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H. B. ROBINSON NEW AND SPENT FUEL CRITICALITY ANALYSIS

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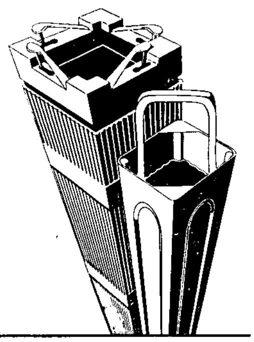

Siemens Power Corporation

Nuclear Division

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H.B. ROBINSON NEW AND SPENT FUEL CRITICALITY ANALYSIS

Prepared By: Calvin D. Manning — 6/29/94
C. D. Manning, Criticality Safety Specialist — Date
Safety, Security, & Licensing

Concur: RCS LAN J. S. Holm — 6/30/94
J. S. Holm, Manager — Date
PWR Nuclear Engineering

R. A. Copeland — 29 Jun 94
R. A. Copeland, Manager — Date
Product Licensing

G. J. Busselman — 7/1/94
G. J. Busselman, Manager — Date
Customer Services Engineering

Approved by: R. E. Vaughan — 6/30/94
R. E. Vaughan, Manager — Date
Safety, Security, and Licensing

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H.B. ROBINSON NEW AND SPENT FUEL CRITICALITY ANALYSIS

1.0 INTRODUCTION

This report describes the criticality safety evaluations performed to support low enriched fuel (up to 5.0 wt.% U^{235}) in the H. B. Robinson Unit 2 new fuel storage area and the H. B. Robinson Unit 2 spent fuel storage areas. The evaluations demonstrate compliance with the current requirements that the k_{eff} for the spent fuel pools remain less than 0.95 when flooded with unborated water and that K_{eff} for the new fuel storage remains less than 0.98 at optimum moderation.

Enrichments of up to 5.0 wt.% (including tolerances) are supported. Because of the higher enrichments, there are additional restrictions on the new fuel storage area and the high and low density spent fuel storage areas. The evaluations also demonstrate the current Technical Specifications on fuel movement remain valid with the higher enrichments.

This report is organized in the following manner. Chapter 2 provides a summary of the results and controls. Chapter 3 provides a brief description of the codes and methodology used. The fuel designs and other input assumptions are described in Chapter 4. Chapter 5 describes the detailed results and the resulting controls.

2.0 SUMMARY AND CONCLUSIONS

Evaluations were performed for the criticality safety of the H. B. Robinson low density spent fuel pool storage, the high density spent fuel pool storage, and the new fuel assembly storage for fuel with up to 5.0 wt.% U-235 enrichment and meeting the fuel design parameters listed in Table 4.2. A list of fuel storage is provided in Table 2.1. The results of these evaluations showed that the k_{eff} remained less than 0.95 with no assembly restrictions for the low density spent fuel storage area except that fuel assemblies with an enrichment greater than 4.25 wt.% U^{235} and with empty rod locations are not allowed in the low density rack.

The high density storage area has no restrictions for assemblies with enrichments less than or equal to 4.0 wt.% U^{235}. Fuel assemblies with enrichments >4.0 and $\leq$4.60 wt.% U^{235} may be stored in the high density racks provided they have no empty rod locations. Fuel assemblies with >4.6 wt.% and $\leq$5.0 wt.% U^{235} enrichment must contain four or more gadolinia bearing rods with a loading of greater than 1.8 wt.% gadolinia in each rod, must meet the axial loading requirements listed in Table 4.3, and must have no empty rod locations. Fuel designs with fewer gadolinia-bearing rods will require an explicit evaluation.

The new fuel storage area can accept 5.0 wt.% enriched assemblies without assembly restrictions on gadolinia. However, only the assembly location option listed in Figure 4.1 is acceptable.

The fuel handling criticality limits were also evaluated. The results of this evaluation demonstrate that 1000 ppm boron is required to be in the water during fuel handling. This limit is within the current Technical Specification limit of 1500 ppm.

The storage and handling of reconstituted assemblies was also assessed. Only assemblies with 4.00 wt.% U^{235} enrichment or less are allowed in the high density spent fuel storage racks with empty rod locations. For the low density rack area, assemblies with enrichments >4.25 wt.% U^{235} cannot be stored with empty rod locations.

TABLE 2.1 FUEL STORAGE REQUIREMENTS

Fuel Storage Location	Wt.% U^{235} Enrichment	Gadolinia Requirements	Worst Case K-eff	Other Special Storage Requirements
New Fuel Storage	≤5.0	None	≤ .98 At Optimum Moderation ≤ .95 at Full Flooding	Plastic Sheaths Around Fuel Bundles Must Be Free Draining. Figure 4.1 Storage Option Is The Only Allowed Storage Arrangement.
High Density Storage Racks	≤4.0	None	≤ .95	None
	>4.0 and ≤4.60	None	≤ .95	No Assemblies With Empty Rod Locations Allowed.
	>4.60 and ≤5.0	4 rods /1.8 $^{w}/_{o}$ and Axial Loading per Table 4.3	≤ .95	No Assemblies With Empty Rod Locations Allowed.
Low Density Storage Racks	≤4.25	None	≤0.95	None.
	>4.25 and ≤5.0	None	≤ .95	No Assemblies With Empty Rod Locations Allowed.

3.0 METHODOLOGY

Siemens Power Corporation-Nuclear Division (SPC-ND) uses the SCALE 4.1 (Reference 1) codes and methods to perform the criticality calculations. With this methodology, cross-sections for the various assembly designs are developed. These cross-sections are then used in a Monte Carlo code, KENO.Va to determine the k_{eff}. The biases and uncertainties are also established by comparison of the Monte Carlo predictions to sub-critical experiments. The 95/95 upper limit of k_{eff} is calculated as follows:

> 95/95 UL k_{eff} = nominal worst case calculated k_{eff} + methodology bias + delta K from fuel, rack, and temperature tolerances + $k * (S^2_{Bias} + S^2_{Monte\ Carlo\ Code})^{1/2}$

where k is the 95/95 multiplier.

The design is considered acceptable if this 95/95 UL k_{eff} is below 0.95 for storage in spent fuel pools and below 0.98 at optimum moderation in new fuel storage racks.

The specific cross-section generation uses the "CSAS25" option with 16 group cross sections. BONAMI and NITAWL are used to prepare case specific cross sections using the HANSEN-ROACH 16 group master library. A 3-dimensional KENO model is used for the Monte Carlo calculations.

The basic methodology capability was established using the Reference 2 critical experiments. The bias estimate from these experiments was -0.00136 ± .00279. This small negative bias indicates the methodology is conservative.

Because the H. B. Robinson high density spent fuel storage area uses Boraflex, benchmarks were also performed from experiments described in Reference 3. The cases selected from

Reference 3 were 3x3 arrays with Boral absorber plates between the assemblies. The KENO calculations used 30,000 neutron histories (100 generations of 300 neutrons) and 50,000 neutron histories (100 generations of 500 neutrons). The calculation results from these benchmarks are presented in Table 3.1. The bias and uncertainty for the 16 cases is -0.00081 ± 0.00181. Although the -0.00136 bias is appropriate for the new fuel storage area and the low density racks and the -0.00081 bias is appropriate for the high density racks, the -0.00081 bias was conservatively used throughout the evaluations in calculating the 95/95 UL k_{eff}.

