NUCLEAR DESIGN ANALYSIS REPORT

FOR THE

NEW FUEL STORAGE RACKS

FOR THE

SURRY NUCLEAR POWER STATION

Prepared Under
NES Project No. 5157
for
The Virginia Electric Power Company
by
Nuclear Energy Services, Inc.

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1. SUMMARY

A detailed nuclear analysis has been performed for the new fuel storage racks for the Surry Nuclear Power Station. The analysis demonstrates that for all normal and abnormal configurations considered, the K_{eff} of the system is less than the criticality criterion of 0.98 for 4.1 w/o Westinghouse fuel asssemblies stored in the rack.

Studies were performed of the effects of variations in the physical parameters of the rack and of the fuel assemblies which could affect the nuclear characteristics. These variations are classified in this report as normal and abnormal.

Normal variations include small changes in water density, fuel eccentrically positioned within a storage cell, fuel enrichment variation, storage cell pitch variation, and the cumulative effect of all of the above, the worst case normal configuration. Abnormal variations include effects of fuel handling incidents, large water density variations, dropped or compacted fuel, and cell displacement due to seismic events.

The abnormal variation resulting in the highest increase in the magnitude of K_{eff} is chosen to represent the worst case abnormal configuration. A margin of error resulting from calculational uncertainty is added to the numerical results. The calculation of K_{eff} values was carried out using the three-dimensional Monte Carlo code KENO-IV.

K_{eff} values were first calculated with a very simple geometric model with reflecting boundaries in the x and y directions that effectively represented a rack of infinite lateral extent. The K_{eff} values determined with this simple model may be summarized as follows:

K_{eff} of the new fuel storage rack dry at 68°F at nominal dimensions	0.474
K_{eff} of the new fuel storage rack including effects of normal variations and calculational uncertainty	0.713

Final K_{eff} of the new fuel storage rack including normal variations, calculational uncertainty and the worst case abnormal configuration. 0.973

Because the resulting K_{eff}, 0.973, is so close to the criticality criterion of 0.98, a further study was performed with a more detailed geometrical model with less inherent conservatism. The results of the more detailed study show the maximum K_{eff} to be approximately 0.86.

These results show clearly that the Surry new fuel storage racks meet the criticality design criterion and are safe under the specifications set forth in the Standard Review Plan (NUREG-75/087).

2. INTRODUCTION

The nuclear analysis performed for the Surry Nuclear Power Station is presented in this report in the following order:

Detailed descriptions of the fuel rack and fuel assemblies to be stored within are given in Section 3 including dimensions, tolerances and materials pertinent to the nuclear characteristics of the loaded rack.

The criticality criterion and calculational assumptions made in order to show compliance with NRC guidelines are outlined in detail in Section 4.

Section 5 contains a description of the individual criticality cases studied. The presentation in Section 5 is intended to expand and clarify the scope of the nuclear analysis required for compliance with the NRC guidelines quoted in Section 4.

The method of analysis and the models used to describe the new fuel storage racks and the fuel assemblies in the various configurations are outlined in Section 6. In addition, the computer codes used to carry out the calculations are discussed.

The results of the calculations are presented in Section 7 with their interpretation. The determination of final K_{eff} values from calculation results is explained and carried out.

A detailed parametric study versus water density, performed with a more complex geometry, is presented in Section 8.

3. DESCRIPTION OF NEW FUEL STORAGE RACKS

The new fuel storage facility at the Surry Nuclear Power Station has a total storage capacity of 126 new fuel assemblies. Each storage location consists of a stainless steel square box 165" tall with 9" I.D. and 1/8" thick walls. These boxes are located in nine parallel rows, with a pitch of 21" between boxes within a row. The pitch between rows is either 21" or 30". The storage facility has concrete walls and floor and is normally empty of water.

The structural supports and bracing which hold the rack together and provide support during potential seismic events will not be considered in this analysis. This omission is justified because these steel supports are at widely separated locations and have a fairly large absorption cross-section for neutrons so that neglecting them is conservative.

4. CRITICALITY DESIGN CRITERION AND CALCULATIONAL ASSUMPTIONS

4.1 CRITICALITY DESIGN CRITERION

The position of the NRC regarding the criticality of new fuel storage (Ref. 1) is as follows:

> "The design of the new fuel storage racks will be such that K_{eff} will not exceed 0.98 with fuel at the highest anticipated enrichment in place assuming optimum moderation."

This guide is adopted without modification as the criticality <u>design</u> <u>criterion</u> for the Surry new fuel storage racks.

4.2 CALCULATIONAL ASSUMPTIONS

The following conservative assumptions have been used in the criticality calculations performed to verify the adequacy of the rack design with respect to the criticality design criterion.

1. The rack is assumed to be infinite in lateral extent.

2. The pitch is assumed to be 21" throughout, whereas in fact some rows are spaced at 30".

5. CRITICALITY CONFIGURATION

To verify the adequacy of the Surry new fuel storage racks for storage of 4.1 w/o fuel, it is necessary to determine multiplication constants corresponding to the different arrangements or configurations possible within the racks. These arrangements or configurations are classified as either normal or abnormal configurations. Normal configurations include the reference configuration, small water density variations, eccentrically positioned fuel, fuel design variation, fuel rack cell pitch variation and the combination of these effects termed the worst case normal configuration.

Abnormal configurations result from accidents and disturbances not normally encountered. These include fuel handling accidents, large water density variations, fuel drop accident, seismic incident and the worst case abnormal configurations.

5.1 NORMAL CONFIGURATIONS

5.1.1 Reference Configuration

The reference configuration consists of an infinite array of storage cells having nominal dimensions, each containing a 15x15 Westinghouse fuel assembly of 4.1 w/o enrichment positioned centrally within the cell. The storage cells are spaced 21.0" on centers and consist of square cans with a 9.0" I.D. and a 1/8" wall thickness.

The new fuel rack and the fuel assemblies are at 68°F. The reference configuration is shown in Figure 5.1.

5.1.2 Eccentrically Positioned Assemblies

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 0.2775" on each side of the fuel assembly. The worst eccentric positioning occurs if four adjacent assemblies are displaced within their storage cells as far as possible towards each other.

5.1.3 Fuel Design Variation

Since 4.1 w/o is the highest enrichment expected to be used at Surry, no calculations have been performed to determine the effects of enrichment changes.

5.1.4 Fuel Rack Cell Pitch Variation

Calculations were performed to determine the sensitivity of K_{eff} to change in pitch, the center-to-center spacing between storage cells. The pitch was varied 2" above and 2" below the nominal value of 21".

5.1.5 Low Density Moderator Variation

The variation of atmospheric humidity in the rack causes a slight variation in moderator (H_2O) density. The sensitivity of K_{eff} to the variations in H_2O density over the density range from 0.0 to 0.01 gm/cc was evaluated and is included under normal configurations. The upper limit of 0.01 gm/cc was chosen deliberately high to assure conservatism.

5.1.6 Worst Case Normal Configuration

Since any of the above normal configurations can occur simultaneously, it is necessary to evaluate their combined maximum adverse effect.

The result is the worst case normal configuration. As the name implies, it represents the state of the rack under normal conditions which has the largest K_{eff} value.

5.2 ABNORMAL CONFIGURATIONS

5.2.1 Fuel Handling Incident

In some fuel storage racks it is possible during fuel handling to inadvertently position an assembly beside the loaded rack in a clearance space between racks or between storage locations within a rack. In the case of Surry new fuel racks however, a steel cover or platform located above the storage cells prevents this incident from occurring. Consequently no calculations have been performed for fuel misplaced in the rack.

5.2.2 High Moderator Density Variation

Accidents such as fire, pipe break, etc. can result in the presence of foams, steam, water and other materials containing water in the new fuel storage area. Under accident conditions it must be assumed the density of water can take any value from 0.0 to 1.0 gm/cc. Therefore, the variation of K_{eff} over the entire range must be evaluated. Since low water densities from 0.0 to 0.01 gm/cc are included under normal configurations, only densities from 0.01 gm/cc to 1.0 gm/cc will be considered as abnormal configurations.

5.2.3 Fuel Drop Incident

A fuel assembly could be dropped during insertion or removal from a storage cell and compacted within. A configuration is, therefore, considered in which one storage location contains compacted fuel. For simplicity, this was modeled as a worst case situation in which each location was filled with compacted fuel.

5.2.4 Seismic Incident

The effects of a seismic incident are evaluated in terms of pitch variation caused by storage cell displacement.

5.2.5 Worst Case Abnormal Configuration

The worst case abnormal configuration is taken to be the single abnormal configuration which results in the most adverse effect on K_{eff}.

6. CRITICALITY CALCULATION METHODS

Calculations in this analysis were performed with KENO-IV using 16 group Hansen Roach cross-sections. The HAMMER code was used as a check for accuracy. This section contains information regarding computer models and codes.

6.1 METHOD OF ANALYSIS

It was stated in Section 4 that the rack was modeled as an infinite array. This was accomplished by modeling one quarter of a storage cell containing one quarter of a fuel assembly and the associated water region surrounding it (see Figure 6.1). Reflecting boundaries on all four sides make this model the equivalent of an infinite array in a horizontal plane. In the vertical direction, nonreflecting boundaries are located below the floor, a concrete slab, and above the top of the storage rack.

The 4.1 w/o 15x15 Westinghouse fuel assemblies were modeled using the values shown in Table 6.1. Individual fuel pins were represented as concentric cylinders of UO_2 and zirconium clad (see Figure 6.2). The pellet diameter is assumed expanded to equal the clad inner diameter, thus eliminating the pellet-clad gap.

6.2 COMPUTER CODES

6.2.1 HAMMER

HAMMER (see Ref. 2) 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.

6.2.2 KENO-IV

KENO-IV is a 3-D multigroup Monte Carlo code used to determine K_{eff} (see Ref. 3).

KENO-IV has been benchmarked against critical experiments consisting of typical light water reactor fuel lattices. Results (see Ref. 5,6) show KENO-IV to be conservative for these configurations.

6.3 UNCERTAINTIES AND BENCHMARK CALCULATIONS

The uncertainties in Monte Carlo criticality calculations can be divided into two classes:

1. Uncertainty due to the statistical nature of the Monte Carlo methods.

2. Uncertainty due to bias in the calculational technique.

The first class of uncertainty can be reduced by simply increasing the number of neutrons tracked. For rack criticality calcuations, the number of neutrons tracked is selected to reduce this error to less than 1%.

