ENCLOSURE 4

TN Calculation NUH32PHB-0600, Criticality Evaluation for NUHOMS 32PHB System

Calvert Cliffs Nuclear Power Plant, LLC
March 26, 2014

AREVA TRANSNUCLEAR INC	Form 3.2-1 Calculation Cover Sheet TIP 3.2 (Revision 4)	Calculation No.:	NUH32PHB-0600
		Revision No.:	0
		Page: 1 of 35	
DCR NO (if applicable) : N/A	PROJECT NAME: NUHOMS® - 32PHB System		
PROJECT NO: 10955	CLIENT: CENG - Calvert Cliff Nuclear Power Plant (CCNPP)		

CALCULATION TITLE: *Criticality Evaluation for NUHOMS 32PHB System*

SUMMARY DESCRIPTION:

1) Calculation Summary

The purpose of this calculation package is to determine a worst-case bounding $k_{EFFECTIVE}$ for the NUHOMS®-32PHB Transportable Storage Canister for normal and accident conditions of storage (10CFR72) for several PWR fuel assembly types and configurations containing intact fuel assemblies. A maximum of 32 intact fuel assemblies can be stored in a single DSC. The criticality analysis calculations are carried out to determine the maximum enrichment of the intact fuel assemblies as a function of fixed poison loading to store PWR fuel assemblies.

2) Storage Media Description

Secure network server initially, then redundant tape backup containing the KENO V.a input and output files, the spreadsheets used in the calculation, and the Word file with the text of the calculation

If original issue, is licensing review per TIP 3.5 required?

Yes ☐ **No** ☒ **(explain below)** **Licensing Review No.:** _____

This calculation is prepared to support a Site Specific License Application by CCNPP that will be reviewed and approved by the NRC. Therefore, a 10CFR72.48 licensing review per TIP 3.5 is not applicable.

Software Utilized (subject to test requirements of TIP 3.3):	**Version:**
SCALE 6 XP	C00750MNYCP00
Calculation is complete: Originator Name and Signature: David Lee *David Lee*	Date: 4/14/10
Calculation has been checked for consistency, completeness and correctness: Checker Name and Signature: Andrew Gerlach	Date: 4/14/10
Calculation is approved for use: Project Engineer Name and Signature: Kamran Tavassoli	Date: 04/15/10

Revision Summary

Revision	Description	Affected Pages
0	Initial Issue	All

Licensing Documents: N/A

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1.0 PURPOSE

This calculation documents a series of criticality calculations performed for the NUHOMS®-32PHB Transportable Dry Storage Canister (referred to as DSC hereafter). The calculation results demonstrate the compliance with the criticality-related portions of 10CFR72 for storage of the DSC.

The DSC is transferred in the CCNPP-FC Transfer Cask and then stored in a NUHOMS® Horizontal Storage Module. The DSC is designed to store 32 PWR intact fuel assemblies with initial U-235 enrichment of 2.0 - 5.0 wt%.

1.1 Hardware Analyzed

The NUHOMS®-32PHB hardware design requirements are specified in the 32PHB Design Criteria Document [1]. The design parameters that are relevant to the criticality calculation are discussed in the following subsections.

1.1.1 NUHOMS® - 32PHB DSC

The DSC dimensions and their references are listed in Table 1.1-1. The DSC exhibits two patterns. One is the 2-dimensional horizontal layout of the 32 guide sleeves as shown in Figure 1.1 [4]. Another pattern is 3-dimensional and involves insert plates and poison plates, as shown in Figure 1.2 [4]. The orientation of the vertical pattern renders two views. One view shows a set of insert plates running along the east-west direction with a vertical spacing of 8.28". Poison plates are between insert plates. Another vertical view shows a set of insert plates running along the north-south direction with a vertical spacing of 8.28". Again, poison plates are between insert plates. There is a vertical gap between the insert plate and its adjacent poison plate.

Those two vertical views intersect at the junction of four guide sleeves. The north-south poison plates and the east-west poison plates intersect each other through the poison plate slots. There are vertical gaps that form inside the slot. The north-south insert plates sit on top of the east-west insert plates. They do not intersect each other. Instead, the north-south insert plates run through the east-west poison plates and the east-west insert plates run through the north-south poison plates. Again, there are vertical gaps that form inside the slot.

