

An important parameter affecting the critical power performance of a BWR is the exposure dependent bundle R-Factor. Table 2-59 through 2-64 shows the fully uncontrolled and fully controlled R-factors for zero mils channel bow as a function of burn-up for all six initial core bundle designs. To further illustrate how these maximum values are derived, the 2-D pin-by-pin R-factors for each bundle are shown in Figures 2-89 though 2-94 at 20 GWd/ST for the fully uncontrolled condition and zero mils channel bow. In general, the bundle design for an ESBWR attempts to achieve optimum thermal margins (i.e., MLHGR and MCPR) by minimizing local peaking and R-factors. The resulting core MCPR performance based on a rodded depletion scenario is described in Section 3.

2.2.4 Doppler Reactivity Coefficient

The Doppler coefficient is a measure of the reactivity change associated with an increase in the absorption of resonance-energy neutrons caused by a change in the temperature of the material in question. The Doppler reactivity coefficient provides instantaneous negative reactivity feedback to any rise in fuel temperature, on either a gross or local basis. The magnitude of the Doppler coefficient is inherent in the fuel design and does not vary significantly among BWR designs. For most structural and moderator materials, resonance absorption is not significant, but in U^{238} and Pu^{240} an increase in temperature produces a comparatively large increase in the effective absorption cross-section. The resulting parasitic absorption of neutrons causes an immediate loss in reactivity.

Analyses were performed for the ESBWR equilibrium core design using the analytical models documented in Reference 1. The values were identical to the analysis supporting compliance for

GE14 found in Reference 2, which consists of examination of the lattice level Doppler coefficients for several lattice configurations. For all cases evaluated, the calculated Doppler coefficient was found to be negative. A typical value of calculated Doppler coefficient is [[ ]](at zero exposure, 0.4 void fraction).

A further demonstration of this can be found by observing the k-infinities at nominal and elevated fuel temperature for the dominant lattices of all six ESBWR initial core GE14E bundle designs. Figure 2-95 through Figure 2-100 illustrate the hot uncontrolled k-infinities for the dominant lattice at 40% voids. The k-infinity data is also provided in Tables 2-65 through 2-70 (note "HOTUNCD" indicated k-infinity data at elevated fuel temperature). For all figures, the effects of Doppler [[ ]]. This trend is consistent for all ESBWR lattices within all reference designs.

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Figure 2-1. Bundle Design for 2990

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Figure 2-2. Fuel Rods for 2990

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Figure 2-3. Fuel Rods for 2990

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Figure 2-4. Splits and Weights for 2990

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Figure 2-5. Bundle Design for 2991

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Figure 2-6. Fuel Rods for 2991

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Figure 2-7. Fuel Rods for 2991

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Figure 2-8. Splits and Weights for 2991

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Figure 2-9. Bundle Design for 2992

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Figure 2-10. Fuel Rods for 2992

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Figure 2-11. Fuel Rods for 2992

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Figure 2-12. Splits and Weights for 2992

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Figure 2-13. Bundle Design for 2993

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Figure 2-14. Fuel Rods for 2993

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Figure 2-15. Fuel Rods for 2993

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Figure 2-16. Splits and Weights for 2993

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Figure 2-17. Bundle Design for 2994

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Figure 2-18. Fuel Rods for 2994

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Figure 2-19. Fuel Rods for 2994

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Figure 2-20. Splits and Weights for 2994

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Figure 2-21. Bundle Design for 2995

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Figure 2-22. Fuel Rods for 2995

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Figure 2-23. Fuel Rods for 2995

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Figure 2-24. Splits and Weights for 2995

Table 2-1. Lattice 7632 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
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22.00			
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24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-25. Lattice 7632 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-2. Lattice 7633 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-26. Lattice 7633 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-3. Lattice 7634 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
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25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			.]]

[[

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Figure 2-27. Lattice 7634 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-4. Lattice 7635 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
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45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-28. Lattice 7635 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-5. Lattice 7636 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
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10.00			
11.00			
12.00			
13.00			
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65.00			]]

[[

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Figure 2-29. Lattice 7636 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-6. Lattice 7637 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
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12.00			
13.00			
14.00			
15.00			
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17.00			
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60.00			
65.00			]]

[[

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Figure 2-30. Lattice 7637 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-7. Lattice 7638 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
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60.00			
65.00			]]

[[

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Figure 2-31. Lattice 7638 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-8. Lattice 7639 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
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65.00			]]

[[

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Figure 2-32. Lattice 7639 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-9. Lattice 7640 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
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60.00			
65.00			]]

[[

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Figure 2-33. Lattice 7640 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-10. Lattice 7641 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
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65.00			]]

[[

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Figure 2-34. Lattice 7641 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-11. Lattice 7642 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
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Figure 2-35. Lattice 7642 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-12. Lattice 7643 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
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[[

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Figure 2-36. Lattice 7643 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-13. Lattice 7644 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
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[[

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Figure 2-37. Lattice 7644 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-14. Lattice 7645 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
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19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-38. Lattice 7645 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-15. Lattice 7646 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-39. Lattice 7646 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-16. Lattice 7647 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-40. Lattice 7647 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-17. Lattice 7648 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-41. Lattice 7648 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-18. Lattice 7649 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-42. Lattice 7649 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-19. Lattice 7650 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-43. Lattice 7650 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-20. Lattice 7651 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-44. Lattice 7651 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-21. Lattice 7652 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-45. Lattice 7652 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-22. Lattice 7653 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-46. Lattice 7653 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-23. Lattice 7654 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-47. Lattice 7654 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-24. Lattice 7655 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-48. Lattice 7655 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-25. Lattice 7656 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-49. Lattice 7656 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-26. Lattice 7657 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-50. Lattice 7657 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-27. Lattice 7658 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-51. Lattice 7658 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-28. Lattice 7659 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-52. Lattice 7659 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-29. Lattice 7660 K-infinity

Exposure (GWd/ST)	K-infinity		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-53. Lattice 7660 K-infinity

(* K-infinity based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-30. Lattice 7632 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-54. Lattice 7632 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-31. Lattice 7633 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			.]]