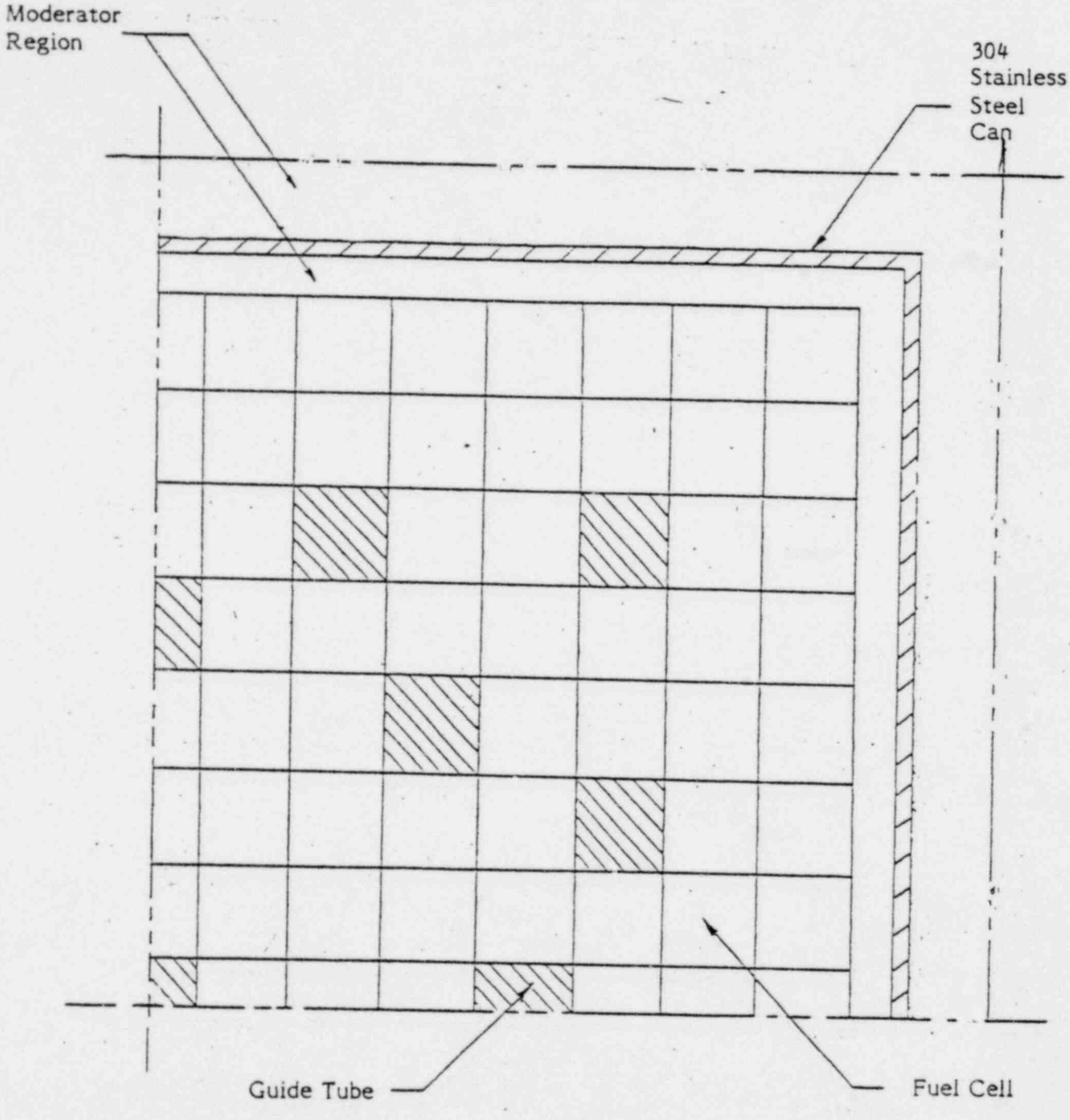
The second class of uncertainty is accounted for by benchmarking the calculational method against experimental results. In the benchmarking process, the calculational method is used to determine the criticality value for a critical experiment configuration. The difference between the calculated criticality value and the experimental value is identified as the calculational bias. Once determined, this bias can be applied to other calculational results obtained for similar configurations to improve the degree of calculational accuracy. If the calculated criticality value found during benchmarking is less than the experimental value, then the bias is added to other calculational results to ensure a conservative criticality value consistent with experimental results. Conversely, if the calculational criticality value is greater than the experimental value, it is appropriate to subtract the bias from the other calculated results to improve the accuracy of the criticality determination.

Both HAMMER and KENO-IV have been benchmarked at NES (Ref. 4) and found to be accurate in all cases to better than $\pm 1\%$ of the experimental K_{eff} value. Benchmark calculations performed outside NES confirm these findings (see Ref. 5, 6). Calculations in this analysis were based on KENO-IV. To check the accuracy of KENO, fuel pin k_{∞} values were determined using both KENO-IV and HAMMER and then compared to assure their agreement to within 1%. Thus HAMMER was used solely to check accuracy.

TABLE 6.1

FUEL PARAMETERS

Fuel Type	15x15 Westinghouse Fuel
Fuel Enrichment	4.1 w/o
UO_2 per Assembly	1122 lb
Clad I.D.	0.3734 inch
Clad O.D.	0.422 inch
Clad Material	Zircaloy-4
Pitch Between Rods	0.563 inch
Active Fuel Length	144.0 inch
Array Dimensions	15x15
Guide Tube Material	Zircaloy-4
Fuel Rods per Assembly	204
Guide Tubes per Assembly	21
Guide Tubes, I.D.	0.455
Guide Tubes, O.D.	0.512



Quarter Storage Location Representation of Infinite Array

FIGURE 6.1

ILLUSTRATION OF SINGLE FUEL PIN

MODEL SHOWING HOMOGENIZED FUEL REGION

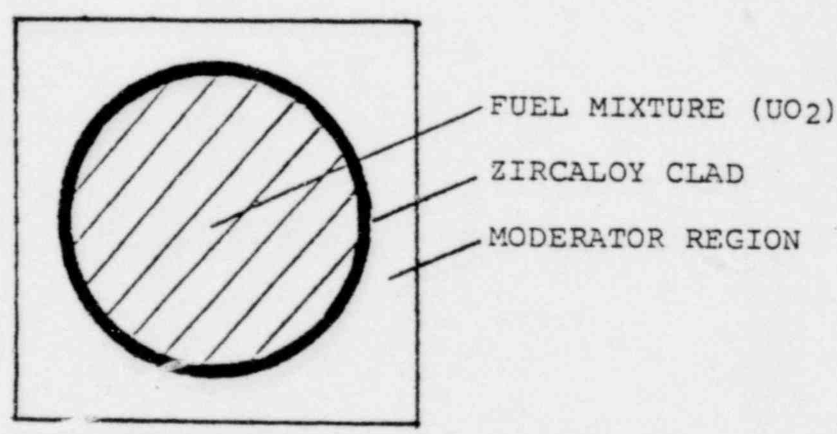


FIGURE 6.2

7. RESULTS OF CRITICALITY CALCULATIONS

Calculations performed with KENO-IV to evaluate K_{eff} for the configurations described in Section 5 resulted in a final K_{eff} value which is below the design limit of 0.98 imposed by the criticality criterion. The final value of $K_{eff} = 0.973$ allows for variations due to normal and abnormal configurations and the effects of calculational uncertainty.

7.1 REFERENCE CONFIGURATION

The K_{eff} determined by KENO-IV using the 16 group Hansen Roach cross-section set was 0.474 with an uncertainty of ± 0.006 at the 95% confidence level.

7.2 K_{eff} VALUES FOR NORMAL CONFIGURATIONS

7.2.1 Moderator Density Variation from 0.0 to 0.1 gm/cc of H_2O

An increase of water density in the rack from 0.0 to 0.01 gm/cc resulted in a ΔK_{eff} of 0.233 (see Figure 7.1 and Table 7.1).

7.2.2 Fuel Assembly Pitch Variation

The pitch was varied up and down by 2"; decreasing pitch by 2" caused an increase in K_{eff} of 0.043. The results of pitch variation are shown in Figure 7.2 and Table 7.1. Since the average pitch in the rack is substantially greater than the reference value of 21", no allowance for normal variation in pitch will be made.

7.2.3 Eccentric Fuel Location

In the worst case of eccentric location of fuel assemblies, four adjacent assemblies will be located in the corners of their respective cans such that all four are as close as possible to their three neighbors. In such a case, the pitch between these four neighbors will be reduced by 2 x 0.2775" where 0.2775" is the assembly to can wall clearance.

This case can conservatively be represented by a configuration in which the average pitch of the whole rack is reduced by 0.555 inches. The average pitch of the rack is much greater than the 21" assigned to the reference case because some gaps are 30". Therefore the reduction of 0.555" for eccentric can be ignored.

7.2.4 Worst Case Normal Configuration

The K_{eff} for the worst case normal configuration results from the sum of the ΔK's due to normal variations added to the K_{eff} for the reference configuration. K_{eff} for the worst case normal configuration is determined as follows:

K_{eff} of reference configuration	0.474
ΔK_{eff} due to moderator density variation	0.233
ΔK_{eff} due to pitch variation	0.00
ΔK_{eff} due to eccentric fuel positioning	0.00
Total ΔK_{eff}	= 0.233

Adding this value to the reference K_{eff} gives the value for the worst case normal configuration:

$$K_{eff} = 0.474 + 0.233$$
$$= 0.707$$

7.3 K_{eff} FOR ABNORMAL VARIATION

7.3.1 Moderator Density Variation from 0.01 gm/cc to 1.0 gm/cc of H_2O

Variation of H_2O density from 0.1 to 1.0 gm/cc resulted in a ΔK_{eff} of 0.260 (see Table 7.1 and Figure 7.1).

7.3.2 Fuel Drop Accident

The accidental drop of a fuel assembly resulting in its being compacted in its storage location was modeled by increasing the pellet O.D. of all fuel contained in the rack by 10%. Densities were maintained at their reference values for conservatism. ΔK for this configuration was found to be 0.06.

7.3.3 Seismic Incident

Rack pitch variations due to a seismic event are limited to appro...nately $\pm$ 0.25 inches. These deflections would likely be in random directions. If, however, we assume they combine in the worst case to reduce the average storage cell pitch 0.25 inches, it remains clear the effect on K_{eff} is small.

Interpolation from Figure 7.2 shows the ΔK_{eff} for a pitch change of 0.25" to be about 0.005 ΔK.

