CRITICALITY SAFETY EVALUATION OF REGION 2

OF THE DIABLO CANYON SPENT FUEL STORAGE RACKS

WITH FUEL OF 5.0% ENRICHMENT

Prepared for the

PACIFIC GAS AND ELECTRIC COMPANY

by

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1.0 INTRODUCTION

The present study is part of an evaluation of the fuel storage facilities at the Diablo Canyon Power Plant in order to qualify the facilities for fuel of 5.0% average initial enrichment. This report addresses Region 2 of the spent fuel pool while companion reports evaluate Region 1 (HI-931076) and the new-fuel vault (HI-931075).

Region 2 of the storage rack is designed to accommodate spent fuel which has attained a minimum average burnup that is dependent on the average initial enrichment of the fuel assembly. These racks are unpoisoned and were previously qualified[1] for fuel of 4.5% enrichment burned to 34.5 MWD/KgU. They use a stainless-steel and water flux-trap between storage cells as a means of augmenting reactivity control. The previous curve of limiting burnups (up to 4.5% enrichment) is extended to encompass 5.0% enriched fuel in the present study. Both the Westinghouse standard and OFA fuel designs were considered. The effect of the axial distribution in burnup is also included as specified by Regulatory Guide 1.13 (draft, Rev.2).

Calculations were made with both the CASMO-3 program and the NITAWL-KENO-5a code package. CASMO-3 was used for burnup and restart calculations and to define an equivalent enrichment for use in the KENO-5a calculations. Both normal and accident conditions are assessed, including the consequences of a cask-drop accident. The cask-drop accident was evaluated for the purpose of eliminating any requirement for an exclusion area. Credit for the soluble poison normally present in the pool water is allowable under accident conditions (double contingency principle).

To assure the criticality safety under all conditions and to conform to the requirements of General Design Criterion 62, "Prevention of Criticality in Fuel Storage and Handling", the definitive criteria contained in the April 14, 1978 USNRC letter and draft Regulatory Guide 1.13 (Rev. 2) are applicable.

2.0 SUMMARY AND CONCLUSIONS

2.1 Normal Storage Conditions

The spent fuel storage racks in Region 2 are unpoisoned racks, using stainless steel boxes to define the storage cells. A water-gap between the steel walls of the storage cells affords a flux-trap to augment reactivity control. Initial calculations at 40 MWD/KgU burnup for both 5.0% Westinghouse standard and OFA fuel determined that the standard fuel gave a slightly higher reactivity in the storage rack (k_{eff} of 0.9088 without uncertainties) than the corresponding OFA fuel (corresponding k_{eff} of 0.8971). This is consistent with results of the previous evaluation[2]. Therefore, subsequent evaluations in Region 2 assumed the Westinghouse standard fuel type.

The analysis for fuel of 5.0% enrichment is based on determining the burnup required to obtain a reactivity less than 0.95, including all uncertainties. A limiting burnup of 40 MWD/KgU was selected, yielding a maximum reactivity of 0.9482 including the penalty associated with the axial burnup distribution. The calculational results for fuel of 5.0% enrichment burned to 40 MWD/KgU are summarized in Table 1. The original burnup limit curves [1,2] were extended to include the 5.0% enriched fuel and the updated curves are shown in Figure 1. For standard fuel, the limiting burnup curve in Figure 1 has been fitted to a polynomial expression that conservatively encompasses the calculated points. This expression, shown below, may be used to calculate the minimum burnup for any initial enrichment, E, up to 5.0%.

Acceptable Burnup in MWD/KgU (Standard Fuel)

$$= -36.50 + (26.71*E) - (3.734*E^2) + (0.2913*E^3)$$

For conservatism in evaluating the maximum k_{eff}, the enriched region was assumed to extend axially for the full length of the active fuel. For fuel assemblies with axial blankets, the reactivity effect of the axial distribution in burnup is negligible, primarily because the blanket of low enrichment fuel reduces the decrease in burnup at the ends of the assemblies that would otherwise occur. It is this low burnup region at the ends of the assemblies that causes the higher reactivity when blankets are not present. In the absence of blankets, the penalty is 0.0124 Δk for fuel with a full length enriched region (evaluated for 5.0% fuel at 40 MWD/KgU burnup). This bounds the case with axial blankets and results in a maximum k_{eff} of 0.9482 for 5.0% enriched fuel burned to 40 MWD/KgU. With axial blankets of natural UO_2, the corresponding maximum reactivity would be 0.9358.

