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NUCLEAR DESIGN ANALYSIS REPORT FOR THE CALVERT CLIFFS UNIT #1 NUCLEAR PLANT HIGH DENSITY SPENT FUEL STORAGE RACKS

PREPARED UNDER NES PROJECT 5134
FOR THE
BALTIMORE GAS & ELECTRIC COMPANY

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1. SUMMARY

A detailed nuclear analysis has been performed for the NES designed fuel storage racks for the Calvert Cliffs Unit #1 Nuclear Plant. This analysis demonstrates that, for all anticipated normal and abnormal configurations of fuel assemblies within the fuel storage racks, the k_{eff} of the system is less than the criticality criterion of 0.95 for 4.10 w/o, 14 x 14 Combustion Engineering fuel assemblies. Certain conservative assumptions about the fuel assemblies and racks have been used in the calculations.

Both normal and abnormal configurations were considered in the analysis. The reference configuration consists of a square array, infinite in lateral extent, of storage cells spaced 9.75" on centers. Each storage location contains one centrally located 14 x 14 Combustion Engineering fuel assembly. Poison slabs containing boron are located in the walls of the storage cells to provide criticality control. The reference configuration provides a base of comparison relative to which effects of normal and abnormal variations have been measured. Normal configurations include: eccentrically positioned fuel, fuel enrichment variation, dimensional and material variations permitted by fabrication tolerences, and variation in the density of the boron in the poison slabs.

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Abnormal configurations include: pitch variation due to seismic events, spent fuel pool temperature variations, and fuel handling accidents including fuel assembly or heavy object drop.

The principal method of calculation was diffusion theory. Fuel, water, and structural cross sections were determined using the HAMMER code, while blackness theory was used to determine boron cross sections. K_{eff} values were calculated using EXTERMINATOR, a multigroup, two-dimensional diffusion theory code. Diffusion theory results were checked using KENO IV, a three-dimensional, Monte-Carlo criticality code. The k_{eff} value calculated by diffusion theory for the reference configuration is 0.9246. Monte Carlo calculations for the base case yielded a k_{eff} value of 0.9314. Combining the variations in k_{eff} due to the normal configurations and calculational uncertainty results in a k_{eff} of 0.9367. Combining the k_{eff} value for the "worst case" abnormal configuration with the bias between diffusion theory and Monte Carlo calculations results in a final k_{eff} value equal to 0.9435. This value meets the criticality design criterion and is substantially below 1.0. Therefore, it has been concluded that the high density storage racks for the Calvert Cliffs Unit #1 Nuclear Plant when loaded with the specified fuel are safe from a criticality standpoint.

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2. INTRODUCTION

The NES design for the Calvert Cliffs Unit #1 Nuclear Plant high density spent fuel storage racks achieves high storage density through the placement of poison slabs in the walls of the storage cells. Details of the rack materials and structure are given in Section 3.

A detailed nuclear analysis has been performed to demonstrate that, for all anticipated normal and abnormal configurations of fuel assemblies within the fuel storage racks, the k_{eff} of the system is substantially below 1.0. Certain conservative assumptions about the fuel assemblies and racks have been used in the calculations. These are described in Section 4 along with the criticality design criterion for the fuel assemblies and racks.

The reference configuration which forms the basis of criticality calculation represents the storage racks in nominal dimensions at 68°F with all fuel assemblies centrally located within their storage cells. Variations from this reference configuration were studied and included effects of wall thickness and pitch variations, fuel enrichment, and poison content variations, water temperature variation and eccentric fuel positioning.

Fuel handling accidents were studied and their effects determined. The configurations studied are described in detail in Section 5.

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The principal calculational method used for the criticality analysis was diffusion theory. Cross-sections were determined through use of the HAMMER code and k_{eff} was determined by EXTERMINATOR, a multigroup, two-dimensional diffusion theory code. Verification calculations have been performed with KENO IV, a Monte Carlo code. A detailed description of the calculational method and the computer codes is presented in Section 6.

The results of the criticality analyses are presented in Section 7.

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3. DESCRIPTION OF SPENT FUEL STORAGE RACKS

Two sizes of fuel storage racks, with 8 x 10 and 10 x 10 storage cell arrays, will be used in the Calvert Cliffs Unit No. 1 spent fuel storage pool (see Figure 3.1). The total number of fuel storage locations within the pool will be 840.

The inner wall of each storage cell is made up of a .060" thick sheet of 304L stainless steel, formed into a square with an inner dimension of 8-9/16".

On the outside of each of the four sides of this inner wall, a poison plate 6 1/2" wide is sandwiched between the inner wall and an external .060" thick stainless steel sheet (see Figure 3.2). The poison slab is .060" thick and contains 0.015 gms/cm^2 of B^{10}. The external sheet extends over two fuel storage cells so that storage cells are grouped into 2 x 2 modules from which the storage racks are built up. The average center to center pitch between all fuel storage boxes is maintained by the external sheets and welded spacers at 9.75 ± .036".

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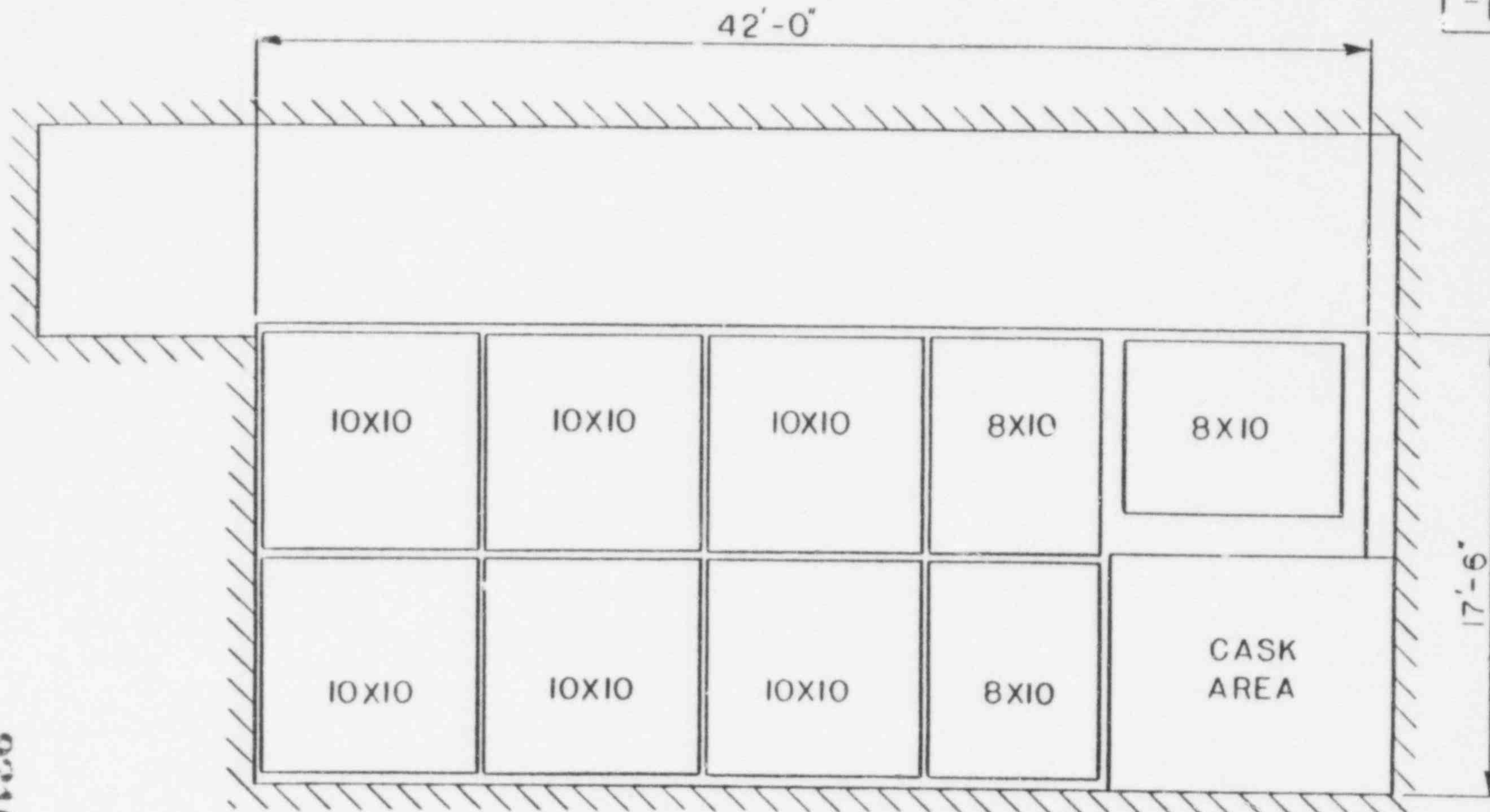

PLAN
FUEL STORAGE RACK ARRANGEMENT
(NORTHERN POOL)