TABLE 3.1 BENCHMARK CASES FROM REF. 3

Case Ident.	k-eff	Histories
2378a	0.99866 ± 0.00342	30k
2378b	1.00166 ± 0.00308	50k
2384a	0.99727 ± 0.00387	30k
2388a	0.99281 ± 0.00317	30k
2388b	1.00176 ± 0.00256	50k
2388c	1.00028 ± 0.00205	100k (100x1000)
2396a	0.99895 ± 0.00370	30k
2396b	1.00025 ± 0.00283	50k
2402a	1.00039 ± 0.00360	30k
2402b	1.00101 ± 0.00248	50k
2407a	1.00074 ± 0.00343	30k
2407b	0.99833 ± 0.00280	50k
2411a	1.00109 ± 0.00286	30k
2411b	1.01041 ± 0.00276	50k
2414a	1.00678 ± 0.00438	30k
2420a	1.00123 ± 0.00427	30k

4.0 APPLICABILITY OF RESULTS

This section discusses the input assumptions used in the evaluations and the resulting ranges of applicability of the calculations. There are assumptions about the storage racks and about the fuel designs.

4.1 New Fuel Storage Rack Assumptions

The new fuel storage racks contain 105 storage locations. The assemblies in the rack are on 21 inch nominal centers in a 10x11 square-pitched array. The eleventh row has only 5 storage locations. The arrangement of these racks is shown in Figure 4.1. This figure shows the allowed configuration for the new fuel storage rack.

The analysis used Figure 4.1 configuration for 72 fresh fuel assemblies. In the analysis, the assembly pitch was conservatively set at 20.875 inches. The reflector assumed in the analysis was closely fitted; the racks were reflected by 30 cm thick concrete at all 6 rack boundaries.

The analysis assumed no water accumulation in the assemblies. Therefore, if the assemblies are enclosed in plastic sheaths, the sheaths must be open at the bottom to allow drainage.

4.2 Low Density Spent Fuel Storage Rack Assumptions

The low density spent fuel storage racks were modelled as an infinite planar array of assemblies. The assembly pitch used was 20.875 inches. Only unborated water is assumed to be between the assemblies and throughout the array. Full water reflection is assumed above and below the active fuel region.

4.3 High Density Spent Fuel Storage Rack Assumptions

The dimensions of the high density storage racks are presented in Table 4.1. Figures 4.2 and 4.3 show the arrangement of the racks and the corner detail of a cell, respectively. The wall of each storage location has a sheet of Boraflex secured by a 304 stainless steel wrapper. This Boraflex sheet has at least a one inch border on both sides due to the smaller width of the Boraflex sheet compared with the cell width. Because each storage location wall has a Boraflex sheet, there are two boraflex sheets between any pair of assemblies. For the locations adjacent to the pool wall or the low density racks, each storage location may have either one or two walls with only one Boraflex sheet, depending on how many edges face the pool wall. There are no unpoisoned edges facing other modules or facing the low density racks.

The KENO analysis used the nominal dimensions given in Table 4.1 except for the Boraflex width and lengths. The minimum Boraflex width of 7.385 inches was used. The Boraflex length used in the analysis assumed a bottom shrinkage of 4 inches and a top shrinkage of 5 inches for all panels. This assumed shrinkage bounds the maximum shrinkage reported from blackness test data in Reference 4. In this report, shrinkage, but no gaps were detected in the 66 panels from the two plants applicable to the H. B. Robinson racks. The gamma dose from these panels was estimated to be $\geq 10^{10}$ rads. Thus, no additional gap growth or shrinkage would be expected. The maximum total end shrinkage detected was about 6 inches with the top end shrinkage typically being larger than the bottom end shrinkage. Therefore, a total shrinkage of about 6% of the nominal panel length of 144 inches is assumed compared with the measured maximum panel shrinkage of 3% to 4%.

The nominal location of the bottom of the Boraflex panel is 4.5 inches above the base plate supporting the fuel assembly lower tie plate. The bottom of the pellet stack (i.e. the active fuel length) is nominally 4.0 inches above the base support plate. Therefore, the bottom end of the pellet stack is about 0.5 inch below the bottom of the Boraflex panel before shrinkage. In the analysis, the pellet stack is assumed to be 4 inches below the end of the Boraflex panel to account for bottom end shrinkage.

Based on a 144 inch pellet stack, using the base support plate as the datum, the pellet stack is nominally 1 inch below the top of the Boraflex panel. In the analysis, the pellet stack is assumed to be 144 inches and extend 5 inches beyond the top of the Boraflex panel to account for top end shrinkage.

4.4 Fuel Design Characteristics

For the specific storage area calculations, these fuel design parameters were biased to provide bounding results. The biasing was based on providing the least restrictive fuel design restrictions that would be required to support a k_{eff} of $\leq$0.95 for 5.0 wt.% enriched fuel. All analyses are performed assuming fresh fuel, i.e. there is no credit for reduction in reactivity from exposure. Because of the assumptions used in the evaluation and the low initial gadolinia content, beginning of life is the most reactive condition for the fuel.

For the new fuel storage area and the low density spent fuel storage area, the specific fuel design parameters used in the analyses are presented in Table 4.2, except the fuel assembly was conservatively modeled with 144 inches of 5.0 wt.% fuel, i.e. no blankets were assumed. No gadolinia rods were required to maintain an acceptable k_{eff}. Because bounding fuel parameters were used in these analyses, there is no fuel parameter uncertainty due to fuel tolerances. Therefore, for the new fuel storage area and the low density spent fuel storage area, the 95/95 UL k_{eff} does not have a fuel tolerance uncertainty.

For the high density spent fuel storage area, the same assembly assumptions of Table 4.2 were initially used to determine the maximum enrichment that can be supported without additional fuel restrictions. Because this maximum enrichment is less than 5.0 wt.%, more fuel design restrictions are required to maintain a k_{eff} of $\leq$0.95 with 5.0 wt.% enrichment. The fuel design restrictions on axial loading and minimum gadolinia content required to support 5.0 wt.% fuel in the high density storage area are given in Table 4.3. Minimal, natural UO_2 axial blankets were established, with 5.0 wt.% enriched UO_2 allowed for the rest of the rod. Gadolinia was required only in the central axial zone of 100 inches. This allows a 19.5 inch zone above and below the

gadolinia zone with 5.0 wt.% enrichment and no gadolinia. The assembly central zone is required to have at least four gadolinia rods each loaded with at least 1.8 wt.% gadolinia.

TABLE 4.1 HIGH DENSITY (POISONED) SPENT FUEL STORAGE RACK DESIGN PARAMETERS

Cell Pitch: 10.5" ± 0.06"
Cell Inner Dimension: 8.75" +0.025" / -0.050"
Boraflex Width: 7.46" ± 0.075"
Boraflex Thickness: 0.075" ± 0.010"
Boraflex Length: 144.25" ± 0.25"
B-10 Areal Density in Boraflex: 0.020 g B-10 per sq.cm.(minimum)
Cell Wall Thickness: 0.0747" ± 0.007"
"Wrapper" Wall Thickness: 0.035" ± 0.003"
Thickness of gap between cell wall & wrapper: 0.100" ± 0.010"

TABLE 4.2 FUEL DESIGN PARAMETERS

Parameter	Value
Enrichment	≤5.0 Wt.% U-235
Pellet Diameter	0.3560 to 0.3675
Pellet Stack Density	≤96% TD
Pellet Stack Length	≤139" Enriched plus ≥2.5" Natural at each End (≤144" Total)
Clad ID	0.3625 to 0.3755
Clad OD	0.4240 ± 0.0020"
Rod Pitch	0.563"

TABLE 4.3 REQUIRED AXIAL ZONE LOADING FOR HIGH DENSITY RACKS

Zone	Material Required	Zone Length
1.	Blanket of Natural UO_2	$\geq$2.5 inch
2.	Cutback Zone With No Gadolinia in Any Rods	$\leq$19.5 inch
3.	Central Zone with $\geq$1.8 Wt.% Gd_2O_3 in $\geq$4 Rods	$\geq$100 inch
4.	Cutback Zone with No Gadolinia in Any Rods	$\leq$19.5 inch
5.	Blanket of Natural UO_2	$\geq$2.5 inch