7.3.4 Worst Case Abnormal Configuration

The worst case abnormal configuration considers the ΔK_{eff} of the most adverse abnormal configuration in combination with the worst case normal K_{eff}. The most adverse abnormal configuration (large moderator density variation) has a ΔK_{eff} of 0.260 which when added to the worst case normal K_{eff} of 0.707 results in the worst case abnormal K_{eff} of 0.967.

7.4 EFFECTS OF CALCULATIONAL UNCERTAINTIES

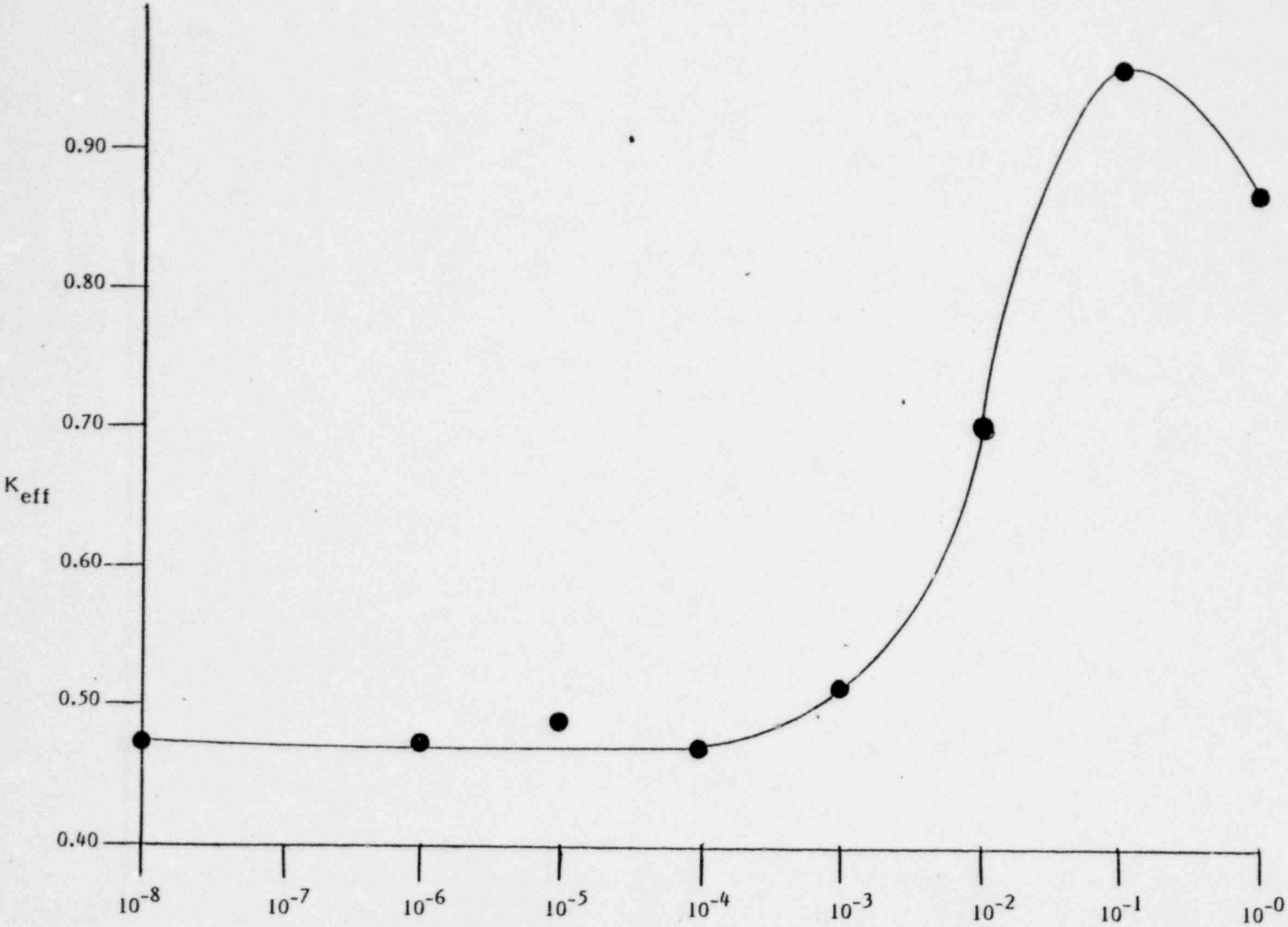
The statistical uncertainty due to KENO-IV is $\pm$ 0.006 at the 95% confidence level. The bias for KENO-IV using 16 groups is negative; in other words, KENO calculates a K_{eff} higher than the actual K_{eff} of a critical experiment. This bias is neglected for conservatism.

The total effect of all uncertainties is taken as $\pm$ 0.006. When added to the worst case abnormal K_{eff} of 0.967 this results in a final K_{eff} including uncertainties of 0.973.

Modeled Configuration	Average Storage Cell Pitch (inches)	Moderator (Water) Density (gm/cc)	Fuel Enrichment (w/o)	K_{eff}
Reference Configuration	21	10^{-8}	4.1	0.474
	21	10^{-6}	4.1	0.475
Moderator Density Variation	21	10^{5}	4.1	0.486
	21	10^{-4}	4.1	0.473
	21	10^{-3}	4.1	0.514
	21	10^{-2}	4.1	0.707
	21	10^{-1}	4.1	0.967
	21	1.0	4.1	0.873
	19	10^{-8}	4.1	0.517
	23	10^{-8}	4.1	0.446

TABLE 7.1

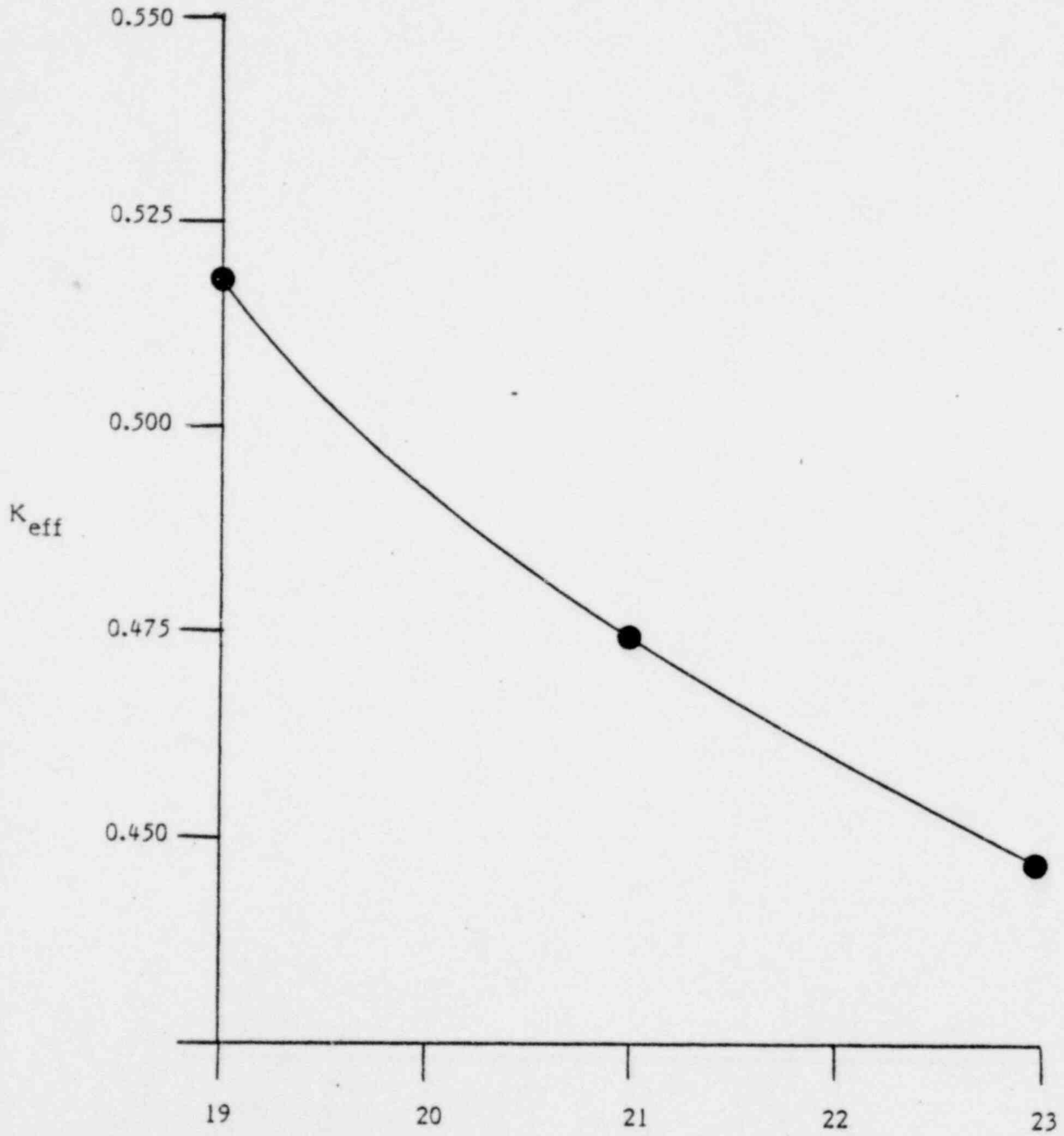
RESULTS OF K_{eff} CALCULATIONS



Water Density (gms/cc)

K_{eff} vs Water Density

FIGURE 7.1



Average Pitch (Inches)

K_{eff} vs Storage Cell Pitch

FIGURE 7.2

8. DETAILED PARAMETRIC STUDY VERSUS WATER DENSITY

Because the peak K_{eff} 0.973, found in Section 7.4, was so close to the allowed criticality criterion of 0.98, and also because it is possible that a somewhat higher value might exist in the neighborhood of the peak shown in Figure 7.1, a further parametric study was performed with a new, more detailed geometric model for KENO.

This model, instead of being infinite in lateral extent, represents the north-south axis of the rack, with the east-west axis remaining infinite in extent (see Figure 8.1). This representation does two things. First, the actual spacings (pitches) between rows are not all 21" but are either 21", 30", or 40", as can be seen from the figure. Second, since the rack is now finite in the north-south axis, a substantial leakage will occur out the north and south faces of the rack, especially at low water densities. (This model was not used at the start of the work because of the increased complexity and cost.)

The results of a detailed parametric study of K_{eff} versus water density in the vicinity of 0.1 gms/cc are shown in Figure 8.2. It is seen that there is indeed a peak K_{eff} somewhat higher than the value at 0.1 gm/cc located at about 0.06 gm/cc. The value of K_{eff} at this point using the more realistic geometric model of Figure 8.1, is 0.896, which is substantially below the peak K_{eff} of 0.967 reported for the simpler model (see Figure 7.1) and also substantially below the criticality criterion of 0.98.