Any boron burnable poison initially on the surface of the pellets in IFBA rods will be burned out by the time the assemblies have reached the minimum burnup required for unconditional storage in Region 2. Therefore, the use of IFBA rods in the fuel assemblies has no effect on the storage requirements in Region 2 of the pool.

As determined in the initial evaluation[1], the temperature coefficient of reactivity is positive, and a temperature of 150°F was used as the design basis temperature. Temperatures above 150°F are considered an accident condition for which credit may be taken for the presence of soluble boron in the pool water.

Based upon the calculations reported here (see Table 1 and Figure 1), it is concluded that fuel of 5.0% initial enrichment is acceptable for storage in Region 2 of the Diablo Canyon storage pool, provided the fuel has attained a minimum burnup of 40 MWD/KgU. OFA fuel and fuel of other initial enrichments that meet the minimum burnup specifications shown in Figure 1 are also acceptable with assurance that the maximum reactivity is within the regulatory limit.

Calculations were also made for checkerboard arrangements of fresh 5.0% enriched fuel. These calculations show that a checkerboard arrangement with empty cells (i.e: filled only with water or non-fissile bearing material) is acceptable with a maximum k_{eff} of 0.941. A linear (row by row) arrangement was unacceptable.

2.2 Abnormal/Accident Conditions

The reactivity consequences of abnormal/accident conditions were considered in the previous analysis[1] and found to be within acceptable bounds. However, with the higher enrichment fuel (5.0%), the consequence of a mis-placed fuel assembly could differ from that previously evaluated. In addition, the consequence of a cask drop accident has also been considered. In both cases, credit for the presence of soluble boron is necessary and is acceptable under accident conditions (double contingency principle).

Calculations with a mis-placed fuel assembly (fresh assembly of 5.0% enrichment accidentally loaded into a Region 2 cell) resulted in a k_{eff} of 0.978 (without uncertainties) with all other cells filled with fuel of the maximum permissible reactivity. To assure the maximum k_{eff} is maintained below 0.95, this would require an estimated 400 ppm soluble boron, which is well within the 2000 ppm normally maintained in the storage pool.

For the accident of crushing of the storage rack by a shipping cask, there is no clear definition of the post-accident fuel and rack configuration that might result. However, to bound possible post-accident configurations, calculations were made for several levels of postulated damage to the racks. These include the crushing of the water gap on one side of each cell, cascading to crushing of the opposite side. This could result in a k_{eff} of 0.981 (uncertainties not included) if the water gap on both sides of the cells are crushed to ½ inch over an infinite radial array of fuel

storage cells. This accident scenario would require 400 ppm boron and is believed to be a very conservative estimate of the consequences of the dropped cask accident. Any further crushing after the elimination of the inner and outer water gaps (reducing the water-to-fuel volume ratio within the fuel assemblies) would result in a reduction in reactivity.

The ultimate bounding condition would be the crushing of the racks until the water-gaps on all sides, both external to the steel box and the gap between the fuel and the box, are completely eliminated. Although this post-accident configuration is not credible, it could hypothetically increase the reactivity above criticality in the absence of soluble boron. With 2000 ppm soluble boron present in the pool water the k_{eff} would be 0.757 under the worst hypothetical accident scenario. Interpolating these data indicates that about 1160 ppm would be sufficient to reduce the maximum k_{eff} to less than 0.95 for any conceivable crushed configuration.