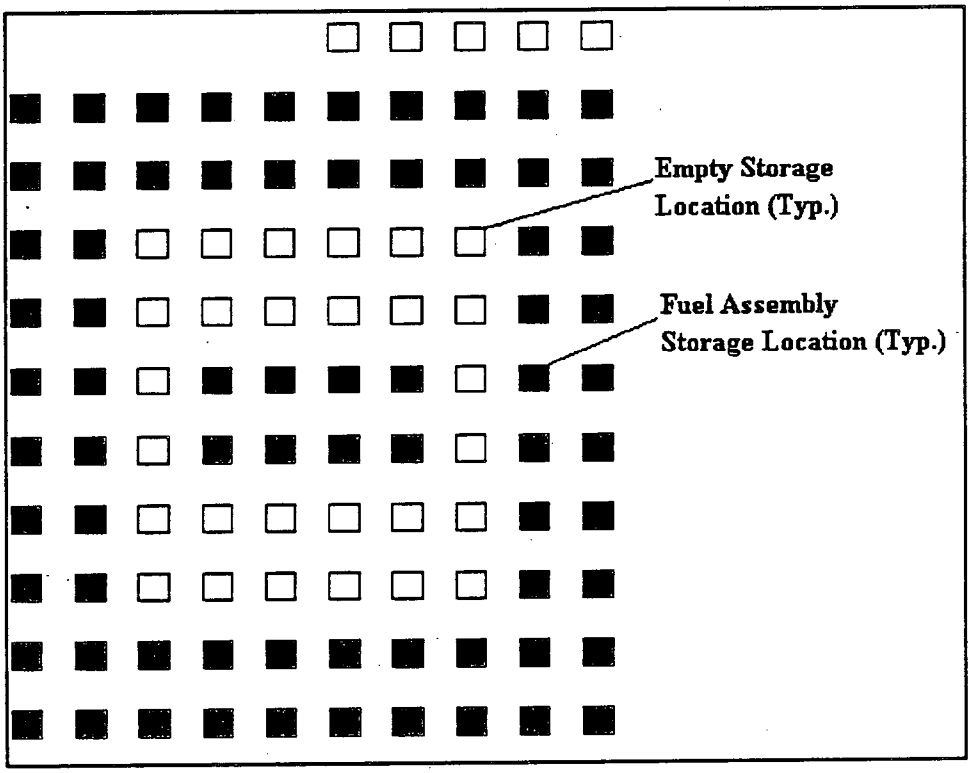


FIGURE 4.1 NEW FUEL STORAGE RACKS
AUTHORIZED FUEL STORAGE ARRANGEMENT

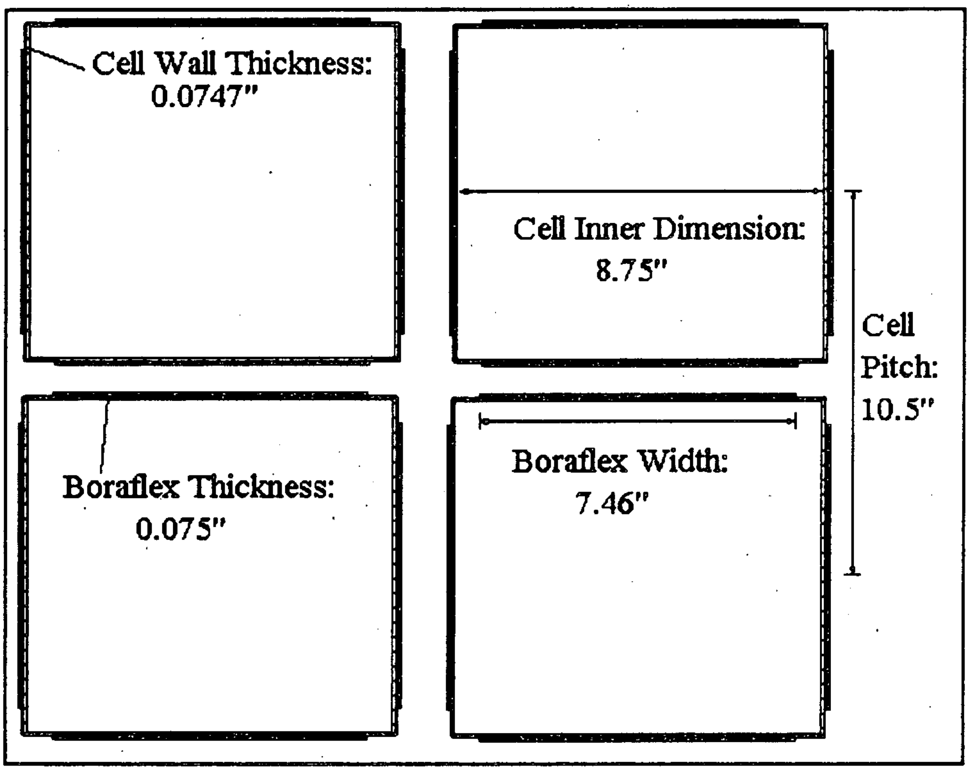


FIGURE 4.2 HIGH DENSITY SPENT FUEL RACK KEY DIMENSIONS

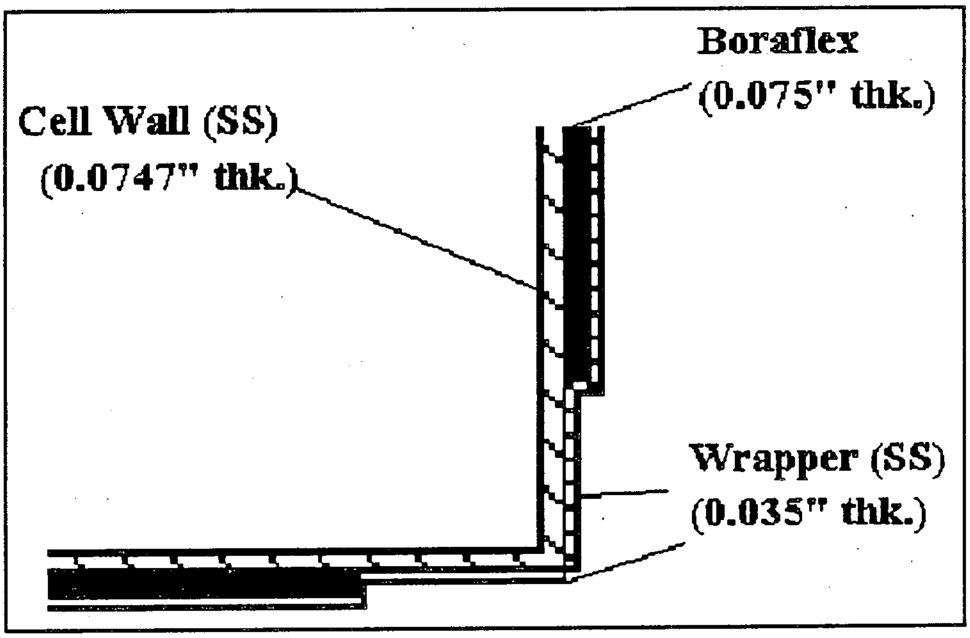


FIGURE 4.3 CORNER DETAIL OF HIGH DENSITY RACKS

5.0 EVALUATION RESULTS

In this section, the detailed evaluation results are presented for each of the storage areas (new, low density, and high density), for fuel handling, and for reconstitution of assemblies.

