ENCLOSURE 4

Westinghouse Non-Proprietary

APP-GW-GLR-029NP

# AP1000 Spent Fuel Storage Racks Criticality Analysis

(Non-Proprietary)

APP-GW-GLR-029NP
Revision 2

September 2009

# AP1000 Spent Fuel Storage Racks Criticality Analysis

## Non-Proprietary Version

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# AP1000 RECORD OF CHANGES

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| 1 | General | See page 6 for general description of changes. This document was revised to incorporate the response to RAI-SRP9.1.1-SRSB-07. | RJM/See EDMS |
| 2 | 5.4 | Added a reference to Table 5.16 and included that pyrex burnable absorbers were considered. | RJM/See EDMS |
| 3 | 10.18 | Added Reference 18. | RJM/See EDMS |
| 4 | Table 5.16 | Added entire table for the specifications of the pyrex inserts that were considered in the analysis. | RJM/See EDMS |

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# CRITICALITY EVALUATION OF THE AP1000 SPENT FUEL STORAGE RACKS

FOR

*WESTINGHOUSE*

**Holtec Report No: HI-2094327**

**Holtec Project No: 1540**

**Sponsoring Holtec Division: HTS**

**Report Class : SAFETY RELATED**

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In accordance with the Holtec Quality Assurance Manual and associated Holtec Quality Procedures (HQPs), this document is categorized as a:

☒ Calculation Package[3] (Per HQP 3.2)

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Summary of Revisions:

Revision 0: Original Issue

Revision 1: Added information to address RAI-SRP9.1.1-SRSB-07. See change bars throughout text.

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# 1. INTRODUCTION

## 1.1 Statement of Purpose

This report documents the criticality safety evaluation for the storage of PWR spent nuclear fuel in Holtec Region 1 & 2 style high-density spent fuel storage racks (SFSRs) for the AP1000 nuclear power plants. The objective of this analysis is to ensure that the effective neutron multiplication factor ($k_{eff}$) is less than or equal to 0.95 with the storage racks fully loaded with fuel of the highest permissible reactivity and the pool flooded with borated water at a temperature corresponding to the highest reactivity. In addition, it is demonstrated that $k_{eff}$ is less than 1.0 under the assumed loss of soluble boron in the pool water, i.e., assuming unborated water in the spent fuel pool. The maximum calculated reactivities include a margin for uncertainty in reactivity calculations, including manufacturing tolerances, and are calculated with a 95% probability at a 95% confidence level [1]. Reactivity effects of abnormal and accident conditions have also been evaluated to assure that under all credible abnormal and accident conditions, the reactivity will not exceed the regulatory limit of 0.95.

## 1.2 About this Document

This Calculation Package will be saved as a Permanent Record under the company's QA System.

## 2. METHODOLOGY

## 3. ACCEPTANCE CRITERIA

The high-density spent fuel PWR storage racks for the AP1000 are designed in accordance with the applicable codes and standards listed below. The objective of this analysis is to ensure that the effective neutron multiplication factor ($k_{eff}$) is less than or equal to 0.95 with the storage racks fully loaded with fuel of the highest permissible reactivity and the pool flooded with borated water at a temperature corresponding to the highest reactivity. In addition, it is demonstrated that $k_{eff}$ is less than 1.0 under the assumed loss of soluble boron in the pool water, i.e. assuming unborated water in the spent fuel pool. The maximum calculated reactivities include a margin for uncertainty in reactivity calculations, including manufacturing tolerances, and are calculated with a 95% probability at a 95% confidence level [1].

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

- 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," General Design Criterion 62, "Prevention of Criticality in Fuel Storage And Handling."

- USNRC Standard Review Plan, NUREG-0800, Section 9.1.1, Criticality Safety of Fresh and Spent Fuel Storage and Handling, Rev. 3 – March 2007.

- L. Kopp, "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," NRC Memorandum from L. Kopp to T. Collins, August 19, 1998 [7].

