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Criticality Analysis of the Donald C. Cook Nuclear Plant New Fuel Storage Vault with Credit for Integral Fuel Burnable Absorbers

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1.0 Introduction

This report presents the results of a criticality analysis of the American Electric Power Donald C. Cook Nuclear Plant New Fuel Storage Vault (NFSV) with credit for Integral Fuel Burnable Absorbers (IFBA).

The NFSV rack design considered herein is an existing array of Donald C. Cook Nuclear Plant NFSV unpoisoned racks previously qualified for storage of Westinghouse 15x15 STD and OFA, and 17x17 STD and OFA fuel assemblies with maximum enrichments up to 4.55 w/o ^{235}U.

In this analysis, credit for IFBA will be used to allow fuel enrichments up to 5.0 w/o ^{235}U.

The Donald C. Cook NFSV rack analysis is based on maintaining $K_{eff} \leq 0.95$ under full water density conditions and ≤ 0.98 under low water density (optimum moderation) conditions.

1.1 Design Description

The Donald C. Cook fresh fuel rack storage rack radial layout is depicted in Figure 1 on page 11 and the axial layout is shown in Figure 2 on page 12, with nominal dimensions provided on each figure.

The fuel parameters relevant to this analysis are given in Table 1 on page 8. With the simplifying assumptions employed in this analysis (no grids, sleeves, axial blankets, etc.), the various types of Westinghouse 15x15 and 17x17 fuel (V5, V5H, V+, and P+) are beneficial in terms of extending burnup capability and improving fuel reliability, but do not contribute to any meaningful increase in the basic assembly reactivity. Therefore, future fuel assembly upgrades do not require a criticality analysis if the fuel parameters specified in Table 1 continue to remain bounding.

1.2 Design Criteria

Criticality of fuel assemblies in a fuel storage rack is prevented by the design of the rack which limits fuel assembly interaction. This is done by fixing the minimum separation between fuel assemblies.

The design basis for preventing criticality outside the reactor is that, including uncertainties, there is a 95 percent probability at a 95 percent confidence level that the effective neutron multiplication factor, K_{eff}, of the NFSV when flooded with full density water will be less than 0.95 as recommended by ANSI 57.3-1983 and NRC guidance(1). Furthermore, the effective neutron multiplication factor, K_{eff}, of the NFSV under low water density (optimum moderation) conditions will be less than 0.98 as recommended by NUREG-0800.

2.0 Analytical Methods

2.1 Reactivity Equivalencing for IFBA Credit

Storage of fuel assemblies with higher initial enrichments than 4.55 w/o ^{235}U is achievable by means of the concept of reactivity equivalencing. Reactivity equivalencing is predicated upon the reactivity decrease associated with the addition of IFBA fuel rods. A series of reactivity calculations is performed to generate a set of enrichment-IFBA ordered pairs which all yield an equivalent K_{eff} when the fuel is stored in the Donald C. Cook Nuclear Plant fresh fuel racks. The data points on the reactivity equivalence curve are generated with the transport theory computer code, PHOENIX-P(3). PHOENIX-P is a depletable, two-dimensional, multigroup, discrete ordinates, transport theory code which utilizes a 42 energy group nuclear data library.

PHOENIX-P has been used to demonstrate its predictive capability in a series of comparisons against direct experimental data from critical experiments. These comparisons provide a good assessment of the code's ability to predict key physics parameters over a wide range of lattice variations. Reactivity comparisons are accomplished by comparing appropriate predictions to Strawbridge and Barry's 101 criticals(4) and the Babcock and Wilcox (B&W) cores XI-1,2,7,8,9 and cores XIV-1,6 spatial criticals(5,6,7).

The range of lattice parameters of the 101 criticals are given in Table 2 on page 8. The resulting mean PHOENIX-P k_{eff} for all 101 criticals is 1.00222 with a standard deviation of 0.00809. This shows PHOENIX-P results to be in excellent agreement with experimental data for all dependent parameters, with no significant bias or trends as a function of lattice parameters. For the specific set of lattice parameters used in this report, the standard deviation of PHOENIX-P K_{eff} results would be much smaller thus allowing PHOENIX-P to be used for reactivity equivalencing calculations.

