ENCLOSURE 2

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SUMMARY REPORT NUCLEAR CRITICALITY ANALYSIS FOR THE SPENT FUEL RACKS OF THE DUANE ARNOLD NUCLEAR POWER PLANT

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SUMMARY REPORT
5.1 # NUCLEAR CRITICALITY ANALYSIS
FOR
THE SPENT FUEL RACKS
OF
THE DUANE ARNOLD NUCLEAR POWER PLANT

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TABLE OF CONTENTS

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LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION - CALCULATION MODELS

This report describes the nuclear criticality analysis for the high density poisoned BWR spent fuel racks of the Duane Arnold Nuclear Power Plant.

The design of the revised fuel storage rack complies with all criteria established for the existing fuel storage rack as described in the DAEC FSAR. For any operating or accident condition which is a design basis for DAEC, the subcritical multiplication factor (K_{eff}) is maintained below 0.95. This includes the worst-case postulation of a dropped fuel element.

1.1 The Principal Analytical Model

The criticality analysis for the DAEC BWR spent fuel racks employs the CHEETAH-B/CORC-BLADE/PDQ-7 model as the basic-engineering tool. CHEETAH-B(1) is NAI's BWR lattice code based on the original LEOPARD code(2) and uses a modified ENDF/B-II cross section library. CORC-BLADE(3) generates equivalent diffusion theory cross sections for the control blade in boiling water reactors. The PDQ-7(4) program is the well-known few-group spatial diffusion theory code widely used by the industry. The CHEETAH-B/CORC-BLADE/PDQ-7 model, which is also a part of the LEAHS (Lifetime Evaluation and Analysis of Heterogeneous Systems) nuclear analysis series of Control Data Corporation, has been extensively tested through benchmarking calculations of measured criticals as well as through core physics calculations for several operating power reactors. (Table 1)

The spent fuel racks consist of concentric square aluminum tubes ("poison cans") with Boral located in the annular gap (Figure 1). The neutron absorber material, Boral, consists of natural B_4C in an aluminum matrix core, clad with an aluminum sheath. The reference case storage rack cell used in the calculations is given in Figure 2.

In the present study, the CHEETAH-B supercell chosen for the fast spectrum calculation is the fuel assembly plus the surrounding water gap. For the thermal spectrum calculation, five separate CHEETAH-B fuel pin cell calculations are made, namely, internal pin, peripheral pin, corner pin, pin adjacent to one water rod, and pin adjacent to two water rods. The peripheral pin cell calculation supplies the input fast and thermal flux spectrum to CORC-BLADE which in turn yields the equivalent Boron cross-sections. The cross-sections for all the other material regions of the reference storage rack cell of Figure 2 come from the appropriate CHEETAH-B calculation. All of these cross sections are input to PDQ-7. A zero current boundary condition is applied to the four sides of the reference storage rack cell to produce an infinite array effect. The two-dimensional, PDQ-7 reference case calculations are made for four neutron energy groups, two mesh intervals per fuel pin, a flat U-235 enrichment distribution and a zero axial buckling to simulate infinite fuel length.

1.2 The Verification Model

The verification calculation employs the KENO-IV(5)/AMPX(6) model. The basic neutron cross section data come from the master library of AMPX - a 123 group GAM-THERMOS neutron library prepared from ENDF/B version II data. The NITAWL module of the AMPX program is used to perform a Nordheim integral treatment of the U-238 resonances accounting for the self-shielding effect. The working library produced by the NITAWL/AMPX module retains the 123 group energy structure and is used directly by KENO-IV.

In the KENO-IV calculation, each fuel and water rod cell is represented discretely. The array option of KENO-IV is applied to arrange the box types into a matrix representing the fuel assembly. Then a water reflector region is added to the outside of this matrix, followed by the aluminum canister, void, and Boral slab regions to complete the reference case storage rack cell.

To simulate the arrangement of a large number of storage rack units, and for a non-leakage condition in the axial directions, a specular reflective condition is applied to all six sides of this storage rack cell.

1.3 Basic Assumptions

To ensure that the analysis follows a conservative approach and conforms to the general guidelines of criticality safety analysis, the calculations are performed with the following assumptions:

1. Enrichment: 3.1 w/o U-235
2. Fuel: fresh and non-depleted
3. Unchanneled fuel
4. Minor Structural Members: replaced by water
5. No soluble poison in pool water nor fixed poison in the fuel assembly.

2.0 REFERENCE CASE CALCULATIONS

2.1 Physical Parameters and the Basic Storage Rack Cell Geometry

The reference storage rack cell (Figure 2) is a 6.625 inch square. The rack cavity is made of aluminum and has an inside dimension of 6.156 inches square. The 8x8 fuel assembly dimension used in the calculations is a 5.120 inch square (8* rod pitch) surrounded by a water gap of 0.518 inch. The Boral slab which is 5.250 inches wide and is separated from the rack wall by a 0.047 inch void, has a nominal overall thickness of 0.125 inch. The Boral core, which is sandwiched between two aluminum sheaths, is assumed to have a thickness of 80 mils and a minimum B-10 density of 0.0232 g/cm^2. The physical parameters of the reference case calculations are summarized in Table 2.

2.2 Results of the Base Case Calculations

The base case for this study is a CHEETAH-B/CORC-BLADE/PDQ-7 calculation for the configuration of Figure 2 at a temperature of 68°F according to the calculation model described in Section 1.1. This calculation yields a K_{eff} value of .8775. The KENO-IV verification calculation gives a K_{eff} value of .8953±.0049 with a 95% confidence interval ranging from .8855 to .9051 (See Figure 3), based on 20,000 neutron histories.

2.3 Temperature Effect

Using the reference storage rack cell geometry, the temperatures of the pool water and the fuel are allowed to range realistically from 68°F to 212°F. The reactivity change, if any, is calculated at 68°F, 95°F, 120°F, 150°F, 180°F, and 212°F. The results given in Table 3 and plotted in Figure 3, show a continuous decrease in reactivity due to increased temperature.