FIGURE 3-1

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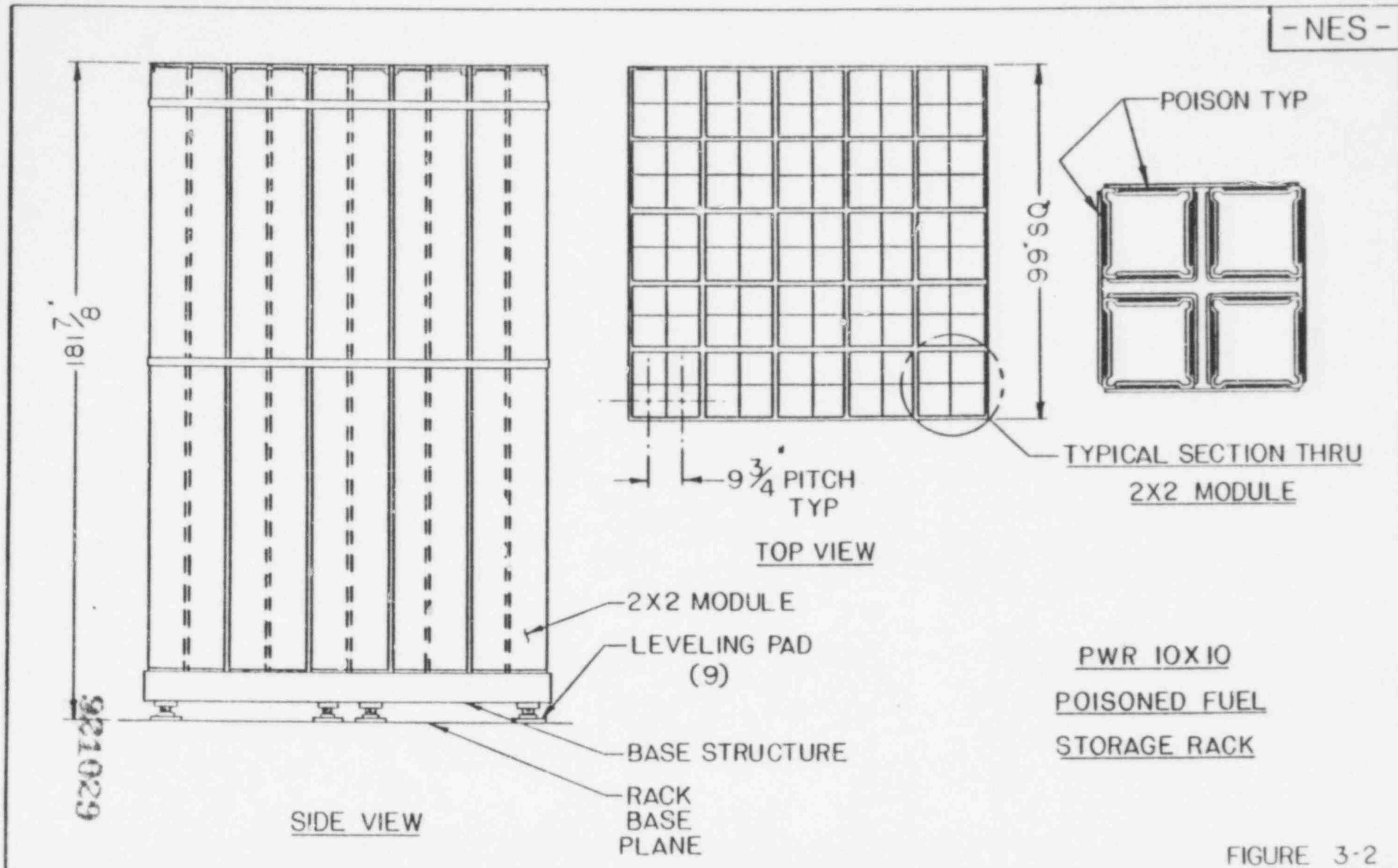

PWR 10X10 POISONED FUEL STORAGE RACK

FIGURE 3-2

4. CRITICALITY DESIGN CRITERION AND CALCULATIONAL ASSUMPTIONS

4.1 Criticality Design Criterion

A satisfactory value of k_{eff} for a spent fuel pool involves considerations of safety, licensability and storage capacity requirements. These factors demand a k_{eff} substantially below 1.0 for safety and licensability but high enough to achieve the required storage capacity.

The published position of the NRC on fuel storage criticality, stated in a communiqué to all reactor licensees[1] is as follows:

> "The neutron multiplication factor in spent fuel pools shall be less than or equal to 0.95, including all uncertainties, under all conditions."

Furthermore, NRC, in evaluating the design, will "check the degree of subcriticality provided, along with the analysis and the assumptions."

On the basis of this information, the following criticality design criterion has been established for the Calvert Cliffs Unit #1 Nuclear Plant high density fuel storage racks: "The multiplication constant (k_{eff}) shall be less than 0.95 for all normal and abnormal configurations as confirmed by Monte Carlo calculation."

4.2 Calculational Assumptions

The following conservative assumptions have been used in the criticality calculations performed to verify the adequacy of the rack design:

1. The fuel is fresh and of a specified enrichment greater than or equal to that of any fuel available (4.1 w/o).

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2. The reference configuration contains an infinite array of storage locations spaced 9.75 x 9.75 in. on centers. Obviously the array is not infinite, but finite.
3. The absorption of the fuel assembly spacers is ignored.
4. Any burnable poisons in the fuel assemblies are ignored.
5. The vertical buckling is ignored, i.e., the fuel assemblies are considered to be infinitely long.
6. Any soluble poison in the pool water is ignored.

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5. CRITICALITY CONFIGURATIONS

In order to verify the design adequacy of the Calvert Cliffs Unit #1 Nuclear Plant high density storage rack, it is necessary to establish the multiplication constants for the various arrangements or configurations of fuel assemblies and storage cells that are possible within the racks. These arrangements or configurations can be classified as either normal or abnormal configurations. Normal configurations result from variation in the placement of fuel within the storage cell the variation in fuel assembly dimensions and/or fuel loading because of the manufacturing process, and the variation in fuel storage rack dimensions permitted in fabrication. Abnormal configurations are typically the result of accidents or malfunctions such as the seismic event, a malfunction of the fuel pool cooling system (excessive changes in pool water temperature), a dropped fuel assembly, etc. The following sections present the normal and abnormal configurations which have been considered in this analysis.

5.1 Normal Configurations

5.1.1 Reference Configuration

The reference configuration consists of an infinite array of storage cells having nominal dimensions (see Section 3) each containing a fresh 14 x 14 Combustion Engineering fuel assembly centrally located within the storage cell. The water temperature within the rack is 68°F.

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5.1.2 Eccentric Configuration

It is possible for a fuel assembly not to be positioned centrally within a storage cell because of the clearance allowed between the assembly and the cell wall. This clearance is nominally 0.221 inches on each side of the fuel assembly.

Calculations have been performed to determine the effect of eccentrically located fuel. In these calculations it was assumed that four fuel assemblies were diagonally displaced within their storage cells as far as possible towards each other (see Figure 5.1).

5.1.3 Fuel Assembly Tolerance

The important fuel assembly parameter determining k_{eff} is the ratio of the amount of U^{235} to that of water. The amount of U^{235} per assembly is controlled to within a few tenths of a percent by weighing pellet stacks as the fuel is built and by using a known enrichment. The fuel assembly parameters which determine the volume of water in an assembly are the clad O.D. and the fuel rod pitch. These parameters are closely controlled to typically within $\pm$0.4 percent. The effects of these fuel assembly tolerances on k_{eff} have been determined to be negligible on the basis of simple k_{∞} cell calculations. Consequently, fuel assembly tolerances were not considered further in this analysis.

5.1.4 Fuel Design Variation

Calculations were performed to determine the sensitivity on k_{eff} to variations of fuel enrichment from the base enrichment of 4.10 w/o. The criticality configuration used for these calculations was that of the reference configuration with the exception of fuel enrichment.

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5.1.5 Fuel Rack Pitch Variation

Calculations were performed to determine the sensitivity of k_{eff} to changes in pitch, the center-to-center spacing between storage cells. The pitch was varied 0.125 inch above and below the nominal value. The criticality configuration was similar to that of the reference configuration except for the obvious change in center-to-center spacing.

5.1.6 Cell Wall Thickness Variation

The base case wall thickness was 0.060" for each of the stainless steel sheets forming the cell walls. This thickness was varied up and down to 0.070" and 0.050" to determine the effect on k_{eff}.

5.1.7 Poison Concentration Variation

The poison slabs contain a nominal concentration of 0.015 gms/cm^2 of B^{10}. This concentration was varied $\pm 10\%$ to determine the sensitivity of k_{eff} to variations in this parameter.

5.1.8 "Worst Case" Normal Configuration

The "worst case" configuration considers the effect of eccentric fuel assembly positioning, the minimum average pitch (center-to center spacing) permitted by fabrication, the minimum wall thickness and the minimum poison concentration.

5.2 Abnormal Configurations

5.2.1 Single Storage Cell Displacement

Displacement of a single storage cell within the array is precluded by the welded construction and the presence of structure between cells. Therefore the effect of such a displacement is taken to be zero.

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5.2.2 Fuel Handling Incident

Accidental placement of fuel between the fuel racks or the racks and pool wall will be prevented by structural material. It is, however, conceivable that an assembly could be laid across the top of a fuel rack. In this case, the distance between the tops of the stored fuel and the bottom of the misplaced fuel will be greater than 25", a distance which according to calculations effectively "decouples" the two groups of fuel. No increase in k_{eff} will result from this incident.

5.2.3 Pool Temperature Variation

Calculations were performed to determine the sensitivity of k_{eff} for the reference configuration to variations in the spent fuel pool temperature. The pool temperature was varied from 39°F, where water density is a maximum, to 250°F, the approximate boiling point of water near the bottom of the fuel rack.

5.2.4 Fuel Drop Incident

The maximum height through which a fuel assembly can be dropped onto the fuel storage racks is limited. The dropped fuel assembly will most likely impact the tops of the fuel storage rack cells. Because of the fuel rack design, damage will be limited to the upper 6 to 8 inches of the storage cells. Since the active fuel region is about 18 inches below this area, no significant change in fuel/cell geometry will occur. However, it is possible for a dropped fuel assembly to enter a cell cleanly and impact directly on the fuel stored in the cell. The effect of this type of fuel drop incident was evaluated from a criticality viewpoint by assuming that the stored assembly would be compressed axially.

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A calculation based on an axial compression of 2 feet yielded a 0.06 decrease in k_{oo} of the fuel cell. It has been concluded, therefore, that this incident would reduce k_{eff} and need not be considered further in this analysis.

5.2.5 Heavy Object Drop

In the unlikely event that a heavy object is dropped on the storage rack with sufficient impact to cause structural deformation, it has been concluded that k_{eff} will decrease. The basis for this conclusion is that the principal effect of dropping a heavy object will be to squeeze water from the rack. Both in the case of compacted fuel and voided pool water, depletion of water leads to a decrease in k_{eff}.

It would not be possible for a dropped heavy object to eject the poison material from the rack; the crushing effect of the heavy object could only act to compress the fuel and poison together.