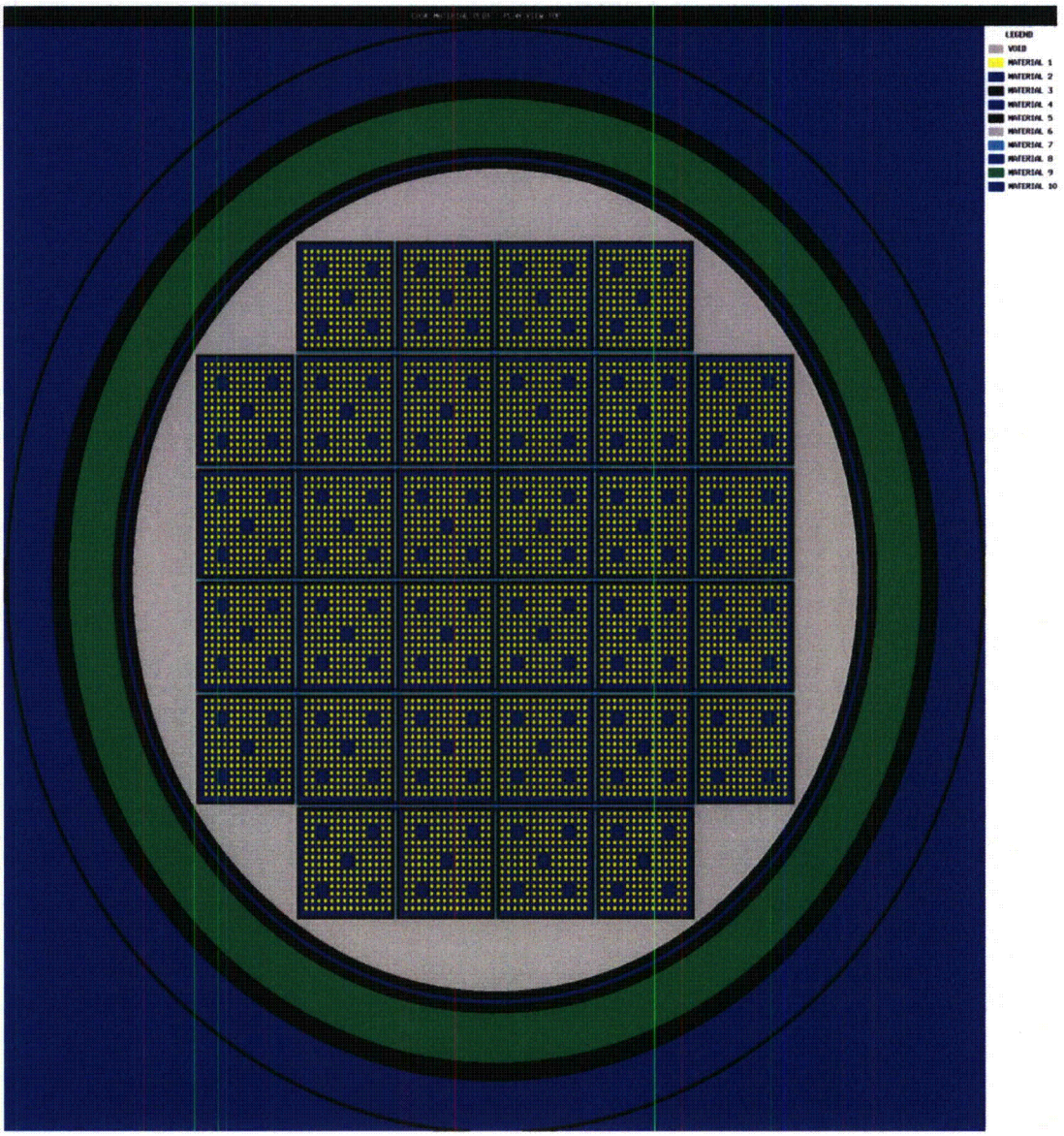

Figure 1-1 DSC 32 Guide Sleeves

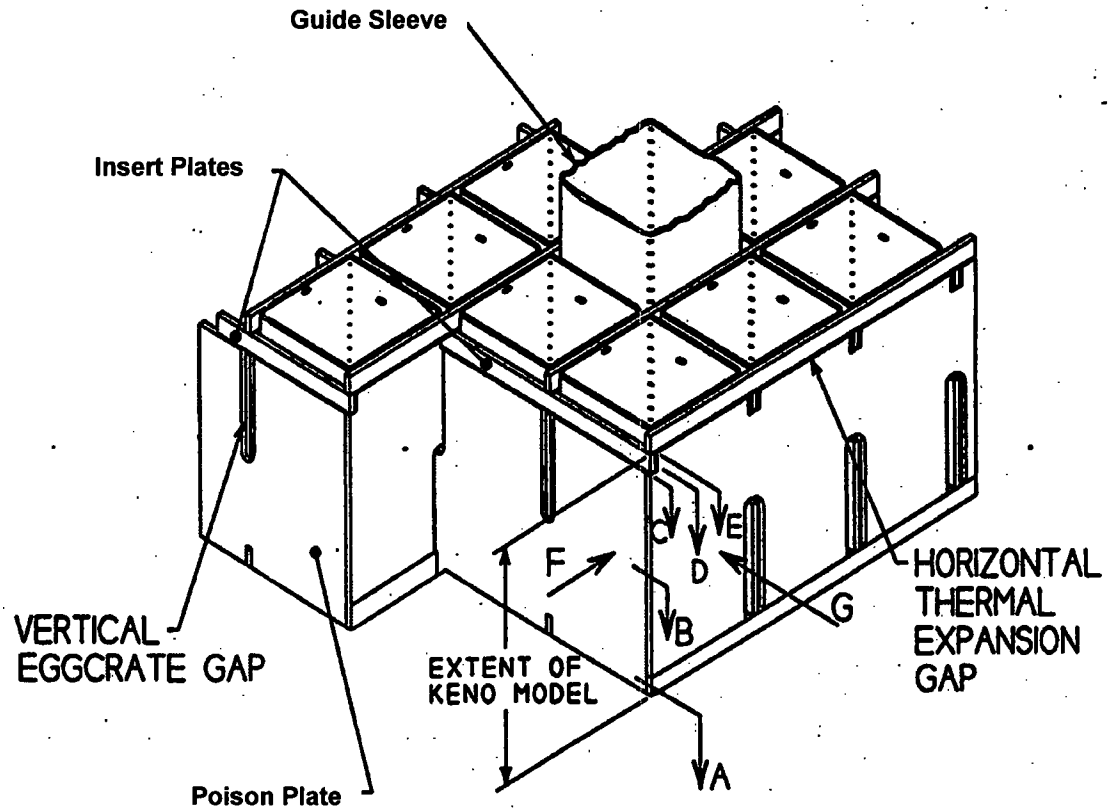

Figure 1-2 Isometric View of DSC Guide Sleeve and Plates

The nominal vertical gap between insert plate and poison plate and the nominal length of the poison plate slots are also given in Table 1.1-1. The nominal vertical gap between an insert plate and its adjacent poison plate shall be consistent with the nominal vertical distance between two insert plates and the nominal poison plate height.

The nominal vertical gaps inside the poison plate slots shall be consistent with the nominal length of the poison plate slot for the poison plate, the nominal length of the poison plate slot for the insert plate, the height of the insert plate and the part of the poison plate that goes through the slots.

Table 1.1-1 DSC Dimensions

DSC Dimension	Nominal	Tolerance	reference
External Diameter	67.25"	0.05"	2
Shell Thickness	0.63"	0.06"	3
Insert Plate Height	2.00"	N/A	4
Insert Plate Thickness	0.250"	0.030"	5
Vertical Distance Between Insert Plates	8.280"	N/A	4
Axial Length to be Modeled	10.28"	0.12"	4
Guide Sleeve Opening	8.500"	0.030"	5
Guide Sleeve Thickness	0.1874"	N/A	5
Aluminum/Poison Plate Pair Thickness	0.245"	N/A	5
Poison Plate Pitch	9.125"	0.03"	6
Poison Plate Height	8.25"	0.12"	6
Poison Plate Slot Width	0.750"	0.03"	6
Poison Plate Slot Length for Insert Plate	2.06"	0.12"	6
Poison Plate Slot Length for Poison Plate	3.18"	0.12"	6
Gap Between Insert Plate and Adjacent Poison Plate	0.015"	N/A	6

1.1.2 CCNNP-FC Transfer Cask

The CCNNP Transfer Cask is made of three concentric cylindrical shells. Their dimensions can be found in reference [7 & 8] and are listed in Table 1.1-2. The materials between shells are also listed.