[[

]]

Figure 2-55. Lattice 7633 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-32. Lattice 7634 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-56. Lattice 7634 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-33. Lattice 7635 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-57. Lattice 7635 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-34. Lattice 7636 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-58. Lattice 7636 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-35. Lattice 7637 Peaking

Exposure (GWd/ST)	**Maximum Local Peaking**		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-59. Lattice 7637 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-36. Lattice 7638 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-60. Lattice 7638 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-37. Lattice 7639 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			.]]

[[

]]

Figure 2-61. Lattice 7639 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-38. Lattice 7640 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-62. Lattice 7640 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-39. Lattice 7641 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			.]]

[[

]]

Figure 2-63. Lattice 7641 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-40. Lattice 7642 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-64. Lattice 7642 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-41. Lattice 7643 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
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18.00			
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21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-65. Lattice 7643 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-42. Lattice 7644 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-66. Lattice 7644 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-43. Lattice 7645 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-67. Lattice 7645 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-44. Lattice 7646 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-68. Lattice 7646 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-45. Lattice 7647 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-69. Lattice 7647 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-46. Lattice 7648 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	**VF 0.4**	**VF 0.7**
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-70. Lattice 7648 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-47. Lattice 7649 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-71. Lattice 7649 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-48. Lattice 7650 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-72. Lattice 7650 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-49. Lattice 7651 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-73. Lattice 7651 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-50. Lattice 7652 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-74. Lattice 7652 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-51. Lattice 7653 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-75. Lattice 7653 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-52. Lattice 7654 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-76. Lattice 7654 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-53. Lattice 7655 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-77. Lattice 7655 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-54. Lattice 7656 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-78. Lattice 7656 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-55. Lattice 7657 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
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23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-79. Lattice 7657 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-56. Lattice 7658 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-80. Lattice 7658 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-57. Lattice 7659 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

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Figure 2-81. Lattice 7659 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

Table 2-58. Lattice 7660 Peaking

Exposure (GWd/ST)	Maximum Local Peaking		
	VF 0.0	VF 0.4	VF 0.7
0.00	[[		
0.20			
1.00			
2.00			
3.00			
4.00			
5.00			
6.00			
7.00			
8.00			
9.00			
10.00			
11.00			
12.00			
13.00			
14.00			
15.00			
16.00			
17.00			
18.00			
19.00			
20.00			
21.00			
22.00			
23.00			
24.00			
25.00			
30.00			
35.00			
40.00			
45.00			
50.00			
55.00			
60.00			
65.00			]]

[[

]]

Figure 2-82. Lattice 7660 Maximum Local Peaking

(* Local peaking based on three void history fractions of 0.0, 0.4 and 0.7)

[[

]]

Figure 2-83. Rod Local Peaking (Bundle 2990, Lattice 7633, VF=40%, BOL)

[[

]]

Figure 2-84. Rod Local Peaking (Bundle 2991, Lattice 7638, VF=40%, BOL)

[[

]]

Figure 2-85. Rod Local Peaking (Bundle 2992, Lattice 7644, VF=40%, BOL)

[[

]]

Figure 2-86. Rod Local Peaking (Bundle 2993, Lattice 7648, VF=40%, BOL)

[[

]]

Figure 2-87. Rod Local Peaking (Bundle 2994, Lattice 7652, VF=40%, BOL)

[[

]]

Figure 2-88. Rod Local Peaking (Bundle 2995, Lattice 7657, VF=40%, BOL)

Table 2-59. Bundle 2990 Uncontrolled and Controlled R-Factors

Exposure (GWd/ST)	R-Factor (Fully Uncontrolled)	R-Factor (Fully Controlled)
0.0	[[	
0.2		
1.0		
2.0		
3.0		
4.0		
5.0		
6.0		
7.0		
8.0		
9.0		
10.0		
11.0		
12.0		
13.0		
14.0		
15.0		
16.0		
17.0		
18.0		
19.0		
20.0		
21.0		
22.0		
23.0		
24.0		
25.0		
30.0		
35.0		
40.0		
45.0		
50.0		
55.0		
60.0		
65.0		]]

Table 2-60. Bundle 2991 Uncontrolled and Controlled R-Factors

Exposure (GWd/ST)	R-Factor (Fully Uncontrolled)	R-Factor (Fully Controlled)
0.0	[[	
0.2		
1.0		
2.0		
3.0		
4.0		
5.0		
6.0		
7.0		
8.0		
9.0		
10.0		
11.0		
12.0		
13.0		
14.0		
15.0		
16.0		
17.0		
18.0		
19.0		
20.0		
21.0		
22.0		
23.0		
24.0		
25.0		
30.0		
35.0		
40.0		
45.0		
50.0		
55.0		
60.0		
65.0		]]

Table 2-61. Bundle 2992 Uncontrolled and Controlled R-Factors

Exposure (GWd/ST)	R-Factor (Fully Uncontrolled)	R-Factor (Fully Controlled)
0.0	[[	
0.2		
1.0		
2.0		
3.0		
4.0		
5.0		
6.0		
7.0		
8.0		
9.0		
10.0		
11.0		
12.0		
13.0		
14.0		
15.0		
16.0		
17.0		
18.0		
19.0		
20.0		
21.0		
22.0		
23.0		
24.0		
25.0		
30.0		
35.0		
40.0		
45.0		
50.0		
55.0		
60.0		
65.0		]]

