72-1025

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April 18, 2002

U.S. Nuclear Regulatory Commission
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Attention: Document Control Desk

Subject: Docket No. 72-1025

Request for Amendment of the Certificate of Compliance for the NAC-MPC System to Incorporate Fuel Enrichment Fabrication Tolerances into the Yankee-Class Fuel Parameters

References:

1. Final Safety Analysis Report (FSAR) for the NAC Multi-Purpose Canister (NAC-MPC) System, Amendment 1, NAC International, February 2002

2. Certificate of Compliance for the NAC International, Inc. Multi-Purpose Canister (MPC) System, Amendment 1, United States Nuclear Regulatory Commission, November 13, 2001

NAC International (NAC) herewith requests that the Certificate of Compliance (CoC) No. 1025 for the NAC-MPC System be amended to incorporate fuel enrichment fabrication tolerances into the Yankee-Class fuel parameters to support continuity of the planned fuel loading campaign at the Yankee Nuclear Power Station (Yankee Rowe). Potential changes to the CoC were discussed with members of the NRC staff in a meeting at NRC headquarters between the NRC, Yankee Atomic Electric Company (YAEC), Duke Engineering & Services (DE&S), and NAC on March 27, 2002.

The changes in the NAC-MPC CoC proposed in this amendment request are simple, straightforward and have no significant effect on any of the analysis results in the FSAR or the CoC, i.e., very minor changes in the maximum enrichments (increases) and minimum enrichments (decreases) of the Yankee-Class fuel that is authorized as contents. This submittal includes changed pages for the FSAR (Reference 1).

The changed pages for this submittal are designated as Revision MPC-02A to provide a unique identification of the pages and changes. Each copy provides the proposed SAR changed pages that should be appropriately inserted into a copy of the MPC FSAR Amendment 1 for review. Revision bars are used in the page margin to indicate changes. All previous revision bars on the MPC-02A pages have been deleted, so that only the revisions associated with this amendment request are marked on those pages. Revision bars are not used to indicate text flow. All of the pages in the List of Effective Pages are designated MPC-02A, but no revision bars are used on those pages.

The changes being proposed are summarized below:

- List of Effective Pages and Master Table of Contents are updated to incorporate the FSAR page revisions.

- Chapter 1 – Section 1.2.3 text is revised to incorporate discussion of the fuel fabrication enrichment tolerances.

- Chapter 2 – Section 2.1.1 text is revised to incorporate discussion of the fuel fabrication enrichment tolerances. The maximum and minimum fuel enrichments listed in Table 2.1-1 are revised to incorporate the fuel fabrication enrichment values that are considered in the FSAR.

- Chapter 5 - Tables 5.2-1 and 5.2-2 are revised to incorporate the fuel fabrication minimum enrichment values that are considered in the FSAR. Section 5.4.3.1 text is revised to incorporate discussion of the minimal effect of the fuel fabrication minimum enrichment tolerances on source strengths and calculated dose rates.

- Chapter 6 – Section 6.2 text is revised to incorporate discussion of the fuel fabrication enrichment tolerances. Table 6.2-1 and 6.4-1 are revised to incorporate the fuel fabrication maximum enrichment values that are considered in the FSAR. Section 6.4.3.1 text is revised to incorporate discussion of the effect of the fuel fabrication maximum enrichment tolerances on the calculated reactivity of the fuel assemblies.

- Chapter 12 – The maximum and minimum fuel enrichments listed in Table 12A2-2 are revised to incorporate the fuel fabrication enrichment values that are considered in the FSAR.

No changes are required in the other chapters of the FSAR.

NAC's fuel loading schedule for Yankee Rowe calls for the start of fuel movement to dry storage at the end of May 2002. Loading of the fuel covered by this amendment is planned to begin at the end of June 2002. YAEC will be submitting an exemption request within the next few days to allow implementation of this amendment by that date. In accordance with the desires of NAC and YAEC to secure the Yankee Rowe fuel in dry storage and to maintain continuity of the fuel loading campaign, NAC requests that the NRC assign a high priority for completion of the review of this amendment request and the review and approval of the associated exemption request.

If you have any questions regarding this submittal, please contact me on my direct line at 678-328-1321.

Sincerely,

TC Thompson

Thomas C. Thompson
Director, Licensing
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Enclosure

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April 2002

Revision MPC-02A

NAC-MPC

FINAL SAFETY ANALYSIS REPORT

for the

NAC Multi-Purpose Canister System

Docket 72-1025

NAC INTERNATIONAL

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The special equipment needed to operate the NAC-MPC system has been described in Section 1.2.1.4. Other items required are miscellaneous hardware, connection hose and fittings, and hand tools typically found at a reactor site.

1.2.3 Cask Contents

The NAC-MPC is designed to store up to 36 Yankee Class spent fuel assemblies. The Yankee Class fuel consists of fuel assemblies manufactured by Westinghouse, United Nuclear, Exxon, and Combustion Engineering. The assemblies vary in initial enrichment from 3.5 to 4.94 wt % ^{235}U. Each manufacturer's types of assemblies include two configurations identified as Type A and Type B. The arrangement of fuel rods differ in each types to allow the fuel assembly to accept a segment of a control blade used for criticality control. The characteristics of the Yankee Class spent fuels are presented in Table 1.2-6. The maximum and minimum enrichments shown in Table 1.2-6 are nominal values for the manufacturer and type of fuel assembly shown. Certain fuel assemblies of the same manufacturer and type have enrichment values nominally above or below these values due to the method in which enrichment tolerance was applied during fabrication. The effects of these minor variations are considered in Sections 5.4.3.1 and 6.4.3.1 and are shown to be not significant. Unenriched fuel assemblies are not evaluated and are not included as a proposed contents.

A canister may contain one or more Reconfigured Fuel Assemblies (RFA) designed to confine Yankee Class intact or damaged spent fuel rods and fuel debris. The RFA is designed to confine its contents during all storage and transport conditions. The assembly can accept up to 64 full length spent fuel rods in an eight by eight array of tubes. A sketch of the assembly is provided in Figure 1.2-4.

The Reconfigured Fuel Assembly consists of a shell (square tube with end fittings), a basket assembly and 64 fuel tubes. The external dimensions of the shell are the same as those of a standard Yankee Class spent fuel assembly and all materials are stainless steel. It is designed such that it can be handled in the same manner as a standard Yankee Class spent fuel assembly. The spent fuel is confined in the fuel tubes. The tubes are supported by a basket assembly within the shell and have end plugs with drilled holes to permit draining drying and inerting with helium. The shell has holes in the top and bottom fittings to permit draining, drying and inerting of the assembly.

The total number of full length rods that can be placed in the Reconfigured Fuel Assembly is less than the number that are in the Yankee Class fuel assemblies (maximum of 64 versus 231 rods of the most reactive fuel). Consequently, the effects of a Reconfigured Fuel Assembly placed in a canister (e.g., criticality, thermal output, source term) are significantly less than the effects of a design basis Yankee Class spent fuel assembly. These effects are evaluated in the appropriate chapters that follow.

Table 1.2-6 NAC-MPC Design Basis Fuel Characteristics

Parameter	Yankee Class Spent Fuel[1, 2, 3,4]		
	United Nuclear Type A	Combustion Type A	Westinghouse Type B
Number of Assemblies per Canister[6]	36	36	34
Assembly Weight, lbs.	850	850	900
Assembly Length, in.	111.25	111.79	111.25
Active Fuel Length, in.	91	91	92
Fuel Rod Cladding	Zircaloy	Zircaloy	Stainless Steel
Maximum Uranium, kgU	245.6	239.4	286.9
Maximum Initial ^{235}U, wt %[7]	4.0	3.9	4.94
Minimum Initial ^{235}U, wt %[7]	4.0	3.7[5]	4.94
Maximum Burnup, MWD/MTU	32,000	36,000[5]	32,000
Maximum Assembly Decay Heat, kW	0.347	0.347	0.347
Maximum Decay Heat, kW	9.3	12.5	9.0
Minimum Cool Time, yr	13.0	8.1[5]	21.0

1. The Yankee Class spent fuel includes United Nuclear Type A and Type B, Combustion Engineering Type A and Type B, Exxon-ANF Type A and Type B, Westinghouse Type A and Type B. The United Nuclear Type A is the most reactive assembly and is used as the design basis fuel for criticality analyses. The Combustion Type A is the design basis fuel for shielding and thermal evaluations. The Westinghouse Type B fuel is the heaviest assembly and is the design basis fuel for structural considerations.

2. The Exxon-ANF fuel was provided by Exxon after Exxon was acquired by Advanced Nuclear Fuel (ANF). Fuel provided by ANF was designated Exxon-ANF. This fuel is considered to be Exxon fuel throughout this report. Except for lower enrichment and fuel hardware, Exxon fuel (and therefore, Exxon-ANF fuel) has the same characteristics as Combustion Engineering fuel.

3. The NAC-MPC can accommodate one or more Reconfigured Fuel Assemblies containing up to 64 fuel rods or rod segments classified as failed.

4. Exxon fuel assemblies with 3.5 wt % ^{235}U and burnups of 36,000 MWD/MTU require a minimum cool time of 9 or 16 years for Zircaloy or stainless steel fuel assemblies, respectively.

5. Combustion Engineering fuel assemblies with an initial minimum enrichment of 3.5 wt %, burnups up to 32,000 MWD/MTU require minimum cooling times of 8.0 years.

6. Up to 36 intact fuel assemblies of any type not exceeding 30,600 pounds total weight are authorized.

7. Minor variations in the maximum and minimum enrichments due to fuel fabrication tolerances are considered in Sections 5.4.3.1 and 6.4.3.1.

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Table 2-1 Summary of the NAC-MPC Design Criteria (Continued)

Design Criteria	
RADIATION PROTECTION/SHIELDING	
Concrete Cask Side Wall Contact Dose Rate	< 50 mrem/hr.
Concrete Cask Top Lid Contact Dose Rate	< 35 mrem/hr.
Concrete Cask Air Inlet/Outlet	< 100 mrem/hr.
Owner Controlled Area Boundary Normal/Off-Normal Annual Whole Body Dose Accident Whole Body Dose	 25 mrem/yr. 5 rem
SPENT FUEL SPECIFICATIONS	
Spent Fuel Type	Yankee Class
Fuel Configuration/Vendor[2]	Westinghouse 18 x 18, 4.94 wt % ^{235}U United Nuclear 16 x 16, 4.0 wt % ^{235}U Combustion Engineering 16 x 16, 3.5 to 3.9 wt % ^{235}U Exxon 16 x 16, 3.5 to 4.0 wt % ^{235}U
Fuel Cladding	Stainless Steel - Westinghouse Zircaloy - All others
Spent Fuel Capacity – Intact Fuel Assemblies (May include one or more Reconfigured Fuel Assemblies)	36 United Nuclear Assemblies 36 Combustion Engineering Assemblies 36 Exxon Assemblies, or 34 Westinghouse Assemblies Up to 36 Fuel Assemblies of any Type Not Exceeding 30,600 pounds Total Weight
Spent Fuel Assembly Burnup (max)	36,000 MWD/MTU[1]
Decay Heat/Fuel Assembly or Reconfigured Fuel Assembly Zircaloy Clad Fuel Stainless Steel Clad Fuel Reconfigured Fuel Assembly	 0.347 kW 0.264 kW 0.102 kW

1. Based on the design basis, Combustion Engineering fuel at 36,000 MWD/MTU cooled 8.1 years. Exxon fuel is limited to 34,000 MWD/MTU and 10 years minimum cool time. The maximum burnup of all other fuel types is 32,000 MWD/MTU.
2. Minor variations in the maximum and minimum enrichments due to fuel fabrication tolerances are considered in Sections 5.4.3.1 and 6.4.3.1.