The following table lists the calculated k_{eff} (without uncertainties) for various postulated configurations assumed to result from a dropped cask:

Condition	KENO-5a Calculated k_{eff}
Reference intact cells	0.9092
Crushed to 1 inch water-gap	1.005
Crushed to ½ inch water-gap	1.062
Crushed to ½ inch gaps, 2 sides	0.981
Crushed to 0.1 inch water-gaps	1.104
Crushed to eliminate outer water-gap	1.119
Same condition with 2000 ppm soluble Boron	0.758
Crushed to eliminate outer and inner water-gap	1.124
Assembly crushed to 50% rod pitch	1.107
Assembly crushed to rods touching	0.959
Same conditions with 2000 ppm soluble Boron	0.858

Based on these analyses, it is concluded that 400 ppm of soluble boron is adequate to protect the spent fuel storage racks from a very conservative cask drop accident. Therefore, as long as there is at least 400 ppm soluble boron present in the pool water, an exclusion area is not necessary. However, procedures should be in place providing for increased frequency of measurements to assure the continued presence of the soluble boron, in the unlikely event of a cask drop accident.

3.0 CRITICALITY SAFETY ANALYSES

3.1 Fuel Assembly Specifications

The fuel assemblies used in the analyses are Westinghouse 17 x 17 standard fuel, the same as that used in the original analyses[1]. For OFA fuel (also considered in Reference 2), initial calculations confirm that, as expected, OFA fuel results in a lower reactivity* (k_{eff} of 0.8971 at 40 MWD/KgU without uncertainties) than the standard fuel (corresponding k_{eff} of 0.9088). Therefore, the standard fuel is controlling. Table 2 attached lists the design specifications for the fuel used in the analyses. The presence of a boron burnable poison coating on the fuel pellets (IFBA rods) does not affect the Region 2 storage requirements.

3.2 Storage Rack Specifications

The storage rack cell design, illustrated in Figure 2 attached, is a 0.090 inch thick stainless steel box of 8.85 inch inside dimension, arranged on a 10.929 inch lattice spacing. This arrangement provides a 1.899 inch water gap between the steel walls of the storage cells. The stainless steel tabs connecting the storage boxes was determined to have a slightly negative reactivity effect and were neglected in the primary calculations.

3.3 Manufacturing Tolerances and Uncertainties

The small reactivity increments associated with manufacturing tolerances obtained in the previous evaluation[1,2] were generally assumed to remain applicable. However, the higher 5.0% enrichment results in a slightly higher penalty due to (1) possible eccentric positioning of the assemblies in the racks and (2) the uncertainty in depletion calculations.

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* Evaluated for fuel of 5.0% initial enrichment burned to 40 MWD/KgU and restarted in the Region 2 storage rack.

Table 3 lists the manufacturing tolerance effects and includes the calculational uncertainties, yielding a total uncertainty of ± 0.0070 Δk for standard fuel and 0.0084 Δk for OFA fuel.

Fuel of 5.0% enrichment also requires an increase in the allowance for uncertainty in the depletion calculations. As in the original evaluation for 4.5% fuel, the depletion uncertainty was assumed to be 0.0005 times the burnup in MWD/KgU, which, for 40 MWD/KgU burnup, amounts to 0.0200 Δk and for 38.75 MWD/KgU is 0.0194

Numerous earlier calculations have demonstrated a continuous reduction in reactivity with storage time (after Xe decay) primarily due to Pu-241 decay and Am-241 growth. No credit is taken for this reduction in reactivity except to acknowledge an additional level of conservatism in the calculations.

3.4 Calculational Methodology

3.4.1 Computer Codes

The principal methods of analysis were CASMO-3, a two-dimensional multigroup transport theory code for fuel assemblies and NITAWL - KENO-5a, a three dimensional Monte Carlo code package, using the 27-group SCALE** cross-section library. The calculational methods used for the present evaluation are comparable to those used in the original calculations, differing only in that updated versions of the codes were used, i.e., CASMO-3 rather than CASMO-2E, and KENO-5a rather than KENO-4. Results of these codes are not significantly different from those of the earlier versions, and benchmarking of the updated codes resulted in a bias of 0.0000 ± 0.0024 for CASMO-3 and 0.0103 ± 0.0018 for NITAWL - KENO-5a (95%

** SCALE is an acronym for Standardized Computer Analyses for Licensing Evaluation, developed for the USNRC by the Oak Ridge National Laboratory.

probability, 95% confidence level[4]). A summary of the detailed bench-marking analyses is included in Appendix A.