2.4 Void Effect

The effect of boiling is studied by varying the amount of voids inside the rack cavities from 0% to 50% for a temperature of 212°F with the reference geometry. The results, given in Table 3 and plotted in Figure 4, show a continuous decrease in K_{eff} as the amount of voids increases.

2.5 Enrichment Sensitivity

The average enrichment of 3.1 w/o of U-235 used in this analysis gives an average U-235 fuel loading of 15.293 grams per axial centimeter of the active section of the assembly. For the purpose of determining the effect of a fuel loading change, the analysis shows that, in the range of interest to the DAEC spent fuel pool facility, the enrichment reactivity coefficient is approximately $0.8\%\Delta k/0.1$ w/o U-235.

2.6 Effect of Boron

The Boral slab which separates two adjacent fuel assemblies has a nominal thickness of 0.125", nominal width of 5.250", and an overall length or height of 12'8". The minimum Boral core thickness is 80 mils. The minimum B-10 loading in the Boral core is guaranteed by the manufacturer to be 0.0232 g/cm^2 which yields a B-10 number density of $0.006905*10^{24}$ atoms/cm^3 (based on 80 mils thickness). Since the present analysis is based on this minimum B-10 loading, no Boron density sensitivity is made. However, the effect of reducing the Boral width is considered. The PDQ-7 calculation for the base case configuration with the Boral width reduced by 1/8 inch to 5.125 inches yields a $K_{eff}=.8800$, or a reactivity increase of approximately $0.3\%\Delta k/0.125$ inch Boral width reduction in the range of interest.

3.0 ADVERSE CASES

Four types of adverse cases are analyzed:

1. Change in pitch
2. Off-center loading
3. Rack module junction - no Boral
4. Loss of Boral

3.1 Change in Pitch

The reactivity effect of mechanical tolerance changes caused by structural, fabrication, installation and seismic factors can be conservatively determined by the pitch sensitivity study. The calculations, carried out for 0.125" increments, determine the pitch reactivity coefficient to be about +0.6%Δk/0.125 inch pitch reduction in the range of interest. The results, given in Table 4 and Figure 5, also show the behavior of K_{eff} if the pitch is reduced to its minimum, i.e., if the water gap is allowed to decrease to zero. The maximum K_{eff} is reached for a pitch of about 5.9375".

The reversal of the relationship between k_{eff} and cavity pitch at small cavity pitch distances as shown in Figure 5 has several contributing factors. On the negative reactivity side, the hardening of the neutron spectrum caused by the reduction of the surrounding water lowers the k_∞ of the fuel. The relative worth of the Boral slabs is increased because:

1. the fixed Boral span (width) which was assumed has a higher volume fraction relative to the cell at a reduced pitch;
2. the closeness between the Boral and the source (fuel) at reduced pitch enhances the neutron capture probability of the Boral.

On the other hand, the removal of the surrounding water reduces the thermal neutron population which can reach the Boral slabs. This has the effect of reducing the thermal absorption of the Boral.

In the presence of Boral slabs interaction between adjacent cavities does not significantly exist. The reactivity of the rack is therefore dominated by the net effect of the two opposing reactivity contributing groups. In the present setting, the negative force is obviously more prevalent.

3.2 Off-Center Loading

The free space existing between a properly centered fuel assembly and the top casting allows an assembly to be loaded off-center in a cavity. The configuration examined is a 4-assembly cluster with assemblies loaded off-center in their cavities and preferentially leaning toward the center of the cluster (Figure 6). The dimensions are the same as in the base case. A zero current boundary condition applied to the other boundaries of a quarter-section produced the effect of an infinite array of these 4-assembly clusters. Two calculations are made. In the first calculation, the base case cross sections are input to PDQ-7. In the second, a "mixed" set of cross-sections is used. Instead of the usual 5 pin cell CHEETAH-B calculations for a properly centered assembly, there are now 8 pin cell calculations possible if a distinction is made between fuel pins on the wide water gap and those on the zero water gap (two separate peripheral pin and three separate corner pin runs). The results of these PDQ-7 runs are K_{eff}=.8540 (base case cross sections) and .8584 ("mixed" cross sections), both well below the base case value. Hence, no adverse effect occurs if the assemblies are loaded off-center.

3.3 Rack Module Junction

There exists a possibility that, at the junction of four individual rack modules, four fuel assemblies may face each other without being separated by Boral slabs. However, since these assemblies lie along the edges of the modules, the normal separation distance between the center of two adjacent assemblies in two different modules is 9.375", instead of the nominal 6.625" pitch. This large separation is caused by the structural design requirement. The configuration studied is shown in Figure 7. The PDQ-7 K_{eff} of 0.8537 for this case indicates no adverse reactivity effect.

3.4 Loss of Boral

To examine the effect of a possible absence of Boron somewhere in the rack, the case of Figure 8 is analyzed. This consists of a 6x9 array of properly centered assemblies with one Boral slab missing at the center of the array. (The slab is replaced by water.) The resultant PDQ-7 K_{eff} value is .8849. The control of Boral materials is also under PaR quality assurance procedures, QCP-60, Rev. 6.)

4.0 ASSEMBLY DROP ACCIDENT

No adverse reactivity effect is expected from dropping a fuel assembly on top of a fully loaded storage rack during fuel handling because of the large water thickness (~10 inches) existing between the top of the assemblies already inside the cavities and the dropped assembly resting on top of the rack. The dropping of an assembly outside of the rack and parallel to an assembly located in the outermost row of the storage array is a possible event because of the unobstructed water area existing between the periphery of the storage array and the side walls of the pool. A conservative analysis to evaluate this situation is illustrated in Figure 9. An assembly, presumed to be dropped during handling, lodges parallel to an assembly in an outer cavity.