The core loadings and compositions studied in the seven B&W core spatial criticals are given in Table 3 on page 9. The resulting mean K_{eff} of the seven critical experiments was 1.00151 with a standard deviation of 0.00098. The overall mean core K_{eff} for this set of critical experiments with diverse lattice configurations is in very good agreement with expected experimental values. The overall standard deviation indicates excellent stability of the PHOENIX-P library and methodology.

Uncertainties associated with the IFBA dependent reactivities computed with PHOENIX-P are accounted for in the development of the individual reactivity equivalence limits. An uncertainty of approximately 10% of the total number of IFBA rods is accounted for in the development of the IFBA requirements. Additional information concerning the specific uncertainties included in the Donald C. Cook IFBA credit limit is provided in Section 3.2 of this report.

3.0 Criticality Analysis of Fresh Fuel Racks

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for storage of fresh fuel in the Donald C. Cook Nuclear Plant New Fuel Storage Vault (NFSV).

Section 3.1 summarizes previous reactivity calculations performed for the fresh fuel storage racks with enrichments up to 4.55 w/o ^{235}U and Section 3.2 describes the analysis which allows for storage of assemblies with enrichments above 4.55 w/o U^{235} and up to 5.00 w/o ^{235}U by taking credit for Integral Fuel Burnable Absorbers (IFBAs).

3.1 Reactivity Calculations

Previous calculations(8) have been performed for the Donald C. Cook Nuclear Plant New Fuel Storage Vault (NFSV) which show that fuel assemblies with enrichments up to 4.55 w/o ^{235}U can be safely stored in the NFSV. The maximum 95/95 K_{eff} determined for full water density flooding is 0.9495 and the maximum 95/95 K_{eff} determined for optimum moderation flooding is 0.8974. Based on these previously calculated K_{eff} values, the acceptance criteria are met for both full and optimum water density flooding of the Donald C. Cook Nuclear Plant fresh fuel storage racks.

3.2 IFBA Credit Reactivity Equivalencing

Storage of fuel assemblies with enrichments greater than 4.55 w/o ^{235}U in the fresh fuel storage racks is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with the addition of Integral Fuel Burnable Absorbers (IFBAs). IFBAs consist of neutron absorbing material applied as a thin ZrB_2 coating on the outside of the UO_2 fuel pellet. As a result, the neutron absorbing material is a non-removable or integral part of the fuel assembly once it is manufactured.

Two analytical techniques are used to establish the criticality criteria for the storage of IFBA fuel in the fresh fuel storage racks. The first method uses reactivity equivalencing to establish the poison material loading required to meet the criticality limits. The poison material considered in this analysis is a zirconium diboride (ZrB_2) coating manufactured by Westinghouse. The second method uses the fuel assembly infinite multiplication factor to establish a reference reactivity. The reference reactivity point is compared to the fuel assembly peak reactivity to determine its acceptability for storage in the fresh fuel racks.

3.2.1 IFBA Requirement Determination

A series of reactivity calculations are performed to generate a set of IFBA rod number versus enrichment ordered pairs which all yield the equivalent K_{eff} when the fuel is stored in the fresh fuel storage racks. The following assumptions were used for the IFBA rod assemblies in the PHOENIX-P models:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 7 for fuel parameters). For this calculation, the Westinghouse 17x17 OFA assembly is the most reactive of the fuel assembly types considered.
2. The fuel assembly is modeled at its most reactive point in life.
3. The fuel pellets are modeled assuming 96% theoretical density and no dishing fraction.
4. No credit is taken for any natural enrichment or reduced enrichment axial blankets.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. The IFBA absorber material is a zirconium diboride (ZrB_2) coating on the fuel pellet. Each IFBA rod has a nominal poison material loading of 1.50 milligrams ^{10}B per inch (1.0X IFBA loading), which is the minimum standard loading offered by Westinghouse for 17x17 OFA fuel assemblies.
8. The IFBA ^{10}B loading is reduced by 5% to conservatively account for manufacturing tolerances and then by an additional 19% to conservatively model a minimum poison length of 116.9 inches. Calculations show that it is conservative to model IFBA in two dimensional geometry by smearing the IFBA poison length over the entire fuel stack.
9. The moderator is pure water (no boron) at a temperature of 68°F with a density of 1.0 gm/cm^3.
10. The array is infinite in lateral (x and y) and axial (vertical) extent. This precludes any neutron leakage from the array.