5.1 New Fuel Storage Area

As stated previously, the new fuel storage was modelled using 5.0 wt.% enriched fuel with no gadolinia stored in the 72 locations allowed by Option D of the current technical specifications (Figure 4.1). Using this arrangement, the nominal k_{eff} and the uncertainty in k_{eff} was determined by KENO as a function of the water volume interspersed in the fuel and storage area. Table 5.1 provides the results of these calculations. The peak k_{eff} remained less than 0.98 with the optimum interspersed moderation and less than 0.95 at flooded conditions.

The optimal moderation condition occurred at about 5% interspersed water volume. At this condition, the nominal k_{eff} was 0.94701 with an uncertainty of 0.00331. Therefore, the 95/95 UL k_{eff} is:

$$0.94701 - 0.00081 + 1.952 * [(0.00331)^2 + (0.00181)^2]^{1/2} = 0.95356$$

This 95/95 UL k_{eff} is less than the 0.98 limit for optimal moderation.

For the fully flooded condition, the nominal k_{eff} is 0.93959 with an uncertainty of 0.00243. Therefore, the 95/95 UL k_{eff} is:

$$0.93959 - 0.00081 + 1.952 * [(0.00243)^2 + (0.00181)^2]^{1/2} = 0.94469$$

This 95/95 UL k_{eff} is less than the 0.95 limit for the fully flooded condition.

Five additional new fuel storage area calculations were performed to address the impact of a mislocation of a fuel assembly. In these calculations, the Option D pattern was used and assumed to contain 72 fuel assemblies. Then an additional assembly was added in each of the five locations shown in Figure 5.1. The calculation was performed assuming the optimum moderation condition of 5 volume percent interspersed water. The results of these calculations are presented in Table 5.2. The 95/95 UL k_{eff} was less than the allowed limit of 0.98 in all cases.

The final new fuel storage evaluation that was performed was to model the assemblies as flooded with no water in the volume between assemblies. This case simulates the condition where sheaths on the assembly are closed and do not permit water to drain. One possible cause of this condition would be from water used to fight a fire in the area. The k_{eff} for this case exceeded 1. Therefore, if assemblies are enclosed in sheaths when in the new fuel storage area, the bottom of the sheaths must be open to allow water to drain freely.

5.2 Low Density Spent Fuel Storage Area

The fuel model used for the low density spent fuel storage area was the same as for the new fuel storage area, i. e. 5.0 wt.% enriched fuel over the entire 144 inch pellet stack length with no gadolinia rods in the assembly. The array was modeled as an infinite array of these assemblies in a fully flooded condition. The resulting nominal k_{eff} is 0.93711 with an uncertainty of 0.00264. Therefore the 95/95 UL k_{eff} is:

$$0.93711 - 0.00081 + 1.952 * [(0.00264)^2 + (0.00181)^2]^{1/2} = 0.94255$$

This value is below the 0.95 limit and is therefore acceptable.

5.3 High Density Spent Fuel Storage Area

Several calculations were performed for the high density spent fuel storage area. The first calculation was to determine the maximum enrichment that could be supported without additional

fuel design restrictions. In this calculation, the high density racks were modelled as described in Section 4.3 and the fuel was modelled with no gadolinia in an infinite array with a uniform enrichment (analogous to the model used for the low density area). The results of this calculation showed that an enrichment of $\leq$4.6 wt.% U-235 could be stored in the high density area without additional fuel assembly restrictions. The results of these calculations are presented in Table 5.3.

Because the high density storage area cannot support fuel with >4.6 wt.% enrichment without gadolinia, additional calculations were done to establish assembly gadolinia limits which could support up to 5.0 wt.% enrichment. The first part of these calculations were CASMO calculations to determine the location of the gadolinia rods which would result in the highest assembly k_{eff}. The results of these calculations are shown in Table 5.4 and illustrated in Figures 5.2 and 5.3. These calculations indicated that the use of four gadolinia rods with greater than 1.8 wt.% gadolinia loading can be supported in all cases for enrichments >4.6 and $\leq$5.0 wt.% U^{235}. There is no restriction on the location of the four gadolinia bearing rods.

To verify the acceptability of using four gadolinia rods, the standard criticality determination of the 95/95 UL k_{eff} was performed. The CASMO results were replicated with KENO, using the fuel assembly description provided in Section 4.4 for the high density storage area, and for the storage area description provided in Section 4.3. The KENO results are presented in Table 5.5. As shown in this table, the nominal k_{eff} agrees well with the CASMO calculations, demonstrating the acceptability of the assembly designs 2A and 2C, and demonstrating that fuel designs with only two gadolinia bearing rods are not generically acceptable. Therefore, for fuel stored in the high density racks with enrichments between 4.6 and 5.0 wt.% U^{235}, either fuel assembly designs 2A, 2C or fuel designs with at least 4 gadolinia bearing rods with $\geq$1.8 wt.% gadolinia are acceptable without additional evaluations.

The previous criticality calculations for the new fuel storage area and the low density storage area used bounding values for the fuel and rack dimensions. For this analysis, the dimensions and temperature uncertainties are treated statistically. To determine the sensitivity of k_{eff} to these

variations, a series of CASMO calculations were performed. In these calculations, the 5.0 wt.% enrichment for the full pellet length of 144 inches was used along with nominal dimensions to establish a baseline. This base geometry will maximize the criticality sensitivity to the variations. The CASMO calculated k_{inf} for this case was 0.94873.

The first sensitivity determined was the temperature sensitivity. The temperature was reduced to 4°C, thus providing the maximum water density. This change in temperature resulted in a change in the k_{inf} of +0.00146. This value is used as the uncertainty due to temperature.

The second series of sensitivities was to the storage rack dimensions. Table 5.6 shows the change in the dimensions and the resulting change in k_{inf}. Combining these changes by the square root sum of the squares method provides an uncertainty due to rack tolerances of 0.00713.

The remaining sensitivity to be determined is the change due to fuel rod tolerances. The analyses used the pellet stack density set at the maximum value. Therefore, no allowance for pellet density or dish volume was necessary. The largest nominal pellet diameter of 0.3670 inch and the largest nominal cladding ID of 0.3740 were used. Table 5.7 provides the variances used and the resulting changes in k_{inf}. The square root sum of the squares method provides an uncertainty due to fuel dimension tolerances of 0.00241.

These uncertainties due to temperature, rack tolerances, and fuel tolerances, along with the bias and bias uncertainty, were used with the most limiting arrangement of four gadolinia rods presented in Table 5.5. The most limiting four rod case, Case 4A, had a nominal k_{eff} of 0.93369 with an uncertainty of 0.00251. Therefore :

95/95 UL k_{eff} = nominal worst case calculated k_{eff} + methodology bias + delta K from fuel, rack, and temperature tolerances + $[k * (S^2_{bias} + S^2_{Monte\ Carlo\ Code})^{1/2}]$

$$0.93369 - 0.00081 + [(0.00146)^2 + (0.00713)^2 + (0.00241)^2]^{1/2} + 1.952[(0.00181)^2 + (0.00251)^2]^{1/2} = 0.94658$$

This 95/95 UL k_{eff} is less than the 0.95 criteria and is therefore acceptable.

5.4 Fuel Handling

The next evaluation performed was to verify the acceptability of the technical specification limit of ≥1500 ppm dissolved boron in the pool during fuel handling. The fuel was modelled in the same manner as for the new fuel storage area and the low density spent fuel storage area, i.e. all fuel rods contain 144 inches of 5.0 wt.% enriched fuel with no gadolinia. The two edge to edge assemblies were reflected by 30 cm of water at all boundaries. The results are presented in Table 5.8 and illustrated in Figure 5.4. One thousand (1,000) ppm dissolved boron is needed to provide criticality safety margin, therefore, the current technical specification limit of 1500 ppm remains valid.