5.2.6 Seismic Incident

Seismic analyses have determined that during an SSE the pitch between two adjacent fuel assemblies could narrow locally by as much as 0.005 inches, due to oscillations about nodal points determined by structural members locating the cells within the racks. However, at the same time, the local pitch at other locations is greater by the same amount, with the net effect that although the pitch may vary locally, the average pitch is unaffected.

In the event that the entire rack is displaced by a seismic event, the average pitch will also be unaffected.

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It is concluded, therefore, that if the fuel assemblies deflect independently in random directions or move together in a single direction, the average pitch between assemblies and, consequently, the k_{eff} are unaffected.

5.2.7 "Worst Case" Abnormal Configuration

The "worst case" abnormal configuration considers the effect of the most adverse abnormal condition in combination with the "worst case" normal configuration. The results of the "worst case" abnormal configuration are presented in Section 7.2.3.

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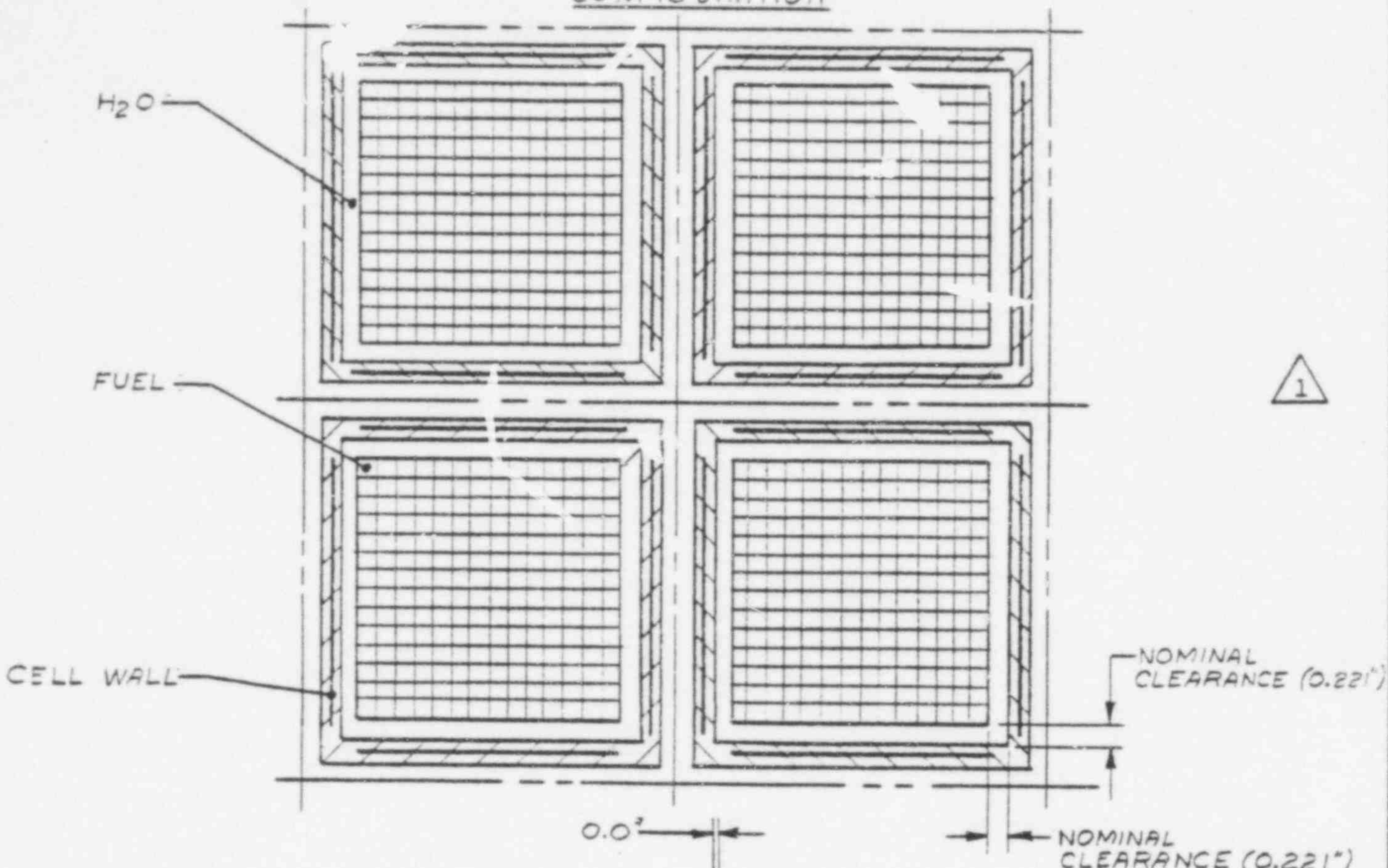
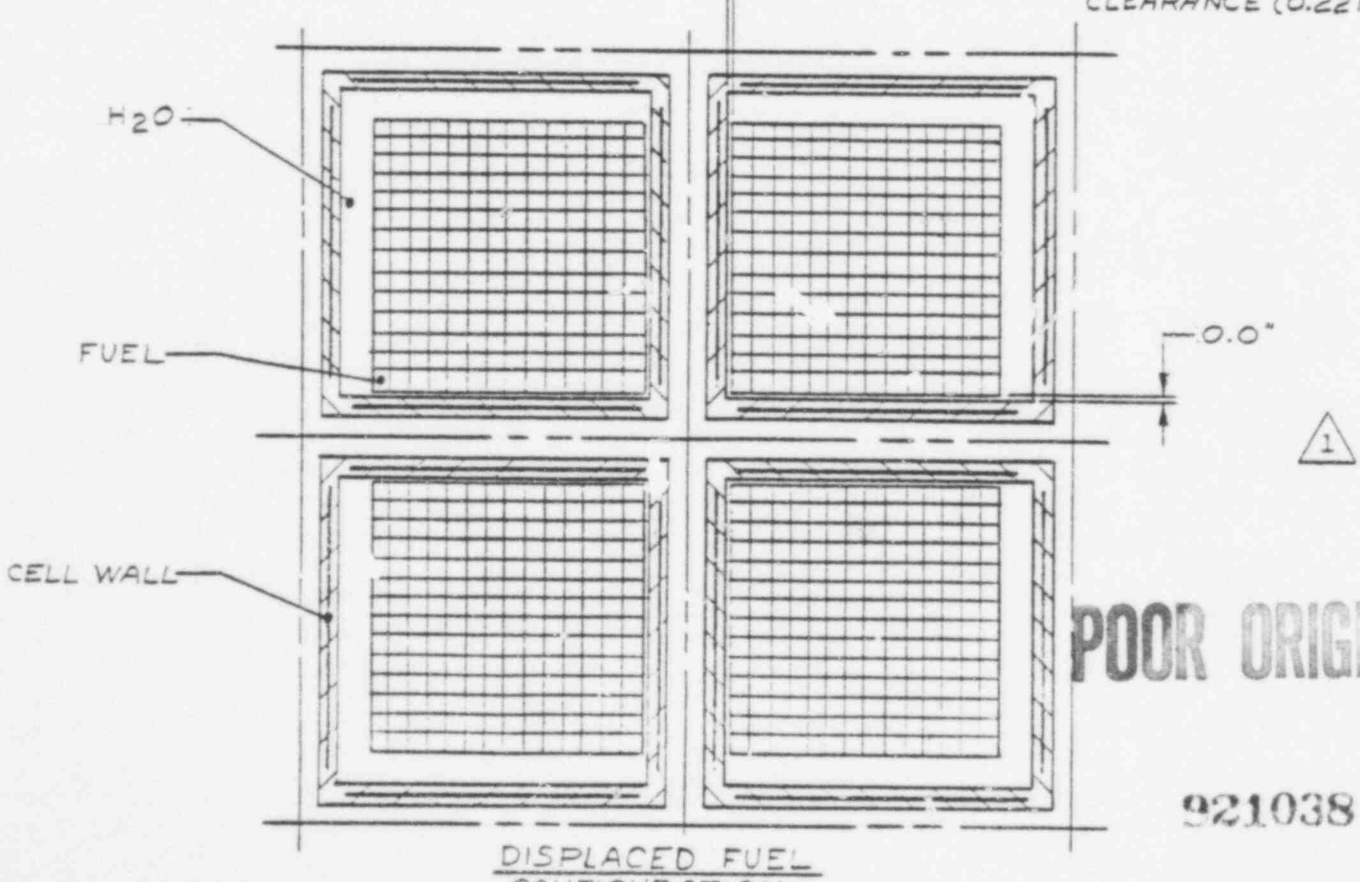
FIG. 5.1

REFERENCE FUEL CONFIGURATION





DISPLACED FUEL CONFIGURATION

6. CRITICALITY CALCULATIONAL METHODS

6.1 Method of Analysis

For each of the normal and abnormal configurations discussed in Section 5, the k_{eff} was determined from a two-dimensional diffusion theory calculation of an infinite array of fuel assemblies loaded in the spent fuel storage racks. An infinite array is used for two reasons: an infinite array has a conservatively higher value of k_{eff} and the problem can be suitably represented by a repeating portion of the array. Figure 6.1 shows a representation of one quarter of a storage location with reflecting boundaries on all sides. This duplicates an infinite array of storage locations. The diffusion theory calculations have been performed using the 2-D diffusion theory code EXTERMINATOR with cross-section input determined by the HAMMER code and BRM, and blackness theory code developed at NES.

Normally for criticality calculations dealing with reactors, diffusion theory gives very satisfactory results since the codes and cross-sections have been normalized to fit experimental data over many years. It is generally assumed that Monte Carlo methods are more accurate than diffusion theory for configurations with large water gaps such as spent fuel storage racks. For this reason, check calculations have been made using the 3-D Monte Carlo code KENO-IV.