Figure 3 on page 13 shows the constant K_{eff} contour generated for the fresh fuel storage racks. Note the endpoint at 0 IFBA rods where the enrichment is 4.55 w/o and at 32(1.0X) IFBA rods where the enrichment is 5.00 w/o. The interpretation of the endpoint data is as follows: the reactivity of the fuel rack array when filled with fuel assemblies enriched to 5.00 w/o ^{235}U with each containing 32(1.0X) IFBA rods is equivalent to the reactivity of the rack when filled with fuel assemblies enriched to 4.55 w/o and containing no IFBA rods. The data in Figure 3 on page 13 is also provided on Table 4 on page 10 for both 1.0X and 2.0X IFBA rods.

It is important to recognize that the curve in Figure 3 on page 13 is based on reactivity equivalence calculations for the specific enrichment and IFBA combinations in actual rack geometry (and not just on simple comparisons of individual fuel assembly infinite multiplication factors). In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered.

The IFBA requirements of Figure 3 on page 13 were developed based on the standard IFBA patterns used by Westinghouse. However, since the worth of individual IFBA rods can change depending on position within the assembly (due to local variations in thermal flux), studies were performed to evaluate this effect and a conservative reactivity margin was included in the

development of the IFBA requirement to account for this effect. This assures that the IFBA requirement remains valid at intermediate enrichments where standard IFBA patterns may not be available and provides margin for future changes in current standard IFBA patterns. In addition, to conservatively account for calculational uncertainties, the IFBA requirements of Figure 3 on page 13 also include a conservatism of approximately 10% on the total number of IFBA rods at the 5.00 w/o end (i.e., about 3 extra IFBA rods for a 5.00 w/o fuel assembly).

Additional IFBA credit calculations were performed to examine the reactivity effects of higher IFBA linear ^{10}B loadings (1.5X and 2.0X). These calculations confirm that assembly reactivity remains constant provided the net ^{10}B material per assembly is preserved. Therefore, with higher IFBA ^{10}B loadings, the required number of IFBA rods per assembly can be reduced by the ratio of the higher loading to the nominal 1.0X loading. For example, using 2.0X IFBA in 5.00 w/o fuel assemblies allows a reduction in the IFBA rod requirement from 32 IFBA rods per assembly to 16 IFBA rods per assembly (32 divided by the ratio 2.0X/1.0X).

3.2.2 Infinite Multiplication Factor

The infinite multiplication factor, K_∞, is used as a reference criticality reactivity point, and offers an alternative method for determining the acceptability of fuel assembly storage in the fresh fuel storage racks. The reference K_∞ is determined for a fresh 4.55 w/o fuel assembly.

The fuel assembly K_∞ calculations are performed using the PHOENIX-P computer code . The following assumptions were used to develop the infinite multiplication factor model:

1. The Westinghouse 17x17 OFA fuel assembly was analyzed (see Table 1 on page 8 for fuel parameters). The fuel assembly is modeled at its most reactive point in life and no credit is taken for any burnable absorbers in the assembly.
2. All fuel rods contain uranium dioxide at an enrichment of 4.55 w/o ^{235}U over the entire length of each rod.
3. The fuel array model is based on a unit assembly configuration (infinite in the lateral and axial extent) in Donald C. Cook reactor geometry (no rack).
4. The moderator is pure water (no boron) at a temperature of 68° F with a density of 1.0 gm/cm^3.