These two parallel assemblies are at the minimum separation distance of 1.737 inches with no Boral slab separating them. Infinite water spectrum cross sections are used for the water gap between the rack and pool walls. The dimensions of the rack units and their spacing is the same as in the reference case. Due to the reflective boundary conditions used, the array is repeated in three directions; the fourth boundary uses a zero flux condition as noted in Figure 9.

Using this conservative approach, the PDQ-7 calculation yields K_{eff}=.8643. A subsequent calculation with the dropped assembly replaced by infinite water yields K_{eff}=.8613. Thus, the net reactivity increase associated with this accident is about $0.3\%\Delta k$.

5.0 SUMMARY AND CONCLUSIONS

The PDQ results of the criticality analysis of the spent fuel storage rack are summarized below:

K_{eff}, Nominal Case		0.878
Dimensional and Positional Tolerance, Δk		0.012
Temperature Effect, Δk		0.000
Boron Width Effect, Δk		0.003
Model Uncertainty, Δk		0.010
	TOTAL	0.903
Design Limit, K_{eff}		0.950
Calculational Margin, Δk		0.047

The k_{eff} due to model uncertainty comes from NAI's model benchmarking experience. It represents the maximum bias NAI has encountered when analytical results are compared with measurements in actual reactor cores.

The KENO-IV results give a k_{eff} value of 0.895 ± 0.005 with a 95% confidence interval ranging from 0.885 to 0.905. The KENO calculation provides an independent verification of the diffusion theory analysis by an entirely different calculational method. The agreement between the two methods is within the uncertainties placed on these methods, and hence the calculational approaches have been verified.

6.0 REFERENCES

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2. R. F. Barry, "LEOPARD - A Spectrum Dependent Non-Spatial Depletion Code for the IBM-7094," WCAP-3741, Westinghouse Electric Corporation (1963).
3. CORC-BLADE Manual, LEAHS Nuclear Fuel Management and Analysis Package, Control Data Corporation, Publication No. 84005400, Minneapolis, Minnesota (1974).
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5. L. M. Petrie and N. F. Cross, "KENO-IV - An Improved Monte Carlo Criticality Program," ORNL-4938, November, 1975.
6. N. M. Greene, J. L. Lucius, W. E. Ford, III, J. E. White, R. Q. Wright, and L.M. Petrie, "AMPX - A Modular Code System for Generating Coupled Multigroup Neutron-Gamma Libraries from ENDF/B," ORNL-TM-3706, 1974.

TABLE 1

Comparison of Measured and Calculated Results for Beginning of Life Critical Configurations

PWR

UTILITY	CONDITION	CALC. PPM	MEAS. PPM
FP&L	HZP	1114	1173
SMUD	HZP	1577	1552
NSP	HZP	1505	1519
DUKE	HZP	1458	1476
WPS	HZP	1563	1576
PGE	HZP	1324	1316

BWR

UTILITY	CONDITION	CALC. k_{eff}	MEAS. k_{eff}
IELP	COLD	.9996	1.0003
		1.0033	1.0024
		.9994	1.0004
PE	COLD	1.0005	1.0007
		1.0012	1.0004
SSI	COLD	1.0000	1.0003
		.9994	1.0002

TABLE 2

Reference Case Spent Fuel Rack Input Parameters

Fuel Assembly (8x8, 2 water rods)

Pellet O.D.	.416"
Clad O.D.	.493"
Clad Thickness	.034"
Clad Material	Zr-2
Fuel Rod Pitch	.640"
Active Fuel length	144". (will use 150")
U-235 Enrichment	3.1w/o
UO_2 Density	95% theoretical
Stack Density	93.92% theoretical
Water Rod O.D.	.493"
Water Rod Thickness	.034"
Water Rod Material	Zr-2

Boral Slab

Sheath thickness	.0225"
Sheath Material	Aluminum
Core thickness	.080"
Core Material	Boral
B_4C density	.185 g/cm^2
w/o B in B_4C	70-77% (will use 70%)
a/o B-10 in B	19.75 ± .30% (will use 19.45%)
B-10 density	.0232 g/cm^2

TABLE 3

Reference Case - Summary of 4-group PDQ-7 results, K_{eff} as a Function of Temperature and Voids (cavity pitch = 6.625 inches)

Reference Geometry: Figure 2

Temperature °F	% voids	K_{eff}
32	0	.8818
68	0	.8775
95	0	.8739
120	0	.8702
150	0	.8656
180	0	.8607
212	0	.8552
212	5	.8468
212	10	.8378
212	15	.8280
212	20	.8174
212	35	.7794
212	50	.7301