- ANSI ANS-8.17, Criticality Safety Criteria for the Handling, Storage and Transportation of LWR Fuel Outside Reactors.
- Code of Federal Regulations, Title 10, Part 50, Section 68, "Criticality Accident Requirements", as referenced in Title 10, Part 52, Section 47.
- Regulatory Guide 1.13, Revision 2, "Spent Fuel Storage Facility Design Basis," March 2007.

# 4. ASSUMPTIONS

# 5. INPUT DATA

## 5.1 Fuel Assembly Specification

The spent fuel storage racks are designed to accommodate the 17x17 fuel assembly used in the AP1000 reactor. The design parameters for this fuel assembly type that are used in the analyses are given in Table 5.1.

## 5.2 Core Operating Parameters

Core operating parameters are necessary for fuel depletion calculations performed with CASMO-4. The core parameters used for the depletion calculations are presented in Table 5.2. The boron letdown curve is presented in Table 5.3. Temperature and soluble boron values are conservatively high values.

## 5.3 Axial Burnup Distribution

The analyses use axial burnup profiles specified based on core locations and discharge cycle from [11, 12]. The bounding profile is presented in Table 5.11.

## 5.4 Burnable Absorbers

Most fuel assemblies for the AP1000 use fuel rods with IFBA and/or WABAs inserted into the guide tubes for reactivity and/or power control. Gray rod cluster assemblies (GRCAs), either Tungsten or AgInCd, are used for power distribution control. Finally, the AP1000 makes use of rod cluster control assemblies (RCCAs) during full power operation. Table 5.4 through Table 5.10 and Table 5.16 provide the specifications for the IFBA rods, WABAs, pyrex burnable absorbers, GRCAs and RCCAs. Additionally, an assembly insert may be used in more than one cycle (i.e. WABA in the first cycle followed by a GRCA in the second cycle). The various combinations of multiple inserts are provided in Table 5.15.

## 5.5 Storage Rack Specification

The storage cell characteristics used in the criticality evaluations are summarized in Table 5.12 and Table 5.13.

### 5.5.1 Region 1 Style Storage Racks

The Region 1 storage cells are composed of stainless steel boxes separated by a water gap, with fixed neutron absorber panels centered on each side. The steel walls define the storage cells, and stainless steel sheathing supports the neutron absorber panel and defines the boundary of the flux-trap water-gaps used to augment reactivity control. Stainless steel channels connect the storage cells in a rigid structure and define the flux-trap between the neutron absorber panels. Neutron absorber panels are installed on all exterior walls where a fuel assembly could be mislocated. For those areas where there is insufficient space to misplace a fuel assembly between the Region 1 rack and the spent fuel pool wall, no neutron absorber is present.

### 5.5.2 Region 2 Style Storage Racks

The Region 2 storage cells are composed of stainless steel boxes with a single fixed neutron absorber panel centered on each side, attached by stainless steel sheathing. The stainless steel boxes are arranged in an alternating pattern such that the connection of the box corners form storage cells between those of the stainless steel boxes. Neutron absorber panels are installed on all exterior walls where a fuel assembly could be mislocated. For those areas where there is insufficient space to misplace a fuel assembly between the Region 2 rack and the spent fuel pool wall, no neutron absorber is present on the exterior surfaces on the rack module.

### 5.5.3 Defective Storage Locations

Rack module C1 (a Region 2 rack module) contains five locations to store defective fuel assemblies. These storage locations are separated from each other by a water gap, similar to the Region 1 racks. Additionally, they are separated from the Region 2 storage cells by a large water gap.

### 5.5.4 Rack Interfaces

## 6. COMPUTER CODES

The following computer codes were used during this analysis.

- MCNP4a [2] is a three-dimensional continuous energy Monte Carlo code developed at Los Alamos National Laboratory. This code offers the capability of performing full three-dimensional calculations for the loaded storage racks. MCNP4a was run on the PCs at Holtec.

- CASMO-4, Version 2.05.14 [4-6] is a two-dimensional multigroup transport theory code developed by Studsvik of Sweden. CASMO-4 performs cell criticality calculations and burnup. CASMO-4 has the capability of analytically restarting burned fuel assemblies in the rack configuration. This code was used to determine the reactivity effects of tolerances and fuel depletion.