Table 1.1-2 CCNNP-FC Transfer Cask Dimensions

	Nominal	Shell Material	In-Between Material
Inner Shell ID	68.00"	SS-304	
Inner Shell Thickness	0.75"		
	4"		Lead
Structural Shell OD	80.5"	SS304	
Structural Shell Thickness	1.5"		
	4"		Neutron Shield
Neutron Shield Panel OD	89.0"	SS-304	DSC
Neutron Shield Panel Thickness	0.25"		

1.2 Regulatory Requirements

1.2.1 Storage - 10CFR72

"§ 72.124 Criteria for nuclear criticali ty safety

(a) Design for criticality safety.

... before a nuclear criticality accident is possible, at least two unlikely, independent, and concurrent or sequential changes have occ urred ... The design ... must include margins of safety ..."

The criticality analysis demonstrates that the DSC basket configuration is subcritical for all normal and off-normal operating conditions, with consideration for fabrication tolerances. The customary design margin of safety is 0.05, i.e. $k_{EFFECTIVE} \leq$ USL (the USL is always below 0.95) including all applicable biases and uncertainties.

"(b) Methods of criticality control.

When practicable, the design of an ISFSI ... must be based on favorable geometry, permanently fixed neutron absorbing materials (poisons), or both. Where solid neutron absorbing materials are used, the design shall provide for positive means to verify their continued efficacy."

The NUHOMS® -32PHB DSC system's criticality safety is ensured by both fixed neutron absorbers and favorable geometry. The neutron absorber is present in the form of borated metallic plates. The absorbers' presence can be verified visually at the time of DSC fabrication or any time before DSC closure.

"(c) Criticality Monitoring ..."

Criticality monitoring is not required for NUHOMS® operations. All fuel handling is performed in either the fuel pool (beneath water shielding) or when the fuel is in dry and sealed canisters.

The analyses presented herein focus on transportation conditions and bound all storage conditions.

2.0 NOT USED

3.0 NOT USED

4.0 NOT USED

5.0 NOT USED

6.0 CRITICALITY EVALUATION

6.1 Discussion and Results

This criticality analysis shows that the NUHOMS®-32PHB system is capable of loading thirty-two (32) intact CE 14x14, VAP or Areva fuel lattices of maximum U-235 enrichment with 5.00 wt%, boron content in the borated water at 2450 PPM and B_{10} areal density of 24.3 mg/cm$_2$. The USL is determined to be 0.9410 and the worst case $k_{EFFECTIVE}$ for loading VAP fuel lattices is 0.9358.

6.2 Package Fuel Loading

The DSC payload is specified in the 32PHB Design Criteria Document [1]. It includes three fuel assembly types; Standard CE 14x14, VAP and AREVA. The fuel parameters that are relevant to the criticality calculation are listed in Table 6.2-1.

Table 6.2-1 Fuel Assembly Types in 32PHB Payload

Fuel Parameter	CE 14x14	VAP	AREVA
Clad Material	Zircaloy-4	Zircaloy-4	Zircaloy-4(1)
Pellet stack UO2 density (%TD)	93.5 - 96%	96%	96%
Number of Rods	176	176	176
Number of Water Holes	5	5	5
Fuel rod pitch	0.580"	0.580"	0.580"
Pellet OD	0.3765"	0.381"	0.3805"
Clad ID	0.384"	0.388"	0.387"
Clad OD	0.440"	0.440"	0.440"
Guide tube ID	1.035"	1.035"	1.035"
Guide tube OD	1.115"	1.115"	1.115"
Maximum Enrichment (wt% U-235)	4.50%	5.00%	5.00%

(1) The clad material of the Areva Fuel is M5 but is modeled as Zircloy-4. The reactivity effect is negligible.

6.3 Model Specification

6.3.1 Calculation Model

The geometric configuration of the calculation model is enclosed in a rectangular cuboid (or cuboid in SCALE terminology). Its height is set to the length that accommodates one east-west insert plate at the bottom and one north-south insert plate at the top. Its base is a square that is tangent to the outmost wall of the transfer cask. The pair of parallel base faces in the vertical direction (z) has a periodic boundary condition and the other two pairs of parallel faces (in the x and y directions) have reflective boundary condition. Therefore, the model simulates infinite many units of the 32PHB Transfer Cask and DSC with infinite repetitions of the vertical pattern.

In the KENO V.a geometric configuration, the DSC guide sleeves, insert plates and poison plates are modeled with SCALE holes [10]. Fuel assemblies are modeled as a square lattice and placed into DSC guide sleeves with SCALE holes. The fuel lattice is positioned in the center of the guide sleeve. The baseline model is specified in Table 6.3-1.

Table 6.3-1 32PHB Baseline Model

Baseline Model	Geometry	Material
Transfer Cask Exterior	Cuboid	Water (VF=1)
Transfer Cask	Nominal dimensions	neutron shield is replaced with H_2O (VF=1)
Gap between TC and DSC	0.375"	Filled with H_2O (VF=1)
DSC	Nominal dimensions	N/A
Fuel Assembly Parameters	Nominal dimensions	CE 14x14 Pellet TD is set at 96%
Gap between Pellet and Clad	Nominal dimension	Filled with H_2O (VF=1)
Poison Plate	poison plate thickness is 0.125"	B_4C MMC
Fuel Assembly Placement Inside Guide Sleeve	Center	N/A

The neutron poisons that are used with the baseline model are specified Table 6.3-2. However, the VF value is to be adjusted during the analysis.

Table 6.3-2 Neutron Poison in 32PHB Baseline Model

Borated Water	Borated H_2O with natural Boron at 2450 PPM (VF=0.7)
B_{10} in Poison Plate (B_4C MMC)	areal density is 23.4 mg/cm^2

6.3.2 Package Regional Densities

The Oak Ridge National Laboratory (ORNL) SCALE code package [10] contains a standard material data library for common elements, compounds, and mixtures. All the materials used for the cask and canister analysis are available in this data library. The neutron shield material in the cask is modeled as water. The material data for the fuel assemblies were obtained from reference [1].