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6.2 Benchmark Calculations for Diffusion Theory and Monte Carlo Methods

Both HAMMER and EXTERMINATOR are used by NES as versions available at Combustion Engineering at Windsor Locks, Connecticut. The combination has been benchmarked against a cold critical experiment performed at the LaCrosse Boiling Water Reactor with excellent results (see Reference 2). The calculated k_{eff} differed from the experimental value by only 0.0017. A similar benchmark has been performed for KENO-IV using 16 group Hansen-Roach cross sections, resulting in a k_{eff} which differed from the experimental value by only 0.001.

6.3 Code Descriptions

6.3.1 The HAMMER Code

HAMMER (see Reference 3) is a multigroup integral transport theory code which is used to calculate lattice cell cross sections for diffusion theory codes. This code has been extensively benchmarked against D_2O and light water moderated lattices with good results.

6.3.2 The EXTERMINATOR Code

EXTERMINATOR (see Reference 4) is a 2-D multigroup diffusion theory code used with input from HAMMER to calculate k_{eff} values.

6.3.3 The KENO IV Code

KENO IV is a 3-D multigroup Monte Carlo criticality code used to determine k_{eff} (see Reference 5).

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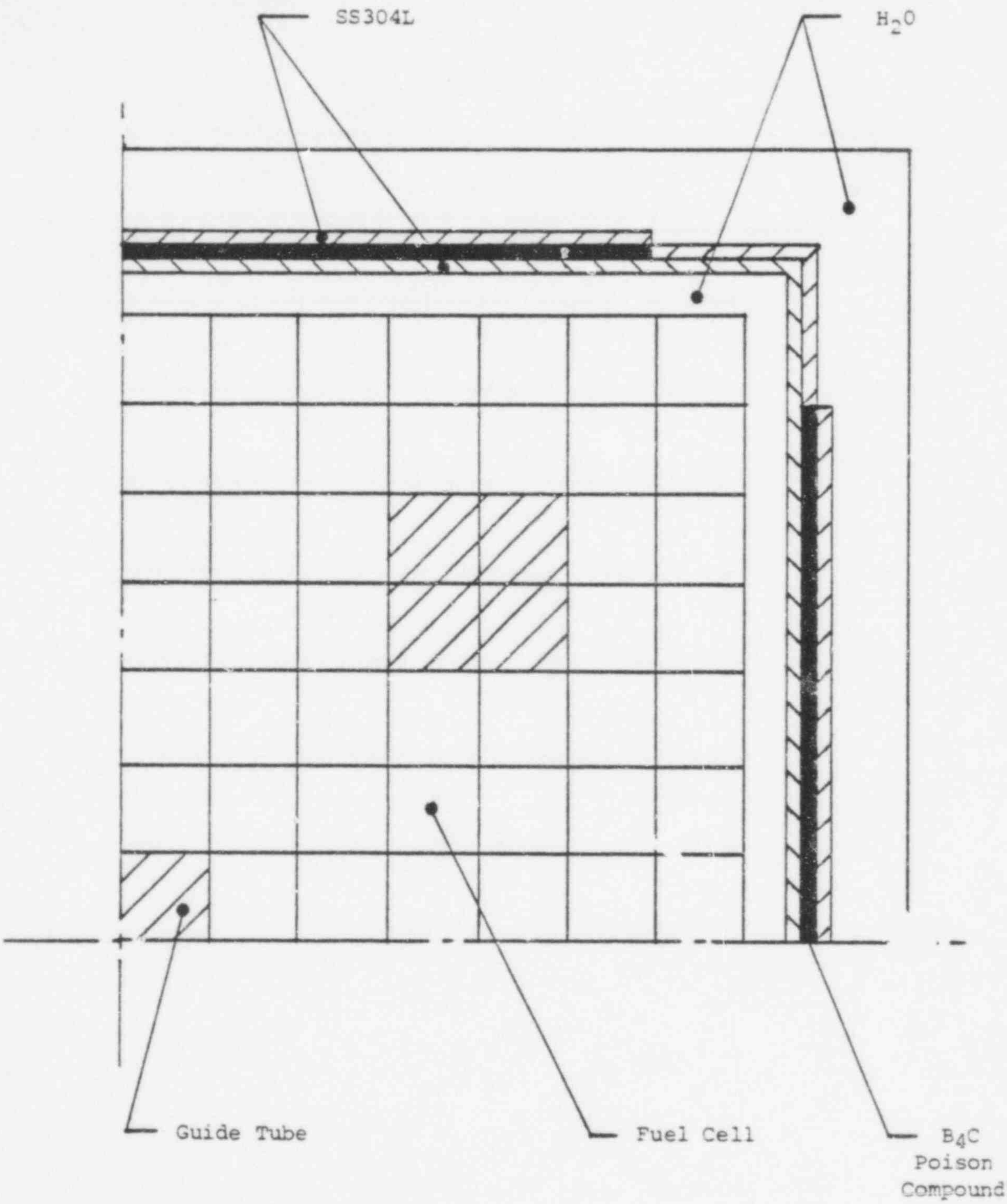

EXTERMINATOR Reference Configuration

Fig. 6.1

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7 RESULTS OF CRITICALITY CALCULATIONS

For the criticality configurations to be evaluated, cross-sections were determined with the HAMMER code and the blackness theory code, BRM. These cross-sections were then used in the 2-D diffusion theory code EXTERMINATOR to determine k_{eff}.

The effects of enrichment changes, temperature, dimensional tolerances of the racks, and abnormal dislocations within racks due to seismic events, fuel handling incidents, fuel drop and heavy object drop were investigated. A Monte Carlo calculation of the reference configuration was performed to establish the Monte Carlo/diffusion theory bias.

7.1 Cross-Sections from HAMMER

The HAMMER input for fuel regions was based on the description of the 14 x 14 Combustion Engineering fuel assembly presented in Reference 6. The properties of the fuel assembly pertinent to the nuclear calculations are summarized in Table 7.1. Figure 6-1 presents the model of the assembly used in the calculations and shows the locations of the fuel rod regions.

The basic fuel rod region considered in a HAMMER problem is a fuel rod including pellets, clad, and the associated water in the area surrounding the rod. This surrounding area is a square with the dimension of one rod pitch (see Figure 7.1). A HAMMER problem was written to represent each variation in fuel cell characteristics: enrichment and temperature.

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Macroscopic cross-sections for stainless steel, water and zirconium were determined from microscopic cross-sections derived from the HAMMER calculations. The fuel was assumed to occupy the total volume inside the clad including the gap, and the correct amount of fuel was determined from the fuel loading information. The input dimensions and atom densities used for the various fuel cell calculations are listed in Table 7.2.

The resulting four group cross-sections for fuel regions are summarized in Table 7.3.

7.2 Two Dimensional Diffusion Theory Calculations - EXTERMINATOR

The 2-D mesh layout and material specifications used for the reference configuration are shown in Figure 6.1. The cross-sections for each of the material regions in Figure 6.1 (fuel, boron, water, and zirconium) were chosen from the appropriate four group cross-sections calculated by HAMMER. Group 3 and 4 cross-sections for the poison slabs were calculated using the blackness theory code BRM.

The cross-section input and mesh spacings used for the reference configuration EXTERMINATOR calculation are listed in Table 7.4. Table 7.5 presents the resulting k_{eff} value for each calculation.

7.3 K_{eff} Values for Normal Configurations

7.3.1 Reference Configuration

The k_{eff} for the reference configuration described in Section 5.1.1 was determined to be 0.9246 by means of HAMMER/EXTERMINATOR.

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7.3.2 Eccentric Configuration

The Δk_{eff} for the eccentric configuration described in Section 5.1.2 (where alternate fuel elements were diagonally displaced) was determined to be $\Delta k_{eff} = -0.0075$. (see Figure 5.1).

7.3.3 Fuel Design Variation

The enrichment of the fuel in the reference configurations was reduced by 0.2 w/o. The results are shown in Figure 7.2 and in Table 7.5.

7.3.4 Fuel Rack Pitch Variation

The k_{eff} variation for a fuel rack average pitch variation of $\pm$.125 inch is shown in Figure 7.3. The mechanical design of the fuel rack is such that the average pitch between boxes is maintained by structural members at 9.75" $\pm$ .036 inches. The change in k_{eff} for a decrease in average pitch of 0.036 inch is +0.0046. (see Figure 7.3).

7.3.5 Fuel Rack CellWall Thickness Variation

The value of the wall thickness used in the reference configuration calculation was chosen to be nominally 0.060". A variation of $\pm$ 0.010" was investigated and the results are shown in Figure 7.4. Since the material used for the wall will have a thickness tolerance of $^{+0.005}_{-0.0000}$ inches, a variation in k_{eff} of 0.0008 is assigned to this parameter.

7.3.6 Poison Content Variation

The effect of poison content variation was studied and results are shown in Figure 7.5 and Table 7.5.

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The poison content is specified as 0.015 ± 0.0015 gm/cm^2 and the effect of a 10% decrease is +0.0050 Δk.

7.3.7 "Worst Case" Normal Configuration

Results for normal configurations can be summarized as follows:

		k_{eff} or Δk_{eff}
1.	Reference Configuration	0.9246
2.	Minimum Cell Pitch	0.0046
3.	Minimum poison concentration	0.0050
4.	Cell wall thickness tolerance	0.0008

No allowance for fuel enrichment variation is required since the fuel on which the calculations were based is of the highest enrichment considered. The Δk due to eccentric location of fuel within cells was determined to be negative and will be ignored. The effects of the above normal variations are combined statistically as follows:

$$\Delta k_{eff} = \sqrt{(.0046)^2 + (.0050)^2 + (.0008)^2} = 0.0068.$$

The diffusion theory result for the worst case normal configuration is 0.9246 ± 0.0068.

7.4 K_{eff} Values for Abnormal Configurations

7.4.1 Fuel Handling Incident

Since it will not be possible to place fuel adjacent to a rack, and since the Δk caused by a fuel assembly lying horizontally on top of the rack is negligible, no allowance on k_{eff} is made for this abnormal configuration.

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7.4.2 Spent Fuel Pool Temperature Variation

The k_{eff} of the rack was studied for temperatures ranging from 39°F to 250°F. Results are given in Figure 7.6 and Table 7.5 and show that the rack has a negative temperature coefficient with the highest k_{eff} occurring at the nominal 68°F temperature.