Table 2-62. Bundle 2993 Uncontrolled and Controlled R-Factors

Exposure (GWd/ST)	R-Factor (Fully Uncontrolled)	R-Factor (Fully Controlled)
0.0	[[	
0.2		
1.0		
2.0		
3.0		
4.0		
5.0		
6.0		
7.0		
8.0		
9.0		
10.0		
11.0		
12.0		
13.0		
14.0		
15.0		
16.0		
17.0		
18.0		
19.0		
20.0		
21.0		
22.0		
23.0		
24.0		
25.0		
30.0		
35.0		
40.0		
45.0		
50.0		
55.0		
60.0		
65.0		]]

Table 2-63. Bundle 2994 Uncontrolled and Controlled R-Factors

Exposure (GWd/ST)	R-Factor (Fully Uncontrolled)	R-Factor (Fully Controlled)
0.0	[[	
0.2		
1.0		
2.0		
3.0		
4.0		
5.0		
6.0		
7.0		
8.0		
9.0		
10.0		
11.0		
12.0		
13.0		
14.0		
15.0		
16.0		
17.0		
18.0		
19.0		
20.0		
21.0		
22.0		
23.0		
24.0		
25.0		
30.0		
35.0		
40.0		
45.0		
50.0		
55.0		
60.0		
65.0		]]

Table 2-64. Bundle 2995 Uncontrolled and Controlled R-Factors

Exposure (GWd/ST)	R-Factor (Fully Uncontrolled)	R-Factor (Fully Controlled)
0.0	[[	
0.2		
1.0		
2.0		
3.0		
4.0		
5.0		
6.0		
7.0		
8.0		
9.0		
10.0		
11.0		
12.0		
13.0		
14.0		
15.0		
16.0		
17.0		
18.0		
19.0		
20.0		
21.0		
22.0		
23.0		
24.0		
25.0		
30.0		
35.0		
40.0		
45.0		
50.0		
55.0		
60.0		
65.0		]]

[[

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Figure 2-89. Uncontrolled Rod R-Factors (Bundle 2990, 20 GWD/ST)

[[

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Figure 2-90. Uncontrolled Rod R-Factors (Bundle 2991, 20 GWD/ST)

[[

]]

Figure 2-91. Uncontrolled Rod R-Factors (Bundle 2992, 20 GWD/ST)

[[

]]

Figure 2-92. Uncontrolled Rod R-Factors (Bundle 2993, 20 GWD/ST)

[[

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Figure 2-93. Uncontrolled Rod R-Factors (Bundle 2994, 20 GWD/ST)

[[

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Figure 2-94. Uncontrolled Rod R-Factors (Bundle 2995, 20 GWD/ST)

Table 2-65. Lattice 7633 K-∞

Exposure (GWd/ST)	K-infinity (40% VF)	
	HOTUNC	HOTUNCD
0.00	[[	
0.20		
1.00		
2.00		
3.00		
4.00		
5.00		
6.00		
7.00		
8.00		
9.00		
10.00		
11.00		
12.00		
13.00		
14.00		
15.00		
16.00		
17.00		
18.00		
19.00		
20.00		
21.00		
22.00		
23.00		
24.00		
25.00		
30.00		
35.00		
40.00		
45.00		
50.00		
55.00		
60.00		
65.00		]]

[[

]]

Figure 2-95. Bundle 2990 Lattice 7633 K-infinity at 40% VF

Table 2-66. Lattice 7638 K-∞

Exposure (GWd/ST)	K-infinity (40% VF)	
	HOTUNC	HOTUNCD
0.00	[[	
0.20		
1.00		
2.00		
3.00		
4.00		
5.00		
6.00		
7.00		
8.00		
9.00		
10.00		
11.00		
12.00		
13.00		
14.00		
15.00		
16.00		
17.00		
18.00		
19.00		
20.00		
21.00		
22.00		
23.00		
24.00		
25.00		
30.00		
35.00		
40.00		
45.00		
50.00		
55.00		
60.00		
65.00		]]

[[

]]

Figure 2-96. Bundle 2991 Lattice 7638 K-infinity at 40% VF

Table 2-67. Lattice 7644 K-∞

Exposure (GWd/ST)	K-infinity (40% VF)	
	HOTUNC	HOTUNCD
0.00	[[	
0.20		
1.00		
2.00		
3.00		
4.00		
5.00		
6.00		
7.00		
8.00		
9.00		
10.00		
11.00		
12.00		
13.00		
14.00		
15.00		
16.00		
17.00		
18.00		
19.00		
20.00		
21.00		
22.00		
23.00		
24.00		
25.00		
30.00		
35.00		
40.00		
45.00		
50.00		
55.00		
60.00		
65.00		]]

[[

]]

Figure 2-97. Bundle 2992 Lattice 7644 K-infinity at 40% VF

Table 2-68. Lattice 7648 K-∞

Exposure (GWd/ST)	K-infinity (40% VF)	
	HOTUNC	HOTUNCD
0.00	[[	
0.20		
1.00		
2.00		
3.00		
4.00		
5.00		
6.00		
7.00		
8.00		
9.00		
10.00		
11.00		
12.00		
13.00		
14.00		
15.00		
16.00		
17.00		
18.00		
19.00		
20.00		
21.00		
22.00		
23.00		
24.00		
25.00		
30.00		
35.00		
40.00		
45.00		
50.00		
55.00		
60.00		
65.00		]]

[[

]]

Figure 2-98. Bundle 2993 Lattice 7648 K-infinity at 40% VF

Table 2-69. Lattice 7652 K-∞

Exposure (GWd/ST)	K-infinity (40% VF)	
	HOTUNC	HOTUNCD
0.00	[[	
0.20		
1.00		
2.00		
3.00		
4.00		
5.00		
6.00		
7.00		
8.00		
9.00		
10.00		
11.00		
12.00		
13.00		
14.00		
15.00		
16.00		
17.00		
18.00		
19.00		
20.00		
21.00		
22.00		
23.00		
24.00		
25.00		
30.00		
35.00		
40.00		
45.00		
50.00		
55.00		
60.00		
65.00		]]