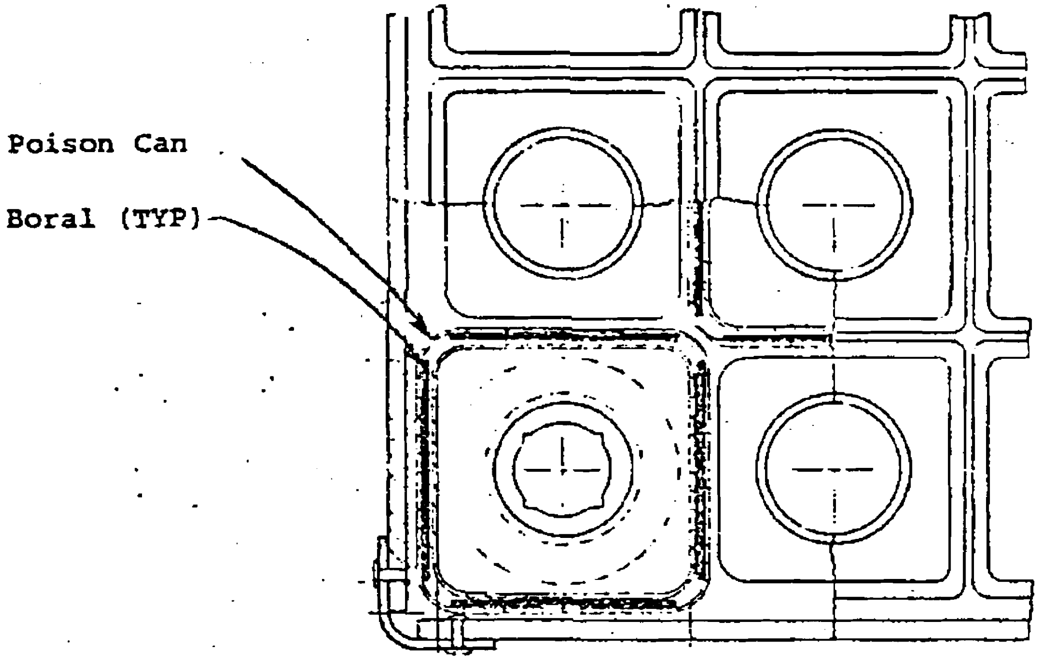
TABLE 4

Reference Case - Summary of 4-group PDQ-7 results, K_{eff} as a function of cavity pitch (Temperature = 68°F, U-235 enrichment = 3.1 w/o)

Reference Geometry: Figure 2

	Cavity Pitch inches	k_{eff}
	6.750	.8713
(base case)	6.625	.8775
	6.500	.8834
	6.375	.8886
	6.125	.8961
	5.723	.8951
	5.589	.8894

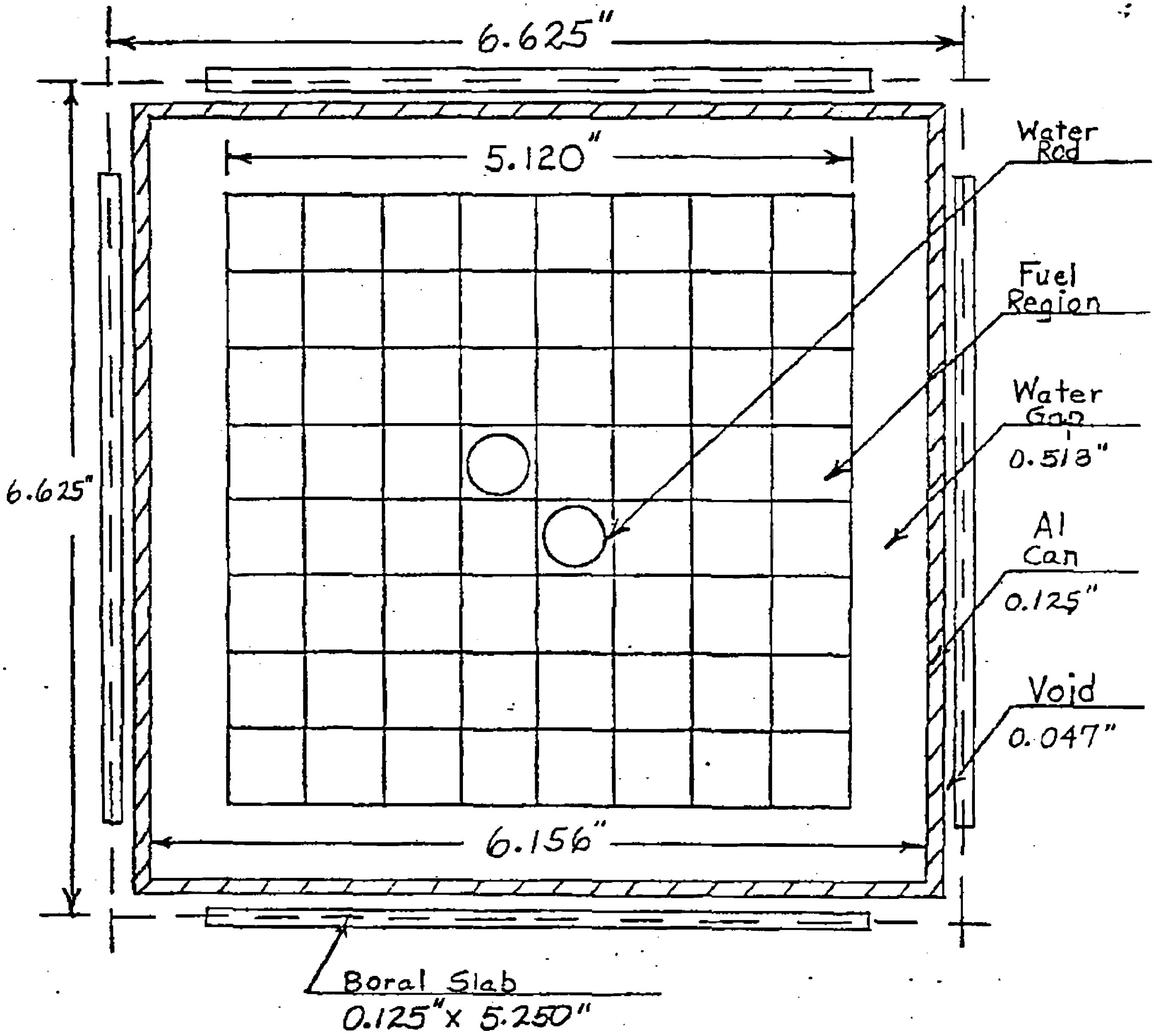
FIGURE 1



SECTION A-A (PARTIAL VIEW OF TOP GRID)

DAEC BWR Spent Fuel Rack

FIGURE 2



NOTE: All dimensions given in inches. Diagram not to scale.