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2.1 Spent Fuel To Be Stored

The NAC-MPC has been designed to safely store up to 36 Yankee Class spent fuel assemblies. The spent fuel designs are delineated by various factors including manufacturer, type, enrichment, burnup, cool time, and cladding material. The design basis consists of two types, designated A and B. The Type A assembly incorporates a protruding corner of fuel pins while the Type B assembly omits one corner of the fuel rods. These fuel types, as well as minor differences among manufacturers, are illustrated in Figures 6.2-1 through 6.2-3. During reactor operations, the symmetric stacking of the alternating assemblies permitted the insertion of cruciform control blades between the assemblies. Table 2.1-1 lists the nominal design parameters and the maximum and minimum enrichments of each fuel design type. These parameters, including the minimum enrichment limit, exclude the loading of unenriched fuel assemblies in the transportable storage canister.

There are two configurations of the basket. The first configuration includes 36 fuel tubes with BORAL on the four sides (standard fuel tubes). The second includes 32 fuel tubes with BORAL on the four sides and four fuel tubes without BORAL (enlarged fuel tubes). The four enlarged fuel tubes are located in the corner positions of the basket as shown in Figure 2.1-1. The enlarged fuel tubes have a larger cross-section than the standard fuel tubes to accommodate the loading of fuel assemblies that exhibit slight physical effects (e.g., bow, twist) that could preclude loading in the smaller cross-section standard fuel tubes. However, fuel assemblies that can be loaded in standard fuel tubes may also be loaded in the enlarged fuel tubes. To permit full access to the enlarged fuel tubes, the basket configuration including the enlarged fuel tubes also has enlarged openings in the top and bottom basket weldments at the four corner locations.

2.1.1 Bounding Fuel Evaluation

The criticality evaluations show that the United Nuclear Type A 16 x 16 fuel assembly is the most reactive fuel type, even though the stainless steel clad Westinghouse fuel has a higher enrichment (4.94 wt % ^{235}U). The criticality evaluation considers a complete assembly fuel rod matrix. Consequently, solid rods fabricated from Zircaloy or Type 304 stainless steel must replace any fuel rod that is removed.

The shielding evaluations show that the Combustion Engineering Type A has the largest dose rates. The United Nuclear assemblies are evaluated for a source term based on an initial enrichment of 4.0 weight percent, a maximum burnup of 32,000 megawatt days per metric ton of uranium, and a minimum cool time of 13 years after reactor discharge. Exxon fuel with Zircaloy

or stainless steel hardware is evaluated at 36,000 MWD/MTU and 9 or 16-years cool time, respectively, with an initial enrichment of 3.5 wt %. Westinghouse fuel is evaluated at 32,000 MWD/MTU and 21-years cool time with an initial minimum enrichment of 4.94 wt %. Combustion Engineering fuel is evaluated for a source term based on an initial minimum enrichment of 3.7 wt %, a maximum burnup of 36,000 megawatt days per metric ton of uranium, and a minimum cool time of 8.1 years after reactor discharge. For Combustion Engineering assemblies at a maximum burnup of 32,000 MWD/MTU and initial minimum enrichment of 3.5 wt %, a minimum cool time of 8 years is required. Nominal deviations to the maximum and minimum enrichments due to tolerance applied during fabrication have been evaluated and shown to not significantly affect the design basis results.

The NAC-MPC maximum decay heat load is 12.5 kilowatts. This results in a maximum decay heat load for the design basis fuel assemblies of 0.347 kilowatt per assembly, based on 36 fuel assemblies per canister.

2.1.2 Reconfigured Fuel Assembly

One or more transportable storage canisters may hold Reconfigured Fuel Assemblies containing intact or damaged spent fuel rods and fuel debris. The Reconfigured Fuel Assembly may consist of up to 64 rod segments or whole rods. The rods, or rod segments, are held in individual tubes in an 8 by 8 array. The array of tubes is positioned in a stainless steel container having the same external dimensions as a standard fuel assembly. It has a top end fitting that has the same configuration as a standard fuel assembly. The container is closed on the top and bottom ends by perforated plates, which act as a barrier to the release of gross particles to the canister, but allow the draining and drying of the container. The tubes are stainless steel and are closed on each end by a plug. Each plug has a small hole drilled through it. The perforated plate screens the drilled hole. The hole allows the draining and drying of the individual tubes during routine closing of the canister. The perforated plate precludes the release of gross particles to the canister. The effects of the RFA container are evaluated in the appropriate sections. The structural, thermal, shielding, confinement, and criticality effects of the Reconfigured Fuel Assembly are bounded by those of an intact fuel assembly.

The physical parameters of the Reconfigured Fuel Assembly are provided in Table 2.1-2.

2.1.3 Stainless Steel-Clad Fuel

The short-term and long-term temperature limits for stainless steel-clad fuel are derived based on the limits presented in EPRI report TR-106440, "Evaluation of Expected Behavior of LWR

Table 2.1-1 Yankee Class Fuel Parameters

	Combustion Engineering	**Combustion Engineering**	**Exxon**	**Exxon**	**Exxon**	**Exxon**	**Westinghouse**	**Westinghouse**	**United Nuclear**	**United Nuclear**
	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
ASSEMBLY CONFIGURATION										
Assembly Length (cm)	283.9	283.9	283.3	283.3	283.9	283.9	282.6	282.6	282.4	282.4
Assembly Width (cm)	19.2	19.2	19.3	19.3	19.3	19.3	19.3	19.3	19.4	19.4
Assembly Cross Section (cm)	18.1	18.1	18.2	18.2	18.2	18.2	18.2	18.2	18.2	18.2
Assembly Array	16x16	16x16	16x16	16x16	16x16	16x16	18x18	18x18	16x16	16x16
Assembly Weight (kg)	352	350.6	372	372	372	372	408.2	408.2	385.5	385.5
Enrichment-wt. % ^{235}U										
Maximum	3.93	3.93	4.03	4.03	4.03	4.03	4.97	4.97	4.03	4.03
Minimum	3.66	3.66	3.46	3.46	3.46	3.46	4.90	4.90	3.96	3.96
Initial Fuel Weight ($KgUO_2$/Assembly)	264.8	264.1	268.3	266.6	266.2	265.0	311	310	273.8	272.6
Initial Heavy Metal (KgU/Assembly)	233.4	232.8	236.5	235	234.5	233.6	274.1	273.2	241.3	240.3
Max. Burnup (MWD/MTU)	36,000[1]	36,000[1]	36,000	36,000	36,000	36,000	32,000	32,000	32,000	32,000
Min. Cool Time (yr)	8.1[1]	8.1[1]	16.0	16.0	9.0	9.0	21.0	21.0	13.0	13.0
Max. Decay Heat (kW)	0.347[1]	0.347[1]	0.269	0.269	0.331	0.331	0.264	0.264	0.257	0.257
FUEL ROD CONFIGURATION										
Fuel Rod Pitch (cm)	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.2	1.2
Rod Length (cm)	242.3	242.3	242.2	242.2	242.2	242.2	237.7	237.7	242.1	242.1
Active Fuel Length (cm)	231.1	231.1	231.1	231.1	231.1	231.1	234.0	234.0	231.1	231.1
Rod OD (cm)	0.9	0.9	0.9	0.9	0.9	0.9	0.86	0.86	0.9	0.9
Clad ID (cm)	0.8	0.8	0.8	0.8	0.8	0.8	0.76	0.76	0.8	0.8
Pellet OD (cm)	0.79	0.79	0.79	0.79	0.79	0.79	0.75	0.75	0.79	0.79
Rods per Assembly	231	230	231	230	231	230	305	304	237	236
Fuel Material	UO2	UO2	UO2	UO2	UO2	UO2	UO2	UO2	UO2	UO2
Clad Material	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	SS 348	SS 348	Zircaloy	Zircaloy
Fill Gas	Helium	Helium	Helium	Helium	Helium	Helium	Air	Air	Helium	Helium
Fill Gas Pressure (psi)	315	315	125	125	125	125	0.0	0.0	140	140
DISPLACEMENT ROD CONFIGURATION										
Displacement Rod Material	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Zircaloy - 4	Zircaloy - 4
Displacement Rod Diameter (cm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.9	0.9
Displacement Rod Length (cm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	242.1	242.1
Number Per Assembly	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2	2

1. Combustion Engineering fuel may be loaded at a cool time of 8.0 years with a maximum burnup of 32,000 MWD/MTU and a minimum enrichment of 3.5 wt%. The maximum decay heat for this assembly is 0.304 kW.

Table 2.1-1 Yankee Class Fuel Parameters (Continued)

	Combustion Engineering	**Combustion Engineering**	**Exxon**	**Exxon**	**Exxon**	**Exxon**	**Westinghouse**	**Westinghouse**	**United Nuclear**	**United Nuclear**
	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
GUIDE BAR CONFIGURATION										
Guide Bar Material	Zircaloy - 4	Zircaloy - 4	SS 304L	SS 304L	Zircaloy	Zircaloy	--	--	N/A[2]	N/A[2]
Guide Bar Width (cm)	1.1	1.1	1.1	1.1	1.1	1.1	--	--	N/A[2]	N/A[2]
Guide Bar Length (cm)	245.2	245.2	244.6	244.6	244.6	244.6	--	--	N/A[2]	N/A[2]
Assembly Configuration	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
Top Nozzle Material	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304
Bottom Nozzle Material	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304	SS 304
Upper Plenum Spring Material	SS 302	SS 302	Inconel X 750	Inconel X 750	Inconel X 750	Inconel X 750	N/A	N/A	Inconel X 750	Inconel X 750
Lower Plenum Spacer Material	N/A	N/A	SS 304	SS 304	SS 304	SS 304	N/A	N/A	SS 304	SS 304
Shroud Material	--	--	--	--	--	--	--	--	SS 304	SS 304
Top Nozzle Length (cm)	20.0	20.0	19.8	19.8	20.4	20.4	22.2	22.2	18.9	18.9
Bottom Nozzle Length (cm)	18.3	18.3	18.9	18.9	18.9	18.9	22.2	22.2	18.9	18.9
Upper Plenum Length (cm)	4.9	4.9	4.9	4.9	4.9	4.9	4.6	4.6	4.8	4.8
Lower Plenum Length (cm)	N/A	N/A	3.2	3.2	3.2	3.2	N/A	N/A	3.1	3.1
Shroud Length (cm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	246.9	246.9
Shroud Thickness (cm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.09	0.09
Top Nozzle Weight (kg)	5.50	5.50	6.70	6.70	6.70	6.70	6.70	6.70	17.02[4]	17.02[4]
Bottom Nozzle Weight (kg)	9.10	9.10	5.18	5.18	5.18	5.18	5.20	5.20	13.21[4]	13.21[4]
Upper Plenum Spring Weight (g)	3.3	3.3	3.3	3.3	3.3	3.3	N/A	N/A	3	3
Lower Plenum Spring Weight (g)	N/A	N/A	4.5	4.5	4.5	4.5	N/A	N/A	7.5	7.5
Grid Spacer Material	Zirc-4/Inconel 625[3]	Zirc-4/Inconel 625[3]	SS 304L	SS 304L	Zircaloy -4	Zircaloy -4	N/A	N/A	Inconel 718	Inconel 718
Grid Spacer Weight (g)	590/960	590/960	622.3	622.3	634.3	648.4	N/A	N/A	0	0
Number of Grid Spacers	6	6	6	6	6	6	N/A	N/A	6	6

2. United Nuclear assemblies fabricated from Zircaloy incorporate displacement rods 95.32-inches long and 0.365-inch in outside diameter.
3. Five grid spacers are Zircaloy 4. The bottom spacer is Inconel 625.
4. Estimated weight.