5.5 Storage of Reconstituted Fuel Assemblies

The remaining criticality calculations were performed to support storage of reconstituted fuel. The criticality aspects of the reconstitution activities are not covered by this report. These calculations are necessary because the nominal fuel design is undermoderated. Therefore, the margin to criticality is reduced as water replaces the volume occupied by a fuel rod.

Rod Removal Effects for Single Assemblies and Those in Low Density Spent Fuel Racks

Removal of fuel rods from a complete assembly was evaluated for effect on the k-eff of a single assembly with full water reflection. A single assembly was modeled at various water-to-fuel

volume ratios (Vw/Vf). The pellet diameter, clad ID, and clad OD were fixed at 0.3675", 0.3755", and 0.422", respectively. The pellet density was 96% TD and the enrichment was 5.0%. The rod pitch was varied to yield a Vw/Vf in the range 1.5 to 4.0. The assembly was modeled in KENO as a single homogeneous 8.445"x8.445"x144" region using cell-weighted cross sections for the unit rod cell. There was zero gadolinia in the modeled assembly and the entire 144" fuel length was enriched; i.e., there were no axial blankets. The results are listed in Table 5.9.

The Vw/Vf for a rod cell is 1.67. With the water in the guide tubes included, the assembly-average Vw/Vf is tabulated below for various number of removed fuel rods. Based on the data in Table 5.10, the maximum Vw/Vf for a k-eff less than 0.95 is about 2.2.

Peak reactivity is reached at a Vw/Vf of about 3.2 which occurs when about 60 rods are removed from the assembly. The peak k-eff is subcritical but unacceptable because it exceeds 0.95. The k-eff for the Low Density Spent Fuel Racks is equal to that for a single bundle with full water reflection since the edge-to-edge spacings in that rack are 12.555" nominal; bundles are essentially decoupled with spacings greater than about 6" filled with full-density water.

In order to establish the enrichment limit which would support unlimited removal of fuel rods in the low density racks, additional analysis was performed using the pellet and clad dimensions listed in Table 4.2. Subject to the specified enrichment limit, this analysis bounds the fuel currently stored at H. B. Robinson. The enrichment limit supported by this additional analysis is $\leq$4.25 wt.% U^{235}.

Rod Removal Effects in High Density Spent Fuel Racks

The effect of removed rods was conservatively modeled as follows: The fuel assembly was modeled using cell-weighted cross sections as one homogeneous region. A 1-D XSDRN model was used to determine the effect of fuel design parameters; a 3-D KENO model was used to replicate several of these cases. The enrichment modeled was 4.0%, the pellet density was 100% TD, and the pellet diameter was varied over the range 0.25" to 0.50". This was done to cover

possible pellet diameters different from those used in current fuel designs. The pellet-clad radial gap was 0.003" in all cases. The clad thickness was 0.020" in all cases. In the XSDRN model, a single rack cell was modeled as concentric cylindrical regions (fuel, water, steel, Boraflex, etc.) with specular reflection at the outer surface, which produced a model of an infinite array of infinite-length cells. The XSDRN results are in Table 5.11.

The data in Table 5.11 is also shown in Figure 5.5.

Selected cases were replicated using CSAS2X, cell-weighted cross sections in KENO-Va model. The results from those replicates are shown in Table 5.12 below. These results are not significantly different from the corresponding XSDRN results listed in Table 5.11. The maximum (not maximum-nominal) acceptable enrichment for assemblies with unlimited numbers of removed fuel rods is 4.0%, using the same uncertainty values derived for the current fuel design.

Rod locations are considered occupied if they contain a solid metal rod, a sealed hollow rod, or a different fuel rod, e.g. a design that displaces the water.

Gadolinia-bearing rods may be removed from a single assembly but, for enrichments greater than 4.6%, the minimum specified gadolinia requirement must be verified before placing the assembly in the high density spent fuel racks. Assemblies with gadolinia rods replaced with non-gadolinia bearing rods may be placed into the low density-unpoisoned spent fuel racks.

TABLE 5.1 NEW FUEL RACKS NORMAL ARRANGEMENT

Case ID	Interspersed Water, Vol.%	k-eff	
		Avg.	Std.Dev.
od03	3	0.91207	0.00316
od04	4	0.93454	0.00318
od05	5	0.94701	0.00331
od06	6	0.93896	0.00338
od07	7	0.93447	0.00348
od10	10	0.92221	0.00296
od20	20	0.79929	0.00415
od40	40	0.69079	0.00394
od60	60	0.75732	0.00423
od80	80	0.86253	0.00396
od100	100	0.93959	0.00243

TABLE 5.2 NEW FUEL RACKS WITH 5 VOLUME % INTERSPERSED WATER ACCIDENTAL MISPLACED ASSEMBLY CASES

Case ID	Accident Arrangement	k-eff	
		Avg.	Std.Dev.
oda05a	A	0.94835	0.00323
oda05b	B	0.96002	0.00312
oda05c	C	0.95854	0.00330
oda05d	D	0.95680	0.00306
oda05e	E	0.95912	0.00344

TABLE 5.3 HIGH DENSITY RACKS WITH ZERO-GADOLINIA ASSEMBLIES

Enrichment, wt% U-235	k-eff	
	Avg.	Std.Dev.
4.2	0.92114	0.00279
4.4	0.93083	0.00275
4.5	0.93145	0.00273
4.6	0.93484	0.00280
4.8	0.94276	0.00304

TABLE 5.4 CASMO CALCULATION RESULTS HIGH-DENSITY SPENT FUEL RACK MODEL

Rod Arrangement	CASMO k-inf
Zero Gadolinia	0.94783
2A (Two 1.8 % Gd_2O_3 Rods)	0.93101
2B (Two 1.8 % Gd_2O_3 Rods)	0.94240
2C (Two 1.8 % Gd_2O_3 Rods)	0.93877
4A (Four 1.8 % Gd_2O_3 Rods)	0.93685
4B (Four 1.8 % Gd_2O_3 Rods)	0.92643
4C (Four 1.8 % Gd_2O_3 Rods)	0.91972

TABLE 5.5 KENO-Va CALCULATION RESULTS HIGH-DENSITY SPENT FUEL RACK MODEL

Rod Arrangement	k-eff	
	Avg.	Std.Dev.
2A (Two 1.8 % Gd_2O_3 Rods)	0.93144	0.00248
2C (Two 1.8 % Gd_2O_3 Rods)	0.93630	0.00247
4A (Four 1.8 % Gd_2O_3 Rods)	0.93369	0.00251
4B (Four 1.8 % Gd_2O_3 Rods)	0.92627	0.00228

TABLE 5.6 HIGH DENSITY FUEL RACK DIMENSION TOLERANCE UNCERTAINTIES

Variable	Change	Change in k_{inf}
Boraflex Thickness	-0.010 inch	+0.00399
Cell Pitch	-0.06 inch	+0.00585
Storage Cell Inner Dimension	+0.025 inch	+0.00062
Cell Wall Thickness	+0.0070 inch	+0.00061
Wrapper Thickness	+0.003 inch	+0.00001
Square Root Sum of Squares		0.00713

TABLE 5.7 FUEL ROD DIMENSION TOLERANCE UNCERTAINTIES

Variable	Change	Change in k_{inf}
Cladding ID	-0.0015 inch	+0.00006
Cladding OD	-0.002 inch	+0.00239
Pellet Diameter	+0.0005 inch	+0.00027
Square Root Sum of Squares		0.00241

**TABLE 5.8 DISSOLVED BORON EFFECTS FOR TWO EDGE-TO-EDGE ASSEMBLIES
144" PELLET STACK, 5.0% ENRICHED, 96%TD
ZERO GADOLINIA, NO NATURAL BLANKETS
FULL WATER REFLECTION**