The final K_{eff} for the more detailed geometric model considering the KENO uncertainty of $\pm$ 0.006 is

$$0.896 + 0.006 = 0.902$$

A further reduction in the calculated K_{eff} would occur if the east-west axis of the pool were modeled instead of being taken as infinite in extent. Such a calculation was not performed because of the great complexity and cost of such a large three-dimensional problem but simple buckling estimates show a further reduction of K_{eff} of about 0.04 would be realized. That is, the final K_{eff} for the Surry racks calculated with a geometry modeled in all three dimensions would be approximately 0.862.

DETAILED GEOMETRIC REPRESENTATION

OF FINITE ARRAY

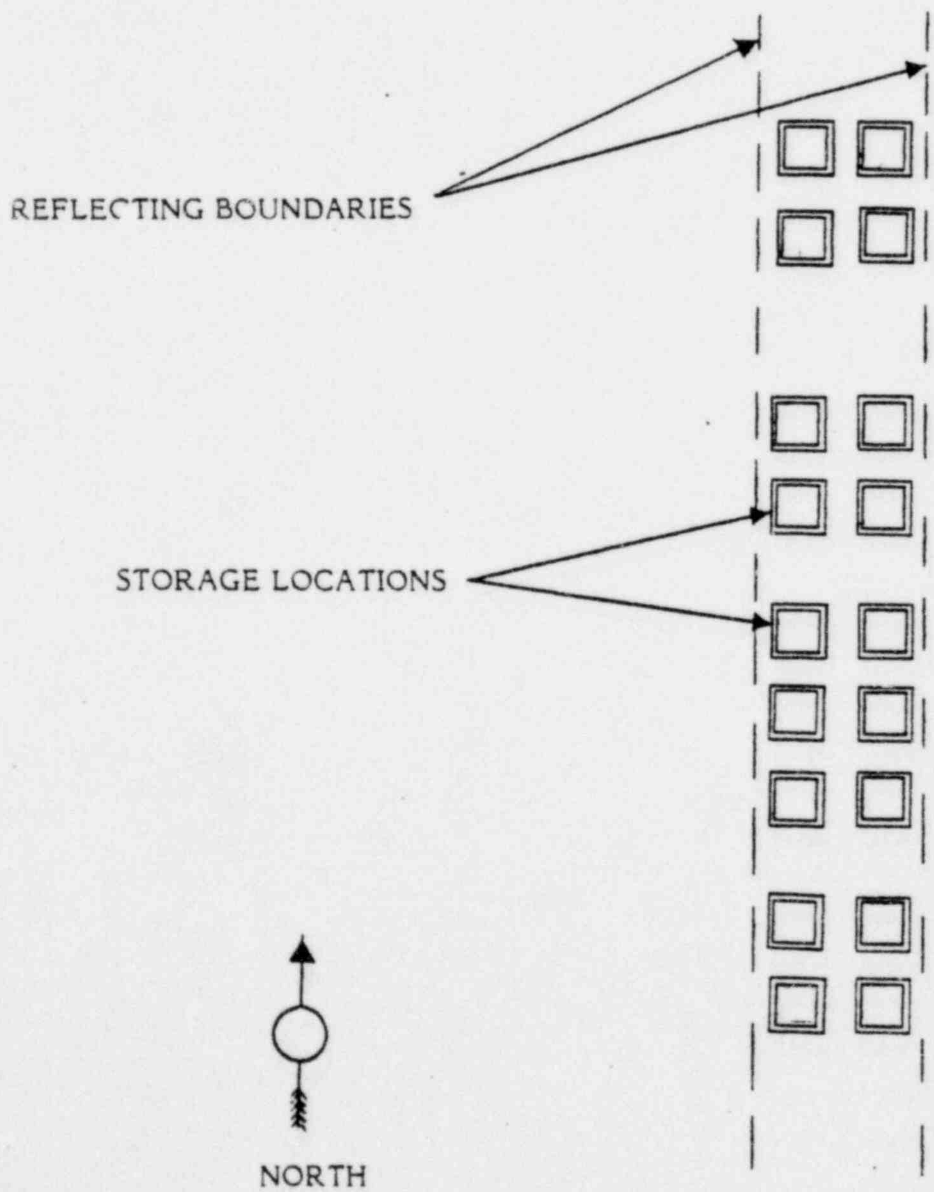


FIGURE 8.1

K_{EFF} VERSUS WATER DENSITY, FINITE ARRAY

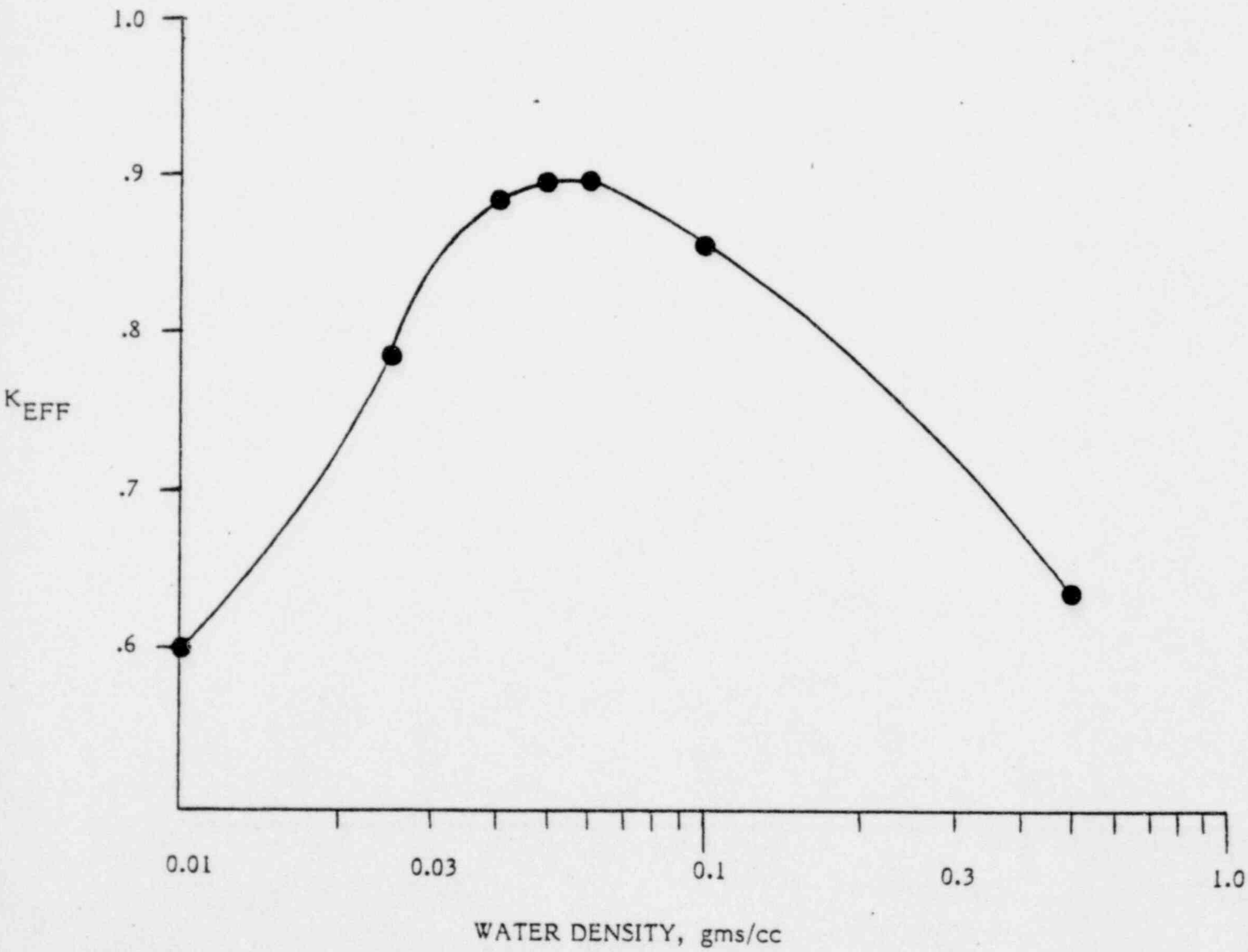


FIGURE 8.2

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1. SUMMARY

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 for 4.1 w/o Westinghouse fuel assemblies is less than the criticality criterion of <0.95. Conservative assumptions about the fuel assemblies and racks have been used in the calculations. The normal configurations considered in the nuclear analysis included the reference configuration (an array of square stainless steel boxes spaced 14.0 inches on centers with centrally positioned fuel), the eccentric positioning of fuel within the storage boxes and the variations permitted in fabrication of the principal fuel rack dimensions. The abnormal configurations included the mislocation of a storage box, box displacement due to a seismic event, and spent fuel pool temperature variations.

The calculations were carried out using the Monte Carlo transport theory code KENO-IV to evaluate the reference configuration K_{eff}. Other calculations to determine the sensitivity of K_{eff} to the normal and abnormal variations mentioned above were performed using the diffusion theory code EXTERMINATOR-2. The final calculated K_{eff} for the system including normal and abnormal variations and the effects of calculational uncertainty is 0.938. This value meets the criticality design criterion and is substantially below 1.0. Therefore, it has been concluded that the Surry Nuclear Power Station high density storage racks when loaded with the specified fuel are safe from a criticality standpoint.

2. INTRODUCTION

The NES design for high density fuel storage racks for Surry consists of a square array of stainless steel boxes (9.12 inches OD with 0.090 inch walls) spaced 14.0 inches on centers. This configuration provides water gaps between the boxes which act as thermal flux traps for neutrons escaping from the fuel assemblies located within the boxes. This flux trap design results in a structurally sound rack which does not depend on additional poisons to achieve a high storage density. A description of the racks is 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 storage racks.

The reference configuration which is the basis of the criticality calculations consists of an array of square stainless steel boxes (9.12 inches OD with a wall thickness of 0.090 inches) spaced 14.0 inches on centers and with fuel assemblies centrally located within the boxes. Variations from this reference configuration were also studied and included the effects of dimensional and spacing variations, fuel enrichment changes, water temperature increases and mislocations of fuel assemblies and boxes. These variations are described in detail in Section 5.

Reference configuration criticality calculations were performed with the transport theory Monte Carlo code combination NITAWL/KENO IV. Sensitivity calculations for normal and abnormal variations on the reference configuration were performed using the diffusion theory code combination HAMMER/EXTERMINATOR. Discussion of computer codes can be found in Section 6. The results of the criticality analyses are presented in Section 7.