Table 2.1-2 Yankee Class Reconfigured Fuel Assembly Parameters

Parameter	**CE** Type A/B	**Exxon** Type A/B	**Exxon** Type A/B	**West.** Type A/B	**United Nuclear** Type A/B
ASSEMBLY CONFIGURATION					
Assembly Array	8x8	8x8	8x8	8x8	8x8
Max. Enrichment (wt % ^{235}U)	3.93	4.03	4.03	4.97	4.03
Max. kgU*	66.33	66.33	66.33	60.21	66.33
FUEL ROD CONFIGURATION (EACH ROD PLACED WITHIN ENCAPSULATING ROD)					
Rod Pitch (cm)	1.905	1.905	1.905	1.905	1.905
Active Fuel Length (cm)	231.1400	231.1400	231.1400	233.9975	231.1400
Rod OD (cm)	0.9271	0.9271	0.9271	0.8636	0.9271
Clad ID (cm)	0.8052	0.8052	0.8052	0.7569	0.8052
Pellet OD (cm)	0.7887	0.7887	0.7887	0.7468	0.7887
Diametrical Gap (cm)	0.0165	0.0165	0.0165	0.0102	0.0165
Max Rods per Assembly	64	64	64	64	64
Fuel Material	UO_2	UO_2	UO_2	UO_2	UO_2
Clad Material	Zircaloy	Zircaloy	Zircaloy	SS 348	Zircaloy
ENCAPSULATING ROD					
Rod OD (cm)	1.27	1.27	1.27	1.27	1.27
Rod ID (cm)	1.1278	1.1278	1.1278	1.1278	1.1278
Rod Material	SS-304	SS-304	SS-304	SS-304	SS-304

* Maximum kgU based on 95% of UO_2 theoretical density for the fuel pellet stack density.

Note: Intact or broken fuel rods may be contained in the reconfigured fuel assembly.

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Figure 5.2-4 NAC-MPC Design Basis Neutron and Gamma Source Axial Profiles

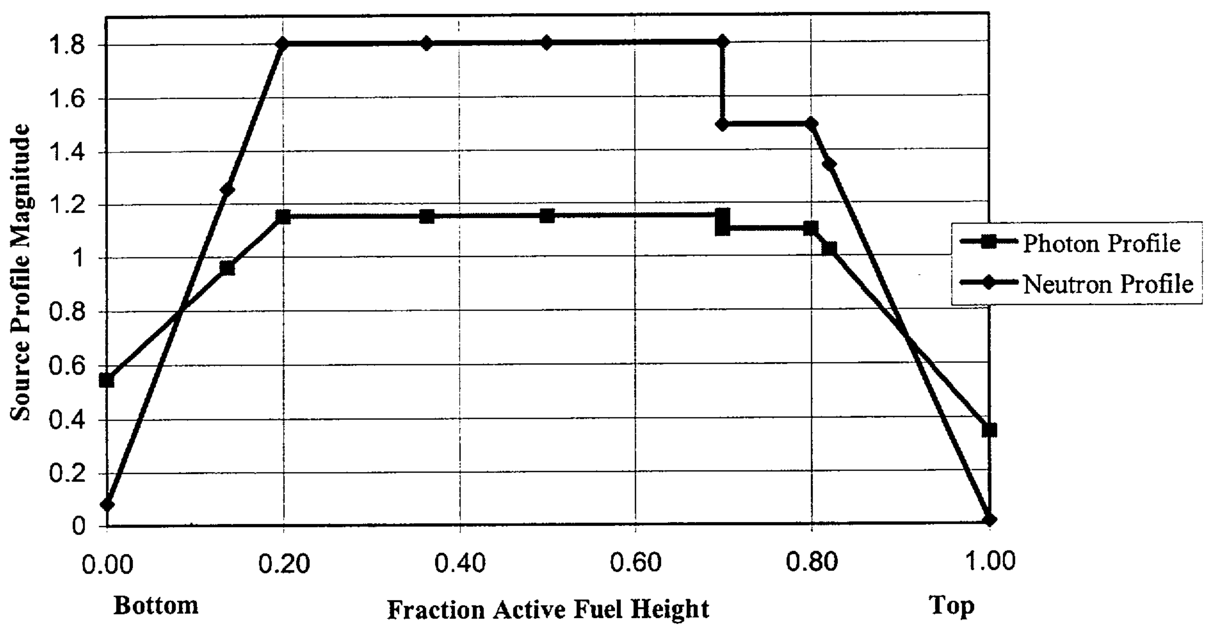

Table 5.2-1 Yankee Class Fuel Assembly Physical Parameters

Parameter	CE Type A	CE Type B	Exxon Type A	Exxon Type B	Exxon Type A	Exxon Type B	Westinghouse Type A	Westinghouse Type B	United Nuclear Type A	United Nuclear Type B
Assembly Configuration	-	-	-	-	-	-	-	-	-	-
Assembly Array	16x16	16x16	16x16	16x16	16x16	16x16	18x18	18x18	16x16	16x16
Min. Enrichment (wt % ^{235}U)[1]	3.50/3.70[2]	3.50/3.70[2]	3.50	3.50	3.50	3.50	4.94	4.94	4.00	4.00
Max. MTU	0.2394	0.2384	0.2394	0.2384	0.2394	0.2384	0.2869	0.2860	0.2456	0.2446
Fuel Rod Configuration	-	-	-	-	-	-	-	-	-	-
Fuel Rod Pitch (cm)	1.1989	1.1989	1.1989	1.1989	1.1989	1.1989	1.0719	1.0719	1.1887	1.1887
Active Fuel Length (cm)	231.1400	231.1400	231.1400	231.1400	231.1400	231.1400	233.9975	233.9975	231.1400	231.1400
Rod OD (cm)	0.9271	0.9271	0.9271	0.9271	0.9271	0.9271	0.8636	0.8636	0.9271	0.9271
Clad ID (cm)	0.8052	0.8052	0.8052	0.8052	0.8052	0.8052	0.7569	0.7569	0.8052	0.8052
Pellet OD (cm)	0.7887	0.7887	0.7887	0.7887	0.7887	0.7887	0.7468	0.7468	0.7887	0.7887
Diametral Gap (cm)	0.0165	0.0165	0.0165	0.0165	0.0165	0.0165	0.0102	0.0102	0.0165	0.0165
Rods per Assembly	231	230	231	230	231	230	305	304	237	236
Fuel Material	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2
Clad Material	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	SS 348	SS 348	Zircaloy	Zircaloy
Displacement Rod Configuration	-	-	-	-	-	-	-	-	-	-
Displacement Rod Material	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Zircaloy - 4	Zircaloy - 4
Displacement Rod Diameter (cm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.9271	0.9271
Number Per Assembly	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2	2
Guide Bar Configuration	-	-	-	-	-	-	-	-	-	-
Guide Bar Material	Zircaloy - 4	Zircaloy - 4	SS 304L	SS 304L	Zircaloy	Zircaloy	N/A	N/A	N/A	N/A
Guide Bar Width (cm)	1.0973	1.0973	1.0566	1.0566	1.0566	1.0566	N/A	N/A	N/A	N/A
Guide Bar Shape (cm)	Square	Square	Square	Square	Square	Square	N/A	N/A	N/A	N/A
Number Per Assembly	8	8	8	8	8	8	N/A	N/A	N/A	N/A
Instrument Tube Configuration	-	-	-	-	-	-	-	-	-	-
Instrument Tube ID (cm)	0.9970	0.9970	0.9970	0.9970	0.9970	0.9970	0.9995	0.9995	0.9995	0.9995
Instrument Tube OD (cm)	1.1481	1.1481	1.0884	1.0884	1.0884	1.0884	1.0884	1.0884	1.0884	1.0884
Number Per Assembly	1	1	1	1	1	1	1	1	1	1
Instrument Tube Material	Zircaloy - 4	Zircaloy - 4	SS 304	SS 304	Zircaloy	Zircaloy	SS 304	SS 304	SS 304	SS 304

1. The effect of nominally lower enrichments is shown in Section 5.4.3.1.
2. Minimum enrichment of 3.50 wt% ^{235}U is based on a maximum burnup of 32,000 MWD/MTU. Minimum enrichment of 3.70 wt% ^{235}U is based on a maximum burnup of 36,000 MWD/MTU.

Table 5.2-2 Yankee Class Design Basis Fuel Characteristics for Shielding Evaluations

Parameter	CE Type A
Assembly Configuration	-
Assembly Length (inches)	111.79
Assembly Array	16x16
Minimum Enrichment (wt % ^{235}U)	3.70[3,4]
UO_2 Fuel Mass (kg) at 95% TD	271.6
Fuel Rod Configuration	-
Fuel Rod Pitch (inches)	0.472
Overall Rod Length (inches)	95.4
Active Fuel Length (inches)	91
Rod OD (inches)	0.365
Clad ID (inches)	0.317
Pellet OD (inches)	0.3105
Diametral Gap (inches)	0.0065
Rods per Assembly	231
Clad Material	Zircaloy
Guide Bar Configuration	-
Guide Bar Material	Zircaloy - 4
Guide Bar Width (inches)	0.432
Guide Bar Length (inches)	96.52
Guide Bar Shape	Square
Number Per Assembly	8
Instrument Tube Configuration	-
Instrument Tube ID (inches)	0.3925
Instrument Tube OD (inches)	0.452
Instrument Tube Length (inches)	97.35
Number Per Assembly	1
Instrument Tube Material	Zircaloy - 4
Hardware Configuration	-
Top Nozzle Material	SS 304
Bottom Nozzle Material	SS 304
Upper Plenum Spring Material	SS 302[1]
Top Nozzle Length (inches)	7.98
Bottom Nozzle Length (inches)	7.19
Upper Plenum Length (inches)	1.942
Top Nozzle Mass (kg)	5.5
Bottom Nozzle Mass (kg)	5.18
Upper Plenum Spring Mass (kg)	0.762
Upper Plenum Grid Mass (kg)	0.590
Lower Plenum Material	Stainless Steel and Inconel[1,2]
Lower Plenum Mass (kg)	1.73[2]
Incore Grid Spacers	Zircaloy -4

Notes:
1. For simplicity, all Inconel and steel are modeled as Type 304 stainless steel.
2. Includes Inconel grid and lower plenum spacer.
3. Combustion Engineering fuel may be loaded at a cool time of 8.0 years with a maximum burnup of 32,000 MWD/MTU and a minimum enrichment of 3.5 wt%.
4. The analyzed minimum enrichment for CE fuel is 3.66 wt% ^{235}U for fuel with a maximum burnup of 36,000 MWD/MTU. This reduction in minimum enrichment does not significantly affect calculated dose rates.

Table 5.2-3 Yankee Class Design Basis Fuel Reactor Operating Conditions

Assembly Power, MW	8.486
$Temperature_{fuel}$, °K	797
$Temperature_{clad}$, °K	600
$Temperature_{mod}$ °K	551
$Density_{mod}$, g/cc	0.766
Boron, ppm	800
Fuel Burnup, MWD/MTU	36,000
Burnup Cycle, days	2 Cycles of 496.22 days
Down Time, days	60

Table 5.2-4 NAC-MPC Design Basis Fuel Source Terms

Decay Heat, kW	12.5
Active Fuel, photons/sec	6.423+16
Active Fuel, neutrons/sec	2.415+9
Upper End fitting, photons/sec	8.330+13
Upper Plenum, photons/sec	2.309+13
Lower End fitting, photons/sec	7.876+13
Lower Plenum, photons/sec	5.242+13

Condition: 36 Combustion Engineering Yankee Class Fuel Assemblies, 8 Years Cooled, and 36,000 MWD/MTU Burnup.

5.4.3 Dose Rates

This section provides detailed dose rate profiles for the NAC-MPC storage and transfer cask based on the source terms presented in Section 5.2. Design basis fuel source terms include contributions from fuel neutron, fuel gamma and activated hardware gamma. The fuel assembly activated hardware gamma source terms include: steel and inconel in the upper and lower fuel assembly end fittings, and upper and lower fuel rod plenum hardware. Peaking factors of 1.15 and 1.80 are applied to the one-dimensional radial fuel gamma and neutron dose rates, respectively. The three-dimensional model dose rates include the axial profiles for neutron and gamma source distributions shown in Figure 5.2-4.

5.4.3.1 One-Dimensional Storage Cask Dose Rates

One-dimensional radial dose rates with design basis fuel were found to be in good agreement with the three-dimensional models at the radial midplane. However, the peaks in the radial dose rates, due to activated endfittings, cannot be captured by one-dimensional analysis. One-dimensional dose rates at the top of the storage cask are significantly lower than those calculated using three-dimensional analysis. This is primarily due to the neutron component of the dose rates and the transverse bucklings applied in the one-dimensional axial model as well as streaming effects caused by the heat transfer annulus and top vents. Except for the neutron component of the top axial model and obvious limitations in geometry, one-dimensional analysis is found to support the results of the more complicated three-dimensional models. Except for the storage cask loss of concrete accident radial dose rates shown in Table 5.4-3, the dose rate results from three-dimensional analysis are reported.