DAEC BWR Spent Fuel Rack Geometry

FIGURE 3 DAEC BWR Spent Fuel Storage, Reactivity temperature effect

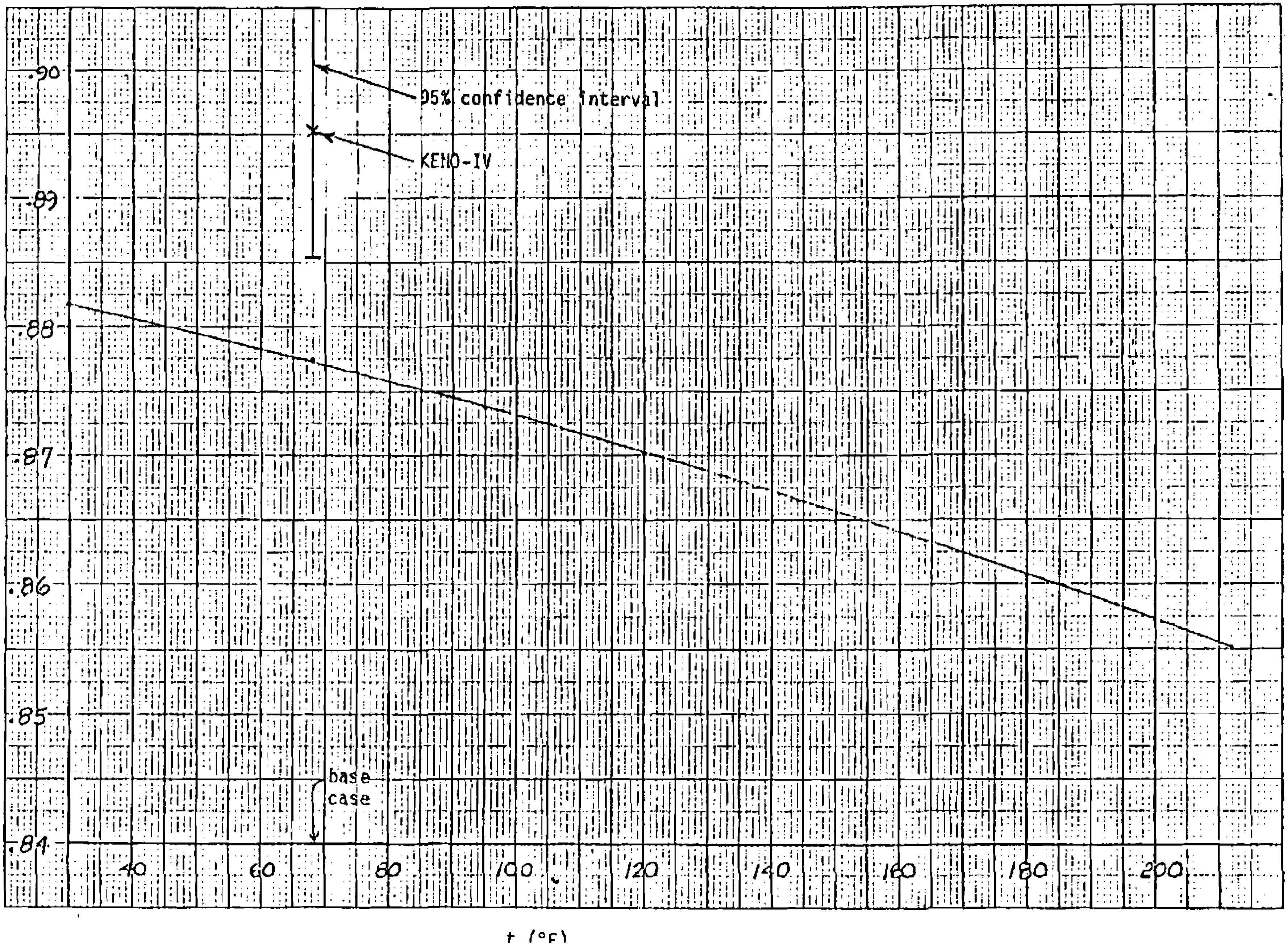


