CRITICALITY ANALYSIS OF BEAVER VALLEY 1
FRESH AND SPENT FUEL RACKS

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1. Introduction

The Beaver Valley Unit 1 spent fuel rack (SFR) design described herein employs one array of racks, which will be considered as two separate spent fuel racks. Both of these fuel racks consists of existing Duquesne Light fuel racks. The smaller array, referred to as Region 1 will be reanalyzed for criticality to show that 4.5 w/o fuel can be stored in the rack in two out of four storage locations and 4.0 STD w/o fuel in three of four storage locations. The larger array, Region 2, will be reanalyzed to take into consideration the changes in fuel and fission product inventory resulting from depletion in the reactor core. The Region 1 and 2 spent fuel rack design is a non-poisoned stainless steel rack design, previously accepted by the NRC, for enrichments up to 3.3 w/o with no credit taken for the reactivity reduction due to fuel burnup for Westinghouse 17x17 STD fuel.

The Region 2 spent fuel rack reanalysis is based on maintaining $K_{eff} \leq$ 0.95 for storage of Westinghouse 17x17 OFA and STD fuel at 4.5 w/o U^{235} with an initial enrichment/burnup combination in the acceptable area of Figure 1, and utilization of every cell permitted for storage of the fuel assemblies.

The Beaver Valley Unit 1 fresh fuel racks also consists of existing Duquesne Light fuel racks. These racks will be reanalyzed for criticality to show that 4.5 w/o OFA and STD fuel can be stored in every storage cell in the rack and maintain $k_{eff} \leq 0.95$. The fresh fuel rack design is a non-poisoned stainless steel design, previously accepted by the NRC for enrichments up to 3.3 w/o for Westinghouse 17x17 STD fuel.

2. Design Description

The Region 1 and 2 spent fuel storage cell design is depicted schematically in Figure 2, with nominal dimensions given on the figure. The fresh fuel rack storage cell design is depicted schematically in Figure 3. The fresh fuel rack layout is shown in Figure 4.

3. Design Criteria

Criticality of fuel assemblies in a fuel storage rack is prevented by the design of the rack which limits fuel assembly interaction. This is done by fixing the minimum separation between assemblies.

The design basis for preventing criticality outside the reactor is that, including uncertainties, there is a 95 percent probability at a 95 percent confidence level that the effective multiplication factor (K_{eff}) of the fuel assembly array will be less than 0.95 as recommended in ANSI 57.2-1983, ANSI 57.3-1983 and in Reference 1.

4. Criticality Analytical Method

The criticality calculation method and cross-section values are verified by comparison with critical experiment data for assemblies similar to those for which the racks are designed. This benchmarking data is sufficiently diverse to establish that the method bias and uncertainty will apply to rack conditions which include strong neutron absorbers, large water gaps and low moderator densities.

The design method which insures the criticality safety of fuel assemblies in the spent fuel storage rack uses the AMPX system of codes[2,3] for cross-section generation and KENO IV[4] for reactivity determination.

The 227 energy group cross-section library[2] that is the common starting point for all cross-sections used for the benchmarks and the storage rack is generated from ENDF/B-V data. The NITAWL program[3] includes, in this library, the self-shielded resonance cross-sections that are appropriate for each particular geometry. The Nordheim Integral Treatment is used. Energy and spatial weighting of cross-sections is performed by the XSDRNPM program[3] which is a one-dimensional S_n transport theory code. These multigroup cross-section sets are then used as input to KENO IV[5] which is a three dimensional Monte Carlo theory program designed for reactivity calculations.

A set of 33 critical experiments has been analyzed using the above method to demonstrate its applicability to criticality analysis and to establish the method bias and variability. The experiments range from water moderated, oxide fuel arrays separated by various materials (boroflex, steel, water, etc) that simulate LWR fuel shipping and storage conditions[5] to dry, harder spectrum uranium metal cylinder arrays with various interspersed materials[6] (Plexiglas and air) that demonstrate the wide range of applicability of the method. Table 1 summarizes these experiments.

The average K_{eff} of the benchmarks is 0.992. The standard deviation of the bias value is 0.0008 Δk. The 95/95 one sided tolerance limit factor for 33 values is 2.19. Thus, there is a 95 percent probability with a 95 percent confidence level that the uncertainty in reactivity, due to the method, is not greater than 0.0018 Δk.