One-dimensional radial surface dose rates are also used to determine the minimum cool times, based on the design basis fuel values, for CE, UN, and WE fuel types with a maximum burnup of 32,000 MWD/MTU and Exxon assemblies at 36,000 MWD/MTU. The calculated minimum cool times for CE, UN, and WE fuel at 32,000 MWD/MTU are 8, 13 and 21 years, respectively. Exxon assemblies with steel hardware require 16 years cooling while the Exxon assemblies with Zircaloy hardware require only 9 years cooling.

For the fuel shown in Table 5.2-1, a nominal decrease in enrichment is evaluated to account for tolerances applied to the enrichment specification during fabrication. The evaluation shows that a reduction in the batch-averaged minimum enrichments shown in Table 5.2-1 does not significantly affect calculated dose rates as shown by the minimal increase in source strength:

Fuel Type	Minimum Enrichment (wt% ^{235}U)	Percent Increase in Source (%)			
		Decay Heat	Neutron	Gamma	Hardware
CE	3.66	0.2	2.2	0.1	0.6
Exxon	3.46	0.2	2.2	0.0	0.7
UN	3.96	0.1	2.2	0.1	0.6
WE	4.90	0.1	2.3	0.0	0.5

5.4.3.2 Three-Dimensional Storage Cask Dose Rates

The NAC-MPC storage cask three-dimensional model dose rates are presented in Figures 5.4-1 through 5.4-7. Approximately 50 million particle histories (neutron and gamma) are tracked to yield the dose rate profiles presented in theses figures. The average standard deviation for the side total dose rate shown in Figures 5.4-1 and 5.4-2 is less than ± 2%, and the average standard deviation for the top total dose rate shown in Figures 5.4-6 and 5.4-7 is less than ± 5%. The average standard deviation for the inlet and outlet vent total dose rates shown in Figures 5.4-3, 5.4-4 and 5.4-5 is less than ± 5%, and the standard deviation for the peak dose rates at the vent opening are less than ± 10%.

The vertical profile along the radial surface of the storage cask, as well as at distances of 30.48 cm (1 foot), 1 meter, and 2 meters from it, are plotted in Figure 5.4-1 as a function of elevation. Each datum represents the circumferentially average dose rate at the corresponding distance and elevations. The negative elevations are the dose rates from the bottom model computations, while the positive elevations are the dose rates from the top model computations. The discontinuity observed at zero elevation (midplane of the fuel) is a modeling artifact due to the decoupling of the upper and lower portions of the cask. In the vertical dose profile, peaking is observed at the upper and lower end fitting locations, as well as at the locations of the lower intake and upper outlet vents. The average and maximum side surface dose rate for the storage cask are 37 (0.3%) and 47.3 (0.4%) mrem/hr, respectively.

The radial surface dose profile is further described by source component in Figure 5.4-2. The source components in both models contribute to the radial doses largely as one would expect, i.e., at the elevations where they are located. Since these doses are circumferential averages, the detailed circumferential dose rate profile at the top vent elevation and the bottom vent inlet are shown radially in Figure 5.4-3 and Figure 5.4-4, respectively. The dose rates shown in Figures 5.4-3 and 5.4-4 were computed using a variance-weighted average of the dose rates in the four

symmetric quadrants at the vent elevation. A maximum dose rate of 24 mrem/hr (5%) is calculated at the surface of the outlet vent and a maximum dose rate of 99 (5.4%) mrem/hr was calculated at the entrance of the inlet vent.

In Figure 5.4-5, the circumferential dose rate profile at the support ring cutout elevation is shown on the storage surface and at distances of 30.48 cm (1 foot), 1 meter, and 2 meters from the surface. The peak in the circumferential dose rate is not at the location of the cutout, but above the inlet vent location. Note that these peak dose rates are higher at 1 foot from the storage cask than they are on the surface of the storage cask. This is due to photon scattering off the storage cask concrete base through the inlet vent opening and up to the cutout elevation.

The dose rate profiles on the top surface of the storage cask and at distances of 1 foot and 1 meter above the lid are shown in Figure 5.4-6. The dose rates are plotted radially out from the centerline of the storage cask. Two dose rate peaks are observed on the storage cask top surface: one in the vicinity of 90 to 100 cm, which corresponds to the location of the heat transfer annular gap and another at approximately 130 cm. The dose rate profile on the top surface of the storage cask is shown by source component in Figure 5.4-7 and indicates that the peak dose rate above the annular gap is caused by neutrons streaming up the gap. The component profile also indicates that the second peak is created by gammas from the end fitting, top fuel, and top plenum source regions. This peak occurs at approximately the same radial location as the vertical leg in the upper outlet vent. Thus, it is a result of a decrease in effective shield thickness caused by the void in the concrete due to the outlet vents. The average dose rate over the top of the storage cask is computed to be 25.1 mrem/hr (1.2%), while the peak dose on top of the storage cask is 54 mrem/hr (4.9%).

5.4.3.3 One-Dimensional Transfer Cask Dose Rates

One-dimensional radial dose rates with design basis fuel are in good agreement with the three-dimensional models at the radial midplane. As with the storage cask one-dimensional radial model, the peaks in the radial dose rates due to activated endfittings cannot be captured by one-dimensional analysis. One-dimensional top dose rates at the top and bottom of the transfer cask were significantly lower than three-dimensional analysis. This was primarily due to the neutron component of the dose rates and the transverse bucklings applied in the one-dimensional axial model as well as streaming effects around the temporary shielding. Except for the neutron component of the top axial model, one-dimensional analysis supports the results of the more complicated three-dimensional models.

5.4.3.4 Three-Dimensional Transfer Cask Dose Rates

The transfer cask three-dimensional model dose rates are presented in Figures 5.4-8 through 5.4-15. Approximately 100 million particle histories (neutron and gamma) are tracked to yield the dose rate profiles presented in theses figures. The average standard deviation for the side total dose rates shown in Figures 5.4-8 through 5.4-11 is less than ± 2%, and the average standard deviation for the top total dose rates shown in Figures 5.4-12 through 5.4-15 is less than ± 2%.

The transfer cask side dose rate profiles with a wet cavity are shown in Figure 5.4-8 as a function of distance and in Figure 5.4-9 as a function of source component. In this condition, the majority of the dose rate is from fuel gamma and activated end fitting gamma. It is assumed in the model that the water level in the canister is lowered for welding operations, thus, the top end fitting is uncovered and causes a large peak in dose rate at the top of the transfer cask due to the gamma source from the activated top end fitting. In this condition, the peak and average dose rates on the side of the transfer cask are 210.2 (0.8%) and 79.5 (0.3%) mrem/hr, respectively, and the peak and average dose rates at 1 meter are 40.5 (0.7%) and 26.4 (0.2 %) mrem/hr, respectively.

The transfer cask side dose rate profiles with a dry cavity are shown in Figure 5.4-10 as a function of distance and in Figure 5.4-11 as a function of source component. In this condition, the majority of the dose rate is from fuel neutron and gamma source, but significant peaks are shown from the activated end fittings. The peak and average dose rates on the side of the transfer cask are 413.4 (1.5%) and 226.3 (0.2%) mrem/hr, respectively, and the peak and average dose rates at 1 meter are 103.4 (0.6%) and 72.2 (0.2 %) mrem/hr, respectively.

The transfer cask peak and average dose rate on the temporary shield surface are 188.7 (1.1%) and 172.0 (0.3%) mrem/hr, respectively. In this condition, the majority of the dose rate is from the activated top end fitting. The peak and average dose rate at 1 meter are 389.1 (5.1%) and 263.7 (1.5%) mrem/hr, respectively.

In the final configuration, the canister cavity is dry, the shield lid and structural lid are in place, and 5" of temporary steel shielding is installed. In this condition, the transfer cask top dose rate are shown in Figure 5.4-12 as a function of distance and in Figure 5.4-13 as a function of component. The majority of the dose rate is from the fuel neutron. The dose rate peaks at the lid edge due to gamma streaming around the tapered edge of the temporary shield. The peak and average dose rates on the top of the transfer cask are 358.9 (2.6%) and 224.6 (0.9%) mrem/hr,

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6.0 CRITICALITY EVALUATION

6.1 Discussion and Results

This chapter demonstrates that the NAC-MPC storage system containing 36 Yankee Class fuel assemblies is subcritical in accordance with the requirements of 10 CFR 72.124(a), 10 CFR 72.236(c) and Chapter 6 of NUREG-1536. These requirements are interpreted to mean that the effective neutron multiplication factor of the NAC-MPC system is less than 0.95, including biases and uncertainties under normal, off-normal and accident conditions.

The NAC-MPC storage system comprises a transportable storage canister (canister), a transfer cask and a vertical concrete cask (storage cask). The canister comprises a stainless steel canister and a basket. The basket comprises 36 fuel tubes held in place with stainless steel support disks and tie rods. The transfer cask containing the canister and basket is loaded underwater in the spent fuel pool. Once loaded with fuel, the canister is drained, dried, inerted, and welded shut. The transfer cask is then used to transfer the canister to the storage cask where it is stored until transported off site.

Under normal conditions, such as loading in a spent fuel pool, moderator (water) is present in the canister while it is in the transfer cask. Also, during draining and drying operations, moderator is present and its density will vary. Thus, the criticality evaluation of the transfer cask includes a variation in moderator density and a determination of optimum moderator density. Off-normal and accident conditions are bounded by assuming the most reactive mechanical basket configuration, as well as moderator intrusion into the fuel cladding (100% fuel failure).

Under normal conditions, moderator is not present in the canister while it is in the storage cask. However, access to the environment is possible via the air inlets in the storage cask and the convective heat transfer annulus between the canister and the storage cask steel liner. This access provides paths for moderator intrusion during a flood. Under off-normal conditions, moderator intrusion into the convective heat transfer annulus is evaluated. Under accident conditions, it is hypothetically assumed that the canister confinement fails, and moderator intrusion into the canister and into the fuel cladding (100% fuel failure) is evaluated. This is a highly conservative assumption, since, as shown in Chapters 3 and 11, there are no design basis normal, off-normal or accident conditions that result in the failure of the canister confinement boundary that would allow the intrusion of water.

Criticality control in the NAC-MPC canister basket is achieved using a flux trap principle. The flux trap principle controls the reactivity in the interior of each of the two basket configurations. In the first of the configurations, all fuel tubes are separated by a flux trap that is formed by surrounding the tube with stainless steel support disks and four 0.01g $^{10}B/cm^2$ (minimum) areal density BORAL sheets, which are held in place by stainless steel covers. In the second configuration, the size of the four fuel tubes (one outer tube in each quadrant of the basket, as shown in Figure 6.3-4) is increased by removing the BORAL sheets from the outside of the tubes. The remainder of the tubes have BORAL sheets on each of the four sides. The spacing of the fuel tubes is maintained by the stainless steel support disks. These disks provide water gap spacings between tubes of 0.875, 0.810, or 0.750 inches, depending on the position of the fuel tube in the basket. When the canister is flooded with water, fast neutrons leaking from the fuel assemblies are thermalized in the water gaps and are absorbed in the BORAL sheets before causing a fission in an adjacent fuel assembly. This NAC-MPC basket can accommodate up to 36 Yankee Class Zircaloy-clad assemblies with a maximum initial enrichment of 4.03 wt % ^{235}U or 36 Yankee Class stainless steel-clad assemblies with a maximum initial enrichment of 4.97 wt % ^{235}U.

The criticality evaluation of the NAC-MPC is performed with the SCALE 4.3 (ORNL) Criticality Safety Analysis Sequence (CSAS)(Landers). This sequence includes KENO-Va (Petrie) Monte Carlo analysis to determine the effective neutron multiplication factor (k_{eff}). The 27 group ENDF/B-IV neutron library (Jordan) is used in all calculations. CSAS with the 27 group library is benchmarked by comparison to 63 critical experiments relevant to Light Water Reactor (LWR) fuel in storage and transport casks.