## 7. ANALYSIS

This section describes the calculations that were used to determine the acceptable storage criteria for the Region 1 and Region 2 style racks. In addition, this section discusses the possible abnormal and accident conditions.

The following sections summarize the calculations that were performed.

## 7.1 Region 1

The goal of the criticality calculations for the Region 1 style racks is to qualify the racks for storage of fuel assemblies with design specifications as shown in Table 5.1 and a maximum nominal initial enrichment of 4.95 wt% $^{235}U$.

### 7.1.1 Eccentric Fuel Assembly Positioning

### 7.1.2 Uncertainties Due to Manufacturing Tolerances

### 7.1.3 Temperature and Water Density Effects

### 7.1.4 Calculation of Maximum $k_{eff}$

### 7.1.5 Abnormal and Accident Conditions

The effects on reactivity of credible abnormal and accident conditions are examined in this section. This section identifies which of the credible abnormal or accident conditions will result in exceeding the limiting reactivity ($k_{eff} \leq 0.95$). For those accident or abnormal conditions that result in exceeding the limiting reactivity, a minimum soluble boron concentration is determined to ensure that $k_{eff} \leq 0.95$.

#### 7.1.5.1 Abnormal Temperature

#### 7.1.5.2 Dropped Assembly - Horizontal

#### 7.1.5.3 Dropped Assembly – Vertical Into a Storage Cell

#### 7.1.5.4 Misloaded Fresh Fuel Assembly

#### 7.1.5.5 Mislocated Fresh Fuel Assembly

### 7.1.6 Summary

Calculations have been performed to qualify the Region 1 racks for storage of fuel assemblies with a maximum nominal initial enrichment of 4.95 wt% $^{235}U$. The results of these calculations are summarized in Table 7.1 and Table 7.2. The calculations demonstrate that the maximum $k_{eff}$ is less than 0.95 without credit for soluble boron. Furthermore, all reactivity effects of abnormal and accident conditions have also been evaluated to assure that under all credible abnormal and accident conditions, the reactivity will not exceed the regulatory limit of 0.95 with credit for soluble boron.

## 7.2 Region 2

The goal of the criticality calculations for the Region 2 style racks is to qualify the racks for uniform storage of spent fuel assemblies with design specifications as shown in Table 5.1 and a maximum nominal initial enrichment of 4.95 wt% $^{235}U$. The purpose of the criticality calculations is to determine the initial enrichment and burnup combinations required for the uniform storage of spent fuel assemblies.

7.2.1

### 7.2.2 Axial Burnup Distributions

### 7.2.3 Isotopic Compositions

### 7.2.4 Uncertainty in Depletion Calculations

### 7.2.5 Eccentric Fuel Assembly Positioning

### 7.2.6 Uncertainties Due to Manufacturing Tolerances

### 7.2.7 Temperature and Water Density Effects

### 7.2.8 Calculation of Maximum $k_{eff}$

### 7.2.9 Determination of Burnup Versus Enrichment Values

### 7.2.10 Soluble Boron Concentration for Maximum $k_{eff}$ of 0.95

### 7.2.11 Measured Burnup Uncertainty

### 7.2.12 Abnormal and Accident Conditions

The effects on reactivity of credible abnormal and accident conditions are examined in this section. This section identifies which of the credible abnormal or accident conditions will result in exceeding the limiting reactivity ($k_{eff} \leq 0.95$). For those accident or abnormal conditions that result in exceeding the limiting reactivity, a minimum soluble boron concentration is determined to ensure that $k_{eff} \leq 0.95$.

#### 7.2.12.1 Abnormal Temperature

#### 7.2.12.2 Dropped Assembly - Horizontal

#### 7.2.12.3 Dropped Assembly - Vertical

#### 7.2.12.4 Misloaded Fresh Fuel Assembly

#### 7.2.12.5 Mislocated Fresh Fuel Assembly

### 7.2.13 Summary

## 7.3 Defective Fuel Storage Cells Attached to Region 2 Racks

## 7.4 Interfaces Between Racks

# 8. COMPUTER FILES

All input files for the calculations are stored in the directory and its subdirectories on the Holtec server.