The cask neutron shield material is conservatively modeled as water. The hydrogen atom density of the solid neutron shield (for the transportation cask) is lower than that of water; therefore, replacing the neutron shield with water is slightly conservative.

6.4 Criticality Calculations

The criticality calculation is performed first by determining the most reactive fuel lattice. The most reactive intact fuel configuration is determined next. The final criticality analysis is to determine the maximum allowable U-235 enrichments for various poison loadings.

6.4.1 Calculation Method

The CSAS5 control module of the SCALE 6 Program [10] is used to calculate the effective multiplication factor ($k_{EFFECTIVE}$) of the fuel in the cask. The maximum $k_{EFFECTIVE}$ for the calculation was determined with the following formula:

$$k_{EFFECTIVE} = k_{KENO} + 2\sigma_{KENO}$$

The CSAS5 control module allows simplified data input to the functional modules BONAMI, NITAWL, and KENO V.a. These modules process the required cross

sections and calculate the $k_{EFFECTIVE}$ of the system. BONAMI performs resonance self-shielding calculations for nuclides that have Bondarenko data associated with their cross sections. NITAWLII applies a Nordheim resonance self-shielding correction to nuclides having resonance parameters. Finally, KENO V.a calculates the $k_{EFFECTIVE}$ of a three-dimensional system. A sufficiently large number of neutron histories are run so that the standard deviation is below 0.0010 for all calculations. The criticality analysis used the 44-group cross-section library built into the SCALE 6 Program. ORNL uses ENDF/B-V data to develop this broad-group library specifically for criticality analysis of a wide variety of thermal systems. The SCALE 6 computer code system was run with the Windows-XP operating system.

This calculation models the intact geometry of the fuel lattice, Transfer Cask, and DSC. However, the neutron shield is conservatively modeled as water. Other conservative assumptions are given as below.

- Temperatures of all materials are set at 293K. For the KENO calculation, it is conservative due to the negative temperature reactivity effect.
- Fuel rods are filled with 100% pure water in the fuel/cladding gap that increases the neutron moderation. For the KENO calculation, the reactivity effect is conservative.
- No credit is taken for burnable absorbers.
- No credit taken for fissile depletion or fission product poisoning.
- In the KENO model, the material inside the DSC is first filled with aluminum and then replaced with fuel and borated water. As a consequence, a small volume of borated water is replaced with aluminum. The reactivity effect is negligible but conservative.

6.4.2 Fuel Loading Optimization

A. Determination of Most Reactive Fuel Lattice

The baseline model is used to determine the most reactive fuel lattice. The results are shown in Table 6.4-1. The k_{KENO} and σ produced by the SCALE 6 runs are given in Table 6.4-1. The $k_{EFFECTIVE}$ is calculated in accordance with the formula given in Section 6.4.1, which is used to determine the most reactive fuel lattice.

Since the CE 14x14 Standard fuel lattice gives a significant lower $k_{EFFECTIVE}$, it is not used for the remaining criticality analysis. Further analysis is needed in order to determine the most reactive fuel lattice.

Table 6.4-1 Most Reactive Fuel Lattice

Fuel Type	k_{KENO}	σ	$k_{EFFECTIVE}$
CE 14x14 Standard	0.89691	0.00067	0.8983
VAP	0.92994	0.00069	0.9313
Areva	0.93054	0.00068	0.9319

B. Determination of Most Reactive Intact Fuel Configuration

This section is to determine the design basis model that is defined as the most reactive intact fuel configuration. The design basis model is used to demonstrate compliance with the criticality-related portions of 10CFR72 for storage of the DSC.

The position of the fuel lattice in the guide sleeve is analyzed first. The baseline model is modified to have the most reactive fuel lattice positioned inwards (toward the DSC center). The $k_{EFFECTIVE}$ values of the two placements for both the VAP and Areva fuel lattice are given in Table 6.4-2. The k_{KENO} and σ produced by the SCALE 6 run are also given. The $k_{EFFECTIVE}$ is calculated in accordance with the formula given in Section 6.4.1, which is used to determine the most reactive intact fuel configuration.

Since the fuel lattice at the inward configuration for both VAP and Areva produces a higher $k_{EFFECTIVE}$, the inward configuration is used in the subsequent criticality calculations for determining the most reactive configuration.

Table 6.4-2 Fuel Lattice Placement

Fuel Type	Fuel Lattice Placement	k_{KENO}	σ	$k_{EFFECTIVE}$
VAP	Centered	0.92994	0.00069	0.9313
	Inward	0.93240	0.00069	0.9338
Areva	Centered	0.93054	0.00068	0.9319
	Inward	0.93139	0.00073	0.9329

In the following analysis, the DSC geometrical dimension and material composition are varied in order to determine the design basis model. The changes in the baseline model are made to one parameter at a time unless there is a constraint among multiple dimensions.

The variation in geometry is mainly to account for hardware tolerance. The variation may go beyond the tolerance in order to accommodate more fabrication discrepancy. The parameter to be varied first is the inner width of the guide sleeve. The nominal value is 8.5". It is reduced to 8.47" in accordance with the tolerance given in Table 1.1-1. The results are shown in Table 6.4-3.

Since the VAP fuel lattice with the 8.47" guide sleeve inner width gives the highest $k_{EFFECTIVE}$ value, it is used for the subsequent calculations.

Table 6.4-3 Variation in Guide Sleeve Inner Width

Fuel Type	Guide Sleeve Inner Width	k_{KENO}	σ	$k_{EFFECTIVE}$
VAP	8.50"	0.93240	0.00069	0.9338
	8.47"	0.93473	0.00076	0.9363
Areva	8.50"	0.93139	0.00073	0.9329
	8.47"	0.93316	0.00070	0.9346

Up to this point, the borated water density is analyzed with VF=0.7 as given in Table 6.3-2. The water density used in the SCALE 6 Program [10] is 0.9982 gm/cm^3. The borated water density is to be varied in order to simulate fuel loading and transfer operations [1]. It is varied indirectly by changing the density multiplier (VF). The results are shown in Table 6.4-4. The borated water density at VF=0.75 produces the highest $k_{EFFECTIVE}$. Thus, it is used in the subsequent calculations.