Boron Concentration in Water, PPM	k-eff
0	1.07242 ± 0.00352
500	0.98112 ± 0.00342
1000	0.91158 ± 0.00316
1500	0.85681 ± 0.00287
2000	0.81439 ± 0.00288

TABLE 5.9 CALCULATION RESULTS SINGLE GENERIC ASSEMBLY AT VARIOUS Vw/Vf RATIOS

Case ID	Vw/Vf	KENO k-eff	
		Avg.	Std.Dev.
va15	1.5	0.90841	0.00530
va20	2.0	0.93839	0.00462
va22	2.2	0.94351	0.00509
va25	2.5	0.95922	0.00443
va30	3.0	0.96261	0.00525
va32	3.2	0.96502	0.00402
va35	3.5	0.95516	0.00469
va40	4.0	0.95904	0.00495

TABLE 5.10 EFFECT OF ROD REMOVAL ON ASSEMBLY-AVERAGE Vw/Vf

Number of Removed Rods	Average Vw/Vf
0	1.96
1	1.97
2	1.99
3	2.01
4	2.02
5	2.04
6	2.06
7	2.07
8	2.09
9	2.11
10	2.13
20	2.31
30	2.52
40	2.76
50	3.02
60	3.32
70	3.67
80	4.07
90	4.54
100	5.11

TABLE 5.11 FUEL ROD REMOVAL EFFECTS IN HIGH DENSITY RACKS XSDRN CALCULATION RESULTS

Vw/Vf	Rack k-eff with Various Pellet Diameters					
	0.25"	0.30"	0.35"	0.40"	0.45"	0.50"
1.6	0.857352	0.871495	0.882823	0.891166	0.897842	0.902897
1.8	0.874455	0.887552	0.897824	0.905437	0.911315	0.915808
2	0.88735	0.900681	0.909131	0.916293	0.92128	0.925078
2.2	0.897347	0.910518	0.917981	0.924281	0.928501	0.931505
2.4	0.905636	0.917663	0.92486	0.929882	0.933482	0.935642
2.6	0.912351	0.922867	0.929823	0.93362	0.936596	0.937922
2.8	0.917317	0.926506	0.933071	0.935906	0.938158	0.938688
3	0.920857	0.928833	0.934886	0.937002	0.938432	0.938195
3.2	0.923214	0.930209	0.935532	0.937071	0.937613	0.936658
3.4	0.92456	0.930854	0.935216	0.936241	0.935896	0.934236
3.6	0.92505	0.930729	0.934123	0.934636	0.933419	0.931074
3.8	0.924817	0.929896	0.932383	0.932349	0.930317	0.927293
4	0.923956	0.928453	0.930079	0.929496	0.92668	0.922988

TABLE 5.12 FUEL ROD REMOVAL EFFECTS IN HIGH DENSITY RACKS KENO-Va CALCULATION RESULTS

Vw/Vf	Pellet Diam., Inch	k-eff	
		Avg.	Std.Dev.
2.8	0.35	0.93062	0.00351
3.2	"	0.93326	0.00269
3.6	"	0.93249	0.00355
2.8	0.50	0.93377	0.00322
3.2	"	0.93916	0.00344
3.6	"	0.93154	0.00334