[[

]]

Figure 2-99. Bundle 2994 Lattice 7652 K-infinity at 40% VF

Table 2-70. Lattice 7657 K-∞

Exposure (GWd/ST)	K-infinity (40% VF)	
	HOTUNC	**HOTUNCD**
0.00	[[	
0.20		
1.00		
2.00		
3.00		
4.00		
5.00		
6.00		
7.00		
8.00		
9.00		
10.00		
11.00		
12.00		
13.00		
14.00		
15.00		
16.00		
17.00		
18.00		
19.00		
20.00		
21.00		
22.00		
23.00		
24.00		
25.00		
30.00		
35.00		
40.00		
45.00		
50.00		
55.00		
60.00		
65.00		]]

[[

]]

Figure 2-100. Bundle 2995 Lattice 7657 K-infinity at 40% VF

3. CORE NUCLEAR DESIGN EVALUATION

The ESBWR core design is performed using the same analytical tools and methods that are applied to steady-state nuclear evaluations of all General Electric BWR cores. These nuclear physics methods, which are described in Reference 1, have proven their abilities and capabilities over hundreds of reactor operating years. This section describes the various core analyses and results for the ESBWR reference initial core based on these methods.

3.1 Nuclear Design and Core Loading Pattern Description

The ESBWR is rated at 4500 MWth and consists of 1132 bundles and 269 control blades. The three-dimensional simulation modeling of the reference initial core design was performed assuming quarter core mirror symmetry. Consequently, results in the upper left quadrant will be mirrored in the remaining three quadrants. Below are the nominal operating conditions for the ESBWR reference initial core.

Parameter	Nominal Value
Power (MWth)	4500
Flow (Mlb/hr)	[[
Pressure (psia)	
Bypass (%)	
Inlet Enthalpy (Btu/lb)	]]

The reference initial core design is characterized by the fuel type loading pattern given in Figure 3-1. [[

]]

This reference core is designed [[

]].

3.2 Eigenvalue Determination

At the beginning of a core design effort, hot and cold eigenvalues are determined in order to calibrate the 3D simulator predictions to actual results of the BWR fleet. Because of the similarities between current operating BWRs and the ESBWR, as well as the identical nature of the lattice physics calculations, exposure dependent eigenvalues could be obtained. Incorporating the actual trends of other large BWR cores, the hot and cold exposure dependent eigenvalues were determined. Table 3-1 and Figure 3-2 show the design basis exposure dependent hot eigenvalue. Table 3-2 and Figure 3-3 show the design basis exposure dependent cold eigenvalue. Eigenvalue determination is used for hot and cold reactivity calculations as well as determining the appropriate control rod inventory needed to provide criticality at full power conditions.

3.3 Control Rod Patterns Including Axial Power Considerations

Figures 3-4 through 3-8 illustrates the control rod patterns for this reference initial core. The maximum number of control rod notches per control blade is defined as 80. That is, for this simulation, a control rod at notch 80 is fully withdrawn; a control rod at notch 0 is fully inserted. The rod patterns utilize [[

]], maximizes operating capacity factor, and provides for improved fuel cycle efficiency.

An inherent advantage of the ESBWR is the [[

]] This classic BWR characteristic is well illustrated in Figures 3-9 through 3-13, which illustrates the progression in axial power shape throughout each of the five major control rod sequences from BOC to EOC. Core average axial power results are also provided in Tables 3-3 through 3-7. Figures 3-14 through 3-18 illustrate the core average axial exposure shape from BOC to EOC for each of the five control rod sequences. Corresponding exposure results are provided in Tables 3-8 through 3-12.

With regard to the target rod patterns, it was previously mentioned that the control rods are selected based on the design basis hot critical eigenvalue as well as thermal limit considerations. Table 3-13 and Figure 3-19 illustrate how well the target control rod patterns satisfy the design basis hot critical eigenvalue. The 2-D EOC bundle average exposure distribution at the end of this rodded burn scenario is shown in Figure 3-20.

3.4 Integrated Power Distribution

Although a bundle integrated power constraint does not exist, this is a helpful parameter when understanding loading pattern influence on individual power generation per bundle. During typical BWR non-initial core operation, the once-burnt high reactivity fuel provides the most influence on power distribution. Similarly, towards the EOC the fresh fuel provides most of the influence. In an exposed core, it is this balance of fresh and once burnt fuel that contributes to a more uniform core power distribution. During initial core operation for the ESBWR, however, the desired reactivity and local peaking characteristics are achieved through proper distribution of enrichment and gadolinia within each bundle design as previously discussed in Section 2. The resulting 2-D bundle integrated powers at the beginning and end of each of the five main control rod pattern sequences are presented in Figures 3-21 through 3-30. The maximum range of values in all of these figures [[
]]

3.5 Thermal Limit Evaluation

The core power distribution is a function of fuel bundle design, core loading, control rod pattern, core exposure distributions and core coolant flow rate. The thermal performance parameters, MLHGR and MCPR, limit the core power distribution. The analysis of the performance of the reference initial core design in terms of power distribution, and the associated MLHGR and MCPR distributions within the core throughout the cycle, are discussed below.