Table 6.4-4 Variation in Borated Water Density

Borated Water Density (VF)	k_{KENO}	σ	$k_{EFFECTIVE}$
1.0	0.92564	0.00064	0.9269
0.9	0.93114	0.00071	0.9326
0.8	0.93452	0.00068	0.9359
0.75	0.93497	0.00079	0.9366
0.7(1)	0.93473	0.00076	0.9363
0.65	0.93302	0.00080	0.9346
0.6	0.92766	0.00065	0.9290
0.5	0.91083	0.00073	0.9123
0.4	0.88328	0.00065	0.8846
0.3	0.83664	0.00063	0.8379
0.2	0.77268	0.00061	0.7739
0.1	0.68454	0.00056	0.6857
0.001	0.57409	0.00039	0.5749

Note: (1) from Table 6.4-3.

Next, the insert plate height is reduced from 2.00" to 1.88" and 1.76". The results are shown in Table 6.4-5. Since the change in $k_{EFFECTIVE}$ is less than one standard deviation, the nominal value is used in the design basis model.

Table 6.4-5 Insert Plate Height

Fuel Type	Borated Water Density (VF)	Insert Plate Length	k_{KENO}	σ	$k_{EFFECTIVE}$
VAP	0.75	2.00" (1)	0.93497	0.00079	0.9366
		1.88"	0.93568	0.00068	0.9370
		1.76"	0.93488	0.00066	0.9362

Note: (1) from Table 6.4-4.

Next, the lengths of the two poison plate slots are increased by 0.12". They are also reduced by an amount that will accommodate other dimensions such as the insert plate. The results are shown in Table 6.4-6. The nominal values 3.18" and 2.06" will be used for the subsequent analysis.

Table 6.4-6 Poison Plate Slot Length

	Borated Water Density	Poison Plate Long Slot Length	Poison Plate Short Slot Length	k_{KENO}	σ	$k_{EFFECTIVE}$
VAP	0.75	3.18" (1)	2.06"	0.93497	0.00079	0.9366
		3.30"	2.06"	0.93488	0.00070	0.9363
		3.12"		0.93444	0.00072	0.9359
		3.18"	2.18"	0.93543	0.00066	0.9368
			2.04"	0.93530	0.00069	0.9367

Note: (1) from Table 6.4-4.

Next, the poison plate slot width is varied. The nominal value is 0.75". Since this dimension affects the amount of poison material more than the slot length, a detailed analysis is performed here.

The results are shown in Table 6.4-7. However, the $k_{EFFECTIVE}$ values differ within one standard deviation. Thus, no conclusion can be drawn regarding the limiting poison plate slot width. Further analysis is necessary for determining the limiting poison plate slot width.

Table 6.4-7 Poison Plate Slot Width

Fuel Type	Borated Water Density	Poison Plate Slot Width	k_{KENO}	σ	$k_{EFFECTIVE}$
VAP	0.75	1.00"	0.93592	0.00067	0.9373
		0.84"	0.93565	0.00076	0.9372
		0.81"	0.93658	0.00066	0.9379
		0.78"	0.93545	0.00086	0.9372
		0.75" (1)	0.93497	0.00079	0.9366
		0.72"	0.93624	0.00070	0.9376
		0.69"	0.93657	0.00071	0.9380
		0.66"	0.93594	0.00070	0.9373
		0.50"	0.93592	0.00067	0.9373

Note: (1) from Table 6.4-4.

Compared to other dimensions, the changes to the poison plate height and the poison plate sloth width have a greater effect on the amount of the poison material present in the DSC. Since the limiting poison plate thickness is not determined yet, the poison plate height and slot width are varied simultaneously. The poison plate height is varied with an increment of 0.12". Furthermore, the poison plate height is reduced to 8.01" in order to accommodate more tolerance as a result of the DSC fabrication.

The results are shown in Table 6.4-8, which indicates that the poison plate with 8.01" in height and 0.75" in slot width produces the highest $k_{EFFECTIVE}$.

Table 6.4-8 Poison Plate Height

Fuel Type	Borated Water Density	Poison Plate Height	Poison Plate Slot Width	k_{KENO}	σ	$k_{EFFECTIVE}$
VAP	0.75	8.37"	0.78"	0.93369	0.00076	0.9352
		8.37"	0.75"	0.93597	0.00066	0.9373
		8.37"	0.72"	0.93506	0.00064	0.9363
		8.13"	0.84"	0.93619	0.00076	0.9377
		8.13"	0.81"	0.93557	0.00073	0.9370
		8.13"	0.78"	0.93588	0.00072	0.9373
		8.13"	0.75"	0.93644	0.00072	0.9379
		8.13"	0.72"	0.93579	0.0008	0.9374
		8.13"	0.69"	0.93539	0.00067	0.9367
		8.13"	0.66"	0.93499	0.00066	0.9363
		8.01"	0.78"	0.93585	0.00067	0.9372
		8.01"	0.75"	0.93738	0.00064	0.9387
		8.01"	0.72"	0.9367	0.00069	0.9381

The nominal thickness of the poison plate is 0.125", which results in a B_4C weight fraction of 19%. The poison plate thickness is varied in such a manner that the B_4C weight fraction would be 23% and 30%. These two weight fractions are the potential upper limits imposed by the DSC fabrication. The resulting poison plate thicknesses are 0.1032" and 0.0791". The nominal poison plate height (8.25") is used in the calculation. The $k_{EFFECTIVE}$ is given in Table 6.4-9. It shows that the difference in $k_{EFFECTIVE}$ is within one standard deviation. Since the 0.0791" thickness corresponds to the maximum B_4C weight fraction, it is adopted in the design basis model.

Table 6.4-9 Poison Plate Thickness

Fuel Type	Borated Water Density	Poison Plate		k_{KENO}	σ	$k_{EFFECTIVE}$
		B4C Weight Fraction in %	Thickness			
VAP	0.75	19 (1)	0.125"	0.93497	0.00079	0.9366
		23	0.1032"	0.93567	0.00085	0.9374
		30	0.0791"	0.93583	0.00067	0.9372

Note: (1) from Table 6.4-4.