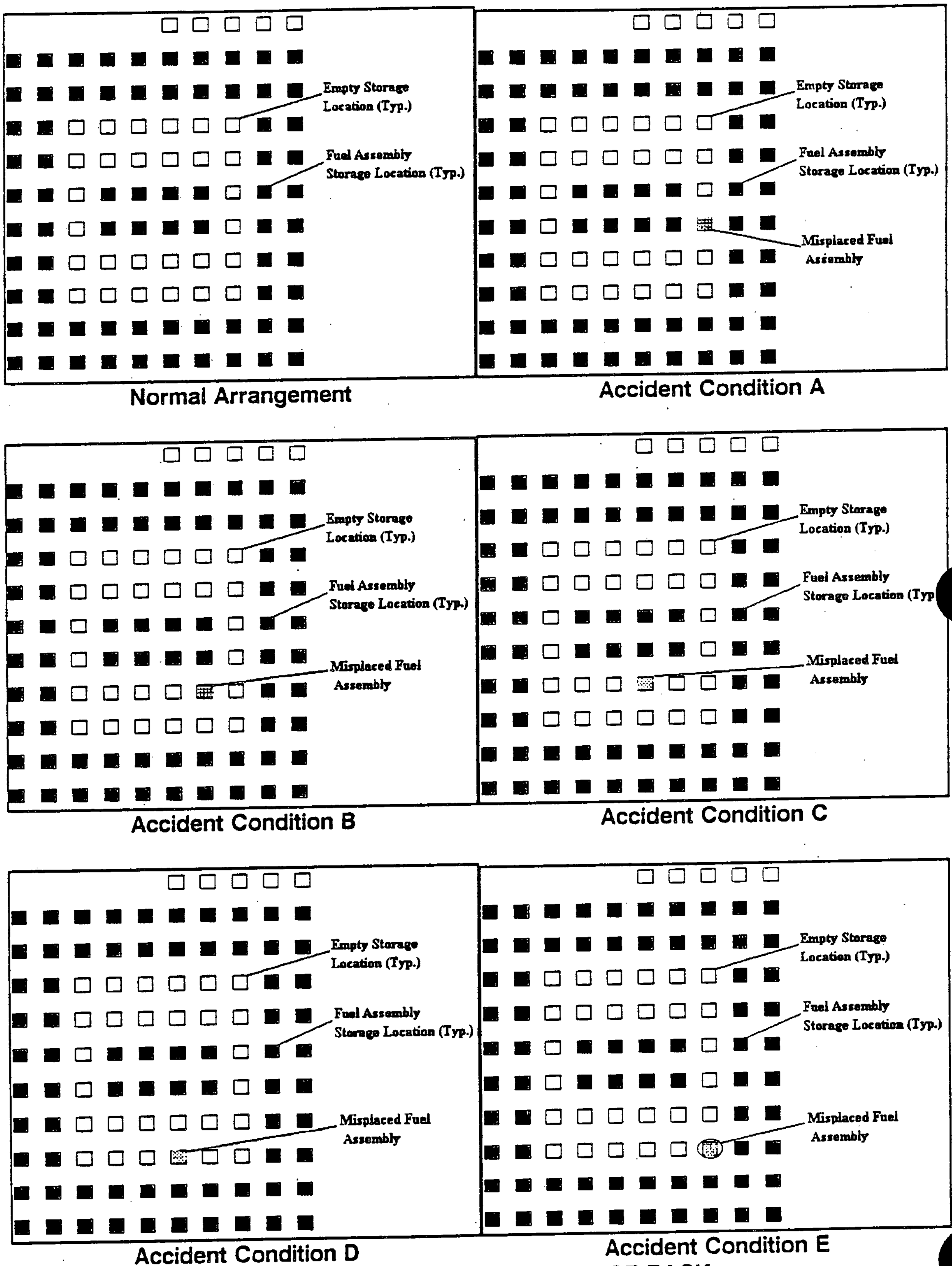


FIGURE 5.1 NEW FUEL STORAGE RACK MODELED ARRANGEMENTS

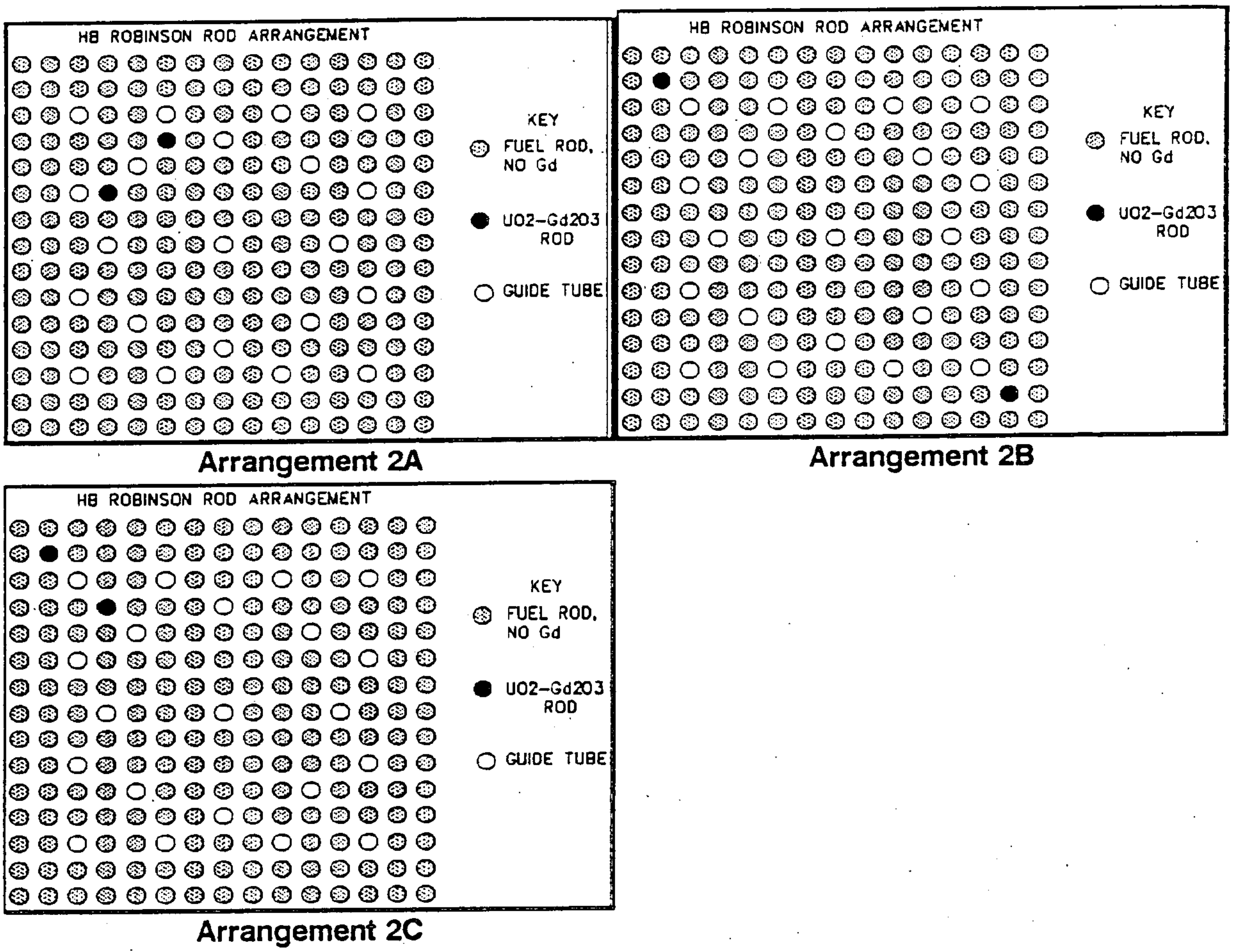


FIGURE 5.2 ROD ARRANGEMENTS WITH TWO 1.8 WT% GADOLINIA RODS

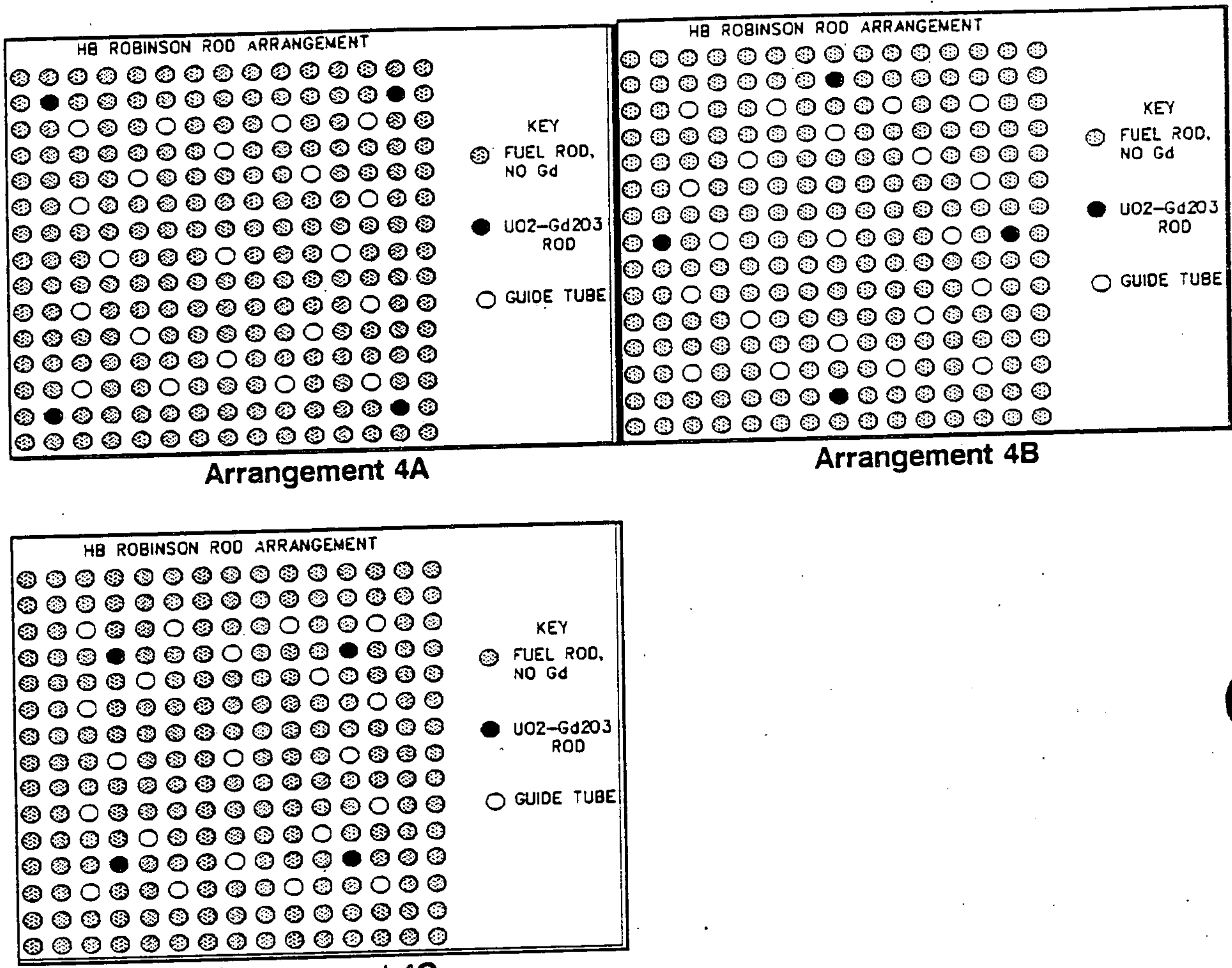
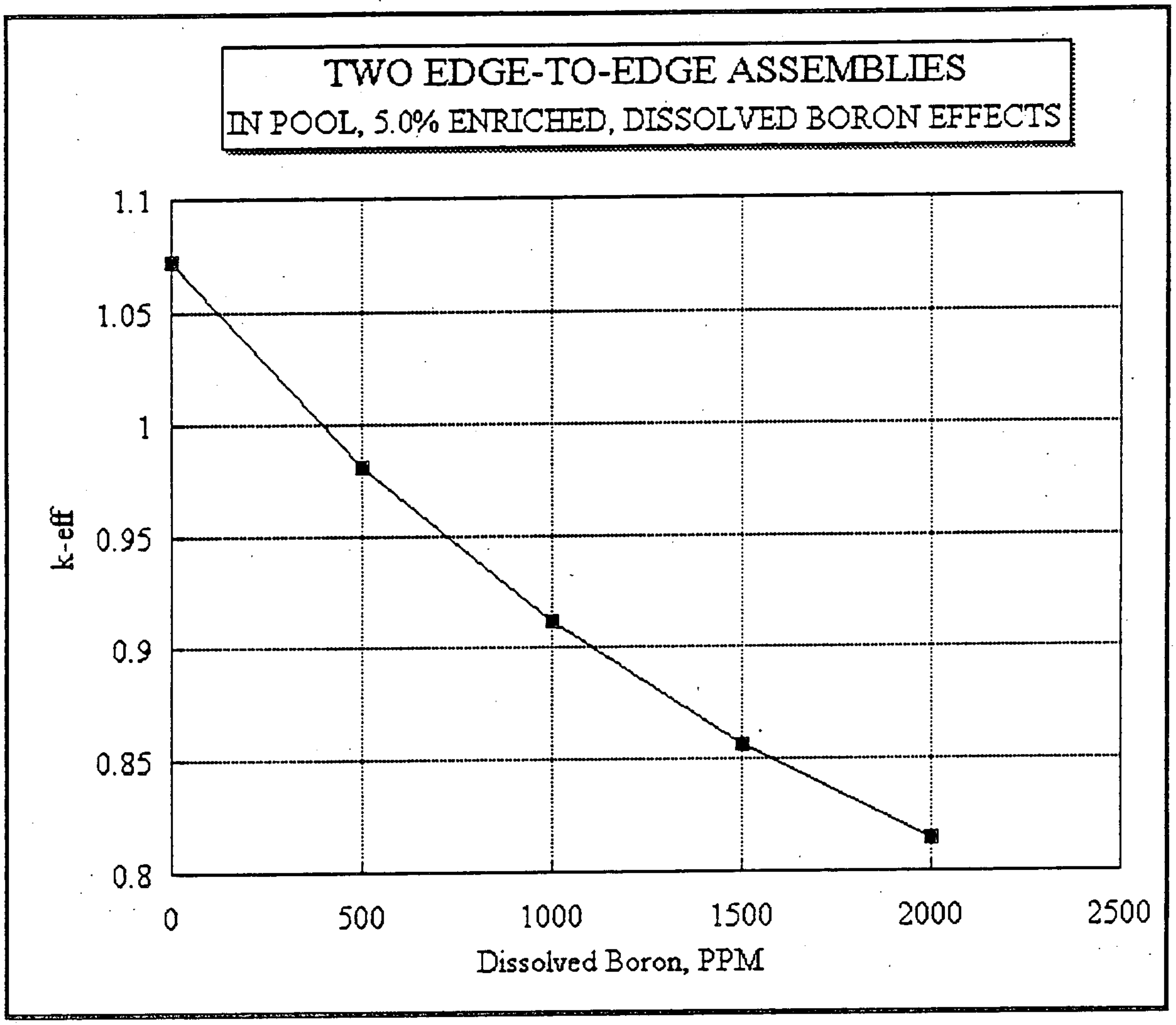