Calculation of the infinite multiplication factor for the Westinghouse 17x17 OFA fuel assembly in the Donald C. Cook core geometry resulted in a reference K_∞ of 1.4857. This includes a 1% ΔK reactivity bias to conservatively account for calculational uncertainties. This bias is consistent with the standard conservatism included in the Donald C. Cook core design refueling shutdown margin calculations.

4.0 Summary of Criticality Results

For the storage of fuel assemblies in the Donald C. Cook Nuclear Plant New Fuel Storage Vault, the acceptance criteria for criticality requires the effective neutron multiplication factor, K_{eff}, to be less than or equal to 0.95, including uncertainties, under full water density flooded conditions and less than or equal to 0.98 under optimum moderation conditions.

This report and previous evaluations(8) shows that the acceptance criteria for criticality is met for the Donald C. Cook Fresh Fuel Storage Racks for the storage of Westinghouse 15x15 and 17x17 fuel assemblies with enrichments no greater than 4.55 w/o ^{235}U with no IFBA and fuel assemblies with enrichments up to 5.0 w/o ^{235}U with the minimum IFBA requirement of Section 3.2.

The analytical methods employed herein conform with ANSI N18.2-1973, "Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants," Section 5.7 Fuel Handling System; ANSI 57.3-1983, "Design Requirements for New Fuel Storage Facilities at Light Water Reactor Plants"; ANSI N16.9-1975, "Validation of Calculational Methods for Nuclear Criticality Safety"; and the NRC Standard Review Plan, Section 9.1.1, "New Fuel Storage".

Table 1. Fuel Parameters Employed in the Criticality Analysis

Parameter	Westinghouse 15x15 STD & OFA	Westinghouse 17x17 OFA	Westinghouse 17x17 STD
Number of Fuel Rods per Assembly	204	264	264
Rod Zirc-4 Clad O.D. (inch)	0.422	0.360	0.374
Clad Thickness (inch)	0.0243	0.0225	0.0225
Fuel Pellet O.D.(inch)	0.3659	0.3088	0.3225
Fuel Pellet Density (% of Theoretical)	96	96	96
Fuel Pellet Dishing Factor (%)	0.0	0.0	0.0
Rod Pitch (inch)	0.563	0.496	0.496
Number of Zirc-4 Guide Tubes	20	24	24
Guide Tube O.D. (inch)	0.533	0.474	0.482
Guide Tube Thickness (inch)	0.017	0.016	0.016
Number of Instrument Tubes	1	1	1
Instrument Tube O.D. (inch)	0.533	0.474	0.484
Instrument Tube Thickness (inch)	0.017	0.016	0.016

Table 2. Summary of Lattice Parameters for Strawbridge and Barry 101 Criticals

Lattice Parameter	Range
Enrichment (a/o)	1.04 to 4.07
Boron Concentration (ppm)	0 to 3392
Water to Uranium Ratio	1.0 to 11.96
Pellet Diameter (cm)	0.44 to 2.35
Lattice Pitch (cm)	0.95 to 4.95
Clad Material	none, aluminum, and stainless steel
Lattice Type	square and hexagonal
Fuel Density (g/cm^3)	7.5 to 18.9

Table 3. B&W Core Loadings and Compositions Studied

Core	Loading	Number of Fuel Rods	Number of Water-Filled Positions	Number of Pyrex Rods	Soluble Boron (ppm)
XI	1	4961	0	0	1511
	2	4808	153	0	1334
	7	4808	81	72	1031
	8	4808	9	144	794
	9	4808	9	144	779
XIV	1	4736	225	0	1289
	6	4736	201	24	1179

Table 4. Donald C. Cook Fresh Fuel Rack IFBA Requirement

Enrichment (w/o)	1.0X (1.50 mg-^{10}B/in) IFBA Rods In Assembly	1.5X (2.25 mg-^{10}B/in) IFBA Rods In Assembly	2.0X (3.00 mg-^{10}B/in) IFBA Rods In Assembly
4.55	0	0	0
4.66	8	6	4
4.77	16	12	8
4.88	24	18	12
5.00	32	24	16