3. DESCRIPTION OF SPENT FUEL STORAGE RACKS

Each fuel storage rack contains 36 storage locations spaced 14.0 inches on centers in an 6x6 square array (see Figure 3.1). Each storage location consists of a Type 304 stainless steel square box, 9.12 inches in outside dimension with 0.090 inch thick walls except the corner boxes which are 9.56 inches OD with 0.25 inch walls. The spent fuel assembly is located within the stainless steel box.

The square boxes are ~172 inches tall so that the 144 inch active length of each fuel assembly is entirely enclosed by the stainless steel box.

Between boxes is a 4.88 inch wide gap which is filled with water when the rack is located in the spent fuel storage pool. Within this gap are also located certain structural grid members, clips and bracing which locate and space the boxes. This structural material occupies only a small fraction of the water gap at essentially two widely separated elevations.

Each storage rack has structure mounted on the outside which will assure that the center-to-center spacing between cells in adjacent racks is maintained at 14.0 inches or greater.

Guard structures are provided at the upper grid of peripheral racks as required to preclude the inadvertent positioning of a fuel assembly too close to a storage rack during fuel handling. The structure will ensure that the center-to-center distance for such incidents will be in excess of 17 inches.

Type 304 stainless steel is used for the square boxes and all of the principal structural grid members, clips and bracing.

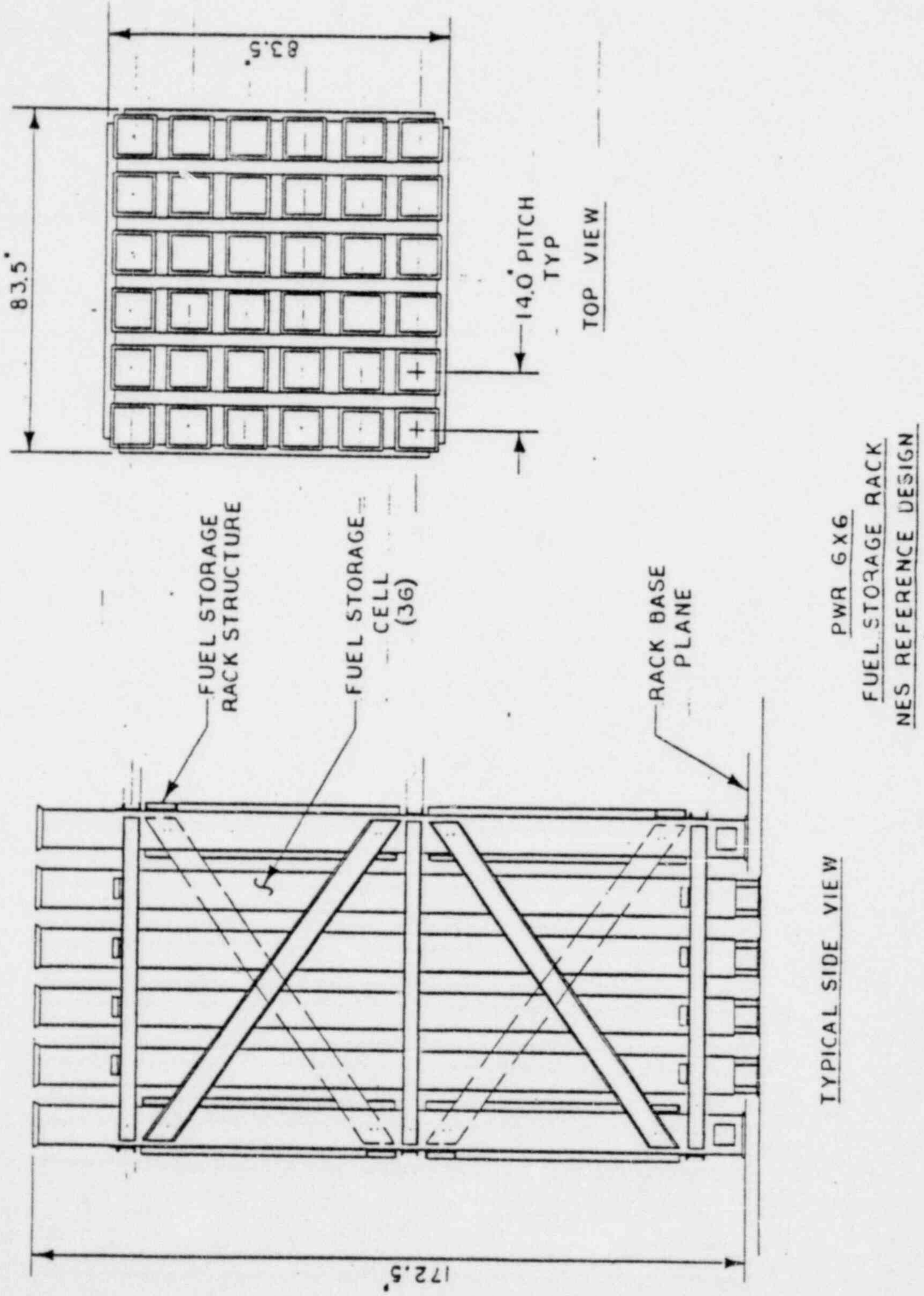
83.5"
83.5"
14.0" PITCH
TYP
TOP VIEW
FUEL STORAGE
RACK STRUCTURE
FUEL STORAGE
CELL
(36)
RACK BASE
PLANE
PWR 6X6
FUEL STORAGE RACK
NES REFERENCE DESIGN
TYPICAL SIDE VIEW
172.5"

Figure 3.1

4. CRITICALITY DESIGN CRITERION AND CALCULATIONAL ASSUMPTIONS

4.1 CRITICALITY DESIGN CRITERION

Determination of a satisfactory value of K_{eff} for a spent fuel pool requires consideration 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 NRC on fuel storage criticality is presented in Section 9.1.2 of the NRC Standard Review Plan (Ref. 1) which states the following:

> "Criticality information (including the associated assumptions and input parameters) in the SAR must show that the center spacing between assemblies results in a subcritical array. A K_{eff} of less than about 0.95 for this condition is acceptable."

The NRC, in evaluating the design, will "check the degree of subcriticality provided, along with the analysis and the assumptions". In addition, it has been suggested that transport theory calculational methods are more accurate than diffusion theory methods because of the large water gaps present in PWR rack designs.

On the basis of this information, the following criticality design criterion has been established for the Surry Nuclear Power Station 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 transport theory."

4.2 CALCULATIONAL ASSUMPTIONS

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

1. The pool water has no soluble poison.

2. The fuel assemblies have no burnable poison.
3. The fuel is fresh and of a specified enrichment higher than that of any fuel available.
4. The rack configuration is infinite in all three dimensions.
5. No credit is taken for structural material other than the stainless steel box.
6. All stainless steel boxes are assumed to be 0.090 inches thick. The minimum allowable thickness for the stainless steel boxes is 0.090 inches except the corner boxes which have a minimum wall thickness of 0.240 inches.

5. CRITICALITY CONFIGURATIONS

In order to verify the design adequacy of the Surry Nuclear Power Station 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 the placement of fuel within the storage cell location, 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 (abnormal 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 Configurations

The reference configuration consists of an infinite array of storage cells having nominal dimensions each containing a 17x17 Westinghouse fuel assembly of 4.1 w/o enrichment positioned centrally within the cell. The storage cells or boxes are 9.12 inches in outside dimensions, have 0.090 inch walls and are spaced 14.0 inches on centers. The spent fuel pool water temperature is assumed to be 68^{o}F. This configuration is shown in Figure 5.1.a.

5.1.2 Eccentric Configuration

It is possible for a fuel assembly not to be positioned centrally within a storage cell or box because of the clearance allowed between the assembly and the box wall. This clearance is approximately 1/4 inch on each side of the fuel assembly.

If one assembly is displaced 1/4 inch from its nominal centered positioned and if all other assemblies remain centered, the effect on K_{eff} is negligibly small (less than 0.001). The most unfavorable condition occurs if each of four adjoining assemblies is diagonally offset so as to be as close as possible to the other three. The effect on K_{eff} of this condition was determined using the eccentric configuration shown in Figure 5.1.b.

5.1.3 Fuel Design Variation

The Surry Nuclear Power Station fuel racks are designed to accommodate both 15x15 and 17x17 fuel designs. Calculations performed by NES show that racks with the 17x17 fuel assemblies were slightly more reactive than the racks with the 15x15 fuel assemblies with equal enrichment. Therefore, NES selected the 17x17 fuel assembly with 4.1 w/o enrichment for the detailed criticality analysis of the Surry fuel storage racks.

5.1.4 Fuel Rack Cell Pitch Variation

Calculations were performed to determine the sensitivity of K_{eff} to changes in cell pitch (center-to-center spacing). The cell pitch was reduced to 13-15/16 inches and to 13-7/8 inches. The criticality configuration was similar to that of the reference configuration except for the obvious change in center-to-center spacing.

5.1.5 Fuel Rack Cell Wall Thickness Variation

Calculations were performed for wall thicknesses of 0.090 and 0.095 inches.

5.1.6 "Worst Case" Normal Configuration

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

5.2 ABNORMAL CONFIGURATIONS

5.2.1 Single Cell Displacement

Welded clips and shims position the stainless steel cells or boxes centrally within the grid members of the rack structure. If the welds on one of these clips or shims fails, the associated box cannot be displaced. However, calculations were performed to determine the sensitivity of K_{eff} for the reference configuration to single cell displacement. A cell was arbitrarily displaced 0.25 inches from its proper location as shown in Figure 5.2. In this configuration, the water gap between the two close boxes is reduced from 4.88 inches to 4.63 inches while the gap on the other side increases to 5.13 inches.

5.2.2 Fuel Handling Incident

Structure is provided on the peripheral fuel storage locations which precludes the positioning of a fuel assembly during fuel handling such that the center-to-center spacing between this assembly and the nearest assembly in the rack would be less than 17 inches.

At this separation and with stainless steel boxes surrounding all but the improperly positioned fuel, the K_{eff} value will be substantially below the criticality design criterion. Reference 2 verifies this by showing that bare 4.1 w/o, 17x17 Westinghouse fuel assemblies spaced 14.2 inches on centers will have a K_{eff} value less than 0.95 including variations in configurations and uncertainties in calculations. It has been concluded that this type of incident need not be considered further in this analysis.

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 ~40°F, where water density is a maximum, to ~250°F, the approximate boiling point of water near the bottom of the fuel rack. In addition, the effect of voids in the water was studied.