7.4.3 "Worst Case" Abnormal Configuration

The "worst case" abnormal configuration combines the change in k_{eff} due to the occurence of the most adverse abnormal condition with the k_{eff} value associated with the worst case normal configuration. However, since none of the abnormal conditions gives a positive Δk, the "worst case" abnormal condition is simply equal to the "worst case" normal condition.

		K_{eff}
1.	Worst Case Normal Configuration (per Section 7.3.7)	0.9314
2.	Most Adverse Abnormal Configuration	+0.0000
3.	Final k_{eff} for "worst abnormal" configuration.	0.9314

1 (revision triangle)

7.5 Monte Carlo Reference Configuration Calculation

KENO-IV, a Monte Carlo code, was used to calculate k_{eff} for the reference configuration in order to check diffusion theory results. The k_{eff} value obtained with KENO is 0.9314. This value differs from the diffusion theory reference k_{eff} by +0.0068.

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Therefore, the "worst case" abnormal condition allowing for the diffusion to Monte Carlo bias is 0.9382.

7.6 Effects of Calculational Uncertainty

The k_{eff} values presented in the previous sections do not include the effect of calculational uncertainties. In order to accurately assess the uncertainty of a specific calculational system, it is necessary to compare many calculational results with the corresponding criticality experiments. Consequently, NES has investigated the open literature to determine what uncertainty values are assigned to criticality computations after comparisons with many experiments have been made. The uncertainties, depending upon the specific combination of codes used to determine the cross-sections and the multiplication constant, range from less than 0.007 to less than 0.015 at the 95 percent confidence level.

Therefore, NES has assumed an average uncertainty of 0.01. When this uncertainty is combined statistically with the uncertainties due to normal variations, the resulting normal configuration result becomes:

$$0.9246 \pm 0.0121.$$

The upper limit for the "worst abnormal" configuration results from taking the normal configuration at the upper limit of its uncertainty and adding the Δk_{eff} values for the worst abnormal configuration and for the calculational bias between diffusion theory and Monte Carlo theory. 1

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0.9246	Reference Configuration
0.0121	Upper limit of uncertainty
0.0000	"Worst Case" Abnormal Configuration
0.0068	Monte Carlo/Diffusion theory Bias
0.9435	

Thus the upper limit for k_{eff} including the effects of normal and abnormal variations, uncertainties, and difference between codes is 0.9435; it is concluded, therefore, that the Calvert Cliffs high density fuel storage racks when loaded with the specified fuel are safe from a criticality standpoint.

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TABLE 7.1

FUEL PARAMETERS

Fuel Type	14 x 14 Combustion Engineering Fuel
Fuel Enrichment, w/o	4.10
Mass of Uranium per Assembly, kg.	395.23
Clad I.D., inches	0.388
Clad O.D., inches	0.440
Clad Thickness, inches	0.026
Clad Material	Zircaloy-4
Pitch Between Rods, inches	0.580
Active Fuel Length, inches	136.7 △1
Array Dimensions	14 x 14

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TABLE 7.2

HAMMER INPUT DIMENSIONS AND ATOM DENSITIES

Enr. w/o	Temp, °F	FUEL atoms/b-cm			CLAD atoms/b-cm	MODERATOR atoms/b-cm	
		U^{235}	U^{238}	Oxygen	Zirconium	Oyxgen	Hydrogen
4.10 w/o	68°F	8.9073-4	2.0571-2	4.2924-2	4.29 -2	3.3357-2	6.6714-2
4.10 w/o	39°F	8.9073-4	2.0571-2	4.2924-2	4.29 -2	3.3416-2	6.6832-2
4.10 w/o	150°F	8.9073-4	2.0571-2	4.2924-2	4.29 -2	3.2758-2	6.5516-2
4.10 w/o	212°F	8.9073-4	2.0571-2	4.2924-2	4.29 -2	3.2025-2	6.4050-2
4.10 w/o	250°F	8.9073-4	2.0571-2	4.2924-2	4.29 -2	3.1495-2	6.2989-2
4.00 w/o	68°F	8.6900-4	2.0593-2	4.2923-2	4.29 -2	3.3357-2	6.6714-3
3.90 w/o	68°F	8.4728-4	2.0614-2	4.2923-2	4.29 -2	3.3357-2	6.6714-2

TABLE 7.3

FOUR GROUP HAMMER CROSS-SECTIONS FOR FUEL REGIONS

Group #	D	Σ_r	Σ_a	$\nu\Sigma_f$
4.10 w/o, 68°F, 0.998 gm/cc				
1	1.9443	.07884	.004365	.008874
2	1.0096	.07973	.002740	.001297
3	.7179	.06944	.026326	.017595
4	.2740	0.	.126509	.220673
4.10 w/o, 39°F, 1.000 gm/cc				
1	1.9426	.07892	.004366	.008875
2	1.0087	.07984	.002740	.001297
3	.7172	.06954	.026329	.017596
4	.2737	0.	.126557	.220737
4.10 w/o, 150°F, 0.980 gm/cc				
1	1.9621	.07780	.004357	.008861
2	1.0189	.07828	.002740	.001297
3	.7269	.06799	.026288	.017583
4	..284	0.	.121670	.212391
4.10 w/o, 212°F, 0.958 gm/cc				
1	1.9843	.07655	.004347	.008846
2	1.0306	.07655	.002739	.001297
3	.7381	.06625	.026241	.017569
4	.2910	0.	.117438	.205186
4.10 w/o, 250°F, 0.942 gm/cc				
1	2.0007	.07565	.004340	.008835
2	1.0393	.07530	.022739	.001296
3	.7464	.06500	.016205	.017559
4	.2968	0.	.115428	.201823
4.00 w/o, 68°F, 0.998 gm/cc				
1	1.9444	.07884	.004359	.008857
2	1.0096	.07974	.002726	.001268
3	.7179	.06954	.026098	.017200
4	.2740	0.	.124778	.216892
3.90 w/o, 68°F, 0.998 gm/cc				
1	1.9444	.07884	.004352	.008840
2	1.0096	.07974	.002712	.001234
3	.7179	.06965	.025869	.016804
4	.2740	0.	.123024	.213062

TABLE 7.4

REFERENCE EXTERMINATOR CONFIGURATION

Calvert Cliffs 4.1W/O .060 PGI .015GM/CM2 9.75 In Pitch No Buckling

OPTION CARD
1 1 1 1 1 1 -0 -0 -0 2 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 -0 1 -0

SPECIFICATIONS
18 ROWS 18 COLS 4 GRPS 6 COMPS -0 NUCS L,T,R,B BND 1 1 1 1 EPI 5.0000E-04 NORM FAC 1.000000E+00

THIS CASE HAS X-Y GEOMETRY,
AND IS AN EIGENVALUE CALC.

FISSION-SOURCE CHI (K)
.7532 .2466 .0002 0.0000

MESH SPECIFICATIONS

I DELTA
1 .701 2 .350 4 .152 5 .076 7 .152 8 .281 10 1.473 11 .584 12 .889 13 1.473 17
2.946 18

J DELTA
1 .701 2 .350 4 .152 5 .076 7 .152 8 .281 10 1.473 11 .584 12 .889 13 1.473 17
2.946 18

DIMENSION SPECIFICATIONS

I DIST.
2 .350 3 .701 4 1.051 5 1.203 6 1.280 7 1.356 8 1.508 9 1.789 10 2.070
11 3.543 12 4.128 13 5.017 14 6.490 15 7.963 16 9.436 17 10.909 18 13.856

J DIST.
2 .350 3 .701 4 1.051 5 1.203 6 1.280 7 1.356 8 1.508 9 1.789 10 2.070
11 3.543 12 4.128 13 5.017 14 6.490 15 7.963 16 9.436 17 10.909 18 13.856

9221052

TABLE 7.4 (CONT'D)

REFERENCE EXTERMINATOR CONFIGURATION

REACTOR MATERIAL PICTURE

J-	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
4	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	
5	3	3	3	3	4	4	4	4	4	4	4	6	6	6	6	6	6	
6	3	3	3	3	4	4	4	4	4	4	4	6	6	6	6	6	6	
7	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	
8	3	3	3	3	4	4	4	3	3	3	3	3	3	3	3	3	3	
9	3	3	3	3	4	4	4	3	3	3	3	3	3	3	3	3	3	
10	3	3	3	3	4	4	4	3	3	1	1	1	1	1	1	1	1	
11	3	3	3	3	4	4	4	3	3	1	1	1	1	1	1	1	1	
12	3	3	3	4	6	6	4	3	3	1	1	1	1	1	1	1	1	
13	3	3	3	4	6	6	4	3	3	1	1	1	2	2	1	1	1	
14	3	3	3	4	6	6	4	3	3	1	1	1	2	2	1	[illegible]	1	
15	3	3	3	4	6	6	4	3	3	1	1	1	1	1	1	1	1	
16	3	3	3	4	6	6	4	3	3	1	1	1	1	1	1	1	1	
17	3	3	3	4	6	6	4	3	3	1	1	1	1	1	1	1	2	
18																		

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TABLE 7.4 (CONT'D)