3.5.1 MLHGR

The Maximum Fraction of Linear Power Density (MFLPD) is shown as a function of cycle exposure in Table 3-14 and Figure 3-31. Note that the value plotted in Figure 3-31 represents the maximum value for any node in the core at the specified exposure point. The MFLPD parameter, in general terms, is defined as:

MFLPD = LHGR / LHGR Limit

It should be noted that the thermal mechanical LHGR limit is exposure dependent which necessitates establishing the MFLPD parameter to capture this. A MFLPD that is equal to 1.0 corresponds to a rod within a six inch node that is operating at its LHGR limit and any further increases in LHGR result in entering a Technical Specification Limiting Condition of Operation (LCO) condition. Every rod within the node has a MFLPD. The rod with the highest MFLPD in any given node defines the maximum MFLPD and this becomes the nodal MFLPD. The node with the highest MFLPD in an assembly can be thought of as the limiting MFLPD for that assembly. The highest MFLPD for any node in the core corresponds to the most limiting node and defines the minimum operating margin (1.0 – MFLPD) in the reactor core. Figures 3-32 through 3-41 show the 2-D MFLPD distribution at the beginning and end of each of the five main control rod sequences. The MLHGR limit used in the calculation of the MFLPD is reported in Reference 3.

3.5.2 MCPR

Table 3-15 and Figure 3-42 illustrates the minimum critical power ratio (MCPR) as a function of exposure throughout the cycle. Figure 3-43 through Figure 3-52 provide the 2-D MCPR distribution at the beginning and end of each of the five control rod sequences. The Operating Limit Minimum Critical Power Ratio (OLMCPR) is expected to be [[
]]. Therefore, the reference initial core will conform to these OLMCPRs with margin. The initial core OLMCPR is determined in a manner consistent with the equilibrium ESBWR core that was described in Reference 4.

3.6 Hot Excess Evaluation

A hot excess reactivity calculation illustrates the amount of excess reactivity a core design provides throughout the cycle. This calculation is performed by withdrawing all control rods at selected state points through the cycle and comparing the difference between the resulting eigenvalue and the design basis hot critical eigenvalue previously shown in Figure 3-2. Table 3-16 and Figure 3-53 shows the hot excess reactivity for this reference initial core design. [[

]]

The excess reactivity described above is designed into the core and controlled by the control rod system and supplemented by gadolinia-urania fuel rods discussed in Section 2. Gadolinia is used to provide partial control of the excess reactivity available during the fuel cycle. The burnable absorber loading controls local peaking behavior and suppresses the reactivity of the fuel bundle. An optimum bundle design will utilize a sufficient number of gadolinia rods to suppress core reactivity at BOC and a sufficient concentration to limit the peak reactivity to a manageable level throughout the cycle with little remaining residual gadolinia at EOC. The burnable absorber reduces the requirement for control rod inventory. Control rods are used primarily to compensate for reactivity changes due to burn-up and to maintain an acceptable core power distribution. A detailed description of the ESBWR initial core bundle designs was presented in Section 2.

3.7 Cold Shutdown Margin Evaluation

The ESBWR control rod system is designed to provide adequate shutdown margin and control of the maximum excess reactivity anticipated during plant operation. For this evaluation the core is assumed to be in the cold, xenon-free condition in order to ensure that the calculated values are conservative. Further discussion of the uncertainty of these calculations is given in Reference 5.

Shutdown margin results through the cycle are shown in Table 3-17 and in Figure 3-55. The shutdown margin is evaluated by calculating the core neutron multiplication with the core simulator at selected exposure points, assuming the highest worth control rod, or rod pair, is stuck in the fully withdrawn position. Since two control rod drives are assigned to a single Hydraulic Control Unit (HCU) for the ESBWR, the shutdown margin evaluation assumes that a rod pair is stuck in the fully withdrawn position. The control rod drive to HCU assignments are shown in Figure 3-54. Note that since there is an odd number of control rods, there is one HCU that is assigned a single control rod; this is HCU number 51, which is in the very center of the core. Since all rod pairs were selected with sufficient separation between them, they may be considered loosely coupled. Figures 3-56 to 3-58 are provided to demonstrate this loose coupling. Control rod worths at BOC, MOC and EOC are compared for the HCU rod pair withdrawn and the corresponding strongest single rod of the rod pair withdrawn. Control rod worths are shown to be essentially the same for the 40 highest worth HCUs in the top half of the core. Given that the core loading is quadrant symmetric, and HCU assignments are half core rotational symmetric, comparing the worths for the 40 highest worth HCUs effectively covers about 60% of the total control rods in the ESBWR. Consequently, 2-D SDM results and SDM results through the cycle based on the highest worth single rod out can be considered equivalent to SDM results for the strongest HCU rod pair withdrawn. A cycle specific assessment shall be performed every cycle to validate this conclusion.

The cold keff is calculated with the highest worth control rod, or rod pair, out at various exposures through the cycle. A value R is defined as the difference between the highest worth rod pair out keff at beginning of cycle (BOC) and the maximum calculated highest worth rod pair out keff at any exposure point. For the ESBWR reference initial core, the minimum shutdown margin occurs at BOC; thus, the value of R is zero. The calculated keff values with all control rods fully inserted (k_{CARI}) and with the strongest rod fully out (k_{SRO}) are shown below at BOC, MOC and EOC conditions. Also shown is the corresponding cold critical design bases eigenvalue (k_{CRIT}).

Control Configuration	BOC K-eff	MOC K-eff	EOC K-eff
Fully Controlled (k_{CARI})	[[		
Strongest Rod Out (k_{SRO})			
Critical k-effective (k_{CRIT})			]]

Based on the design k_{CRIT} value, the predicted shutdown margin is [[
]], which is significantly above the minimum required technical specification shutdown

margin value. Additional 2-D SDM results are provided in Figures 3-59 through 3-61 at BOC, MOC and EOC conditions.

3.8 Standby Liquid Control System Evaluation

The Standby Liquid Control System (SLCS) is designed to provide the capability of bringing the reactor, at any time in a cycle, from full power with a minimum control rod inventory (which is defined to be at the peak of the xenon transient) to a sub-critical condition with the reactor in the most reactive xenon-free state.