# 9. CONCLUSIONS

This report documents the criticality analysis for the storage of PWR spent nuclear fuel in the Region 1 and Region 2 style high-density spent fuel storage racks at the AP1000 nuclear power plant. The results of the analyses are summarized as follows:

- Region 1 racks can be loaded with fresh fuel of up to 4.95 wt% $^{235}U$.

- For Region 2 racks a minimum burnup is required as a function of the initial enrichment. These minimum burnups are listed in Table 7.4.
- The damaged fuel cells can be loaded with fresh fuel of up to 4.95 wt% $^{235}U$.
- Under accident conditions, a minimum soluble boron level of 800 ppm in the pool is required.

# 10. REFERENCES[1]


1. M.G. Natrella, Experimental Statistics, National Bureau of Standards, Handbook 91, August 1963.

2. J.F. Briesmeister, Editor, "MCNP - A General Monte Carlo N-Particle Transport Code, Version 4A," LA-12625, Los Alamos National Laboratory (1993).

3. "Lumped Fission Product and Pm148m Cross Sections for MCNP," Holtec Report HI-2033031, Rev 0, September 2003.

4. M. Edenius, K. Ekberg, B.H. Forssén, and D. Knott, "CASMO-4 A Fuel Assembly Burnup Program User's Manual," Studsvik/SOA-95/1, Studsvik of America, Inc. and Studsvik Core Analysis AB (proprietary), Revision 1, August 2001.

5. D. Knott, "CASMO-4 Benchmark Against Critical Experiments", SOA-94/13, Studsvik of America, Inc., (proprietary), December 1995.

6. D. Knott, "CASMO-4 Benchmark Against MCNP," SOA-94/12, Studsvik of America, Inc., (proprietary), December 1995.

7. L.I. Kopp, "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," NRC Memorandum from L. Kopp to T. Collins, August 19, 1998.

8. Holtec Position Paper DS-292/WS-138, "Standardization of Metamic Specifications in Wet and Dry Storage, January 2004.

9. Holtec Rack Data Sheet, Project 1540, Revision 9.

10. Holtec Drawing 4743, Revision 1.

11. Westinghouse Letter NRFE-09-50, Rev. 2, "Transmittal of AP1000 Information for HOLTEC Criticality Analysis," May 14, 2009 (proprietary).


[1] Note: The revision status of Holtec documents cited above is subject to updates as the project progresses. This document will be revised if a revision to any of the above-referenced Holtec work materially affects the instructions, results, conclusions or analyses contained in this document. Otherwise, a revision to this document will not be made and the latest revision of the referenced Holtec documents shall be assumed to supercede the revision numbers cited above. The Holtec Project Manager bears the undivided responsibility to ensure that there is no intra-document conflict with respect to the information contained in all Holtec generated documents on a safety-significant project. The latest revision number of all documents produced by Holtec International in a safety significant project is readily available from the company's electronic network.

12. Westinghouse Letter NRFE-09-63, Rev. 1, "Transmittal of AP1000 MSHIM Rodded Operation Information for HOLTEC Criticality Analysis," May 14, 2009 (proprietary).

13. Westinghouse Letter NRFE-09-76, Rev 0, "Confirmation of Limiting Burnup Shape for HOLTEC Criticality Analysis," May 14, 2009 (proprietary).

14. Nuclides and Isotopes, 15th Edition, GE Co. and KAPL Inc, 1996.

15. S.E. Turner, "Uncertainty Analysis - Burnup Distributions", presented at the DOE/SANDIA Technical Meeting on Fuel Burnup Credit, Special Session, ANS/ENS Conference, Washington, D.C., November 2, 1988.

16. "Study of the Effect of Integral Burnable Absorbers for PWR Burnup Credit," NUREG/CR-6760, ORNL/TM-2000-321, March 2002.