5.2.4 Fuel Drop Incident

The maximum height through which a fuel assembly can be dropped onto the fuel storage racks is limited to 2?.5 inches. The dropped fuel assembly will most likely impact the flared tops the fuel storage rack cells or boxes.

While minor deformation of the flared tops will occur, the close proximity of the upper grid structure to the impact point will preclude any significant lateral displacement of the storage cells. Consequently, the change in K_{eff} will be negligible. However, it is possible for a dropped fuel assembly to enter a box cleanly and impact directly on the fuel stored in the box. The effect of this type of fuel drop incident was evaluated from a criticality veiwpoint by assuming that the stored assembly would be compressed axially. A calculation based on an axial compression of 2 feet yielded a 0.06 decrease in k_∞ 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 Seismic Incident

The seismic analyses indicate that the maximum rack structure deflections will be very small (less than 0.120 inches). These deflections have negligible effect on K_{eff} since they do not change the center-to-center spacing between the storage cells or boxes significantly.

The maximum deflection of the storage cells or boxes due to a seismic event occurs at the middle of the box and is less than 0.050 inches. The effect of box deflections on K_{eff} is negligible since the average center-to-center spacing between cells or boxes will not change appreciably if the boxes deflect independently in random directions or act together in a single direction.

5.2.6 "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 for the "worst case" abnormal configuration are presented in Section 7.2.4.

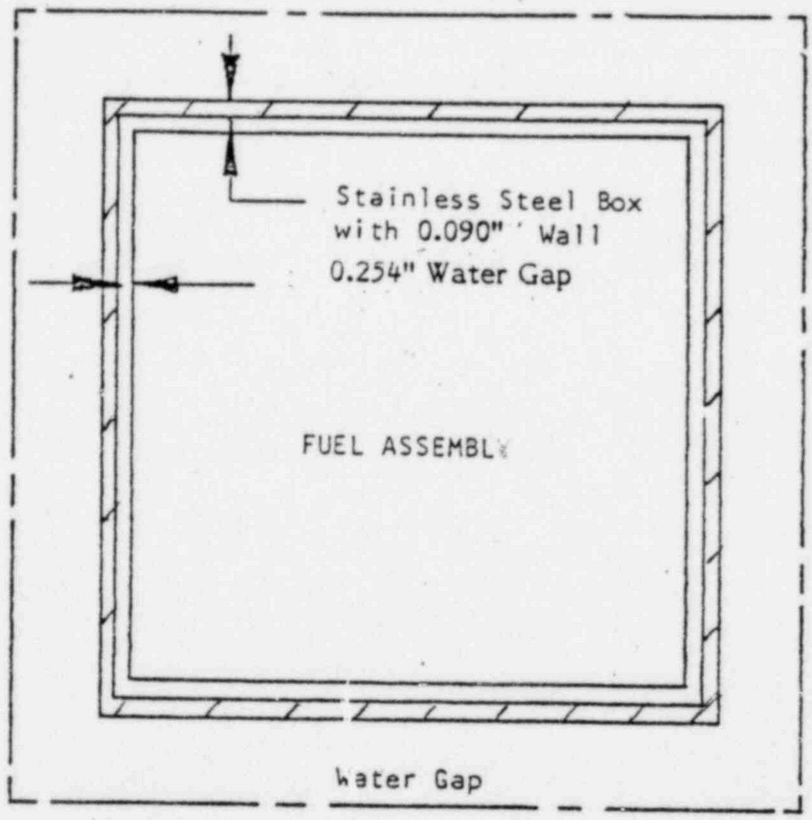

FIGURE 5.1A REFERENCE CONFIGURATION

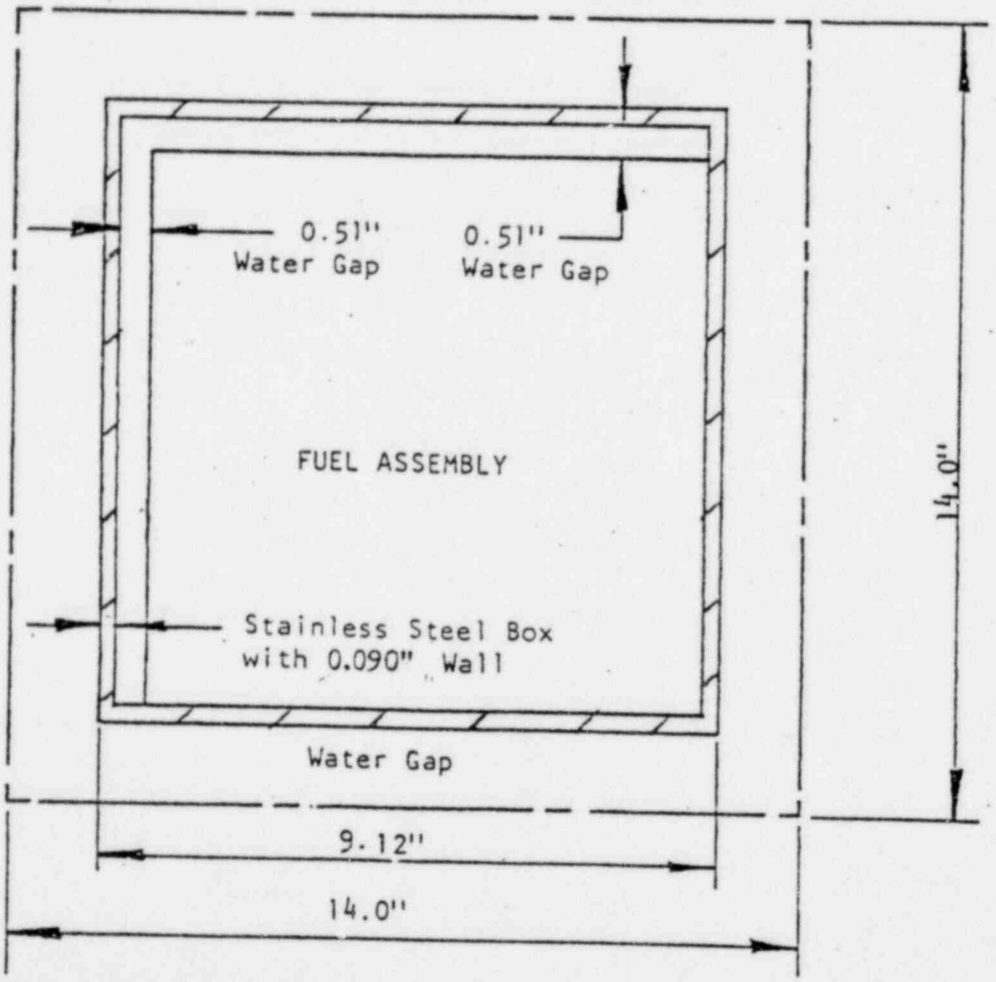

FIGURE 5.1B ECCENTRIC CONFIGURATION

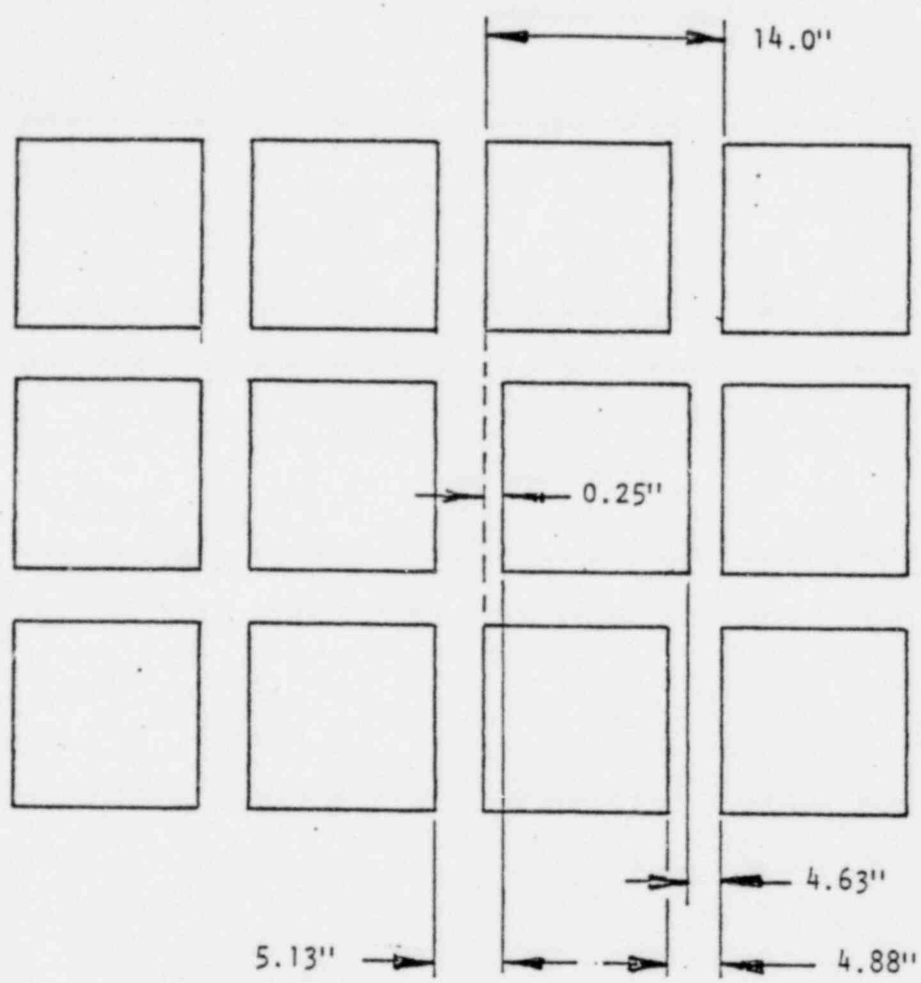

FIGURE 5.2 CONFIGURATION USED FOR DISPLACED BOX (BROKEN CLIP)

TABLE 5.1

PARAMETERS OF 17x17 AND 15x15 WESTINGHOUSE FUEL ASSEMBLIES

	17x17	15x15
Mass of UO_2 in Assembly, lbs	1154	1122
Number of Fuel Rods	264	204
Number of Guide Tubes	25	21
Clad, ID, inches	0.329	0.3734
Clad, OD, inches	0.374	0.422
Clad Thickness, inches	0.0225	0.0243
Clad Material	Zr	Zr
Spacer Mass, lbs in Active Fuel Length	12.0	10.5
Spacer Material	Inc 718	Inc 718
Number of Spacers	8	7
Pitch Between Fuel Rods, inches	0.496	0.563
Guide, Tube OD, inches	0.482	0.512
Guide, Tube ID, inches	0.450	0.455

6. CRITICALITY CALCULATIONAL METHODS

6.1 METHOD OF ANALYSIS

For the reference configuration discussed in Section 5.1.1, the K_{eff} was determined from a three-dimensional Monte Carlo calculation using NITAWL/KENO IV with the 123 group XSDRN cross-section set. Check calculations of the reference configuration as well as the parametric studies were performed with two-dimensional diffusion theory using HAMMER and EXTERMINATOR. In both the Monte Carlo and diffusion theory methods, an infinite array of fuel assemblies loaded in spent fuel storage locations was represented by use of appropriate boundary conditions. An infinite array is used for two reasons: (1) an infinite array has a conservatively higher value of K_{eff} and (2) 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.