The requirements of this system are dependent primarily on the reactor power level and on the reactivity effects of voids and temperature between full power and cold, xenon-free conditions. The shutdown margin is calculated for a uniformly mixed equivalent concentration of natural boron, which is required in the reactor core to provide adequate cold shutdown margin after initiation of the SLCS. Calculations are performed throughout the cycle including the most reactive critical, xenon-free condition. Calculations are performed with all control rods withdrawn. The shutdown capability of the SLCS for the ESBWR reference initial core was calculated using [[

]]. Table 3-18 and Figure 3-62 shows that significant SLCS shutdown margin exists for the ESBWR core compared to a limit of 1%.

3.9 Criticality of Reactor During Refueling Evaluation

The basis for maintaining the reactor in a sub-critical condition during refueling is presented in Subsection 1.2, and a discussion of how control requirements are met is given in Section 3.7. The minimum required shutdown margin is given in the technical specifications.

3.10 Negative Reactivity Feedback Evaluation

Reactivity coefficients are a measure of the differential changes in reactivity produced by differential changes in core conditions. These coefficients are useful in understanding the response of the core to external disturbances. The Doppler reactivity coefficient, previously discussed in Section 2, and the moderator void reactivity coefficient are the two primary reactivity coefficients that characterize the dynamic behavior of BWRs.

The safety analysis methods are based on system and core models that include an explicit representation of the core space-time kinetics. Therefore, the reactivity coefficients are not directly used in the safety analysis methods, but are useful in the general understanding and discussion of the core response to perturbations.

3.10.1 Moderator Temperature Coefficient Evaluation

The moderator temperature coefficient is associated with the change in the water moderating capability. A negative moderator temperature coefficient during power operation provides inherent protection against power excursions. Hot standby is the condition under which the BWR core coolant has reached rated pressure and the temperature at which boiling has begun. Once boiling begins, the moderator temperature remains essentially constant in the boiling regions.

Analyses of the moderator temperature coefficient of the reference initial core design were performed. Table 3-19 and Figure 3-63 show the eigenvalues as a function of moderator temperature at three exposure state points for the critical rod pattern configuration. These eigenvalues were then used to determine the temperature coefficient for the reference initial core. The variation of the moderator temperature coefficient as a function of temperature is shown in Table 3-20 and Figure 3-64 for three exposure points through the cycle.

The most limiting state condition was determined to be at the end of the reference initial cycle for the critical core configuration. The results demonstrated [[

]]

The results of these analyses at these conditions indicate that the moderator temperature coefficient is negative for all moderator temperatures in the operating temperature range.

3.10.2 Moderator Void Coefficient Evaluation

The moderator void coefficient should be large enough to prevent power oscillation due to spatial xenon changes yet small enough that pressurization transients do not unduly limit plant operation. In addition, the void coefficient has the ability to flatten the radial power distribution and to provide ease of reactor control due to the void feedback mechanism. The overall void coefficient is always negative over the complete operating range.

The results of these analyses show that boiling of the moderator in the active channel flow area results in negative reactivity feedback for all expected modes of operation. The operating mode selected to represent the most limiting condition (the least negative value of moderator void coefficient) was the cold critical state at the end of the initial cycle. The value of moderator void coefficient for this condition was calculated to be [[
]] Table 3-21 and Figure 3-65 show the variation in eigenvalue as a function of moderator temperature and voids at three exposure state points for the critical rod configuration. These eigenvalues were then used to determine the void coefficient for the reference initial core. The variation of the void coefficient as a function of temperature is shown in Table 3-22 and Figure 3-66 for three exposure points through the cycle.

3.11 Xenon Stability Evaluation

Boiling water reactors do not have instability problems due to xenon. This has been demonstrated by:

- Never having observed xenon instabilities in operating BWRs;
- Special tests which have been conducted on operating BWRs in an attempt to force the reactor into xenon instability; and
- Calculations.

All of these indicators have proven that xenon transients are highly damped in a BWR due to the large negative moderator void feedback. Xenon stability analysis and experiments are reported in Reference 6. Specific evaluations demonstrating the damping of xenon transients (oscillations) for the ESBWR equilibrium core were are reported in Reference 1.

3.11.1 BWR Xenon Trends

Spatial stability measurements and analytical studies for the current BWR fleet have demonstrated very stable xenon transient performance characteristics. This stability is attributed to the large negative power coefficient that characterizes the BWR design. The negative power coefficient provides for strong spatial damping of transient reactor performance that results from xenon transients. The ESBWR shares the same negative power coefficient characteristics with current BWR designs, and is similarly stable with respect to xenon transient performance.

The large negative power coefficient of reactivity is a unique characteristic that results from moderator boiling. The large change in moderator density in the boiling environment of the reactor core is primarily responsible for the large negative power coefficient.

Non-linear trends also exist in the axial xenon distributions in an ESBWR core. As the moderator density changes axially in the reactor core, the neutron spectrum also changes. As the moderator density decreases, the neutron spectrum hardens. Since the Xe^{135} isotope has a smaller absorption cross section at higher neutron energies, the Xe^{135} distribution is affected axially by the non-uniform moderator density. The I^{135} isotope, which decays to produce Xe^{135}, is substantially proportional to the axial power distribution as it is a direct result of the fission process, and is not strongly affected by the axial changes in the neutron spectrum. The resulting differences in the Xe^{135} and I^{135} distributions lead to non-linear axial trends in the transient performance, which help to dampen any oscillatory behavior caused by transient concentration differences.

The non-linear axial trends in nuclear characteristics, coupled with the negative power coefficient resulting from the non-uniform moderator density, result in non-linear axial responses that cause axial xenon redistributions to be damped in one cycle. Additionally, although large reactor cores exhibit loosely coupled characteristics, local feedback at each point in the reactor core is provided by moderator boiling. The large negative power coefficient, coupled with the local feedback provided by localized boiling, work together to effectively damp azimuthal and radial oscillations.