Based on the analysis so far, the geometrical differences between the design basis model and the baseline model are shown in Table 6.4-10.

Table 6.4-10 32PHB Design Basis Model

Fuel Lattice	VAP
Fuel assembly placement inside guide sleeve	Inward
Guide Sleeve Inner Width	8.47"
Poison Plate Height	8.01"
Poison Plate Thickness	0.0791"

The design basis model is used for verifying that the VAP fuel lattice is more reactive than the Areva Fuel lattice. It is also used to verify that the most reactive water density is at VF=0.75.

The results are shown in Table 6.4-11. In conclusion, the design basis model as shown in Table 6.4-10 combined with the borated water density of 0.75 and the VAP fuel lattice is the most reactive intact fuel configuration. It will be used in the criticality analysis.

Table 6.4-11 Verification of Fuel Type and Water Density

Fuel Type	Borated Water Density	Poison Plate Height	Poison Plate Slot Width	k_{KENO}	σ	$k_{EFFECTIVE}$
VAP	0.80	8.01"	0.75"	0.93668	0.00072	0.9381
	0.75			0.93653	0.00086	0.9383
	0.70			0.93572	0.00067	0.9371
Areva	0.80	8.01"	0.75"	0.93432	0.00064	0.9356
	0.75			0.93507	0.00069	0.9365
	0.70			0.93494	0.00069	0.9363

6.4.3 Criticality Results

The minimum B_{10} areal density of the poison plate is determined as a function of the maximum U-235 enrichment and the minimum boron content in borated water. Since the VAP fuel lattice is determined to be the most reactive fuel lattice, its maximum enrichment of 5.00 wt% is used in the criticality analysis. The minimum boron content in the borated water is 2450 PPM.

In the previous calculations, the B_{10} areal density of the poison plate is 23.4 mg/cm^2. For the criticality analysis, it is increased to 24.3 mg/cm^2 in order to achieve sufficient margin. As shown in Table 6.4-12, the $k_{EFFECTIVE}$ is 0.9358, which is less than the USL of 0.9410, as determined in Section 6.5.2.

Table 6.4-12 Minimum B_{10} areal density

Fuel Lattice	U-235 Enrichment in wt%	Boron Content in Borated Water in PPM	k_{KENO}	σ	$k_{EFFECTIVE}$	Minimum B_{10} Areal Density of Poison Plate in mg/cm^2
VAP	5.00	2450	0.93439	0.0007	0.9358	24.3

Next, the maximum allowable U-235 enrichment is determined as a function of B_{10} areal density of the poison plate and the boron content in borated water. The B_{10} areal density is set to 17.1 mg/cm^2. For boron content of 2450 PPM, the maximum allowable U-235 enrichment is determined to be 4.75 wt%.

If the boron content is increased to 2550 PPM, the maximum allowable U-235 enrichment is determined to be 4.85 wt%. As shown in Table 6.4-13, both values of $k_{EFFECTIVE}$ are below the USL of 0.9410.

Table 6.4-13 Maximum Allowable U-235 Enrichment

Fuel Lattice	B_{10} Areal Density of Poison Plate in mg/cm^2	Boron Content in Borated Water in PPM	k_{KENO}	σ	$k_{EFFECTIVE}$	U-235 Enrichment in wt%
VAP	17.1	2450	0.93493	0.00069	0.9363	4.75
		2550	0.93332	0.00072	0.9348	4.85

The B_{10} areal densities in Table 6.4-12 and Table 6.4-13 are 24.3 and 17.1 mg/cm^2. These are the actual values used in the criticality analysis. Adjustment is to be made in the next section for taking 90% credit for the B10 poison content.

6.4.4 Conclusions

The 32PHB basket containing poison plates with minimum B_{10} areal density of 17.1 mg/cm^2 is assigned as "Basket A" and the 32PHB basket containing poison plates with minimum B_{10} areal density of 24.3 mg/cm^2 is assigned as "Basket B".

Only 90% of the physically available B10 in the poison plate can be taken credit for in the criticality analysis [1]. Therefore, the minimum physically available B10 in the poison plates for Basket A and B shall be 19.0 mg/cm^2 and 27.0 mg/cm^2, respectively.

The results of the criticality analysis for the NUHOMS®-32PHB system are summarized in Table 6.4-14.

Table 6.4-14 NUHOMS®-32PHB Criticality Analysis

Maximum Allowable U-235 Enrichment		Minimum Physically Available B_{10} Areal Density of Poison Plate (1)	
		Basket A	Basket B
		19.0 mg/cm^2	27.0 mg/cm^2
Boron Content in Borated Water	2450 PPM	4.75 wt%	5.00 wt%
	2550 PPM	4.85 wt%	NA

(1) The criticality analysis takes credit for only 90% of the minimum physically available B_{10} areal density in the poison plates.

End Drop Accident

The fuel end drop analysis [11] shows that there is no plastic deformation after the end drop accident. Thus, there is no need to analyze the fuel pin deformation geometry caused by the end drop event.

Side Drop Accident

The fuel side drop analysis [12] concludes that the fuel rods are compressed instead of expanded and they are also constrained by the outer boundaries of the spacer grids.

The rod pitch of some fuel rods may be reduced to the clad outside diameter (0.440", see Table 6.2-1). The USL as a function of the rod pitch decreases from 0.9424 to 0.9422 (see Table 6.5-1 and Table 6.5-2) under these conditions. Thus, the final USL is not affected. Reduced rod pitch also leads to less neutron moderation and, subsequently, k-effective decreases. Thus, the criticality results are not adversely affected.

The separation distance of fuel assemblies may increase. The USL as the function of separation distance increases with more fuel separation (see Table 6.5-1). Thus the final USL is not affected.

Since both the USL and reactivity are not negatively affected by the side drop event, there is no need to analyze the fuel pin deformation caused by the side drop event.

Reconstituted Fuel

The reactivity of a DSC loaded with less than 32 CE 14x14 Standard fuel assemblies is lower than that calculated here since the more absorbing borated water replaces the fuel in the empty locations. Reconstituted fuel assemblies, where the fuel pins are replaced by lower enriched fuel pins or non-fuel pins that displace the same amount of borated water, are considered intact fuel assemblies. The reactivity of the fuel assemblies with reconstituted pins will be bounded by those without reconstituted pins because the regular pins are modeled with the highest allowable enrichment while those with the reconstituted pins will contain lower enriched UO_2 or other non-fuel material.