REFERENCE EXTERMINATOR CONFIGURATION

COMPOSITION SPECIFICATIONS

COMP	GRP	D	SIGR	SIGA	NUSIGF	SOURCE	BSQ	SIGF
1	1	1.94431E+00	7.88410E-02	4.36500E-03	8.87400E-03	-0.	6.84000E-09	0.
	2	1.00958E+00	7.97320E-02	2.74000E-03	1.29700E-03	-0.	6.84000E-09	0.
	3	7.17919E-01	6.94370E-02	2.63260E-02	1.75950E-02	-0.	6.84000E-09	0.
	4	2.74047E-01	-0.	1.26509E-01	2.20673E-01		6.84000E-09	0.
2	1	2.00572E+00	1.02058E-01	7.24000E-04	-0.	-0.	6.84000E-09	0
	2	1.05777E+00	1.35313E-01	9.00000E-05	-0.	-0.	6.84000E-09	0.
	3	5.46516E-01	1.32850E-01	2.21500E-03	-0.	-0.	6.84000E-09	0.
	4	1.64717E-01	-0.	3.60718E-02	-0.	-0.	6.84000E-09	0.
3	1	3.07970E+00	1.12060E-01	3.21000E-04	0.	-0.	6.84000E-09	0.
	2	1.07220E+00	1.44000E-01	1.30000E-05	0.	-0.	6.84000E-09	0.
	3	5.71160E-01	1.03420E-01	8.15000E-04	0.	-0.	6.84000E-09	0.
	4	2.21360E-01	0.	1.35830E-02	0.	-0.	6.84000E-09	0.
4.	1	1.81360E+00	2.83990E-02	8.94000E-04	0.	-0.	6.84000E-09	0.
	2	1.19730E+00	2.85200E-03	9.68000E-04	0.	-0.	6.84000E-09	0.
	3	4.40240E-01	2.04800E-03	9.84400E-03	0.	-0.	6.84000E-09	0.
	4	3.26750E-01	0.	1.30490E-01	0.	-0.	6.84000E-09	0.
5	1	0.	0.	0.	0.	0.	6.84000E-09	0.
	2	0.	0.	0.	0.	0.	6.84000E-09	0.
	3	0.	0.	0.	0.	0.	6.84000E-09	0.
	4	0.	0.	0.	0.	0.	6.84000E-09	0.
6	1	1.48780E+01	2.86900E-03	1.26600E-03	0.	-0.	6.84000E-09	0.
	2	6.25540E+00	8.75000E-04	1.24120E-02	0.	-0.	6.84000E-09	0.
	3	2.91470E-01	5.59000E-04	9.53740E-01	0.	-0.	6.84000E-09	0.
	4	1.62270E-02	0.	8.71570E+00	0.	-0.	6.84000E-09	0.

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TABLE 7.4 (CONT'D)

REFERENCE EXTERMINATPR CONFIGURATION

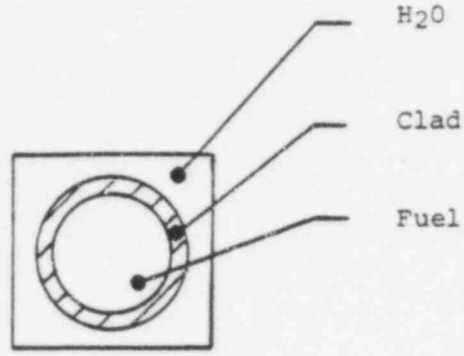
SCATTERING MATRIX

COMP	GRP	TO GRP 1	2	3	4
1	1	0.	7.88410E-02	0.	0.
	2	0.	0.	7.97320E-02	0.
	3	0.	0.	0.	6.94370E-02
	4	-0.	0.	0.	0.
2	1	0.	1.02058E-01	0.	0.
	2	0.	0.	1.35313E-01	0.
	3	0.	0.	0.	1.32850E-01
	4	-0.	0.	0.	0.
3	1	0.	1.12060E-01	0.	0.
	2	0.	0.	1.44000E-01	0.
	3	0.	0.	0.	1.03420E-01
	4	0.	-0.	-0.	-0.
4	1	0.	2.83990E-02	0.	0.
	2	0.	0.	2.85200E-03	0.
	3	0.	0.	0.	2.04800E-03
	4	0.	-0.	-0.	-0.
5	1	0.	0.	0.	0.
	2	0.	0.	0.	0.
	3	0.	0.	0.	0.
	4	0.	0.	0.	0.
6	1	0.	2.86900E-03	0.	0.
	2	0.	0.	8.75000E-04	0.
	3	0.	0.	0.	5.59000E-04
	4	0.	-0.	-0.	-0.

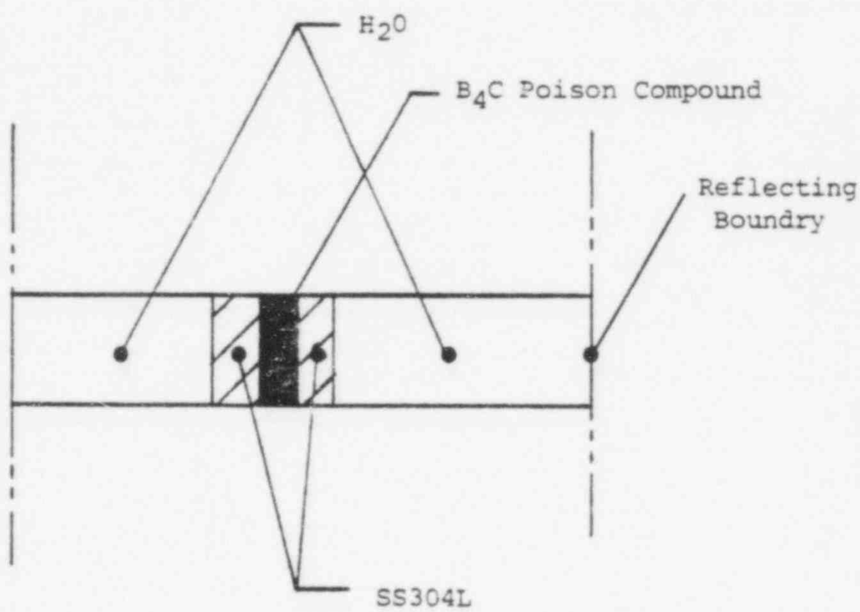
TABLE 5

PARAMETERS AND RESULTS OF EXTERMINATOR CALCULATIONS

	Enrichment, w/o	Average Cell Pitch, Inches	Temp. °F	H_2O Dens. gm/cc	Poison Content gm B^{10}/cm^2	k_{eff} or Δk_{eff}
Reference Configuration	4.10	9.75	68	.998	0.015	0.9246
Maximum Water Density	4.10	9.75	39	1.000	0.015	0.0000
150°F, Temp. Case	4.10	9.75	150	.980	0.015	-0.0050
212°F, Temp. Case	4.10	9.75	212	.958	0.015	-0.0145
250°F, Temp. Case	4.10	9.75	250	.942	0.015	-0.0165
Pitch Variation, +0.125 inch	4.10	9.875	68	.998	0.015	-0.0151
Pitch Variation, -0.125 inch	4.10	9.625	68	.998	0.015	+0.0160
Low Enrichment, 4.00 w/o	4.00	9.75	68	.998	0.015	-0.0050
Low Enrichment, 3.90 w/0	3.90	9.75	68	.998	0.015	-0.0101
High Poison Content, +10%	4.10	9.75	68	.998	0.0165	-0.0045
Low Poison Content, -10%	4.10	9.75	68	.998	0.0135	+0.0050
Eccentric Fuel	4.10	9.75	68	.998	0.015	-0.0075
Low Wall Thickness, .050"	4.10	9.75	68	.988	0.015	-0.0016
High Wall Thickness, .070"	4.10	9.75	68	.988	0.015	+0.0016