FIGURE 4 DAEC BWR Spent Fuel Storage, Reactivity Void Effect, 212°F

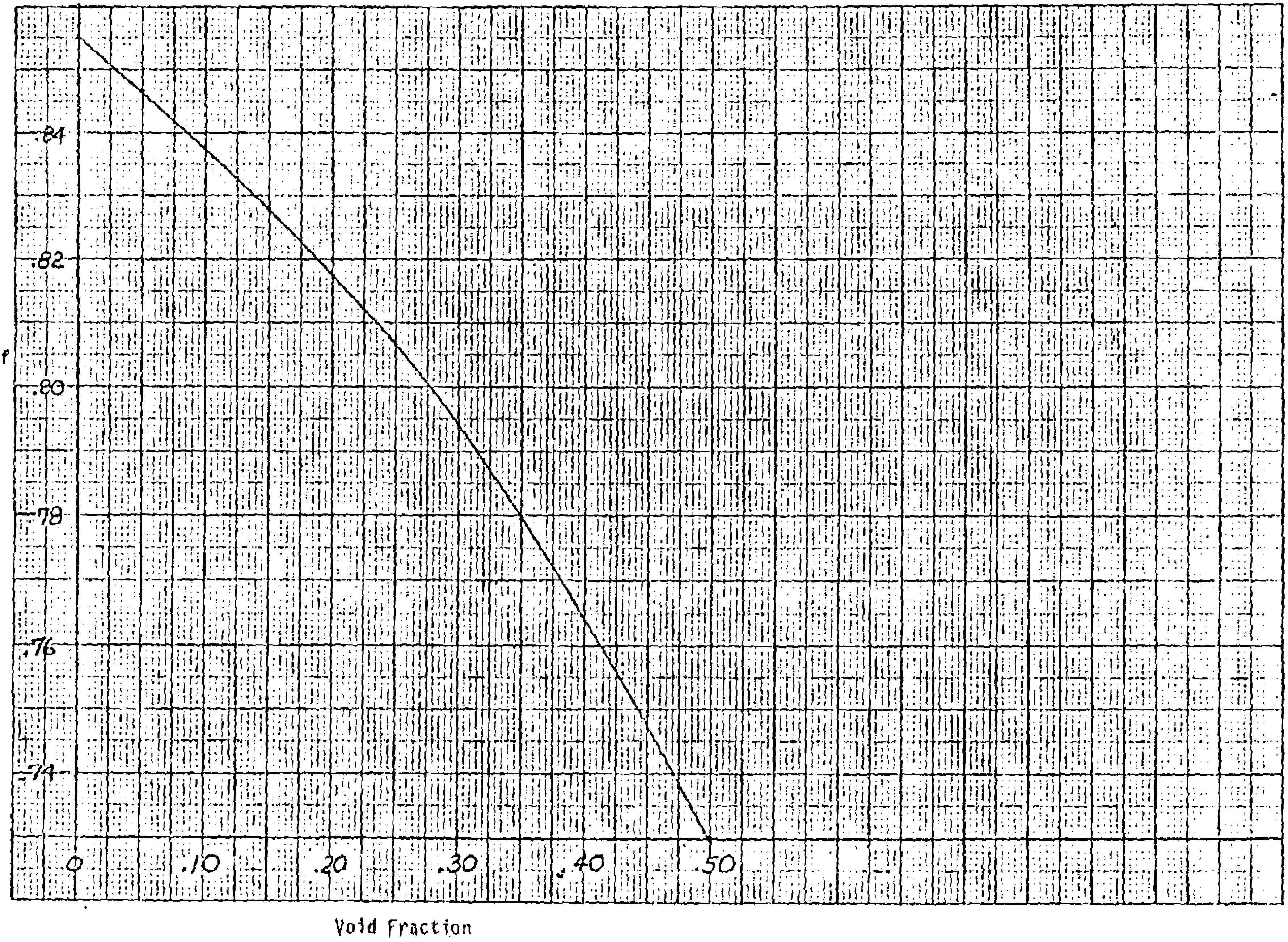
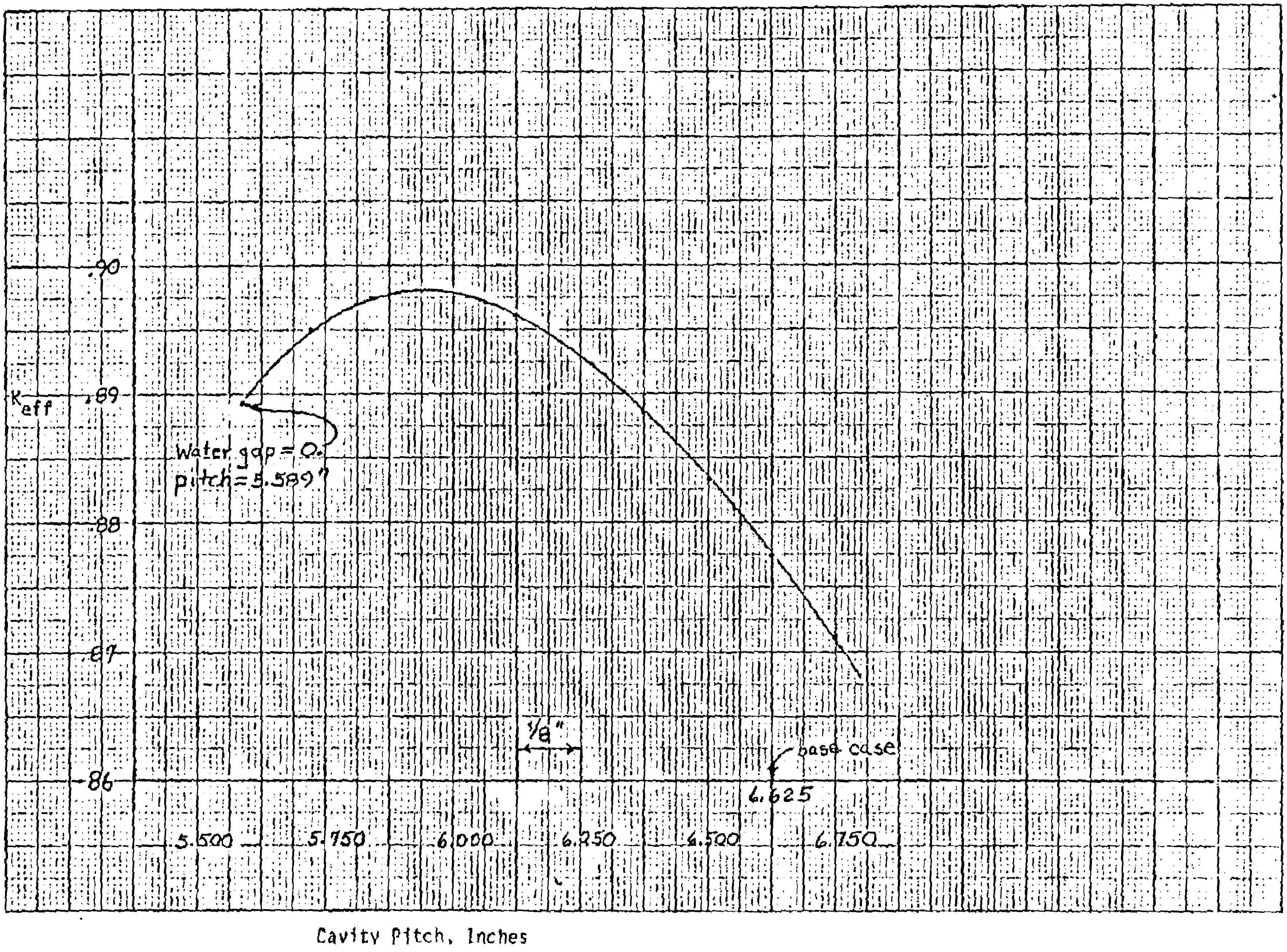