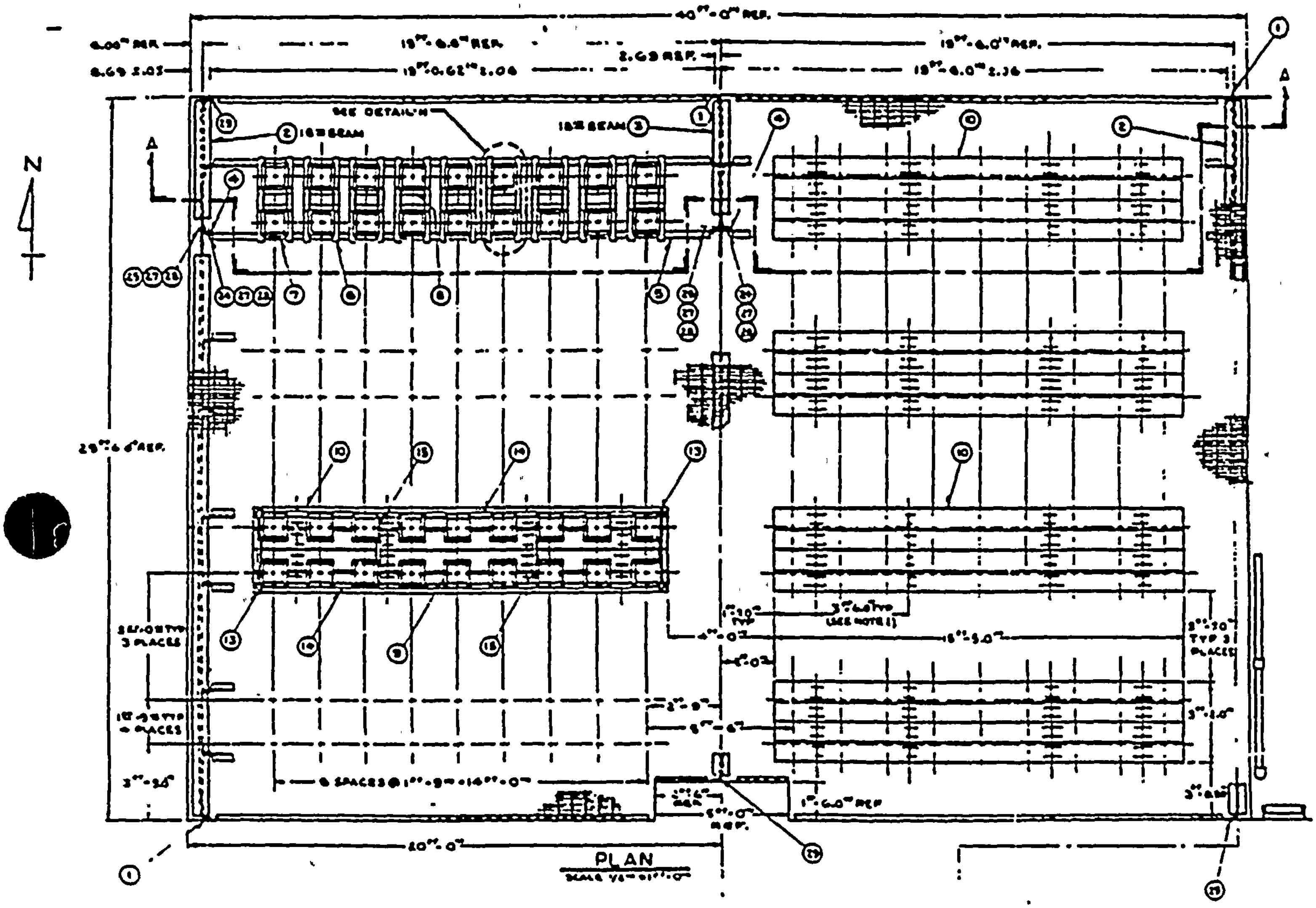

Figure 1. Donald C. Cook Nuclear Plant Fresh Fuel Rack Radial Layout