6.5 Critical Benchmark Experiments

6.5.1 Benchmark Experiments and Applicability

One-hundred and two (102) critical experiments are available for the USL evaluation [9]. The selection of specific critical experiments for a USL parameter is determined based on the similarity of the geometrical, material composition and neutronic characteristics between the critical experiments and the NUHOMS®-32PHB system.

6.5.2 Results of Benchmark Calculations

The USL functions are given in Table 6.5-1. The parameters of USL functions are U-235 enrichment, energy of average lethargy of fission (EALF), H_2O-to-UO_2 volume ratio, the fuel rod pitch, the separation distance between fuel lattice and the soluble boron loading.

Table 6.5-1 32PHB USL Functions

Parameter	Applicable Range	USL Function	
EALF in eV	[0.0826, 1.4006]	0.9429 - 2.4237E-04 * X	X > 0.093812
		0.9428	X <= 0.093812
Boron Loading in PPM	[15, 3389]	0.9429 + 3.8975E-07 * X	
Separation Distance in cm	[0.18973, 20.78]	0.9398 + 5.9633E-04 * X	X < 7.9338
		0.9445	X >= 7.9338
U-235 Enrichment in wt%	[2.35, 5.74]	0.9382 + 1.6994E-03 * X	X < 3.4333
		0.9440	X >= 3.4333
H_2O/UO_2 Volume Ratio	[1.376, 1.933]	0.9560 - 7.3789E-03 * X	X > 1.6517
		0.9438	X <= 1.6517
Pitch in cm	[1.209, 1.715]	0.9418 + 4.0604E-04 * X	

The USL evaluation is shown in Table 6.5-2. The limiting values of the USL parameters are calculated for the NUHOMS®-32PHB system with the exception that the EALF is obtained from the SCALE 6 output. The limiting separation distance is determined using the inward fuel lattice position as a conservative approach. The H_2O/UO_2 volume ratio is determined by the formula given as below,

(Pin Cell Area – Fuel Pin Area) / (Pellet Area)

The USL for the NUHOMS®-32PHB system is 0.9410, which is rendered by the USL parameter Separation Distance.

Table 6.5-2 USL Evaluation

Parameter	Limiting Value	USL
EALF in eV	0.9655	0.9427
Boron Loading in PPM	2450	0.9439
Separation Distance	2.03(1)	0.9410
U-235 Enrichment	5.0	0.9440
H2O/UO2 Volume Ratio	1.617	0.9441
Pitch in cm	1.4732	0.9424

(1) The separation distance for the 4 fuel assemblies loaded in the center of the DSC is 1.59cm. The remaining 28 fuel assemblies have a separation distance of 2.03cm. If the 1.59cm is used for the USL evaluation, the limiting value is changed by 0.0003 (from 0.9410 to 0.9407). The difference is less than one-half of the standard deviation (1/2σ) in the KENO results.

6.6 Appendix

6.6.1 Reference Documents

1. Transnuclear Design Criteria Document NUH32PHB.0101, Rev. 0.
2. Transnuclear Design Drawing NUH32PHB-30-1-1, Rev. 0.
3. Transnuclear Design Drawing NUH32PHB-30-1-2, Rev. 0.
4. Transnuclear Design Drawing NUH32PHB-30-6, Rev. 0.
5. Transnuclear Design Drawing NUH32PHB-30-7, Rev. 0.
6. Transnuclear Design Drawing NUH32PHB-30-9, Rev. 0.
7. Calvert Cliffs Drawing BGE-01-3001.
8. Calvert Cliffs Drawing BGE-01-3002.
9. Transnuclear Calculation NUH32PHB-0603, "USL Evaluation for the NUHOMS 32PHB System," Rev. 0.
10. SCALE 6: Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers, Oak Ridge National Laboratory, Radiation Shielding Information Center Code Package CCC-750, February 2009.
11. Transnuclear Calculation NUH32PHB-0207, "Fuel End Drop Analysis for NUH32PHB Using LS-DYNA," Rev. 0.
12. Transnuclear Calculation NUH32PHB-0203, "PWR Fuel Rod Accident Side Drop Loading Stress Analysis for NUHOMS 32PHB System," Rev. 0.

6.7 Computer Runs

Table 6.7-1 Most Reactive Fuel Lattice

Case Identifier	Input		Output	
Areva_nominal_e500_2450_70_23.4mg	Nov 23 15:51	11292	Nov 23 15:58	508402
CE14x14_nominal_e450_2450_70_23.4mg	Nov 23 15:47	11294	Nov 23 15:54	508123
VAP_nominal_e500_2450_70_23.4mg	Nov 23 15:51	11290	Nov 23 16:01	508090

Table 6.7-2 Centered vs. Inward

Case Identifier	Input		Output	
Inward_Areva_nominal_e500_2450_70_23.4mg	Nov 23 16:04	12184	Nov 23 16:07	515454
Inward_VAP_nominal_e500_2450_70_23.4mg	Nov 23 16:04	12182	Nov 23 16:10	515589

Table 6.7-3 Guide Sleeve Thickness

Case Identifier	Input		Output	
Inward_Areva_e500_2450_70_23.4mg	Nov 23 16:21	12184	Nov 23 16:30	515745
Inward_VAP_e500_2450_70_23.4mg	Nov 23 16:21	12182	Nov 23 16:24	515502