Fuel Model



Cell Wall Model

HAMMER Models of Fuel and Cell Wall

Fig. 7.1

921057

ΔK_{eff} Vs. Enrichment

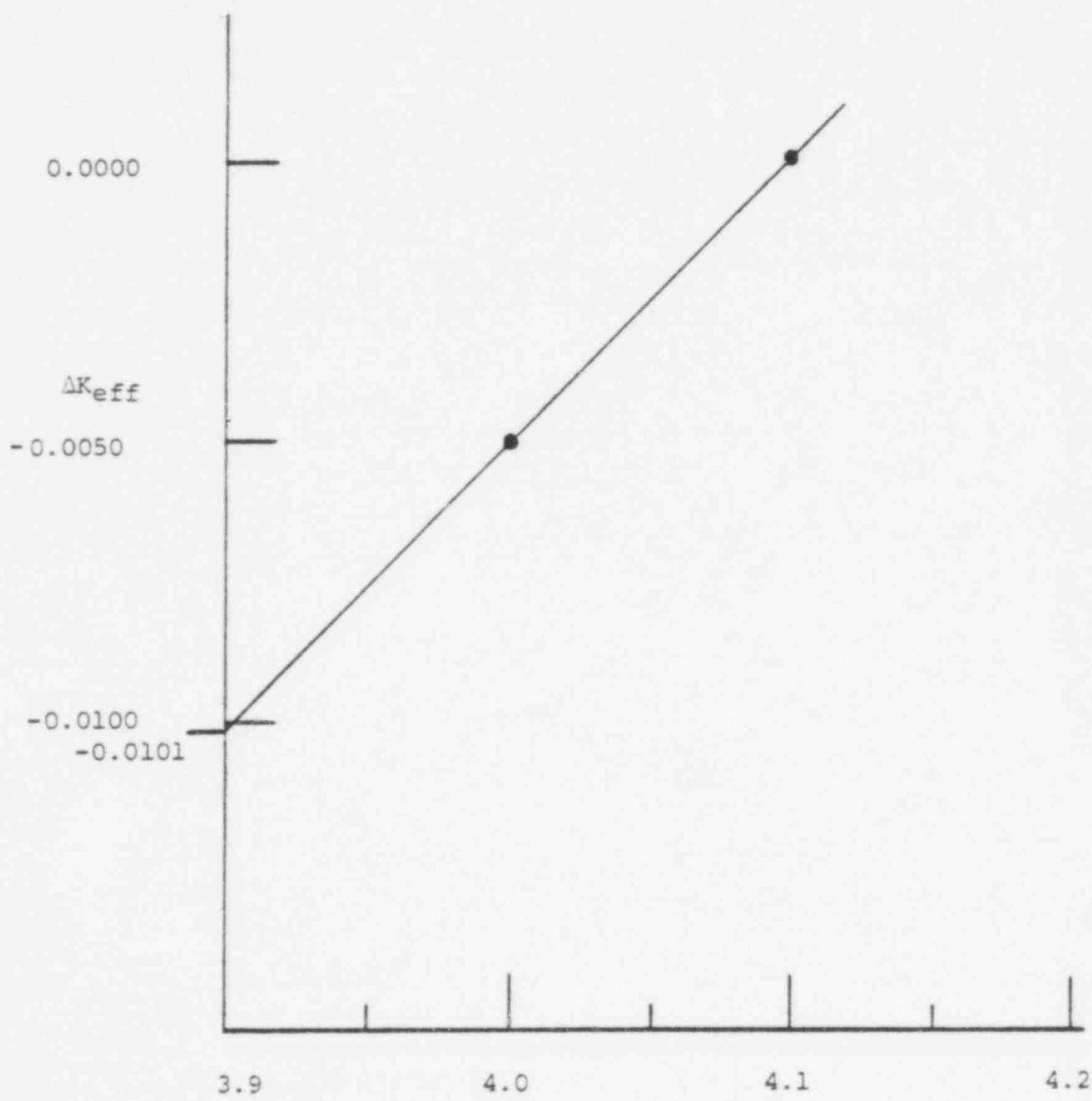


Figure 7.2

921058

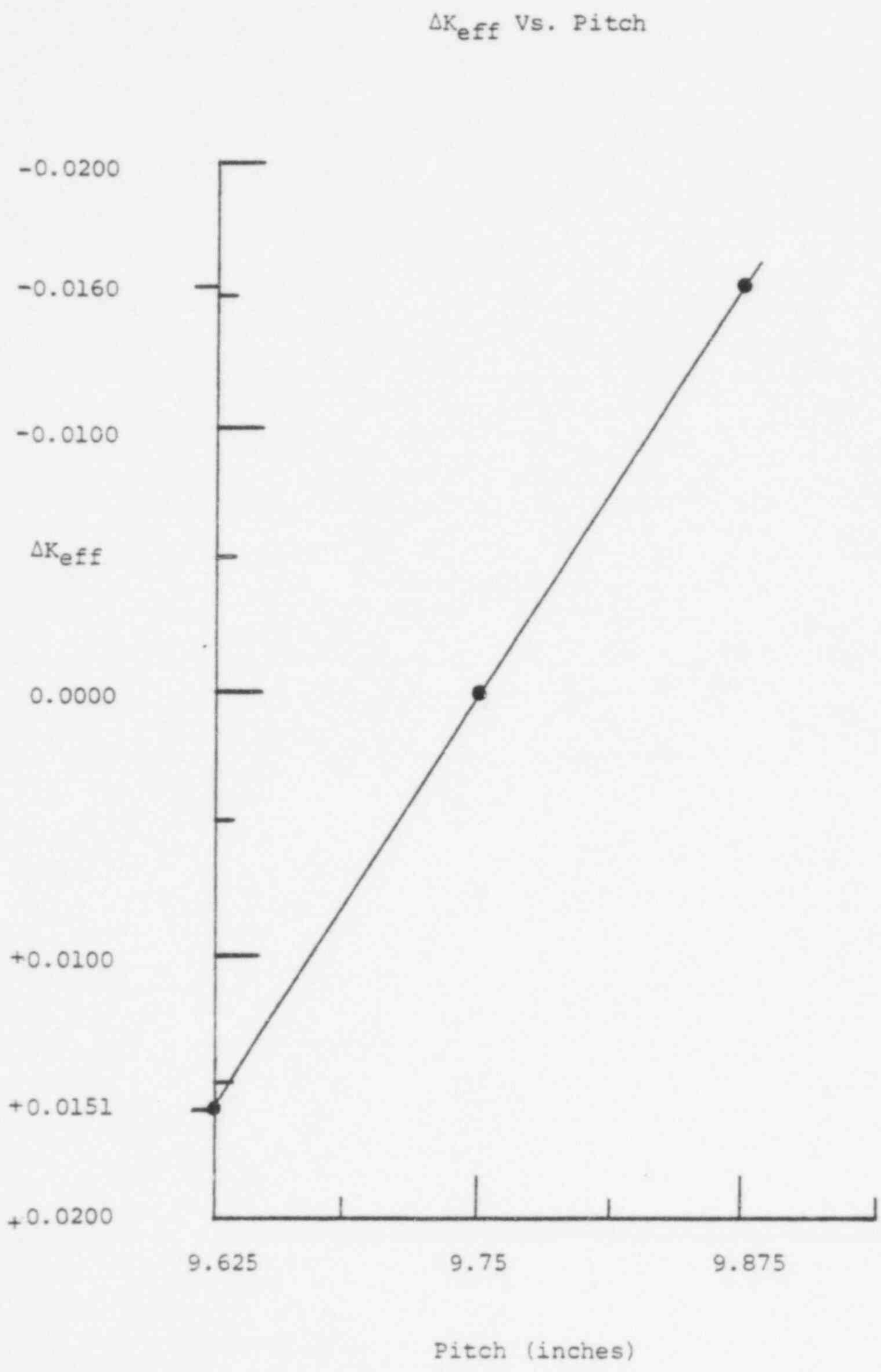


Fig. 7.3

921059

ΔKeff Vs. Wall Thickness

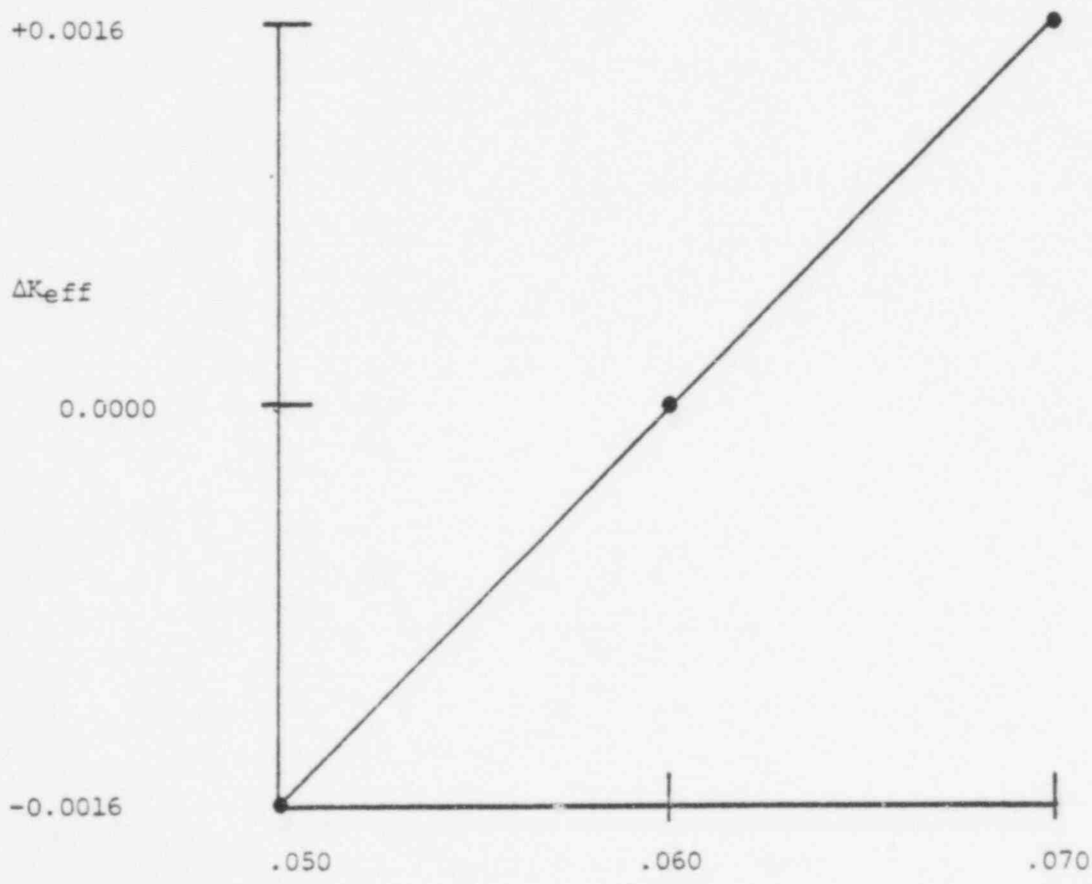


Fig. 7.4

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ΔK_{eff} Vs. Poison Content

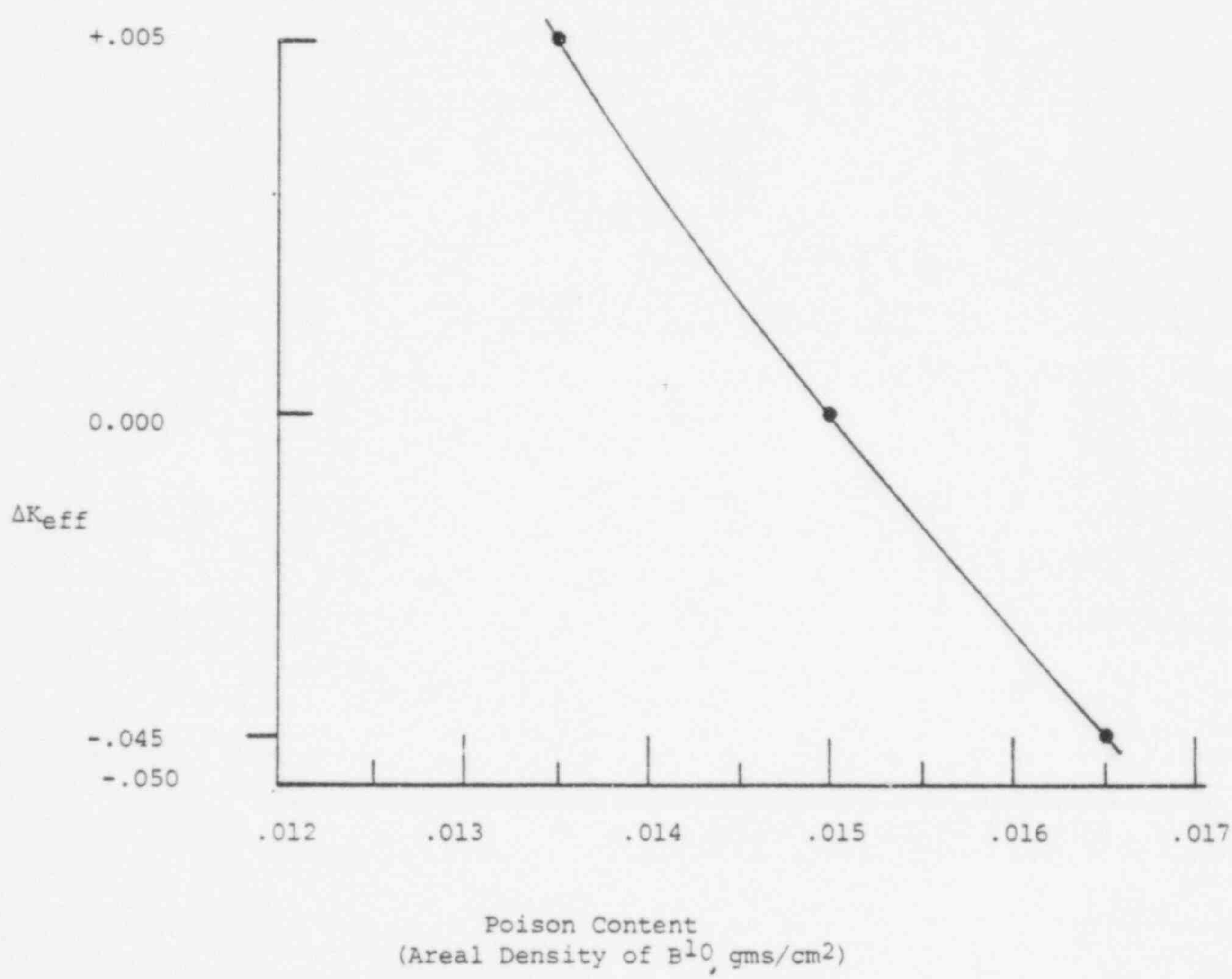

Fig. 7.5

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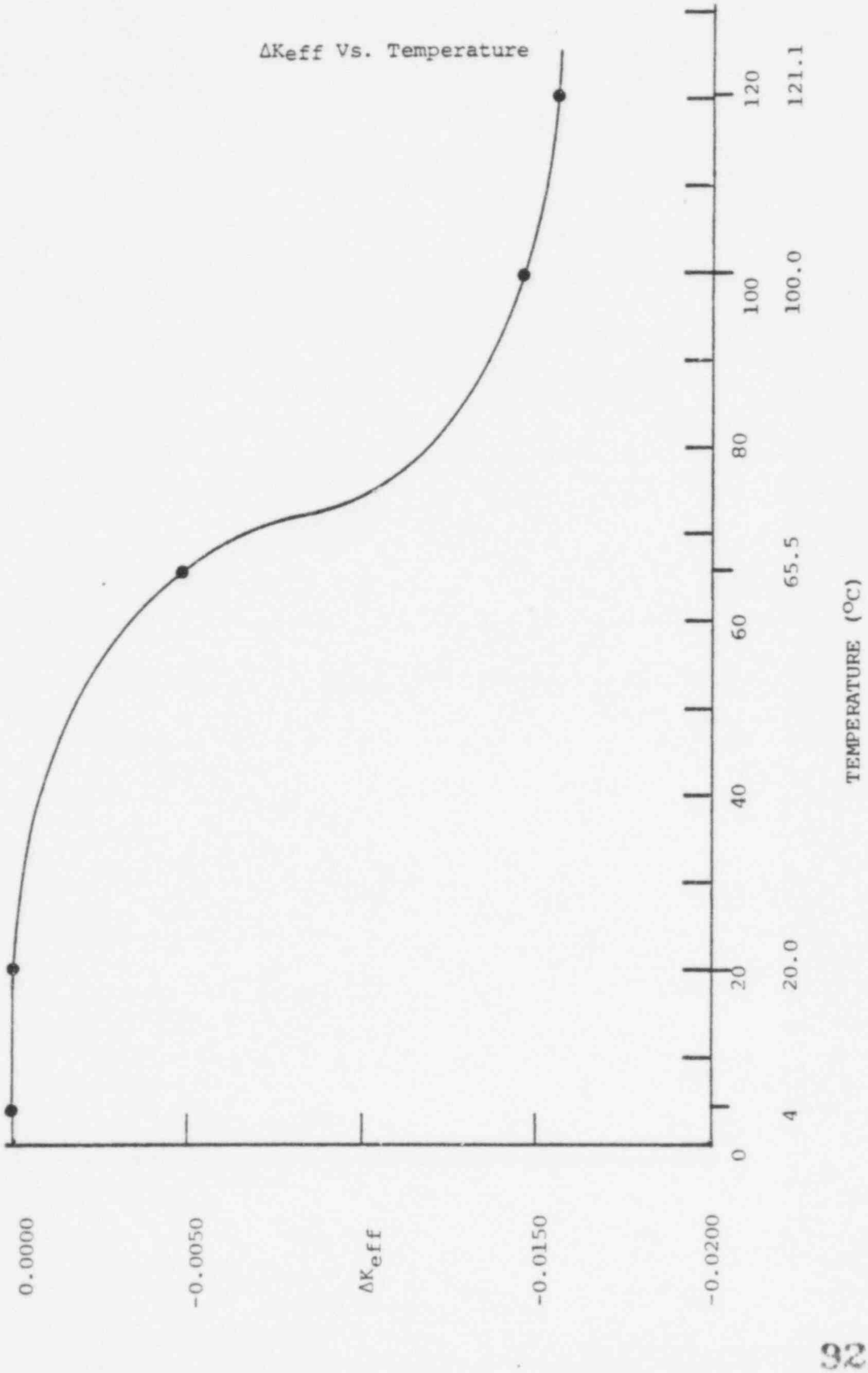

Fig. 7.6

921062