Criticality evaluations are performed for both the transfer and storage casks under normal, off-normal and accident conditions. Considerations are given to the most reactive fuel assembly type, worst case mechanical basket configuration and variations in moderator density. The maximum effective neutron multiplication factor with bias and uncertainties for the transfer cask containing the basket with four BORAL sheets on all fuel tubes is 0.9021 under normal, off-normal or accident conditions. The maximum multiplication factor with bias and uncertainties for the storage cask is 0.4503 under normal dry storage conditions and 0.9018 under the hypothetical accident conditions involving full moderator intrusion. The maximum bias and uncertainty adjusted reactivities for the basket containing the four enlarged fuel tubes are slightly higher at 0.9175 for transfer conditions and 0.9182 for a hypothetical storage accident condition involving full moderator intrusion.

6.2 Package Fuel Loading

The NAC-MPC storage system can safely transfer and store 36 Yankee Class fuel assemblies. As shown in Figures 6.3-2 and 6.3-3, there are 37 fuel tube positions in the support and heat transfer disks that form the canister basket. Loading of fuel in the center tube position is prevented by the design of the top weldment, which blocks this position (Drawing 455-892). The various Yankee Class assemblies to be transferred and stored in the NAC-MPC are presented in Table 6.2-1. Five vendor categories, each with two fuel rod configurations (types), are available within the Yankee Class. These are: Combustion Engineering (CE) 16 x 16 Type A and Type B, two categories of Exxon 16 x 16 Type A and Type B, United Nuclear 16 x 16 Type A and Type B, and Westinghouse 18 x 18 stainless steel clad Type A and Type B. See Figures 6.2-1, 6.2-2 and 6.2-3 for the fuel array configurations. The Combustion Engineering manufactured fuel has the same fuel rod arrays for Types A and B as the Exxon fuel. The Type A and Type B fuel array configurations allow a cruciform control rod to be inserted between assemblies during core operation. The most reactive Yankee Class fuel assembly is the United Nuclear, Type A, 16 x 16 fuel assembly with 4.0 wt % ^{235}U initial enrichment. This fuel assembly type bounds all of the Yankee Class fuel assemblies, including the Westinghouse stainless steel clad fuel with a 4.94 wt % ^{235}U initial enrichment. The United Nuclear Type A fuel assembly with 4.0 wt % ^{235}U initial enrichment is the design basis fuel assembly used in NAC-MPC storage system criticality evaluations. As described in Section 6.4.3.1 and Table 6.2-1, certain fuel assemblies have enrichments nominally greater than the maximum enrichments considered in the design basis analysis. These nominally higher enrichments are considered in Section 6.4.3.1, and are shown to not be significant. To preclude any potential increase in reactivity due to empty fuel rod positions in the spent fuel assembly, any fuel rods removed from the assembly lattice must be replaced with solid filler rods fabricated from Zircaloy or Type 304 stainless steel.

A canister may contain one or more reconfigured fuel assemblies. The reconfigured fuel assembly is designed to confine the Yankee Class spent fuel rods, or portions thereof, which are classified as failed fuel and to maintain the geometric configuration of those fuel rods. This assembly can accept up to 64 full length spent fuel rods in an eight by eight array of tubes.

The reconfigured fuel assembly consists of a shell (square tube with end fittings), a basket assembly and 64 fuel tubes. Reconfigured fuel assembly parameters are presented in Table 6.2-2. The external dimensions of the shell are the same as those of a standard Yankee Class fuel assembly and all materials are stainless steel. It is designed such that it can be handled in the same manner as a standard Yankee Class fuel assembly. The spent fuel is confined in the

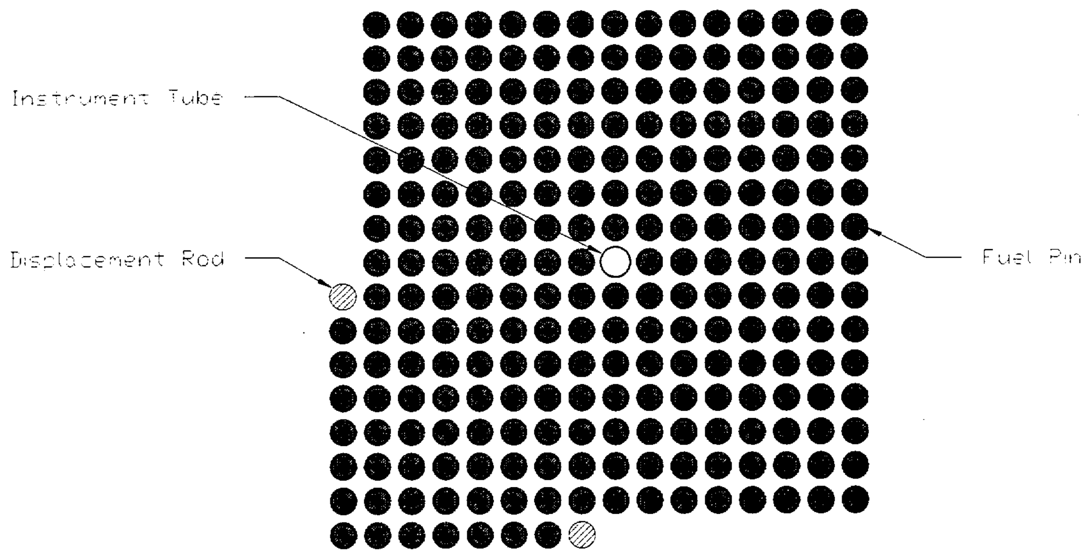
fuel tubes. The tubes are supported by a basket assembly within the shell and have end plugs with drilled holes to permit draining, drying and inerting with helium. The shell has holes in the top and bottom fittings to permit draining, drying and inerting of the assembly.

The total number of full length pins that can be placed in the reconfigured fuel assembly is less than the number that are in the Yankee Class fuel assemblies (maximum of 64 versus 256 rods). Consequently, the reactivity of the reconfigured fuel assembly, even with the most reactive fuel rods, is less than the design basis fuel assembly used in criticality evaluations.

A comparison of the reactivity of the reconfigured fuel assembly to intact assemblies is made in conjunction with the most reactive assembly evaluation in Section 6.4.3.1.

Figure 6.2-3 Yankee Class Type A and Type B United Nuclear Fuel Assembly Arrays

Type A



Type B

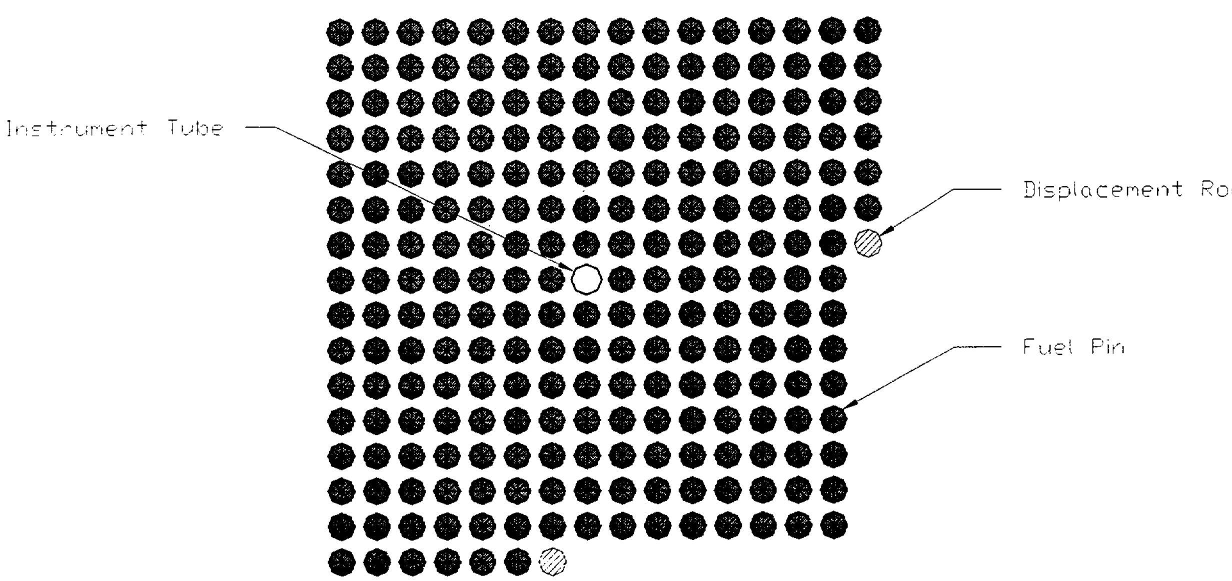


Table 6.2-1 Yankee Class Fuel Assembly Parameters

Parameter	CE Type A	CE Type B	Exxon Type A	Exxon Type B	Exxon Type A	Exxon Type B	West. Type A	West. Type B	United Nuclear Type A	United Nuclear Type B
Assembly Configuration	-	-	-	-	-	-	-	-	-	-
Assembly Array	16 x 16	16 x 16	16 x 16	16 x 16	16 x 16	16 x 16	18 x 18	18 x 18	16 x 16	16 x 16
Max. Enrichment (wt% ^{235}U)[1]	3.90	3.90	4.00	4.00	3.70	3.70	4.94	4.94	4.00	4.00
Max. MTU[2]	0.2394	0.2384	0.2394	0.2384	0.2394	0.2384	0.2869	0.2860	0.2456	0.2446
Fuel Rod Configuration	-	-	-	-	-	-	-	-	-	-
Fuel Rod Pitch (cm)	1.1989	1.1989	1.1989	1.1989	1.1989	1.1989	1.0719	1.0719	1.1887	1.1887
Active Fuel Length (cm)	231.1400	231.1400	231.1400	231.1400	231.1400	231.1400	233.9975	233.9975	231.1400	231.1400
Rod OD (cm)	0.9271	0.9271	0.9271	0.9271	0.9271	0.9271	0.8636	0.8636	0.9271	0.9271
Clad ID (cm)	0.8052	0.8052	0.8052	0.8052	0.8052	0.8052	0.7569	0.7569	0.8052	0.8052
Pellet OD (cm)	0.7887	0.7887	0.7887	0.7887	0.7887	0.7887	0.7468	0.7468	0.7887	0.7887
Diametral Gap (cm)	0.0165	0.0165	0.0165	0.0165	0.0165	0.0165	0.0102	0.0102	0.0165	0.0165
Rods per Assembly	231	230	231	230	231	230	305	304	237	236
Fuel Material	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2
Clad Material	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	SS 348	SS 348	Zircaloy	Zircaloy
Displacement Rod Configuration	-	-	-	-	-	-	-	-	-	-
Displacement Rod Material	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Zircaloy - 4	Zircaloy - 4
Displacement Rod Diameter (cm)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.9271	0.9271
Number Per Assembly	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2	2
Guide Bar Configuration	-	-	-	-	-	-	-	-	-	-
Guide Bar Material	Zircaloy - 4	Zircaloy - 4	SS 304L	SS 304L	Zircaloy	Zircaloy	N/A	N/A	N/A	N/A
Guide Bar Width (cm)	1.0973	1.0973	1.0566	1.0566	1.0566	1.0566	N/A	N/A	N/A	N/A
Guide Bar Shape (cm)	Square	Square	Square	Square	Square	Square	N/A	N/A	N/A	N/A
Number Per Assembly	8	8	8	8	8	8	N/A	N/A	N/A	N/A
Instrument Tube Configuration	-	-	-	-	-	-	-	-	-	-
Instrument Tube ID (cm)	0.9970	0.9970	0.9970	0.9970	0.9970	0.9970	0.9995	0.9995	0.9995	0.9995
Instrument Tube OD (cm)	1.1481	1.1481	1.0884	1.0884	1.0884	1.0884	1.0884	1.0884	1.0884	1.0884
Number Per Assembly	1	1	1	1	1	1	1	1	1	1
Instrument Tube Material	Zircaloy - 4	Zircaloy - 4	SS 304	SS 304	Zircaloy	Zircaloy	SS 304	SS 304	SS 304	SS 304

1. Certain fuel assemblies of the type specified may have a maximum enrichment up to 0.03 wt% ^{235}U higher than the value shown.
2. Maximum MTU based on 95% of UO_2 theoretical density for the fuel pellet stack density.