17. "Parametric Study of the Effect of Burnable Poison Rods for PWR Burnup Credit", ORNL-TM-2000/373, NUREG/CR-6761, USNRC Office of Nuclear Regulatory Research, March 2002.

18. Westinghouse Letter NRFE-09-134, Rev. 0, "Transmittal of DCD Rev. 17 PYREX Information for Holtec Criticality Analysis," August 26, 2009.

Table 5.1
Fuel Assembly Specification [11]

| **Fuel Rod Data** | |
|---|---|
| Assembly type | **AP1000** |
| Fuel pellet outside diameter, in. | |
| Cladding inside diameter, in. | |
| Cladding outside diameter, in. | |
| Cladding material | |
| Stack density, g/cc | |
| Maximum enrichment, wt% $^{235}U$ | |
| Blanket Length, in | |
| **Fuel Assembly Data** | |
| Fuel rod array | |
| Number of fuel rods | |
| Fuel rod pitch, in. | |
| Number of guide tubes | |
| Guide Tube outside diameter, in. | |
| Guide Tube inside diameter, in. | |
| Number of instrument tubes | |
| Instrument Tube outside diameter, in. | |
| Instrument Tube inside diameter, in. | |
| Instrument Tube and Guide Tube Material | |
| Active fuel Length, in. | |

Table 5.2
Core Operating Parameter for Depletion Analyses [11]

| Parameter | Value |
|---|---|
| Reactor Specific Power, MW/MTU | power: 3400 MWt<br>loading: 84.075 – 84.708 MTU |
| Core Average Fuel Temperature, °F | 1200.1 |
| Core Average Moderator Temperature at the Top of the Active Region, °F | 616.4 |
| In-Core Assembly Pitch, Inches | 8.466 |
| Cycle Average Soluble Boron, ppm | |

Table 5.3
Peak Boron Letdown Curve [11]

| **Burnup (MWD/MTU)** | **Boron Concentration (ppm)** |
|---|---|
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Table 5.4: WABA Data [11]

| Parameter | Value |
|---|---|
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Table 5.5: IFBA Data [11]

| Parameter | Value |
|---|---|
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| | |

Table 5.6: IFBA Patterns and Enrichments [11]

| Enrichment | Blanket Enrichment | IFBA Patterns |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

Table 5.7 IFBA and WABA Combinations [11]

| WABA Pattern | IFBA Patterns |
|---|---|
| | |
| | |
| | |

Table 5.8: GRCA Dimensions [12]

| Parameter | Value |
|---|---|
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Table 5.9: GRCA Dimensions[2] [12]

| Parameter | Value |
|---|---|
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Table 5.10: Ag-In-Cd GRCA Design [12]

| Parameter | Value |
|---|---|
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Table 5.11
Bounding Axial Burnup Profile (see Appendix E)

| Node Length | Relative Burnup |
|---|---|

Table 5.12
Storage Rack Parameters ([9], [10])

| Region 1 | |
|---|---|
| **Parameter** | **Value** |
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| **Region 2** | |
| **Parameter** | **Value** |
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Table 5.13
Damaged Fuel Cell Parameters ([10])

| Region 1 | |
|---|---|
| **Parameter** | **Value** |
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Table 5.14
Analyzed Insert/IFBA Combinations for a Single Cycle

| Insert | # of IFBA Rods |
|---|---|
| | |
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Table 5.15
Assembly Insert Combinations During AP1000 Core Operation [12]

| 1st Cycle | 2nd Cycle | 3rd Cycle |
|---|---|---|
| | | |
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Table 5.16
Pyrex Inserts Design [18]

| Parameter | Value |
|---|---|
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Table 7.1
Summary of the Criticality Safety Analysis for Region 1

| | | |
|---|---|---|
| Enrichment [wt% $^{235}U$] | | 4.95 |
| **Uncertainties** | | |
| MCNP4a Bias Uncertainty (95%/95%) | ± | |
| CASMO-4 Bias Uncertainty (95%/95%) | ± | |
| Calculational Statistics (95%/95%, 2.0×σ) | ± 0.0014 | |
| Fuel Eccentricity | Negative | |
| Rack Tolerances | ± | |
| Fuel Tolerances | ± | |
| Statistical Combination of Uncertainties | ± 0.0143 | |
| Reference $k_{eff}$ (MCNP4a) | | 0.9028 |
| **Biases** | | |
| Temperature Bias | | |
| MCNP4a Bias (see Appendix A) | | |
| **Maximum $k_{eff}$** | | **0.9207** |
| **Regulatory Limiting $k_{eff}$** | | **0.9500** |