The physical and nuclear characteristics of the ESBWR design have different effects upon the magnitude of the power coefficient. A summary of the important design characteristics and their influence on the power coefficient are shown below. These characteristics are consistent between BWR and ESBWR designs.

Increased Variable	**Effect on Power Coefficient**
moderator to fuel ratio	less negative
fuel rod diameter	less negative
fuel enrichment	more negative
fuel exposure	less negative
bypass water fraction	less negative
core size	less negative
void content	more negative

The primary differences between current operating BWRs and the ESBWR design include core size, core height, and the lack of forced recirculation flow in the ESBWR. [[ ]]. This results in slightly improved xenon stability for the ESBWR since the axial moderator density change associated with boiling occurs over a shorter distance. The natural recirculation characteristic of the ESBWR is also an important difference, because most power maneuvers require the use of control rods to control core reactivity and core power. The control rods have a strong negative influence on the power coefficient. Control rod worth increases rapidly as water density is decreased because of the increase in the thermal neutron diffusion length with decreased moderator density. The required use of control rods to control core power complements the negative power coefficient associated with the non-uniform moderator density to effectively damp transient xenon effects.

3.11.2 ESBWR Xenon Transient Conclusions

The negative power coefficient trends of an ESBWR have a pronounced effect on spatial xenon stability. The negative power coefficient results naturally from the non-uniform moderator distribution in the reactor core. This characteristic, coupled with the non-linear axial trends in nuclear characteristics, result in non-linear axial responses that cause the effects of xenon transients to be damped in one cycle. The effects of localized boiling provide direct local feedback that suppresses radial and azimuthal perturbations.

[[

]]

Figure 3-1. Reference Initial Core Fuel Types and Quantities

[[

Table 3-1. Hot Design Eigenvalues

Exposure (MWd/ST)	Distributed K-eff
[[	
	]]

]]

Figure 3-2. Hot Design Eigenvalue vs. Exposure

[[

Table 3-2. Cold Design Eigenvalues

Exposure (MWd/ST)	Distributed K-eff	Local K-eff
[[		
		]]

]]

Figure 3-3. Cold Design Eigenvalue vs. Exposure

[[

]]

Figure 3-4. Rod Patterns - Sequence 1 of 5

[[

]]

Figure 3-5. Rod Patterns - Sequence 2 of 5

[[

]]

Figure 3-6. Rod Patterns - Sequence 3 of 5

[[

]]

Figure 3-7. Rod Patterns - Sequence 4 of 5

[[

]]

Figure 3-8. Rod Patterns - Sequence 5 of 5

Table 3-3. Axial Nodal Power Seq-1

Axial Node	Beginning of Sequence 1 Axial Power	End of Sequence 1 Axial Power
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-9. Sequence 1 Core Average Axial Power Distributions

Table 3-4. Axial Nodal Power Seq-2

Axial Node	Beginning of Sequence 2 Axial Power	End of Sequence 2 Axial Power
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-10. Sequence 2 Core Average Axial Power Distributions

Table 3-5. Axial Nodal Power Seq-3

Axial Node	Beginning of Sequence 3 Axial Power	End of Sequence 3 Axial Power
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-11. Sequence 3 Core Average Axial Power Distributions

Table 3-6. Axial Nodal Power Seq-4

Axial Node	Beginning of Sequence 4 Axial Power	End of Sequence 4 Axial Power
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-12. Sequence 4 Core Average Axial Power Distributions

Table 3-7. Axial Nodal Power Seq-5

Axial Node	Beginning of *Sequence 5* Axial Power	End of *Sequence 5* Axial Power
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-13. Sequence 5 Core Average Axial Power Distributions

Table 3-8. Axial Nodal Exposure Seq-1

Axial Node	Beginning of Sequence 1 Axial Exposure	End of Sequence 1 Axial Exposure
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-14. Sequence 1 Core Average Axial Exposure Distributions

Table 3-9. Axial Nodal Exposure Seq-2

Axial Node	Beginning of Sequence 2 Axial Exposure	End of Sequence 2 Axial Exposure
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-15. Sequence 2 Core Average Axial Exposure Distributions

Table 3-10. Axial Nodal Exposure Seq-3

Axial Node	Beginning of Sequence 3 Axial Exposure	End of Sequence 3 Axial Exposure
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-16. Sequence 3 Core Average Axial Exposure Distributions

Table 3-11. Axial Nodal Exposure Seq-4

Axial Node	Beginning of Sequence 4 Axial Exposure	End of Sequence 4 Axial Exposure
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-17. Sequence 4 Core Average Axial Exposure Distributions

Table 3-12. Axial Nodal Exposure Seq-5

Axial Node	Beginning of Sequence 5 Axial Exposure	End of Sequence 5 Axial Exposure
20	[[	
19		
18		
17		
16		
15		
14		
13		
12		
11		
10		
9		
8		
7		
6		
5		
4		
3		
2		
1		]]

[[

]]

Figure 3-18. Sequence 5 Core Average Axial Exposure Distributions

Table 3-13. Hot K-eff vs Exposure

Exposure (MWD/ST)	K-eff
[[	
	]]

[[

]]

Figure 3-19. Hot Eigenvalue vs. Cycle Exposure

[[

]]

Figure 3-20. End of Sequence 5 Bundle Average Exposure (10.66 GWd/ST)

[[

]]

Figure 3-21. Beginning of Sequence 1 Integrated Bundle Power (0.0 GWd/ST)

[[

]]

Figure 3-22. End of Sequence 1 Integrated Bundle Power (2.14 GWd/ST)

[[

]]

Figure 3-23. Beginning of Sequence 2 Integrated Bundle Power (2.14 GWd/ST)

[[

]]

Figure 3-24. End of Sequence 2 Integrated Bundle Power (4.29 GWd/ST)

[[

]]