CASMO-3 was also used both for burnup calculations and for restart calculations in the rack geometry. Since KENO cannot perform burnup analyses, CASMO-3 is used to define an equivalent enrichment, i.e., the U-235 enrichment that yields the same reactivity in the racks as the burned fuel. It was found that an enrichment of 1.698% yields the same reactivity in the storage racks as 5.0% standard Westinghouse fuel burned to 40 MWD/KgU.

In the geometric model used in the calculations, each fuel rod and its cladding were described explicitly in both the CASMO-3 and KENO-5a models. Reflecting boundary conditions (zero neutron current) were used in the radial direction which has the effect of creating an infinite array of storage cells in X-Y directions. In the KENO-5a model, the actual fuel assembly length was used in the axial direction, assuming thick (30 cm) water reflectors top and bottom. Monte Carlo (KENO-5a) calculations inherently include a statistical uncertainty due to the random nature of neutron tracking. To minimize the statistical uncertainty of the KENO-calculated reactivity, a minimum of 500,000 neutron histories in 1000 generations of 500 neutrons each, were accumulated in each calculation.

3.4.2 Axial Distribution in Burnup

Because of the higher burnup required for 5.0% fuel, it was necessary to assess the consequence of the axial distribution in burnup. Axial burnup distributions from detailed nodal analyses were provided by PG&E[5], as shown in Figure 3. Based upon these distributions, the axial dimension was divided into 10 zones of differing burnup, corresponding to an average burnup of 40 MWD/KgU. For each zone the equivalent enrichment (i.e., enrichments determined by CASMO-3 to yield the same reactivity in the rack as

the burned fuel) were determined. These enrichments were then used in a three dimensional KENO-5a calculation, assuming 30 cm water reflectors, to determine the effect of the axial distribution in burnup. For fuel of 5.0% enrichment burned to 40 MWD/KgU, the axial burnup effect was found to be 0.0124 Δk for the Westinghouse standard fuel, conservatively estimated for fuel without axial blankets.

For fuel assemblies with 6-inch axial blankets of natural UO_2, calculations determined that the incremental reactivity effect due to axially distributed burnups at 40 MWD/KgU is negligible in contrast to 0.0124 Δk for fuel assemblies in which the enriched zone extended the full length of the active fuel. The more conservative penalty for axial burnup (± 0.0124) was used in the present evaluation.

3.5 Analytical Results

The design basis fuel enrichment was 5.0%. Calculations for other enrichments and for OFA fuel are summarized in Table 4, all yielding the same maximum reactivity, evaluated on a conservative basis. The empirical fit to the bounding burnups are shown below for fuel of various initial enrichments (E in wt% U-235).

Acceptable Burnup in MWD/KgU (Standard Fuel)
$= -36.50 + (26.71*E) - (3.734*E^2) + (0.2913*E^3)$

For OFA fuel the following fitted equation will apply:

$$\text{Acceptable Burnup in MWD/KgU (OFA Fuel)} = -39.82 + (29.87*E) - (4.924*E^2) + (0.421*E^3)$$

Fuel up to 5% initial enrichment may also be stored in a checkerboard pattern, alternating with cells filled with only water or non-fissile material. For this case, the maximum reactivity was calculated (KENO-5a) to be 0.9392, including uncertainties, which is below the USNRC guideline and therefore acceptable.

An independent check calculation for the reference case with NITAWL-KENO-5a (cell calculation for k_∞) gave a bias corrected k_∞ of 0.9096 ± 0.0008 (1 σ, without uncertainties) which confirms the CASMO-3 calculation (k_∞ of 0.9088).

4.0 REFERENCES

1. Licensing Report on High Density Spent Fuel Racks for Diablo Canyon Units 1 and 2, NRC Docket Nos. 50-275 and 50-323, September 1985.