Table 6.7-4 Borated Water Density

Case Identifier	Input		Output	
Inward_VAP_e500_2450_100_23.4mg	Nov 23 16:57	12182	Nov 23 17:01	515988
Inward_VAP_e500_2450_90_23.4mg	Nov 23 16:59	12182	Nov 23 17:04	514764
Inward_VAP_e500_2450_80_23.4mg	Nov 23 17:02	12182	Nov 23 17:06	514569
Inward_VAP_e500_2450_75_23.4mg	Nov 23 17:08	12182	Nov 23 17:13	515258
Inward_VAP_e500_2450_65_23.4mg	Nov 23 17:08	12182	Nov 23 17:17	515136
Inward_VAP_e500_2450_60_23.4mg	Nov 23 17:02	12182	Nov 23 17:10	515509
Inward_VAP_e500_2450_50_23.4mg	Nov 23 17:03	12182	Nov 23 17:22	515877
Inward_VAP_e500_2450_40_23.4mg	Nov 23 17:03	12182	Nov 23 17:26	516101
Inward_VAP_e500_2450_30_23.4mg	Nov 23 17:09	12182	Nov 25 09:45	515203
Inward_VAP_e500_2450_20_23.4mg	Nov 23 17:09	12182	Nov 25 09:50	516188
Inward_VAP_e500_2450_10_23.4mg	Nov 23 17:09	12182	Nov 25 09:58	517029
Inward_VAP_e500_2450_0_23.4mg	Nov 23 17:09	12186	Nov 23 17:42	518931

Table 6.7-5 Insert Plate Length

Case Identifier	Input		Output	
Inward_VAP_e500_2450_75_23.4mg-176	Nov 29 16:21	12182	Nov 29 16:23	515754
Inward_VAP_e500_2450_75_23.4mg-188	Nov 29 16:15	12182	Nov 29 16:18	516204

Table 6.7-6 Poison Plate Thickness

Case Identifier	Input		Output	
Inward_VAP_e500_2450_75_23.4mg-23	Nov 25 12:20	12183	Nov 25 12:24	514835
Inward_VAP_e500_2450_75_23.4mg-30	Nov 25 12:21	12183	Nov 25 12:31	515652

Table 6.7-7 Poison Plate Slot Length

Slot	Case Identifier	Input		Output	
Short	Inward_VAP_e500_2450_75_23.4mg-001	Nov 29 12:09	12182	Nov 29 12:12	515182
	Inward_VAP_e500_2450_75_23.4mg-015	Nov 29 12:02	12182	Nov 29 12:07	515650
Long	Inward_VAP_e500_2450_75_23.4mg-001	Nov 25 15:54	12182	Nov 25 16:01	515644
	Inward_VAP_e500_2450_75_23.4mg-019	Nov 25 15:45	12182	Nov 25 15:48	515619

Table 6.7-8 Poison Plate Width

Case Identifier	Input		Output	
Inward_VAP_e500_2450_75_23.4mg-050	Nov 24 18:07	12182	Nov 24 18:10	515322
Inward_VAP_e500_2450_75_23.4mg-066	Nov 29 10:42	12182	Nov 29 10:44	515838
Inward_VAP_e500_2450_75_23.4mg-069	Nov 29 10:36	12182	Nov 29 10:39	515820
Inward_VAP_e500_2450_75_23.4mg-072	Nov 24 11:51	12182	Nov 24 11:55	516106
Inward_VAP_e500_2450_75_23.4mg-078	Nov 24 11:42	12182	Nov 24 11:45	515399
Inward_VAP_e500_2450_75_23.4mg-081	Nov 29 10:46	12182	Nov 29 10:48	514753
Inward_VAP_e500_2450_75_23.4mg-084	Nov 29 10:52	12182	Nov 29 10:55	515000
Inward_VAP_e500_2450_75_23.4mg-100	Nov 24 17:25	12182	Nov 24 17:29	514939

Table 6.7-9 Poison Plate Height

Case Identifier	Input		Output	
Inward_VAP_e500_2450_75_23.4mg-1004-072	Nov 29 11:52	12182	Nov 29 11:55	516153
Inward_VAP_e500_2450_75_23.4mg-1004-075	Nov 29 11:43	12182	Nov 29 11:46	515483
Inward_VAP_e500_2450_75_23.4mg-1004-078	Nov 29 11:48	12182	Nov 29 11:51	514859
Inward_VAP_e500_2450_75_23.4mg-1016-066	Nov 29 11:02	12182	Nov 29 11:06	515329
Inward_VAP_e500_2450_75_23.4mg-1016-069	Nov 29 11:10	12182	Nov 29 11:14	516176
Inward_VAP_e500_2450_75_23.4mg-1016-072	Nov 29 11:14	12182	Nov 29 11:17	515450
Inward_VAP_e500_2450_75_23.4mg-1016-075	Nov 29 11:16	12182	Nov 29 11:20	515565
Inward_VAP_e500_2450_75_23.4mg-1016-078	Nov 29 11:21	12182	Nov 29 11:24	515482
Inward_VAP_e500_2450_75_23.4mg-1016-081	Nov 29 11:22	12182	Nov 29 11:35	514994
Inward_VAP_e500_2450_75_23.4mg-1016-084	Nov 29 11:32	12182	Nov 29 11:38	515649
Inward_VAP_e500_2450_75_23.4mg-1040-072	Nov 29 15:19	12182	Nov 29 15:22	514981
Inward_VAP_e500_2450_75_23.4mg-1040-075	Nov 29 15:08	12182	Nov 29 15:12	516253
Inward_VAP_e500_2450_75_23.4mg-1040-078	Nov 29 15:17	12182	Nov 29 15:19	515627

Table 6.7-10 Design Base Composit ion

Case Identifier	Input		Output	
Inward_Areva_e500_2450_70_23.4mg	Nov 29 15:47	12185	Nov 29 15:51	515030
Inward_Areva_e500_2450_75_23.4mg	Nov 29 15:47	12185	Nov 29 15:53	514853
Inward_Areva_e500_2450_80_23.4mg	Nov 29 15:55	12185	Nov 29 15:57	515355
Inward_VAP_e500_2450_70_23.4mg	Nov 29 15:45	12183	Nov 29 15:48	515459
Inward_VAP_e500_2450_75_23.4mg	Dec 1 17:58	12183	Dec 1 18:02	515496
Inward_VAP_e500_2450_80_23.4mg	Nov 29 15:39	12183	Nov 29 15:42	515092

Table 6.7-11 Design Base Composit ion

Case Identifier	Input		Output	
Inward_VAP_e475_2450_75_17.1mg	Nov 29 17:46	12183	Nov 29 17:50	515595
Inward_VAP_e485_2550_75_17.1mg	Nov 29 17:51	12183	Nov 29 17:54	514901
Inward_VAP_e500_2450_75_24.3mg	Nov 29 17:38	12183	Nov 29 17:42	515880