6.2 BENCHMARK CALCULATIONS

In order to establish the accuracy of the computer codes used for this analysis, several benchmark calculations have been performed both at NES and elsewhere (Ref. 3,4). The NITAWL/KENO IV code combination using the 123 group XSDRN cross-section set was benchmarked against several recent criticality experiments. Calculated K_{eff} values for experimental configurations similar to the Surry high density spent fuel storage racks were observed to be ~ 2% higher than the experimental values. No credit will be taken for this conservatism.

Both HAMMER and EXTERMINATOR are used by NES as versions available at Combustion Engineering at Winsdor Locks, Connecticut. This combination has been benchmarked against a cold critical experiment performed at the LaCrosse Boiling Water Reactor with excellent results (Ref. 5). The calculated K_{eff} differed from the experimental value by only 0.0017.

6.3 UNCERTAINTIES

The reference configuration K_{eff} value calculated by KENO IV forms the basis for the final reported K_{eff} value. To this value we must attach an uncertainty. The errors in Monte Carlo criticality calculations can be divided into two classes:

1. Uncertainty due to the statistical nature of the Monte Carlo methods.
2. Errors due to bias in the calculational technique.

The first class of errors can be reduced by simply increasing the number of neutrons tracked. For rack criticality calculations, the number of neutrons tracked is selected to reduce this error to less than 1%, and in this case $\pm$ 0.006. The second class of errors has already been discussed in Section 6.2.

No credit will be taken for the 2% experimental bias. However the statistical error will be conservatively set as $\pm$0.01.

6.4 COMPUTER CODES

6.4.1 NITAWL

NITAWL performs resonance self-shielding correction and creates a formatted working library based on the XSDRN cross-section set for use in KENO IV using the Nordheim Integral Method.

6.4.2 KENO IV (Ref. 6)

KENO IV is a 3-D multigroup Monte Carlo code used to determine K_{eff}.

6.4.3 HAMMER (Ref. 7)

HAMMER 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.

6.4.4 EXTERMINATOR (Ref. 8)

EXTERMINATOR is a 2-D multigroup diffusion theory code used with input from HAMMER to calculate K_{eff} values.

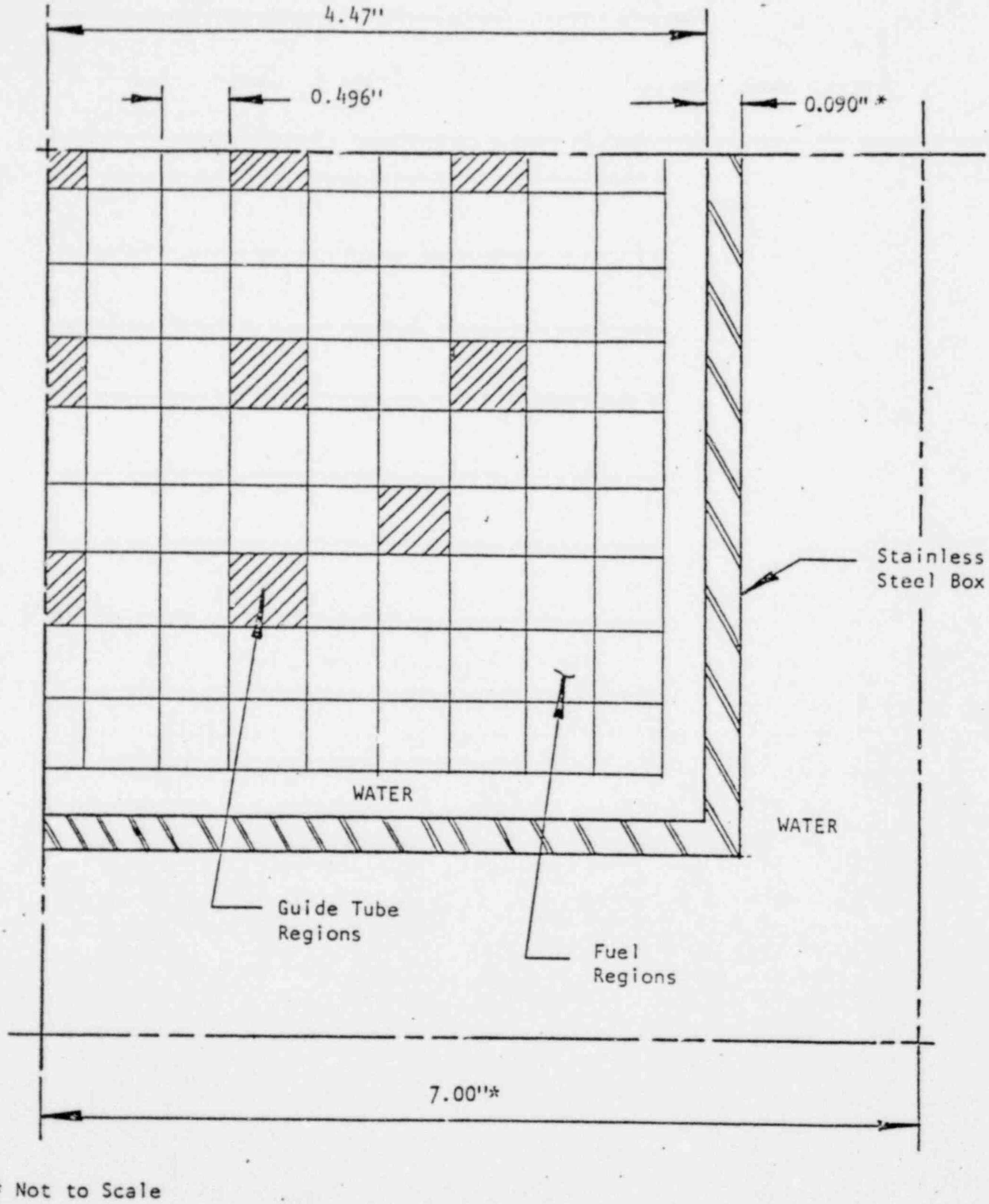

Figure 6.1 Quarter - Assembly Repeating Array For Surry High Density Fuel Storage Rack

7. RESULTS OF CRITICALITY CALCULATIONS

The following presents the results of calculations for each of the configurations discussed in Section 5 and subsequent contribution to the final rack K_{eff}.

7.1 K_{eff} VALUES FOR NORMAL CONFIGURATIONS

7.1.1 Reference Configuration

The K_{eff} value for the reference configuration described in Section 5.1.1 was calculated to be 0.914 using NITAWL/KENO IV.

7.1.2 Eccentric Configuration

The K_{eff} value for the eccentric configuration described in Section 5.1.2 (four assemblies displaced diagonally toward each other the maximum amount allowed by clearance) was determined to increase over the reference configuration value by $\Delta K = 0.006$.

7.1.3 Fuel Design Variation

There are two fuel designs used at the Surry facility which can be placed in the high density fuel storage racks (see Section 5). Calculations have been performed which show the 17x17 Westinghouse design to have a K_{eff} value 0.007 higher that the 15x15 Westinghouse design of the same enrichment. Variation of K_{eff} with fuel enrichment was calculated using both KENO IV and EXTERMINATOR. Results show that the fuel rack K_{eff} increases 0.056 per weight percent increase in fuel enrichment. Since the fuel enrichment used in this analysis (4.1 w/o) is higher than any fuel available at the Surry facility, the reference configuration value of K_{eff} will be conservative with respect to enrichment and fuel design.

7.1.4 Fuel Rack Cell Pitch Variation

The K_{eff} variation for fuel rack cell pitch values ranging down to 13-7/8 inches are shown in Figure 7.1. The cell pitch of interest, of course, is the minimum value that can occur in fabrication. The mechanical design of the fuel rack is such that the average pitch (center-to-center distance) between the cells or boxes in one rack is 14.0 ± 0.062 inches. The change in K_{eff} for a 0.062 inch reduction in the average pitch is $\Delta K = 0.002$.

7.1.5 Fuel Rack Cell Wall Thickness Variation

Fuel rack cell wall thickness will be controlled to 0.090 $^{+0.005}_{-0.000}$ inches. The change in K_{eff} due to variation in cell wall thickness was calculated to be ΔK = 0.003 for a 0.005 inch increase in cell wall thickness. Since 0.090 inch is the minimum allowed value of cell wall thickness, the reference configuration value of K_{eff} will always be conservative relative to this parameter.

7.1.6 Combined Effects of Normal Variations on the Reference Configuration K_{eff}

To establish the maximum variation of the reference configuration K_{eff} due to normal variations, we statistically add the individual positive components. For this case the positive components are those of:

	ΔK_{eff}
Minimum Average Pitch	+0.002
Eccentric Positioning of Four Assemblies	+0.006

Statistical combination of the above normal variations yields:

$$\Delta K_{eff} = \sqrt{(0.002)^2 + (0.006)^2} = 0.007$$

The "worst case" normal configuration is defined as the reference configuration K_{eff} value plus the variation in K_{eff} ue to the combined effect of all adverse normal variations.

$$\text{Worst case normal } K_{eff} = 0.914 + 0.007 = 0.921$$

7.2 K_{eff} VALUES FOR ABNORMAL CONFIGURATIONS

7.2.1 Single Cell Displacement

Calculations were performed in which a single fuel cell was arbitrarily displaced 0.25 inches towards an adjacent cell. The resultant ΔK was 0.001.

7.2.2 Pool Temperature Variation

The K_{eff} as a function of pool water temperature and water density is presented in Figure 7.4 for pool temperatures up to 250°F. The maximum K_{eff} value, reached at approximately 250°F, is 0.007 greater than the K_{eff} value for the reference configuration.