2. S. E. Turner, "Criticality Safety Analyses For Vantage 5 Fuel Assemblies in the Spent Fuel Storage Racks of the Diablo Canyon Nuclear Power Plant", Holtec International, Report HI-88306, October 1988.

3. R.M. Westfall, et. al., "NITAWL-S: Scale System Module for Performing Resonance Shielding and Working Library Production" in SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation., NUREG/CR-0200, 1979.

   L.M. Petrie and N.F. Landers,"KENO 5a. An Improved Monte Carlo Criticality Program with Supergrouping" in Scale: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation, NUREG/V-0200, 1979.

   R.M. Westfall et al., "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," NUREG/V-0200, 1979.

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

5. Letter from T. P. Lee, Pacific Gas & Electric Co., to S. E. Turner, Holtec International, July 23, 1993

Table 1

SUMMARY OF CRITICALITY SAFETY ANALYSES
REGION 2 STORAGE RACKS

Type of Fuel (Westinghouse)	OFA	Standard
Fuel Enrichment, wt% U-235	5.00	5.00
Design Burnup, MWD/KgU	38.75	40
Reference Temperature, °F	150	150
Reference k_{eff} (CASMO-3)	0.9060	0.9088
Calculational Bias, Δk[1]	0.0000	0.0000
Axial Burnup Distribution	0.0124	0.0124
Total (without uncertainties)	0.9184	0.9212
Δk Uncertainties[2]	±0.0084	±0.0070
Δk allowance for depletion calculations[2]	±0.0194	±0.0200
Maximum Reactivity	0.9462	0.9482

(1) Appendix A

(2) Section 3.3 and Table 3

Table 2

DESIGN BASIS FUEL ASSEMBLY SPECIFICATIONS

FUEL ROD DATA	OFA	STANDARD
Outside diameter, in.	0.360	0.374
Cladding inside diameter, in.	0.315	0.329
Cladding material	Zr-4	
Stack density, g UO_2/cc	10.41 ± 0.20	
Pellet diameter, in.	0.3088	0.3225
Maximum enrichment, wt % U-235[1]	5.00 ± 0.05	
<u>IFBA Rods</u>		
IFBA Rod Loading, mg/inch	-	2.25
Axial Length of IFBA Coating, ft.	-	10
IFBA Cutback Top and Bottom, inches	-	12
<u>FUEL ASSEMBLY DATA</u>		
Fuel rod array	17x17	
Number of fuel rods	264	
Fuel rod pitch, in.	0.496	
Number of control rod guide and instrument thimbles	25	
Thimble O.D., in. (nominal)	0.474[2]	0.482
Thimble I.D., in. (nominal)	0.442[2]	0.450

(1) Enriched fuel zone, excluding any axial blanket.
(2) Alternative Thimble Dimensions of 0.440" ID and 0.476" OD have a negligible effect on reactivity.

Table 3

REACTIVITY EFFECTS OF MANUFACTURING TOLERANCE AND CALCULATIONAL UNCERTAINTIES (REGION 2)

Quantity	Δk OFA	Δk Stnd	Reference
Uncertainty in Bias	±0.0024	±0.0024	Appendix A
Inner Box Dimension	±0.0001	±0.0002	References 1,2
Water Gap Thickness	±0.0039	±0.0041	References 1,2
SS Thickness	±0.0022	±0.0028	References 1,2
Fuel Enrichment	±0.0020	±0.0011	References 1,2
Fuel Density	±0.0018	±0.0029	References 1,2
Eccentric Position	±0.0061	±0.0031	Section 3.3
Statistical combination[1] of uncertainties	±0.0084	±0.0070	

(1) Square root of sum of squares of all independent tolerance effects.