Table 7.2

Region 1 Abnormal and Accident Conditions

| **Abnormal/Accident Condition** | **Soluble Boron Requirement (ppm)** |
|---|---|
| Abnormal Temperature | None |
| Dropped Assembly – Horizontal | Negligible |
| Dropped Assembly – Vertical Into Storage Cell | Negligible |
| Misloaded Assembly | N/A |
| Mislocated Assembly | 250 |

Table 7.3
Summary of the Criticality Safety Analysis for Region 2 Without Soluble Boron

| | | |
|---|---|---|
| Enrichment [wt% $^{235}U$] | | 4.95 |
| Burnup [GWD/MTU] | | 42.6 |
| **Uncertainties** | | |
| MCNP4a Bias Uncertainty (95%/95%) | ± | |
| CASMO-4 Bias Uncertainty (95%/95%) | ± | |
| Calculational Statistics (95%/95%, 2.0×σ) | ± 0.0016 | |
| Fuel Eccentricity | ± 0.0000 | |
| Rack Tolerances | ± | |
| Fuel Tolerances | ± | |
| Depletion Uncertainty | ± | |
| Statistical Combination of Uncertainties | ± 0.0177 | |
| Reference $k_{eff}$ (MCNP4a) | | 0.9737 |
| **Biases** | | |
| Temperature Bias | | |
| MCNP4a Bias (see Appendix A) | | |
| **Maximum $k_{eff}$** | | **0.9950** |
| **Regulatory Limiting $k_{eff}$** | | **1.0000** |

Table 7.4
Region 2 Burnup Versus Enrichment Curve

| Enrichment (wt% U-235) | Minimum Burnup (GWD/MTU) |
|---|---|
| 2.0 | 0.0 |
| 2.5 | 6.8 |
| 3.0 | 13.0 |
| 3.5 | 19.6 |
| 4.0 | 27.0 |
| 4.5 | 35.5 |
| 4.95 | 42.6 |

Table 7.5
Region 2 Abnormal and Accident Conditions

| Abnormal/Accident Condition | Soluble Boron Requirement |
|---|---|
| Abnormal Temperature | None |
| Dropped Assembly – Horizontal | Negligible |
| Dropped Assembly – Vertical Into Storage Cell | Negligible |
| Misloaded Assembly | 800 ppm |
| Mislocated Assembly | 650 ppm |

Table 7.6

Figure 5.1 IFBA Patterns [11]

X=IFBA Rod

Figure 5.2: Discrete Inserts Figure [12]

1 - 6 = guide tubes or WABA
7 = instrumentation tube

**12 WABA pattern [12]**

| | |
|---|---|
| | |
| | |
| | |

**GRCA Design [12]**

| | |
|---|---|
| | |
| | |

**GRCA Design [12]**

| | |
|---|---|
| | |

Figure 5.3 Region 1 Calculational Model (MCNP)

Figure 5.4 Region 2 Calculational Model (MCNP)

Figure 5.5: Region 1 Misplaced Assembly Model in MCNP (entire model not shown)

Figure 5.6: Region 2 Misloaded Assembly Model in MCNP (entire model not shown)

Figure 5.7: Region 2 Misplaced Assembly Model in MCNP (entire model not shown)

Figure 5.8: Region 2 with Defective Fuel Model in MCNP4a (entire model not shown)