7.2.3 Seismic Event

The maximum deflection of a storage cell or box in the active fuel region is less than 0.050 inches for the Safe Shutdown Earthquake (SSE). As stated in Section 5.2.5, cell or box deflections will not result in significant reductions in the average cell pitch. For conservatism, however, it will be assumed that the SSE reduces the average pitch by the cell deflection, 0.050 inches. A reduction in cell pitch of 0.050 inches will increase K_{eff} by 0.002. If the SSE is assumed to occur with the pool temperature at 170°F (the maximum temperature during a full core off load) the increase in K_{eff} due to the combined seismic and temperature effect is 0.006.

7.2.4 "Worst Case" Abnormal Configuration

The "worst case" abnormal configuration combines the change in K_{eff} due to the occurrence of the most adverse abnormal condition (increase in pool temperature) with the K_{eff} value associated with the worst case normal configuration.

		K_{eff}
1.	Worst Case Normal Configuration (per Section 7.1.6)	0.921
2.	Most Adverse Abnormal Configuration (pool temperature increase per Section 7.2.2)	0.007
3.	Resulting K_{eff}	0.928

7.2.5 Effects of Calculational Uncertainity

As discussed in Section 6, a value of 0.01 will be added to the result of 0.928 obtained thus far to account for any statistical fluctuations in the KENO IV result. The final resulting K_{eff} for the Surry high density spent fuel storage racks is 0.938. This conservative result meets the criticality design criterion set forth in Section 4 and clearly shows that the racks are safe from a criticality standpoint.

TABLE 7.1

PARAMETERS AND RESULTS OF CRITICALITY CALCULATIONS

Configuration	Enrichment (w/o)	Spacing (inches)	Temp (°F)	Water Density (gm/cc)	Box Wall Thickness (inches)	K_{eff} or ΔK_{eff}
Reference Configurations	4.10	14.0	68	0.998	0.090	0.914
Maximum Water Density, 39°F	4.10	14.0	39	1.000	0.090	3.50-4
90°F	4.10	14.0	90	0.995	0.090	1.25-3
150°F	4.10	14.0	150	0.980	0.090	3.60-3
212°F	4.10	14.0	212	0.958	0.090	5.92-3
250°F	4.10	14.0	250	0.941	0.090	6.16-3
250°F, voided	4.10	14.0	250	0.925	0.090	3.86-3
Close Spacing	4.10	13-15/16	68	0.998	0.090	1.75-3
		13-7/8	68	0.998	0.090	3.68-3
Eccentric Position	4.10	14.0	68	0.998	0.090	5.69-3
Displaced Can (base can)	4.10	14.0	68	0.998	0.090	1.42-3
Displaced Can (can moved ¼")	4.10				0.090	1.73-3

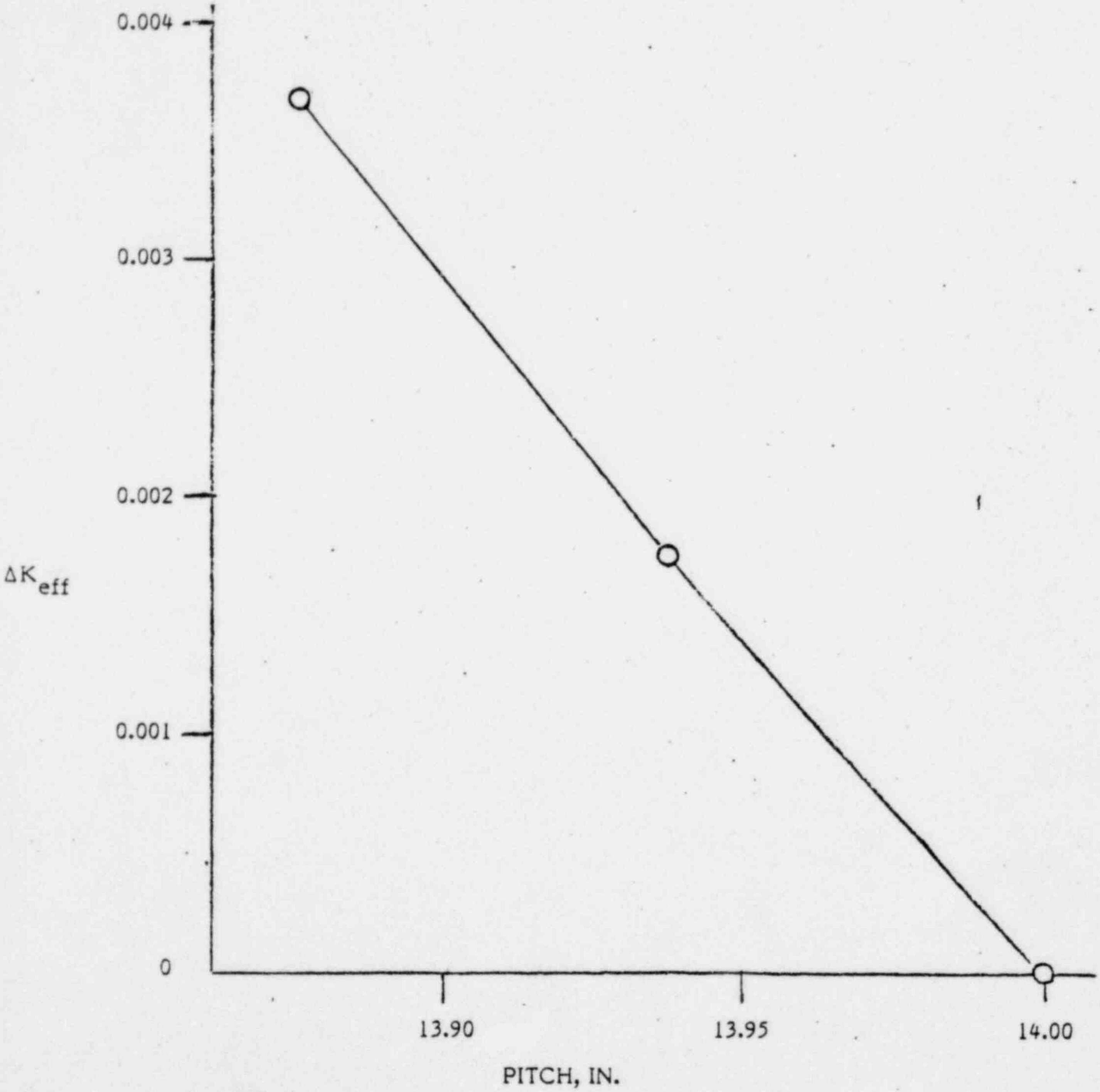

Figure 7.1

ΔK_{eff} vs Pitch For 17 x 17 Westinghouse Fuel,
4.1 w/o, 0.090" Stainless Steel Boxes, 68^{o}F

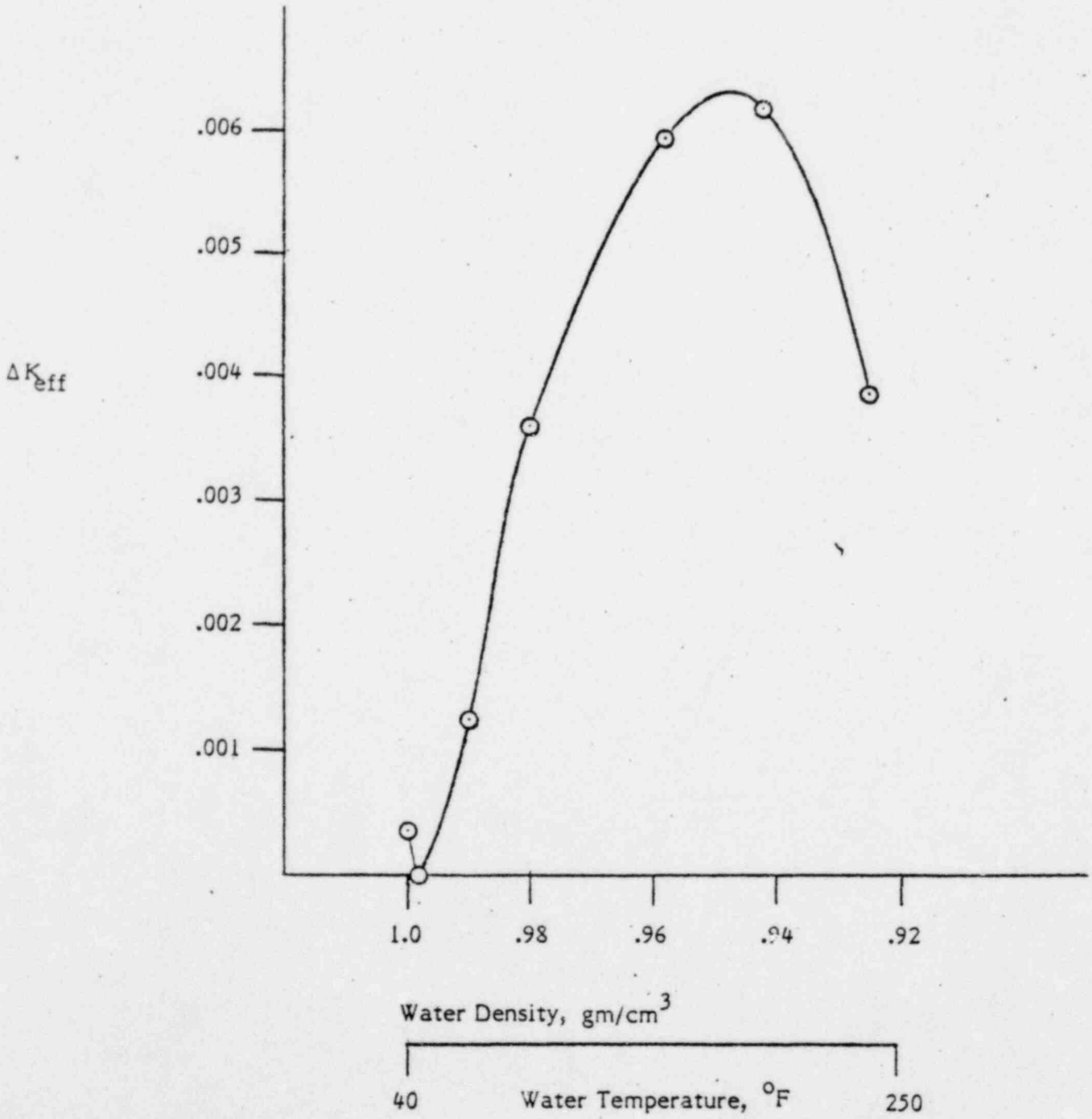

Figure 7.2

K_{eff} vs Water Density for 17 x 17 4.1 w/o Westinghouse Fuel, 0.090" Stainless Steel Boxes, 14.0" Spacing

8. REFERENCES

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