Table 4

LIMITING BURNUPS FOR FUEL
OF VARIOUS ENRICHMENTS

OFA		Standard	
Initial Enrichment,%	Limiting Burnup MWD/KgU	Initial Enrichment,%	Limiting Burnup MWD/KgU
1.79	0	1.74	0
2.5	10.55	2.5	11.53
3.2	18.80	3.0	17.673
3.7	24.34	3.6	24.755
4.2	29.67	4.3	32.47
4.5	33.21	4.5	34.50
5.0	38.75	5.0	40.00

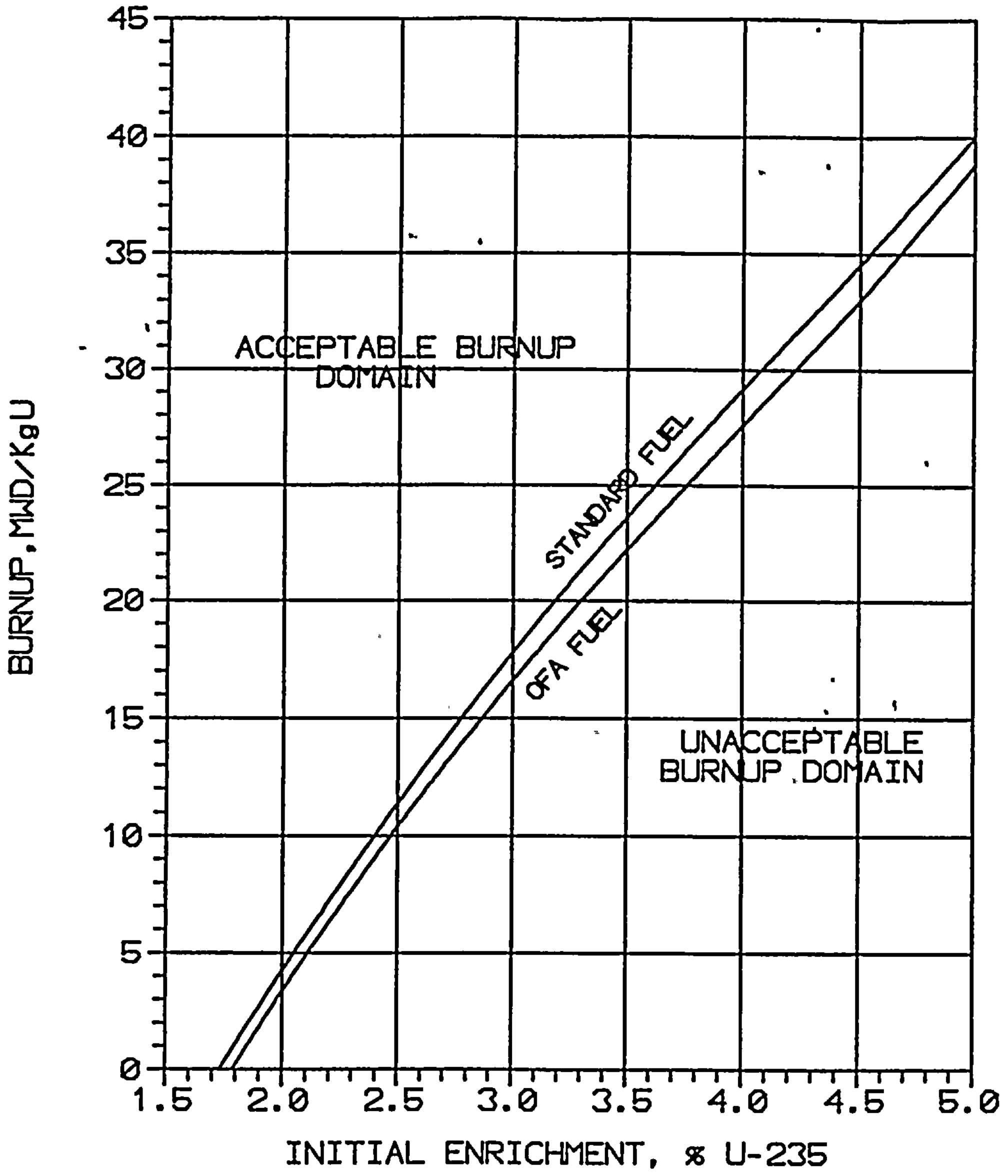

Fig. 1 ACCEPTABLE BURNUP DOMAIN IN REGION 2 OF THE DIABLO CANYON STORAGE RACKS