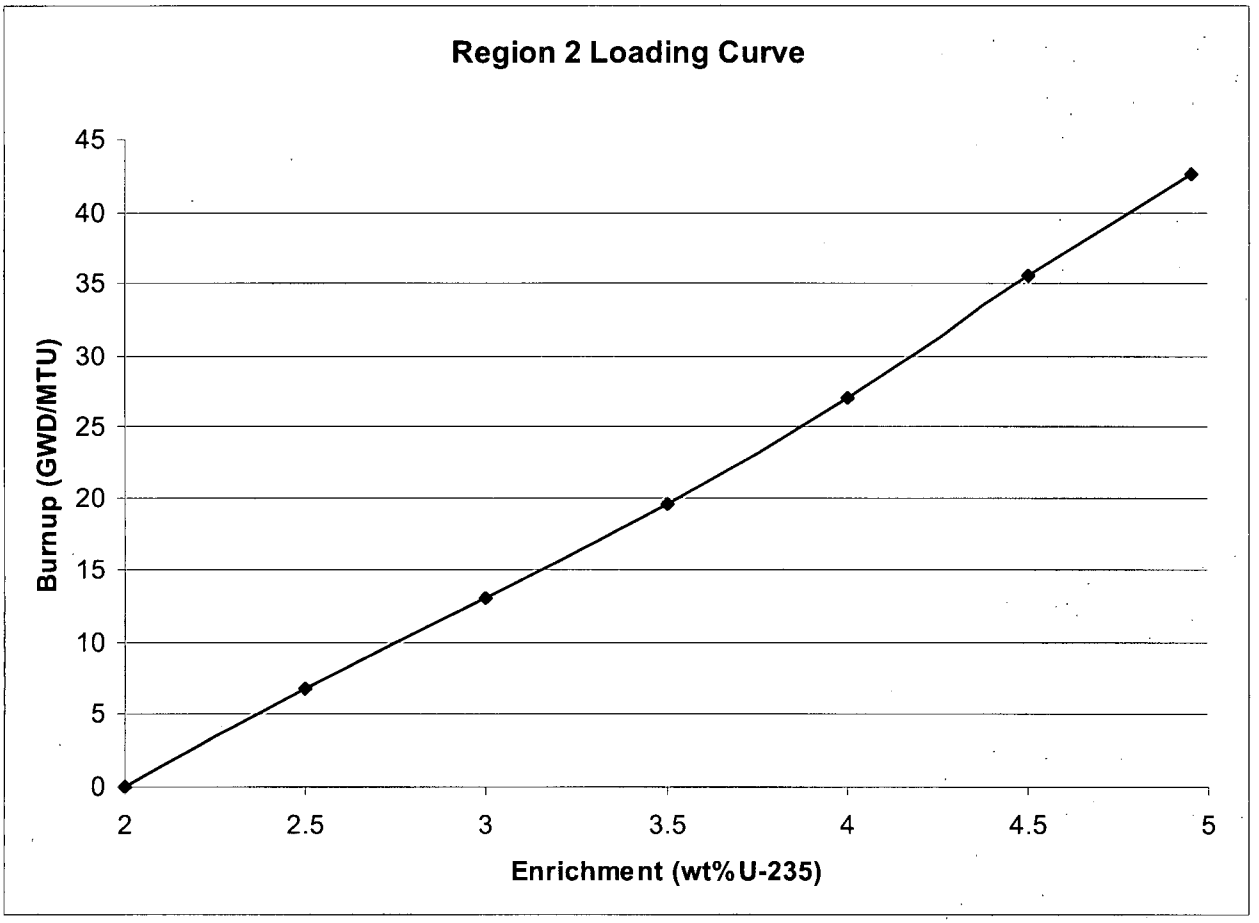


Figure 7.1 Loading Curve for Region 2 Racks

# Appendix A
Benchmark Calculations

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# Appendix B

CASMO-4 Benchmark

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# Appendix C

Metamic Composition

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# Appendix D

Region 1 MCNP4a Calculations

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# Appendix E

Axial Burnup Distributions

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# Appendix F

Region 2 Fuel Assembly Insert Calculations

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# Appendix G

Region 2 Tolerance and Temperature Calculations

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# Appendix H

Region 2 MCNP4a Calculations

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