FIGURE 5 DAEC BWR Spent Fuel Storage, Pitch Sensitivity



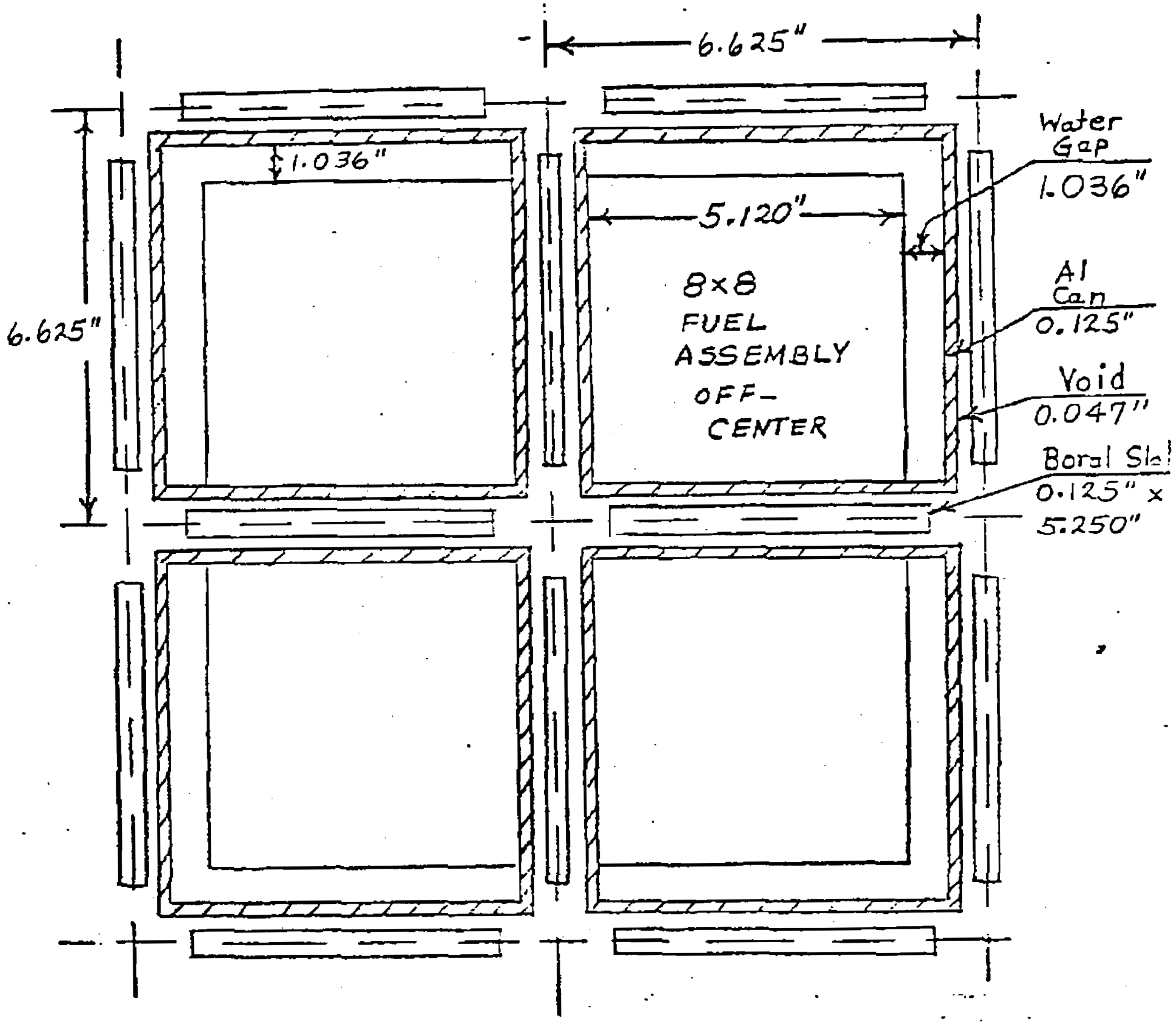


FIGURE 6 DAEC Spent Fuel Storage, Cluster Geometry of Four Off-centered Fuel Assemblies