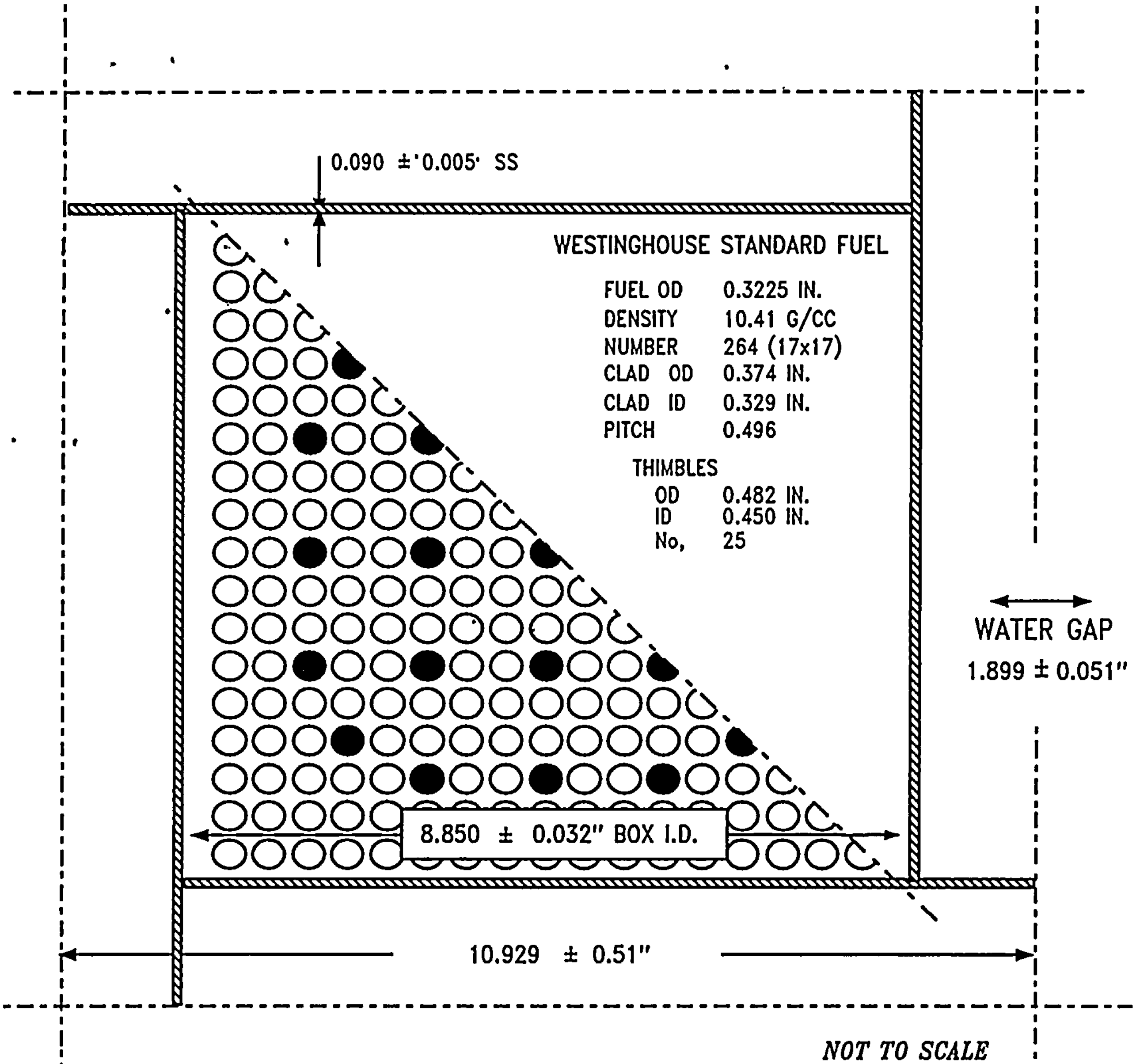

Fig. 2 CALCULATIONAL MODEL FOR REGION 2 FUEL STORAGE CELL

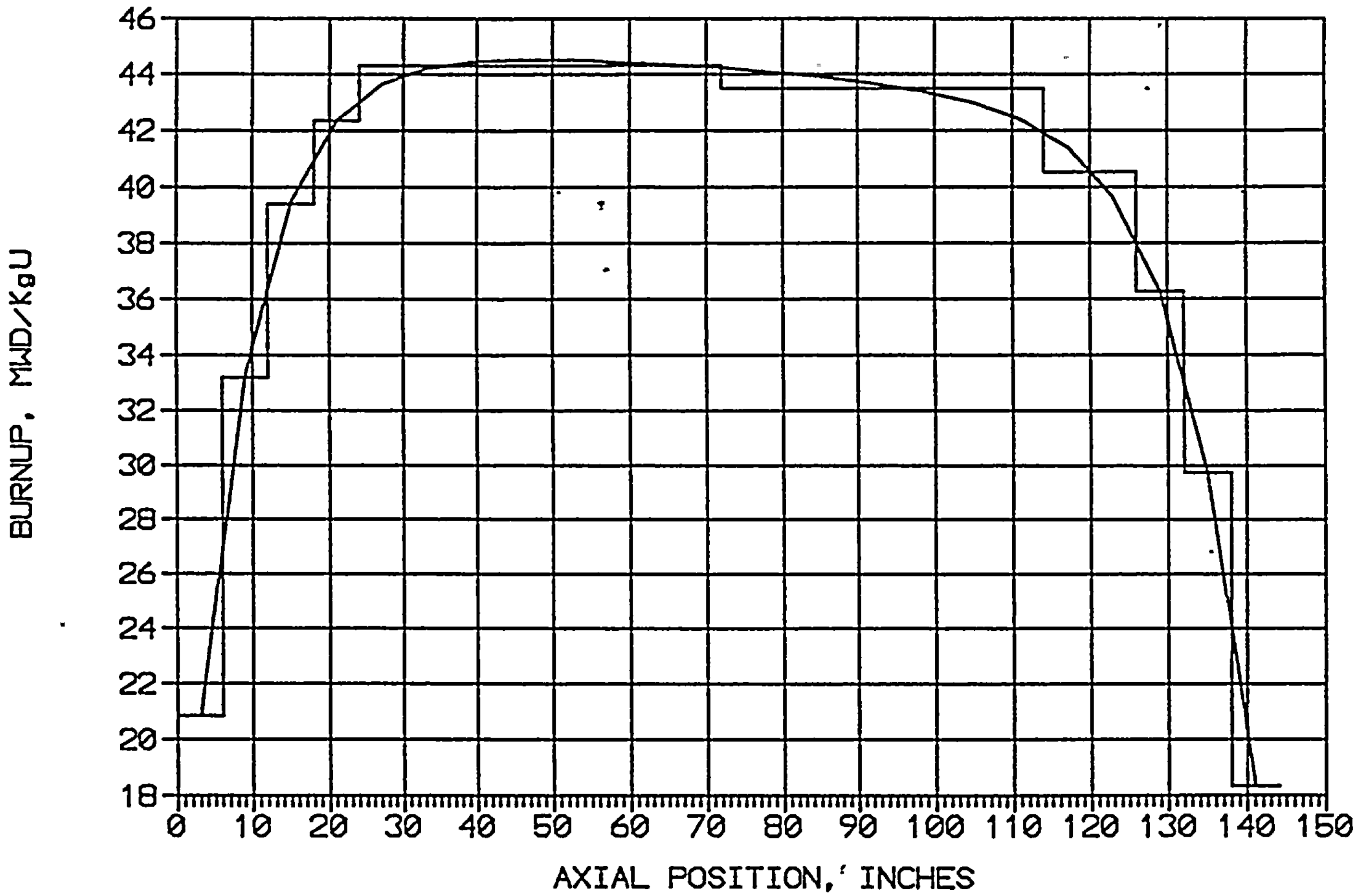

Fig. 3 AXIAL DISTRIBUTION IN FUEL BURNUP
(5.0% ENRICHED FUEL AT 40 MWD/KgU)

[illegible]