Table 6.2-2 Yankee Class Reconfigured Fuel Assembly Parameters

Parameter	CE Type A/B	Exxon Type A/B	Exxon Type A/B	West. Type A/B	United Nuclear Type A/B
ASSEMBLY CONFIGURATION					
Assembly Array	8x8	8x8	8x8	8x8	8x8
Max. Enrichment (wt % ^{235}U)	3.93	4.03	4.03	4.97	4.03
Max. kgU*	66.33	66.33	66.33	60.21	66.33
FUEL ROD CONFIGURATION (EACH ROD PLACED WITHIN ENCAPSULATING ROD)					
Rod Pitch (cm)	1.905	1.905	1.905	1.905	1.905
Active Fuel Length (cm)	231.1400	231.1400	231.1400	233.9975	231.1400
Rod OD (cm)	0.9271	0.9271	0.9271	0.8636	0.9271
Clad ID (cm)	0.8052	0.8052	0.8052	0.7569	0.8052
Pellet OD (cm)	0.7887	0.7887	0.7887	0.7468	0.7887
Diametrical Gap (cm)	0.0165	0.0165	0.0165	0.0102	0.0165
Max Rods per Assembly	64	64	64	64	64
Fuel Material	UO_2	UO_2	UO_2	UO_2	UO_2
Clad Material	Zircaloy	Zircaloy	Zircaloy	SS 348	Zircaloy
ENCAPSULATING ROD					
Rod OD (cm)	1.27	1.27	1.27	1.27	1.27
Rod ID (cm)	1.1278	1.1278	1.1278	1.1278	1.1278
Rod Material	SS 304	SS 304	SS 304	SS 304	SS 304

* Maximum kgU based on 95% of UO_2 theoretical density for the fuel pellet stack density.

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6.4 Criticality Calculation

This section demonstrates that the criticality analysis of the NAC-MPC is sufficient to satisfy the requirements of 10 CFR 72.124(a), 10 CFR 72.236(c) and Chapter 6 of NUREG 1536. The calculational method is described. Criticality calculations are performed to determine: the most reactive Yankee Class fuel assembly type; the most reactive mechanical configuration in the NAC-MPC basket; and the most reactive moderator density under normal, off-normal and accident conditions.

6.4.1 Calculational Method

The criticality evaluation of the NAC-MPC is performed with the SCALE 4.3 (ORNL) Criticality Safety Analysis Sequence (CSAS) (Landers) for the PC. CSAS includes: the SCALE Material Information Processor (Bucholz), BONAMI (Greene), NITAWL-II (Westfall), and KENO-Va (Petrie). The Material Information Processor generates number densities for standard compositions, prepares geometry data for resonance self-shielding, and creates data input files for the cross section processing codes. The BONAMI and NITAWL-II codes are used to prepare a resonance-corrected cross section library in AMPX working format. The KENO-Va code calculates the model k_{eff} using Monte Carlo techniques. The 27 group ENDF/B-IV neutron cross section library (Jordan) is used in this calculation. The NAC-MPC KENO-Va models are described in further detail below.

6.4.2 Fuel Loading Optimization

The fuel loading is optimized in the NAC-MPC cask criticality models by using: 1) fresh fuel, 2) the most reactive Yankee Class fuel assembly type, 3) the highest possible fuel stack density (95 % of theoretical) and 4) the most reactive basket configuration. The cask models represent fully loaded baskets with 36 design basis fuel assemblies. The models use reflecting boundary conditions on the sides and periodic boundary conditions on the top and bottom. These boundary conditions simulate an infinite array of casks of infinite axial extent.

6.4.3 Criticality Results

This section establishes the most reactive Yankee Class fuel and the most reactive configuration of the fuel within the canister basket. These results are used to calculate the effective neutron multiplication factor for the transfer cask and storage cask assuming full moderation. Sections 6.4.3.3 and 6.4.3.4 contain the results for the basket in transfer and storage configurations (respectively) without enlarged fuel tubes, while Section 6.4.3.5 extends the evaluation results to the basket with four enlarged fuel tubes.

6.4.3.1 Most Reactive Assembly

Using the fuel/basket model of the NAC-MPC basket, each of the Yankee Class fuel assembly vendor categories shown in Table 6.2-1 is evaluated. Each particular fuel rod array is explicitly modeled. This includes the Westinghouse 18 x 18 Types A and B at 4.94 wt % ^{235}U, United Nuclear 16 x 16 Types A and B at 4.0 wt % ^{235}U, Exxon 16 x 16 Types A and B with steel guide bars and instrument tube at 4.0 wt % ^{235}U, and CE Type A and B at 3.90 wt % ^{235}U, as well as the reconfigured fuel assembly with the most reactive fuel rods. Note, the Exxon 16 x 16 Types A and B with Zircaloy guide bars and instrument tube is identical to the CE configuration. In order to standardize the comparison, each assembly is evaluated with the fuel UO_2 at 95% theoretical density.

Table 6.4-1 shows the multiplication factor for each Yankee Class fuel type in the NAC-MPC basket. This table shows that either the United Nuclear Type A or Type B has the highest multiplication factor of the Yankee Class fuel assembly vendor categories. Table 6.4-1 also shows that it is difficult to resolve the difference between Type A and Type B fuel assemblies. There is only one fuel rod difference in loading. However, since the United Nuclear Type A has the highest UO_2 mass, this fuel rod array is chosen as the most reactive design basis fuel assembly for the NAC-MPC. This design basis fuel assembly is used in all subsequent transfer and storage cask evaluations.

Additional analyses were performed to account for certain United Nuclear, Combustion Engineering, Exxon and Westinghouse Type A and Type B fuel assemblies having nominally higher maximum enrichment than that considered in the design basis. The base case unit cell models of the United Nuclear, Combustion Engineering, Exxon and Westinghouse fuel were modified to increase the enrichment of the fuel to 4.03 wt % ^{235}U, 3.93 wt % ^{235}U, 4.03 wt % ^{235}U and 4.97 wt % ^{235}U, respectively. These nominal increases resulted from variances in the method in which the enrichment tolerance was applied during fabrication.

The calculated differences in reactivity for these fuel assemblies show that the increased enrichments do not result in a statistically significant increase in reactivity for all fuel types, except the Westinghouse Type A fuel. However, the reactivity of the Westinghouse Type A fuel with increased enrichment is significantly less than the United Nuclear Type A or B fuel at the nominal enrichment. No statistically significant differences in reactivity exists between the United Nuclear Type A or Type B fuels at 4.00 or 4.03 wt % ^{235}U. Therefore, the design basis analysis, which uses United Nuclear Type A fuel at 4.00 wt % ^{235}U, is adequate to demonstrate the criticality safety of the NAC-MPC system.

6.4.3.2 Most Reactive Mechanical Configuration

Using the fuel/basket model with the design basis fuel assembly, an evaluation of the effect of different NAC-MPC basket perturbations is made. This criticality analysis determines the most reactive basket mechanical configuration by altering the nominal fuel/basket model with the design basis assembly and comparing the perturbed k_{eff} to the nominal result. If Δk_{eff} ($k_{perturbed}$ - $k_{nominal}$) is positive, the tolerance causes an increase in reactivity. Conversely, if Δk_{eff} is negative, the tolerance causes a decrease in reactivity. Two sets of perturbations are assessed in this evaluation of the criticality control: fabrication tolerances and component movement within the basket.

Four major fabrication tolerances are evaluated: the fuel tube opening, the disk opening, the disk thickness and the disk opening placement. Modifications to the nominal fuel/basket model dimensions are made based on the basket and fuel tube tolerances given on the NAC-MPC drawings provided in Chapter 1.0. The tolerance analysis results are shown in Table 6.4-2. Table 6.4-2 shows that the most reactive set of basket tolerances are maximum fuel tube opening, minimum disk opening, maximum disk thickness and minimum (close packed) disk opening placement.

Increasing the fuel tube opening brings more moderator into the gap between the assembly and the tube lowering the efficiency of the BORAL sheets, hence increasing the reactivity of the system. Minimizing the disk opening and maximizing the disk thickness removes water from the flux trap, consequently increasing k_{eff}. Finally, decreasing the web thickness, decreases the flux trap size and also moves assemblies closer together producing an increase in k_{eff}. With respect to fabrication tolerances, this is the most reactive configuration.

Two major component movements within the basket are evaluated: the assembly within the tube and the tube within the basket. Unique to this package is the Yankee Class diagonally symmetric fuel assembly. Consequently, movement toward the three corners must be evaluated as opposed to one corner for a fully symmetric assembly. This assembly produces five movement perturbations: fuel tube movement to the upper right corner, the upper left corner, the lower left corner and side to side. Table 6.4-3 shows the assembly movement analysis results. These results show that the most reactive assembly position is centered within the basket tube. This centering provides the most optimum moderating water gap within the tube.

Similar to the fuel assembly movement analysis, five possible fuel tube movements are evaluated: the upper right corner, the upper left corner, the lower left corner and side to side. Mirror and periodic boundary conditions on the sides of the model are evaluated. Table 6.4-4 shows the tube movement evaluations. These results indicate that the most reactive fuel tube location is shifted to the right side of the tube with mirrored boundary conditions. This result is reasonable given the orientation of the assembly. Shifting the tube to the right side with mirrored boundary conditions moves a complete fuel pin row of two assemblies closer together, hence pushing the largest amount of fuel together and minimizing the flux trap gap between tubes. In general, these results show that moving the tubes towards each other with the fuel assembly centered in the tube is the most reactive component configuration.

Thus, the following most reactive mechanical configuration is imposed on the NAC-MPC basket model: assemblies centered in the tubes, fuel tubes moved toward the center of the basket, maximum fuel tube opening, minimum disk opening, maximum disk thickness and close packed disk opening locations. The reactivity penalty associated with this configuration versus the nominal configuration is discussed in the transfer cask and storage cask criticality evaluations below.

The fuel/basket model clusters the fuel in groups of four (mirrored boundary), or shifts the fuel to one side of the tube (periodic boundary) and, therefore, does not represent the closest fuel material approach feasible in a model with fuel moved radially inward. To document the maximum reactivity configuration, both tube and assembly movement analyses are repeated in the full cask model. The k_{eff} of these analyses are compared to the nominal cask model. Based on the storage cask and transfer cask reactivity evaluation, the shield configuration of the transport cask does not impact k_{eff} significantly. Therefore, the results of the transport cask analysis, shown below, are applicable to the storage and transfer cask results.

Position	k_{eff}	σ	Δk_{eff}
Nominal	0.8637	0.0007	---
Tubes Moved Toward the Basket Center	0.8689	0.0008	0.0052
Tubes Moved Toward the Basket Shell	0.8596	0.0008	-0.0041
Assemblies Moved Toward the Basket Center	0.8677	0.0007	0.0040
Assemblies Moved Toward the Basket Shell	0.8590	0.0008	-0.0047

Based on the cask analysis of the basket model without enlarged fuel tubes, the assembly moved towards the cask center configuration adds a Δk_{eff} of 0.004 to the reactivity of the nominal configuration. The model, documented as worst case mechanical configuration in the fuel/basket evaluation, and employed in optimum moderator and enlarged fuel tube studies, is not adjusted from its assembly centered configuration. The Δk_{eff} associated with the assembly movement is accounted for by adding the Δk_{eff} of 0.004 to the KENO-Va neutron multiplication factor (k_{eff}) during k_s calculations.

To verify that the criticality axial models represent the most reactive configuration, the transfer cask accident condition, with full density water, is evaluated assuming that the aluminum heat transfer disk is replaced with water. The results show a decrease in reactivity (Δk_{eff} = - 0.014) for the water replacement condition. Consequently, the axial model incorporating the aluminum heat transfer disk is conservative.

6.4.3.3 Transfer Cask Criticality Evaluation

Under normal conditions, such as loading in a spent fuel pool, moderator (water) is present in the canister while it is in the transfer cask. Also, during draining and drying operations, moderator is present and its density will vary. Thus, the criticality evaluation of the transfer cask includes an evaluation of the reactivity effects of moderator density variation inside the cask. Off-normal and accident conditions are bounded by assuming the most reactive mechanical basket configuration as well as moderator intrusion into the fuel cladding (100% fuel failure).