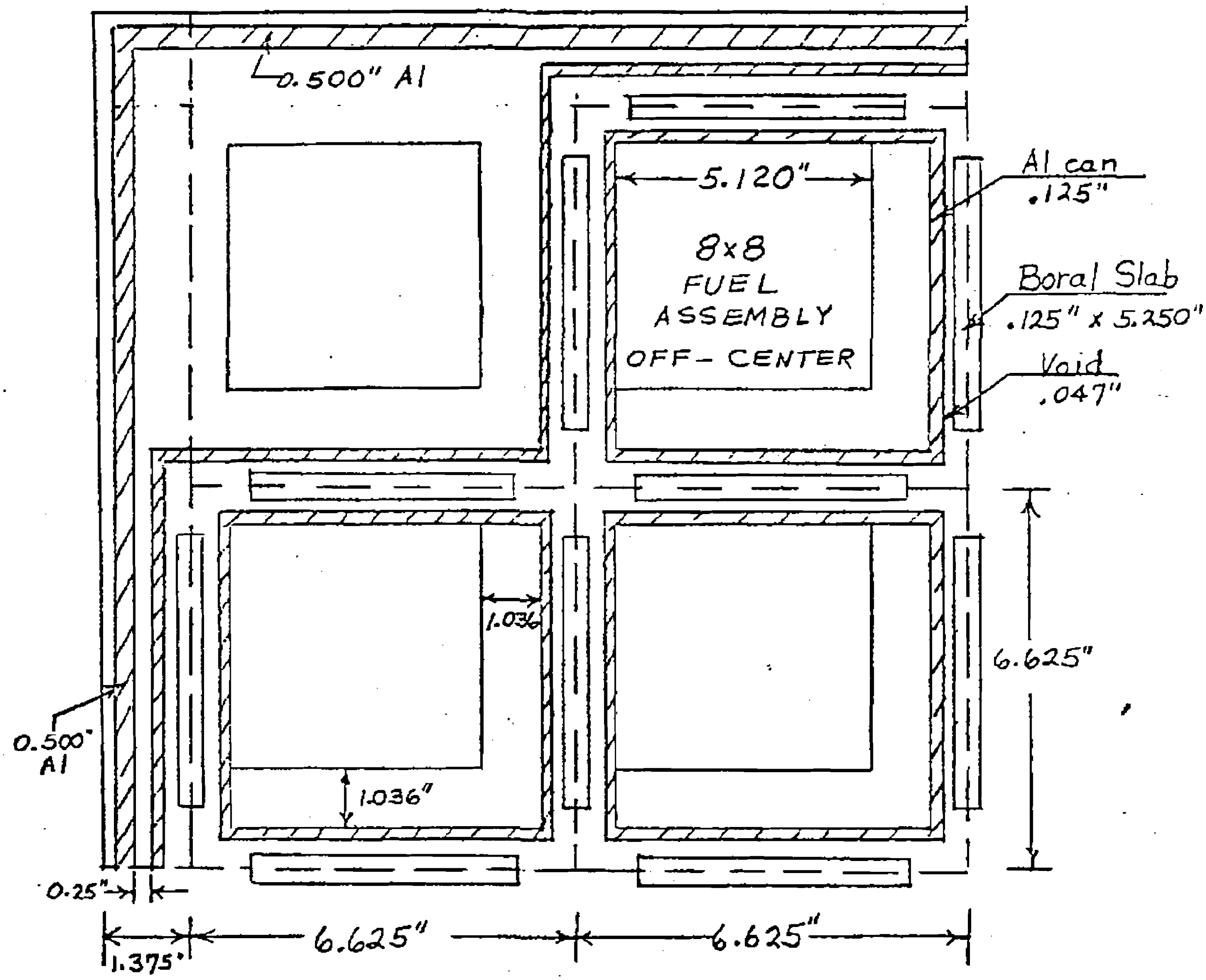


FIGURE 7 DAEC BWR Spent Fuel Storage Rack Module Junction, Off-centered Fuel

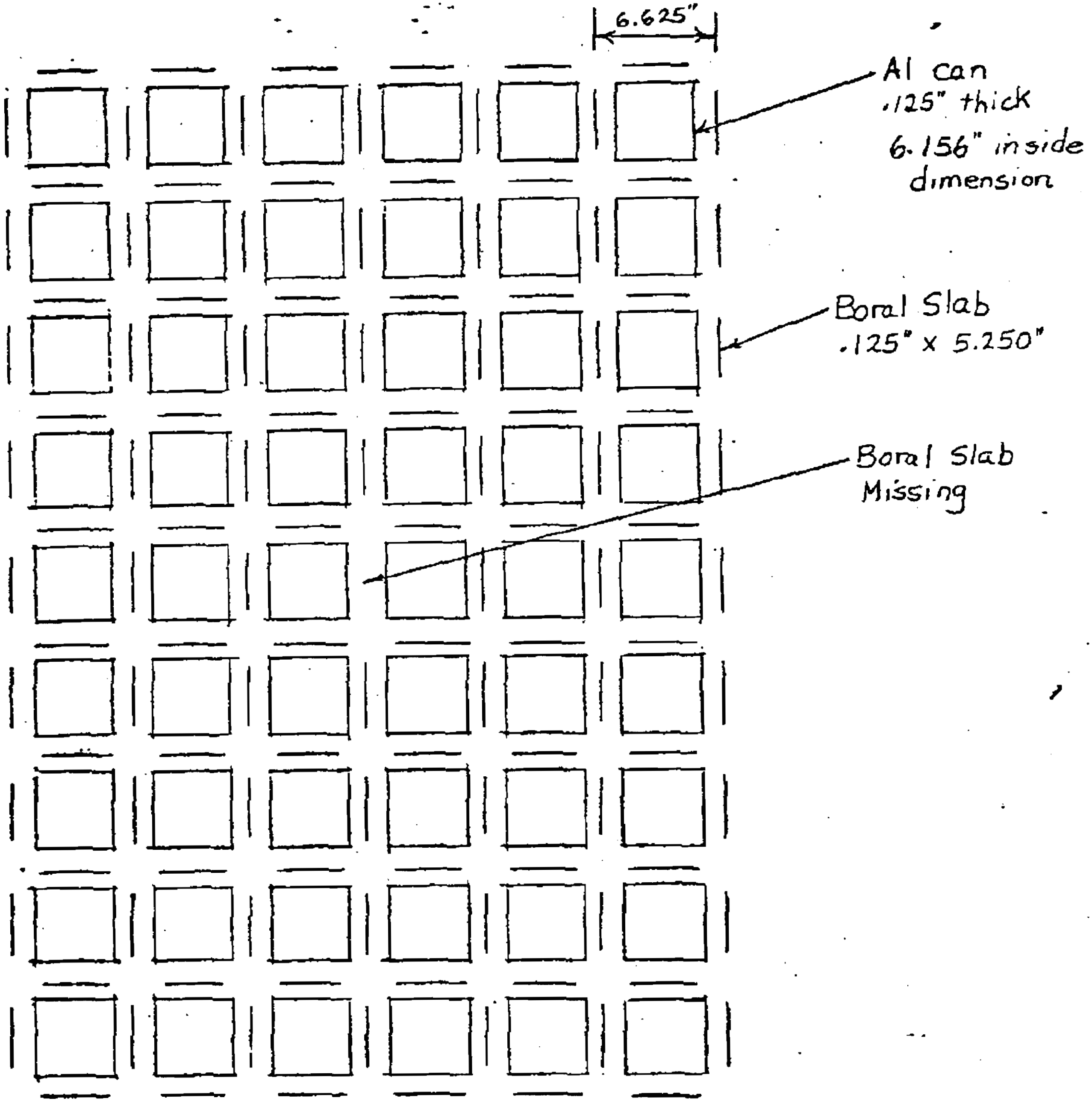


FIGURE 8 DAEC BWR Spent Fuel Storage, Loss of Boral: 6x9 array with one Boral slab missing.