FIGURE 5.3 ROD ARRANGEMENTS WITH FOUR 1.8 WT% GADOLINIA RODS



K-EFF VS. PPM DISSOLVED BORON

FIGURE 5.4 K-EFF VERSUS PPM DISSOLVED BORON

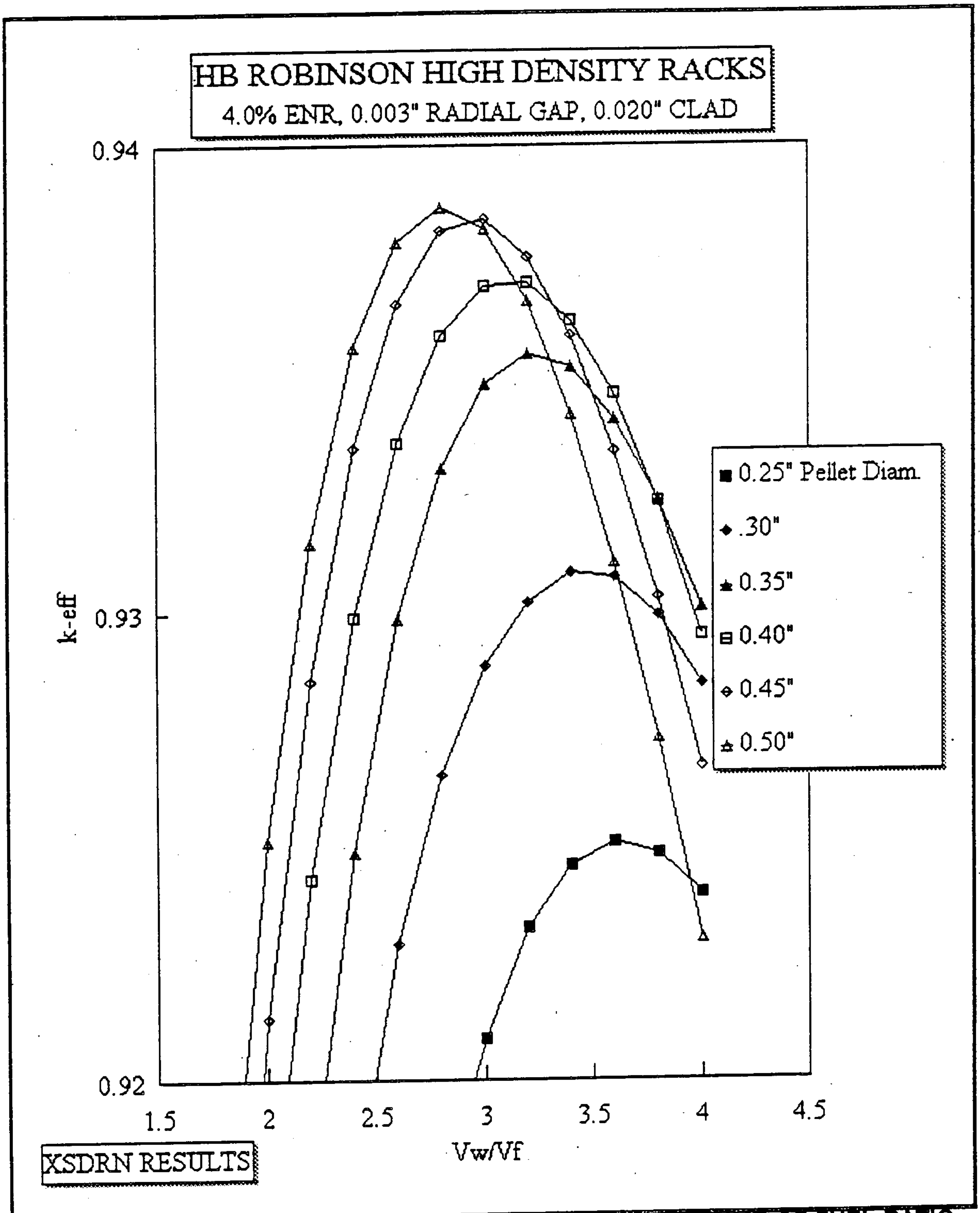


FIGURE 5.5 K-INF VERSUS VOLUME OF WATER TO VOLUME OF FUEL RATIO

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