Using the transfer cask criticality model, an evaluation of the assumption of 75% of ^{10}B in BORAL, the cumulative effect of worst case mechanical perturbations and the effect of moderator density variation is made. Table 6.4-5 shows transfer cask multiplication factors at various conditions. Table 6.4-5 shows that the assumption of 75% of the BORAL ^{10}B loading results in a 1.5% reactivity penalty and the cumulative effect of the worst case mechanical configuration results in an additional 1% reactivity penalty from the nominal configuration.

Table 6.4-5 also shows that reactivity decreases monotonically with decreasing moderator density, and the optimum moderator density is at 1 g/cc. Under normal conditions involving loading, draining and drying, the maximum k_{eff} including bias and uncertainties is 0.8929. The CSAS output file (including an input listing) is shown in Figure 6.7-1. In the off-normal or accident situation involving fuel failure and moderator intrusion, the maximum k_{eff}, including biases and uncertainties, is 0.9021. The CSAS output file (including an output listing) is shown in Figure 6.7-2. Thus, the NAC-MPC transfer cask containing 36 Yankee Class fuel assemblies of the most reactive type in the most reactive configuration is well below the 0.95 NRC criticality safety limit, including all biases and uncertainties under normal, off-normal and accident conditions.

6.4.3.4 Storage Cask Criticality Evaluation

Under normal conditions, moderator is not present in the storage cask. However, access to the environment is possible via air inlets and the convective heat transfer annulus between the canister and the storage cask steel liner. This access provides paths for moderator intrusion during a flood. Off-normal conditions evaluate moderator intrusion into the convective heat ransfer annulus. Under accident conditions, it is assumed that the canister confinement fails and moderator intrudes into the canister and fuel cladding (100% failure) is evaluated along with moderator density variation. The accident condition analyses also examine the effect of interior/exterior moderator density variations.

Using the storage cask criticality model, an evaluation is performed of moderator intrusion into the heat transfer annulus under off-normal conditions and into the canister under accident conditions. Table 6.4-6 shows the storage cask multiplication factors at various conditions. Under normal dry conditions, maximum k_{eff}, including biases and uncertainty, is 0.4503, which is well subcritical. The CSAS output file (including an input listing) is shown in Figure 6.7-3. Under off-normal conditions involving flooding of the heat transfer annulus, the k_{eff} of the cask is even less. Under accident conditions involving full moderator intrusion into the canister and fuel clad gap, the maximum k_{eff} of the cask is 0.9018. The CSAS output file (including an input listing) is shown in Figure 6.7-4. Similar to the transfer cask analysis, the storage cask accident condition moderator density study evaluates a monotonic decrease in reactivity with moderator density inside and outside the cask. Thus, the NAC-MPC storage cask containing 36 fuel assemblies of the most reactive Yankee Class type in the most reactive configuration is well below the 0.95 NRC criticality safety limit, including all biases and uncertainties under normal, off-normal and accident conditions.

Based on the results of the criticality analysis for the transfer cask and the storage cask presented in Tables 6.4-5 and 6.4-6, respectively, there is no significant impact on system reactivity when changing reflector dimensions and material composition.

6.4.3.5 Storage and Transfer Cask Evaluation for a Basket Containing Enlarged Fuel Tubes

The maximum reactivity, fully moderated, cask models documented in Section 6.4.3.3 and 6.4.3.4 are evaluated with four enlarged fuel tubes replacing standard fuel tubes (BORAL sheets on four sides) on the basket periphery. As expected, the reactivity of these systems increases slightly due to the increased neutron interaction between fuel tubes in those locations where BORAL sheets were removed. Adjusting for the 0.004 Δk_{eff} associated with the assembly movement in the tubes results in a maximum bias and uncertainty adjusted k_{eff} (k_s) of 0.9175 for transfer conditions and 0.9182 for a hypothetical storage accident condition involving full moderator intrusion. Both storage and transfer maximum reactivities for the enlarged fuel tube basket are, therefore, well below the 0.95 criticality safety limit.

Table 6.4-1 Assembly Type Reactivity Evaluations

Assembly	**Initial Enrichment (wt % ^{235}U)**	**In Basket k_{eff}**	**σ**
Westinghouse Type A[1]	4.94	0.8642	0.00105
Westinghouse Type B	4.94	0.8664	0.00102
United Nuclear Type A	4.00	0.8974	0.00087
United Nuclear Type B[2]	4.00	0.8974	0.00106
Exxon Type A	4.00	0.8870	0.00111
Exxon Type B	4.00	0.8877	0.00111
Combustion Engineering Type A	3.90	0.8943	0.00060
Combustion Engineering Type B	3.90	0.8939	0.00163
Reconfigured Fuel Assembly	4.00	0.6280	0.0007

1. At an enrichment of 4.97 wt % ^{235}U, k_{eff} is 0.8670.
2. At an enrichment of 4.03 wt % ^{235}U, k_{eff} is 0.8992.

Table 6.4-2 Basket Tolerance Reactivity Evaluations

Analysis	**k_{eff}**	**σ**	**Δk_{eff}**
Nominal	0.8981	0.0007	-
Fuel Tube Maximum Opening	0.9018	0.0007	0.0037
Fuel Tube Minimum Opening	0.8916	0.0007	-0.0065
Disk Maximum Opening	0.8972	0.0007	-0.0009
Disk Minimum Opening	0.8991	0.0008	0.0010
Disk Maximum Thickness	0.8987	0.0008	0.0006
Disk Minimum Thickness	0.8972	0.0008	-0.0009
Loose Packed Disk Opening	0.8974	0.0008	-0.0007
Close Packed Disk Opening	0.8993	0.0007	0.0012

Table 6.4-3 Fuel Movement Reactivity Evaluations

Assembly Movement	Boundary Conditions	k_{eff}	σ	Δk_{eff}
Nominal	Reflective	0.8981	0.0007	-
Upper Right Corner	Mirrored	0.8954	0.0007	-0.0027
Upper Right Corner	Periodic	0.8943	0.0007	-0.0038
Lower Left Corner	Mirrored	0.8977	0.0007	-0.0004
Lower Left Corner	Periodic	0.8978	0.0008	-0.0003
Upper Left Corner	Mirrored	0.8963	0.0007	-0.0018
Upper Left Corner	Periodic	0.8961	0.0008	-0.0020
Right Side	Mirrored	0.8949	0.0007	-0.0032
Right Side	Periodic	0.8951	0.0007	-0.0030
Left Side	Mirrored	0.8978	0.0007	-0.0003
Left Side	Periodic	0.8972	0.0007	-0.0009

Table 6.4-4 Tube Movement Reactivity Evaluations

Tube Movement	Boundary Conditions	k_{eff}	σ	Δk_{eff}
Nominal	Reflective	0.8981	0.0007	-
Upper Right Corner	Mirrored	0.8999	0.0007	0.0018
Upper Right Corner	Periodic	0.8979	0.0007	-0.0002
Lower Left Corner	Mirrored	0.8984	0.0008	0.0003
Lower Left Corner	Periodic	0.8962	0.0007	-0.0019
Upper Left Corner	Mirrored	0.8991	0.0008	0.0010
Upper Left Corner	Periodic	0.8959	0.0007	-0.0022
Right Side	Mirrored	0.9005	0.0008	0.0024
Right Side	Periodic	0.8966	0.0007	-0.0015
Left Side	Mirrored	0.8968	0.0007	-0.0013
Left Side	Periodic	0.8976	0.0007	-0.0005

Table 6.4-5 Criticality Results for Transfer Cask

Cask Pitch (cm)	**Basket Configuration**	**H_2O Inside (density g/cc)**	**H_2O Outside (density g/cc)**	**^{10}B in BORAL**	k_{eff}	σ	k_s [1]
319.71	Nominal	1.0	1.0	100%	0.85035	0.00076	0.8684
319.71	Nominal	1.0	1.0	75%	0.86504	0.00070	0.8831
319.71	Worst Case	1.0	1.0	75%	0.87422	0.00076	0.8923
319.71	Worst Case	1.0	0.0001	75%	0.87488	0.00076	0.8929
319.71	Worst Case	0.8	0.0001	75%	0.82355	0.00074	0.8416
319.71	Worst Case	0.6	0.0001	75%	0.76550	0.00069	0.7835
319.71	Worst Case	0.4	0.0001	75%	0.69378	0.00064	0.7118
319.71	Worst Case	0.2	0.0001	75%	0.60267	0.00051	0.6206
319.71	Worst Case	0.1	0.0001	75%	0.55065	0.00042	0.5686
319.71	Worst Case	0.05	0.0001	75%	0.51859	0.00034	0.5365
319.71	Worst Case	0.01	0.0001	75%	0.46634	0.00032	0.4843
319.71	Worst Case + Water in Gap	1.0	1.0	75%	0.88403	0.00074	0.9021

1. Includes a Δk of 0.004 due to radial movement of fuel assembly toward basket center.

Table 6.4-6 Criticality Results for Storage Cask

Cask Pitch (cm)	Basket Configuration	H_2O Inside (density g/cc)	H_2O[1] Outside (density g/cc)	^{10}B	k	σ	k_s[2]
457.2	Nominal	0.0001	0.0001	75%	0.43088	0.00029	0.4488
457.2	Worst Case	0.0001	1.0	75%	0.39800	0.00030	0.4159
457.2	"	0.0001	0.8	75%	0.39906	0.00031	0.4170
457.2	"	0.0001	0.6	75%	0.39869	0.00032	0.4166
457.2	"	0.0001	0.4	75%	0.40071	0.00031	0.4186
457.2	"	0.0001	0.2	75%	0.40963	0.00031	0.4276
457.2	"	0.0001	0.1	75%	0.42134	0.00031	0.4393
457.2	"	0.0001	0.05	75%	0.42924	0.00031	0.4472
457.2	"	0.0001	0.01	75%	0.43241	0.00030	0.4503
457.2	Worst Case + water in gap	1.0	1.0	75%	0.88376	0.00072	0.9018
457.2	"	0.8	0.8	75%	0.83228	0.00072	0.8503
457.2	"	0.6	0.6	75%	0.77378	0.00068	0.7918
457.2	"	0.4	0.4	75%	0.69781	0.00062	0.7158
457.2	"	0.2	0.2	75%	0.59996	0.00053	0.6179
457.2	"	0.1	0.1	75%	0.54264	0.00042	0.5606
457.2	"	0.05	0.05	75%	0.51048	0.00036	0.5284
457.2	"	0.01	0.01	75%	0.46246	0.00031	0.4804

1. Includes heat transfer annulus region.
2. Includes a Δk of 0.004 due to radial movement of fuel assembly toward basket center.

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6.5.1 Benchmark Experiments and Applicability

The criticality safety method is CSAS25 embedded in SCALE version 4.3 for the PC. CSAS25 includes: the SCALE Material Information Processor, BONAMI, NITAWL-II, and KENO-Va. The Material Information Processor generates number densities for standard compositions, prepares geometry data for resonance self-shielding, and creates data input files for the cross section processing codes. The BONAMI and NITAWL-II codes are used to prepare a resonance-corrected cross section library in AMPX working format. The KENO-Va code calculates the model k_{eff} using Monte Carlo techniques. The 27 group ENDF/B-IV neutron cross section library is used in this validation.

6.5.1.1 Description of Experiments

Sixty-three critical experiments were selected; nine Babcox and Wilcox (B&W) 2.46 wt % ^{235}U fuel storage (Baldwin), 10 Pacific Northwest Laboratory (PNL) 4.31 wt % ^{235}U lattice (Bierman, 1980), 21 PNL 2.35 and 4.31 wt % ^{235}U with metal reflectors (Bierman, 1979 & 1981), twelve PNL flux trap (Bierman 1980 and 1988) and 11 Valduc Critical Mass Laboratory (VCML) 4.74 wt % ^{235}U experiments, some involving moderator density variations (Manaranche). These experiments span a range of fuel enrichments, fuel rod pitches, neutron absorber sheet characteristics, shielding materials and geometries that are typical of LWR fuel in a cask.