Figure 3-25. Beginning of Sequence 3 Integrated Bundle Power (4.29 GWd/ST)

[[

]]

Figure 3-26. End of Sequence 3 Integrated Bundle Power (6.43 MWd/ST)

[[

]]

Figure 3-27. Beginning of Sequence 4 Integrated Bundle Power (6.43 MWd/ST)

[[

]]

Figure 3-28. End of Sequence 4 Integrated Bundle Power (8.58 GWd/ST)

[[

]]

Figure 3-29. Beginning of Sequence 5 Integrated Bundle Power (8.58 GWd/ST)

[[

]]

Figure 3-30. End of Sequence 5 Integrated Bundle Power (10.66 GWd/ST)

Table 3-14. MFLPD vs Exposure

Exposure (MWD/ST)	MFLPD
[[	
	]]

[[

]]

Figure 3-31. MFLPD vs. Cycle Exposure

[[

]]

Figure 3-32. Beginning of Sequence 1 MFLPD (0.0 GWd/ST)

[[

]]

Figure 3-33. End of Sequence 1 MFLPD (2.14 GWd/ST)

[[

]]

Figure 3-34. Beginning of Sequence 2 MFLPD (2.14 GWd/ST)

[[

]]

Figure 3-35. End of Sequence 2 MFLPD (4.29 GWd/ST)

[[

]]

Figure 3-36. Beginning of Sequence 3 MFLPD (4.29 GWd/ST)

[[

]]

Figure 3-37. End of Sequence 3 MFLPD (6.43 MWd/ST)

[[

]]

Figure 3-38. Beginning of Sequence 4 MFLPD (6.43 MWd/ST)

[[

]]

Figure 3-39. End of Sequence 4 MFLPD (8.58 GWd/ST)

[[

]]

Figure 3-40. Beginning of Sequence 5 MFLPD (8.58 GWd/ST)

[[

]]

Figure 3-41. End of Sequence 5 MFLPD (10.66 GWd/ST)

Table 3-15. MCPR vs Exposure

Exposure (MWD/ST)	MCPR
[[	
	]]

[[

]]

Figure 3-42. MCPR vs. Cycle Exposure

[[

]]

Figure 3-43. Beginning of Sequence 1 MCPR (0.0 GWd/ST)

[[

]]

Figure 3-44. End of Sequence 1 MCPR (2.14 GWd/ST)

[[

]]

Figure 3-45. Beginning of Sequence 2 MCPR (2.14 GWd/ST)

[[

]]

Figure 3-46. End of Sequence 2 MCPR (4.29 GWd/ST)

[[

]]

Figure 3-47. Beginning of Sequence 3 MCPR (4.29 GWd/ST)

[[

]]

Figure 3-48. End of Sequence 3 MCPR (6.43 MWd/ST)

[[

]]

Figure 3-49. Beginning of Sequence 4 MCPR (6.43 GWd/ST)

[[

]]

Figure 3-50. End of Sequence 4 MCPR (8.58 GWd/ST)

[[

]]

Figure 3-51. Beginning of Sequence 5 MCPR (8.58 GWd/ST)

[[

]]

Figure 3-52. End of Sequence 5 MCPR (10.66 GWd/ST)

Table 3-16. Hot Excess Reactivity

Exposure (MWD/ST)	Hot Excess (%)
[[	
	]]

[[

]]

Figure 3-53. Hot Excess Reactivity vs. Cycle Exposure

[[

]]

Figure 3-54. Hydraulic Control Unit Assignments

Table 3-17. Cold Shutdown Margin

Exposure (MWD/ST)	Cold SDM (%)
[[	
	]]

[[

]]

Figure 3-55. Cold Shutdown Margin vs. Cycle Exposure

[[

]]

Figure 3-56. Control Rod Worth Comparisons at BOC (0.00 GWd/ST)

[[

]]

Figure 3-57. Control Rod Worth Comparisons at MOC (5.15 GWd/ST)

[[

]]

Figure 3-58. Control Rod Worth Comparisons at EOC (10.66 GWd/ST)

[[

]]

Figure 3-59. Cold Shutdown Margin Distribution (%) at BOC (0.00 GWd/ST)

[[

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Figure 3-60. Cold Shutdown Margin Distribution (%) at MOC (5.15 GWd/ST)

[[

]]

Figure 3-61. Cold Shutdown Margin Distribution (%) at EOC (10.66 GWd/ST)

Table 3-18. SLCS Shutdown Margin

Exposure (MWD/ST)	SLCS (%)
[[	
	]]

[[

]]

Figure 3-62. Standby Liquid Control Margin vs. Cycle Exposure

Table 3-19. Eigenvalues for Critical CRP

Temperature (°C)	Eigenvalue
BOC	
[[	
	]]
MOC	
[[	
	]]
EOC	
[[	
	]]

[[

]]

Figure 3-63. Eigenvalues vs. Moderator Temperature (for MTC)

Table 3-20. MTC for Critical CRP

Temperature (˚C)	MTC (1/k)(dk/dT)
BOC	
[[	
	]]
MOC	
[[	
	]]
EOC	
[[	
	]]

[[

]]

Figure 3-64. Moderator Temperature Coefficient

Table 3-21. Eigenvalues for Critical CRP

Temperature (°C)	Eigenvalue 0% Void	Eigenvalue 5% Void
	BOC	
[[		
		]]
	MOC	
[[		
		]]
	EOC	
[[		
		]]

[[

]]

Figure 3-65. Eigenvalues vs. Moderator Temperature (for MVC)

Table 3-22. MVC for Critical CRP

Temperature (°C)	MVC (1/k)(dk/dV)
BOC	
[[	
	]]
MOC	
[[	
	]]
EOC	
[[	
	]]

[[

]]

Figure 3-66. Moderator Void Coefficient

4. REFERENCES

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