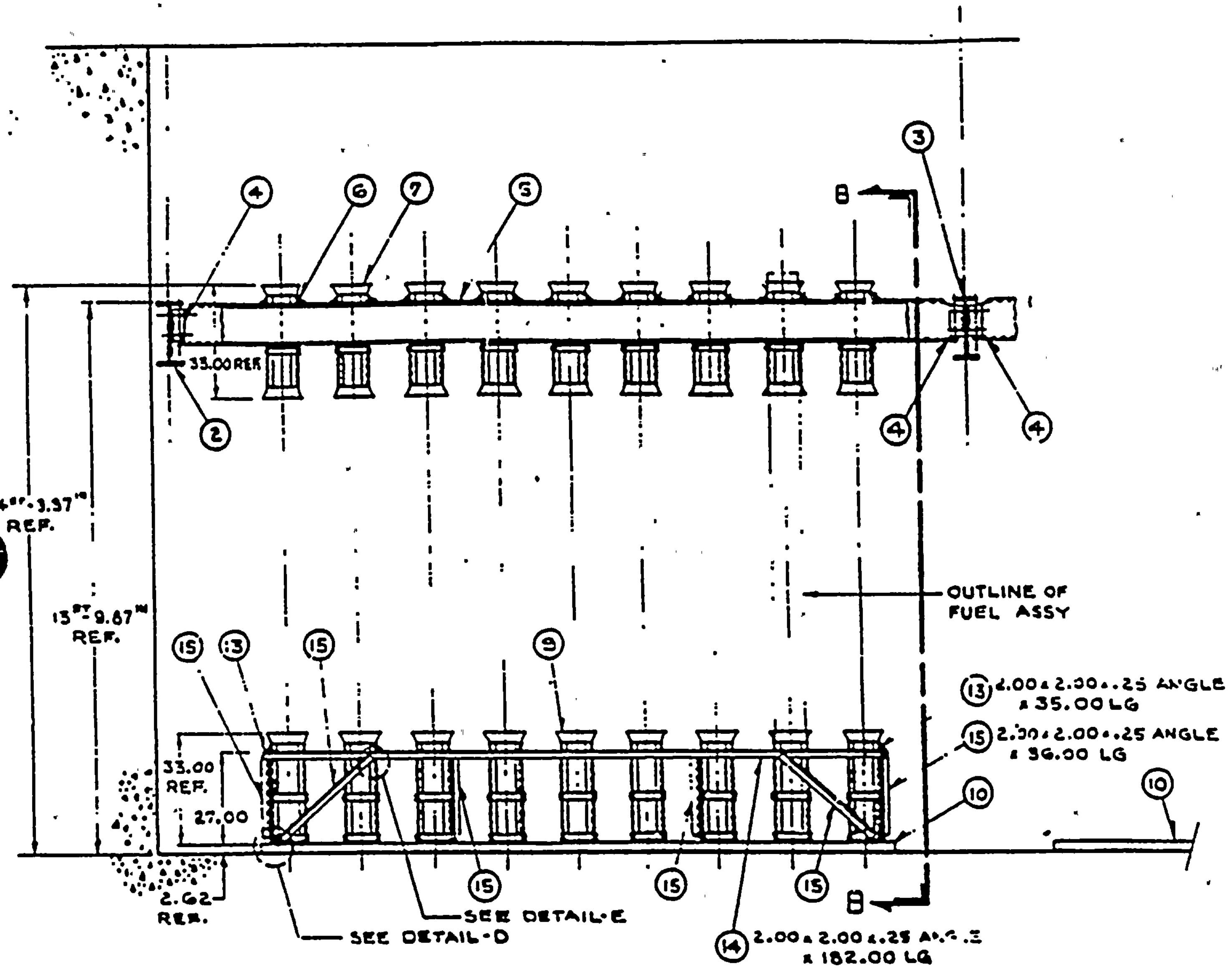

Figure 2. Donald C. Cook Nuclear Plant Fresh Fuel Rack Axial Layout

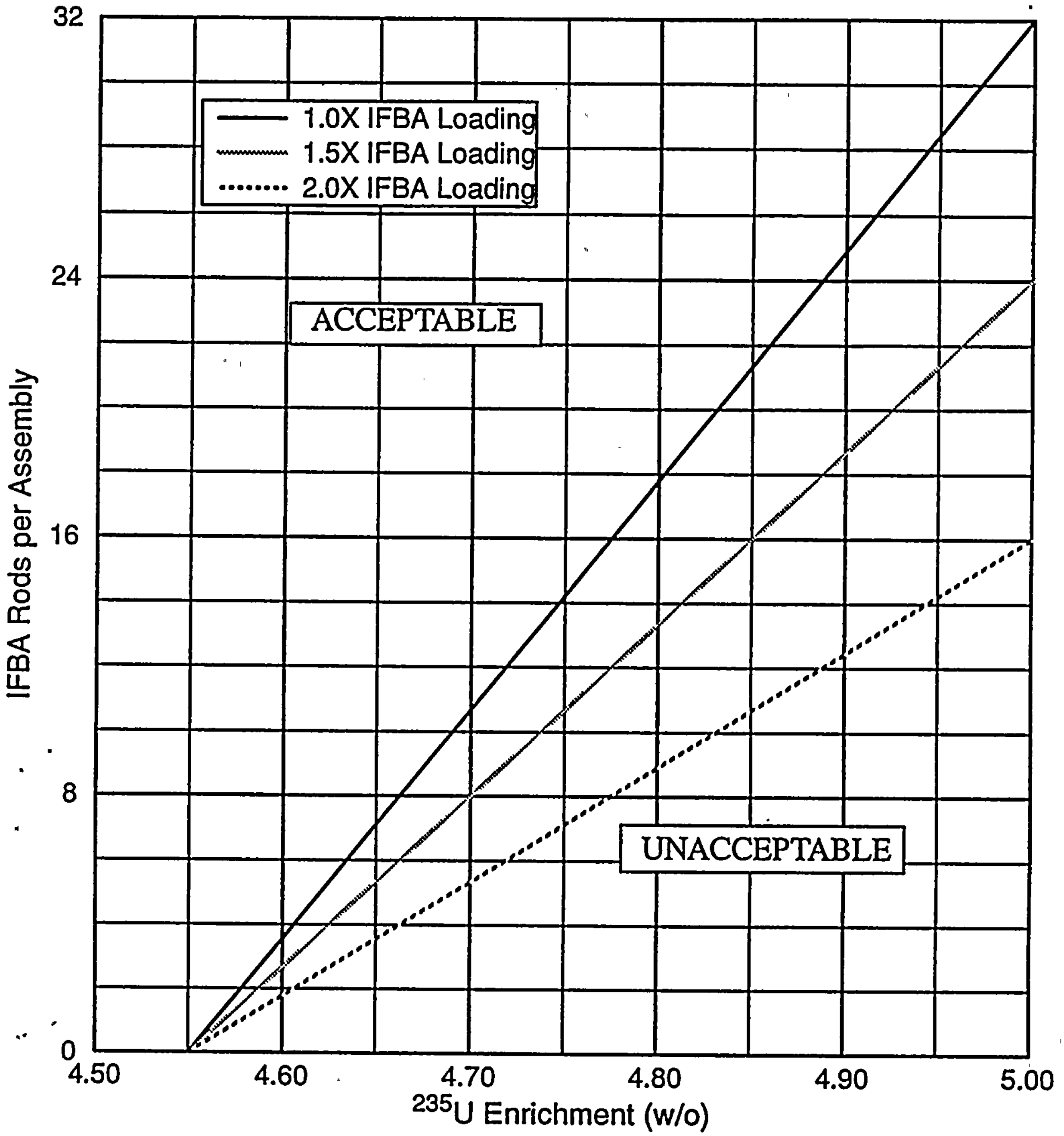

Figure 3. Donald C. Cook Nuclear Plant Fresh Fuel Rack IFBA Requirement

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