The experiments are evaluated using three-dimensional models, as close to the actual experiment as possible, to achieve accurate results. Stochastic Monte Carlo error is kept within ±0.1 percent by executing at least 1,000 neutrons/generation for more than 400 generations.

6.5.1.2 Applicability of Experiments

All of the experiments chosen in this validation are applicable to either PWR, including Yankee Class, or BWR fuel. Fuel enrichments have covered a range from 2.35 up to 4.74 wt % ^{235}U typical of LWR fuel presently used. The experiment fuel rod and pitch characteristics are within the range of standard PWR or BWR fuel rods (i.e., pellet diameters from 0.78 to 1.2 cm, rod outside diameters from 0.95 to 1.88 cm and pitches from 1.26 to 1.87 cm). This is particularly true of the VCML (PWR rod type) and B&W experiments (BWR rod type). The H/U volume ratios of the experimental fuel arrays are within the range of PWR fuel assemblies (1.6 to 2.32) and BWR fuel assemblies (1.6 to 1.9).

For Yankee Class fuel, the majority of the Zircaloy-clad fuel is enriched below 4.03 wt % ^{235}U. For the stainless steel-clad fuel, the maximum enrichment is 4.97 wt % ^{235}U, which is just outside the benchmark experimental range. However, the stainless steel-clad fuel is much less reactive than the Zircaloy clad and is not limiting. Also, in the case of the Yankee Class fuel, the pellet diameter varies from 0.747 to 0.789 cm, the rod outside diameter varies from 0.864 to 0.927 cm and the pitch varies from 1.07 to 1.20 cm, and the resultant H/U volume ratio varies from 1.28 to 1.57. These fuel parameters are all slightly outside of the range of experiments, but given the lack of statistically significant trends as demonstrated in Figures 6.5-2 through 6.5-7, confidence in criticality prediction by extrapolation to the Yankee fuel parameters is high.

Experiments covered the geometry and neutron absorber sheet arrangements typical of NAC basket designs. This included flux trap gap spacings of 3.81 cm such as in the NAC-STC basket and gap spacing as low as 1.91 cm as in the NAC-MPC. The ^{10}B neutron absorber loadings are also typical of NAC basket designs (0.005 to 0.025). The experiments covered the influence of water and metal reflector regions, including steel and lead, which are present in storage and transport cask shielding.

Confidence in predicting criticality, including bias and uncertainty, has been demonstrated for LWR fuel with enrichments up to 4.74 wt % ^{235}U and, based on the lack of significant trend with enrichment, confidence in extrapolating up to 4.97 wt % ^{235}U is high. Confidence in predicting criticality has been demonstrated for storage and transport arrays using flux trap or single neutron absorber sheet or simple spacing criticality control. Confidence in predicting criticality has been demonstrated for LWR fuel storage and transport arrays next to water and metal reflector regions.

6.5.2 Results of Benchmark Calculations

The k-effective results for the experiments are shown in Table 6.5-1, and a frequency distribution plot is provided in Figure 6.5-1. Five sets of cases are presented: Set 1 - B&W, Set 2 - PNL lattice, Set 3 - PNL reflector, Set 4 - PNL flux trap and Set 5 - VCML critical experiments.

The overall average and standard deviation of the sixty-three cases is 0.9948 ± 0.0044. The average Monte Carlo error (statistical convergence) is ±0.0012 for the sixty-three cases. This uncertainty component is statistically subtracted from the uncertainties because it is previously included in the above standard deviation. The KENO-Va models are three-dimensional, fully explicit representations (no homogenization) of the experimental geometry. Therefore, the uncertainty due to limitations of geometrical modeling is taken to be 0.0. The experiments modeled cover the range

Table 6.5-1 KENO-Va and 27 Group Library Validation Statistics (continued)

Criticals	Configuration	wt % ^{235}U	Pitch (cm)	Clad OD (cm)	Pellet OD (cm)	H/U	Sol. B (ppm)	Poison	g $^{10}B/cm^2$	Gap(cm)	Gap Den.	Ave. Gfis	K_{eff}	σ
Set 4														
PNL-229	2x2 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	Aluminum	0	3.81	0.9982	22.4	0.9989	0.0012
PNL-230	2x2 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.05	3.75	0.9982	21.7	0.9921	0.0012
PNL-228	2x2 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.13	3.73	0.9982	21.7	0.9911	0.0012
PNL-214	2x2 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.36	3.73	0.9982	21.7	0.9968	0.0013
PNL-231	2x2 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.45	3.71	0.9982	21.7	0.9938	0.0012
PNL-127	2x1 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.026	0.64	0.9982	21.8	0.9934	0.0010
PNL-126	2x1 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.026	1.54	0.9982	21.8	0.9931	0.0010
PNL-123	2x1 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.026	3.80	0.9982	21.8	0.9943	0.0010
PNL-125	2x1 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.026	5.16	0.9982	21.8	0.9932	0.0010
PNL-124	2x1 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	BORAL	0.026	INF	0.9982	21.8	0.9949	0.0010
PNL-123-S	2x1 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	Steel	0	3.80	0.9982	22.1	0.9920	0.0010
PNL-124-S	2x1 Flux Trap	4.31	1.89	1.415	1.265	1.6	0	Steel	0	INF	0.9982	21.9	0.9962	0.0010
												Average	0.9941	0.0022
Set 5														
VCML	2x2 Water Gap	4.74	1.35	0.94	0.79	2.3	0	NA	NA	1.90	0	22.0	0.9922	0.0013
VCML	2x2 Water Gap	4.74	1.35	0.94	0.79	2.3	0	NA	NA	1.90	0.0323	22.0	0.9889	0.0013
VCML	2x2 Water Gap	4.74	1.35	0.94	0.79	2.3	0	NA	NA	1.90	0.2879	22.1	0.9957	0.0013
VCML	2x2 Water Gap	4.74	1.35	0.94	0.79	2.3	0	NA	NA	1.90	0.5540	22.2	1.0053	0.0011
VCML	2x2 Water Gap	4.74	1.35	0.94	0.79	2.3	0	NA	NA	2.50	0.9982	22.3	0.9955	0.0012
VCML	2x2 Water Gap	4.74	1.35	0.94	0.79	2.3	0	NA	NA	5.00	0.9982	22.5	0.9948	0.0013
VCML	Square Lattice	4.74	1.26	0.94	0.79	1.8	0	NA	NA	NA	NA	22.2	0.9958	0.0012
VCML	Square Lattice	4.74	1.35	0.94	0.79	2.3	0	NA	NA	NA	NA	22.0	0.9952	0.0012
VCML	Square Lattice	4.74	1.60	0.94	0.79	3.8	0	NA	NA	NA	NA	23.3	0.9989	0.0013
VCML	Square Lattice	4.74	2.10	0.94	0.79	7.6	0	NA	NA	NA	NA	24.0	0.9974	0.0012
VCML	Square Lattice	4.74	2.52	0.94	0.79	11.5	0	NA	NA	NA	NA	24.2	0.9977	0.0011
												Average	0.9961	0.0041

Table 6.5-2 Correlation Coefficient for Linear Curve-Fit of Critical Benchmarks

Correlation Studied	Correlation Coefficient (R)
k_{eff} versus enrichment	0.361
k_{eff} versus rod pitch	0.328
k_{eff} versus H/U volume ratio	0.246
k_{eff} versus ^{10}B loading	0.069
k_{eff} versus average group causing fission	0.133
k_{eff} versus flux gap thickness	0.137

Table 6.5-3 Most Reactive Configuration System Parameters

Parameters	Value
Enrichment (wt % ^{235}U)(2)	4.0
Rod pitch (cm)	1.1887
H/U volume ratio	1.52
^{10}B loading (g/cm^2)	0.01
Average group causing fission	21.6(1)
Flux gap thickness (cm)	1.9 to 2.25

(1) 21.7 for the maximum reactivity enlarged fuel tube evaluation.
(2) Minor variations in the maximum enrichment due to fuel fabrication tolerances are considered in Section 6.4.3.1.

Table 12A2-1

Fuel Assembly Limits (Continued)

ii. Stainless Steel-Clad Fuel:	As specified in Table 12A2-2 for the applicable fuel assembly type.
e. Nominal Original Fuel Assembly Length:	≤ 111.8 inches
f. Nominal Original Fuel Assembly Width:	≤ 7.64 inches
g. Maximum Weight:	≤ 850 lbs, including RFA
h. Maximum mass U per RFA:	66.33 kg

3. Uranium oxide Yankee Class fuel requiring preferential loading to meet CANISTER reduced heat load configurations.
   a. Fuel shall be as described in Items A1 and/or A2, except that the maximum fuel assembly decay heat is limited to 320 watts.
   b. Fuel assemblies having a decay heat up to 320 watts may be loaded in any fuel loading position.

B. Quantity per CANISTER:
Up to 36 INTACT FUEL ASSEMBLIES and RFAs to the maximum content weight limit of 30,600 pounds.

C. INTACT FUEL ASSEMBLIES and RFAs shall not contain control components.

D. INTACT FUEL ASSEMBLIES shall not contain empty fuel rod positions. A solid Zircaloy or stainless steel rod that would displace an equivalent amount of water as an intact fuel rod shall replace any missing fuel rods.

Table 12A2-2 INTACT FUEL ASSEMBLY Characteristics

Fuel Assembly Type	Combustion Engineering Type A	Combustion Engineering Type B	Exxon Type A	Exxon Type B	Exxon Type A	Exxon Type B	Westinghouse Type A	Westinghouse Type B	United Nuclear Type A	United Nuclear Type B
ASSEMBLY CONFIGURATION[2]										
Assembly Length (cm)	283.9	283.9	283.3	283.3	283.9	283.9	282.6	282.6	282.4	282.4
Assembly Width (cm)	19.2	19.2	19.3	19.3	19.3	19.3	19.3	19.3	19.4	19.4
Assembly Weight (kg)	352	350.6	372	372	372	372	408.2	408.2	385.5	385.5
Enrichment-wt. % ^{235}U										
Maximum	3.93	3.93	4.03	4.03	4.03	4.03	4.97	4.97	4.03	4.03
Minimum	3.66	3.66	3.46	3.46	3.46	3.46	4.90	4.90	3.96	3.96
Max. Burnup (MWD/MTU)	36,000[1]	36,000[1]	36,000	36,000	36,000	36,000	32,000	32,000	32,000	32,000
Max. Initial Heavy Metal KgU/assembly	239.4	238.4	239.4	238.4	239.4	238.4	286.9	286.0	245.6	244.6
Min. Cool Time (yr)	8.1[1]	8.1[1]	16.0	16.0	9.0	9.0	21.0	21.0	13.0	13.0
Max. Decay Heat (kW)	0.347[1]	0.347[1]	0.269	0.269	0.331	0.331	0.264	0.264	0.257	0.257
FUEL ROD CONFIGURATION										
Fuel Rod Pitch (cm)	1.20	1.20	1.20	1.20	1.20	1.20	1.07	1.07	1.19	1.19
Active Fuel Length (cm)	231.1	231.1	231.1	231.1	231.1	231.1	234.0	234.0	231.1	231.1
Rod OD (cm)	0.93	0.93	0.93	0.93	0.93	0.93	0.86	0.86	0.93	0.93
Clad ID (cm)	0.81	0.81	0.81	0.81	0.81	0.81	0.76	0.76	0.81	0.81
Clad Material	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	Zircaloy	SS	SS	Zircaloy	Zircaloy
Pellet OD (cm)	0.79	0.79	0.79	0.79	0.79	0.79	0.75	0.75	0.79	0.79
Rods per Assembly	231	230	231	230	231	230	305	304	237	236

1. Combustion Engineering fuel may be loaded at a maximum burnup of 32,000 MWD/MTU, a minimum enrichment of 3.5 wt% ^{235}U and cool time of 8.0 years. The maximum decay heat for this assembly is 0.304 kW.

2. Type A and Type B configurations identify variations in the arrangement of the outer row of fuel rods that accommodate the insertion of control blades in the reactor.