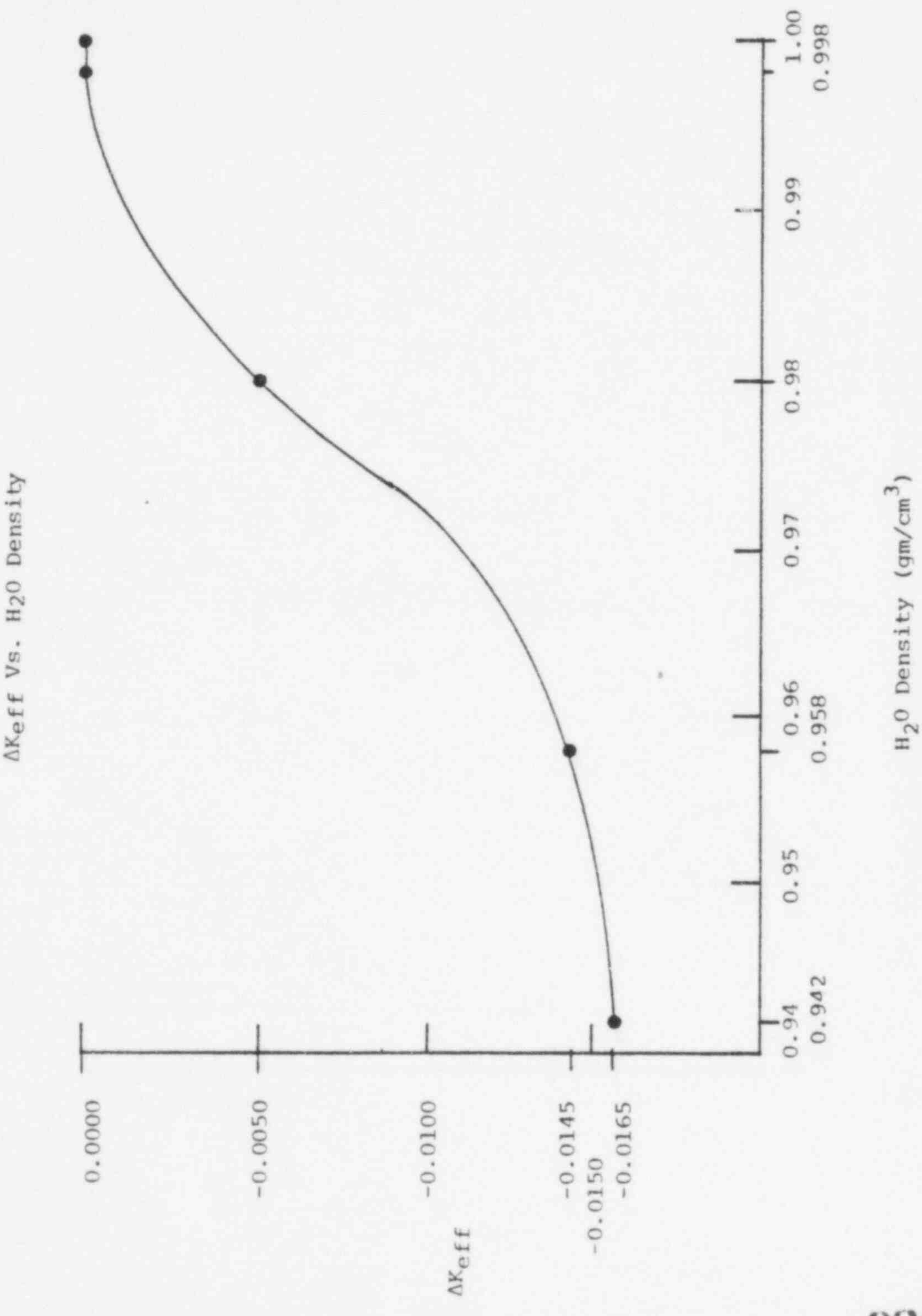

Fig. 7.7

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3. DP-1064, the HAMMER System, J.E. Sutch and H.C. Honeck, January, 1967.

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6. Letter to R. Milos from M.C. Key of Baltimore Gas and Electric Company, dated July 24, 1978.

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NUCLEAR ENERGY SERVICES, INC.

DOCUMENT NO. 81A0567

REVISION LOG

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1	5/9/79		See CRA No. 821	RAM
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