5. <u>Criticality Analysis - Spent fuel Rack Region 1 - Two of Four Storage</u>

The following assumptions were used to develop the nominal case KENO model for the spent fuel rack Region 1 storage of fresh fuel using two out of four storage locations:

a. The fuel assembly contains the highest enrichment authorized, is at its most reactive point in life, and no credit is taken for any burnable poison in the fuel rods. Historically, calculations for spent fuel racks similar to the Region 1 racks analyzed herein have shown that the W 17X17 OFA fuel assembly yields a larger K_{eff} than does the W 17X17 Standard fuel assembly when both fuel assemblies have the same U^{235} enrichment. Thus, only the W 17X17 OFA fuel assembly was analyzed for Region 1. (See Table 2 for fuel parameters).

b. All fuel rods contain uranium dioxide at an enrichment of 4.5 w/o U^{235} over the infinite length of each rod.

c. No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken for the buildup of fission product poison material.

d. The moderator is pure water at a temperature of 68°F. A conservative value of 1.0 gm/cm^3 is used for the density of water.

e. No credit is taken for any spacer grids or spacer sleeves.

f. Fuel assemblies are loaded into two of every four cells in a checkerboard pattern in the storage cells as shown in Figure 5.

g. The array is infinite in lateral and axial extent which precludes any neutron leakage from the array.

The KENO calculation for the nominal case resulted in a K_{eff} of 0.8889 with a 95 percent probability/95 percent confidence level uncertainty of $\pm$0.0054.

The maximum K_{eff} under normal conditions arises from consideration of mechanical and material thickness tolerances resulting from the manufacturing process in addition to asymmetric positioning of fuel assemblies within the storage cells. Studies of asymmetric positioning of fuel assemblies within the storage cells has shown that symmetrically placed fuel assemblies yield conservative results in rack K_{eff}. The manufacturing tolerances are stacked in such a manner to minimize the water gap between adjacent cells, thereby causing an increase in reactivity. The sheet metal tolerances are considered along with construction tolerances related to the cell I.D., and cell center-to-center spacing. For the Region 1 storage racks, the water gap is reduced from a nominal value of 2.62" to a minimum of 2.59". Thus, the most conservative, or "worst case", KENO model of the Region 1 storage racks contains a minimum water gap of 2.59" with symmetrically placed fuel assemblies.

Based on the analysis described above, the following equation is used to develop the maximum K_{eff} for the Beaver Valley Region 1 spent fuel storage racks with two out of four storage:

$$K_{eff} = K_{worst} + B_{method} + [(ks)^2_{worst} + (ks)^2_{method}]^{1/2}$$

Where:

K_{worst} = worst case KENO K_{eff} that includes material tolerances, and mechanical tolerances which can result in spacings between assemblies less than nominal

B_{method} = method bias determined from benchmark critical comparisons

ks_{worst} = 95/95 uncertainty in the worst case KENO K_{eff}

ks_{method} = 95/95 uncertainty in the method bias

Substituting calculated values in the order listed above, the result is:

$$K_{eff} = 0.8902 + 0.0083 + [(0.0061)^2 + (0.0018)^2]^{1/2} = 0.9049$$

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/ confidence level, the acceptance criteria for criticality is met.

6. Criticality Analysis - Spent Fuel Rack - Region 1 - Three of Four Storage

The same assumptions that were used to develop the nominal case KENO model for two out of four storage were use to develop the nominal model for three out of four storage except, only Westinghouse 17x17 STD fuel at 4.0 w/o was considered and the model is finite in the axial extent. Figure 6 shows a diagram of fuel assemblies loaded into three of every four storage cells.

The KENO calculations for the nominal case resulted in a k_{eff} of 0.9348 (model is infinite in axial extent) with a 95 percent probability/ 95 percent confidence level uncertainty of $\pm$0.0061.

The maximum K_{eff} under normal conditions was determined with the same consideration of the mechanical and material tolerances that was used in the two out of four portion of the analysis discussed in Section 5. Based on this discussion the same equation is used to develop the maximum K_{eff} for the Beaver Valley Region 1 spent fuel storage racks with three out of four storage.

Substituting calculated values in order into the equation in Section 5, the result is:

$$K_{eff} = 0.9329 + 0.0083 + [(0.0051)^2 + (0.0018)^2]^{1/2} = 0.9466$$

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/ confidence level, the acceptance criteria for criticality is met.

7. Postulated Accidents - Spent Fuel Rack Region 1

Most accident conditions will not result in an increase in K_{eff} of the rack. Examples are the loss of cooling systems (reactivity decreases with decreasing water density) and dropping a fuel assembly on top of the rack (the rack structure pertinent for criticality is not excessively deformed and the dropped assembly has more than eight inches of water separating it from the active fuel height of stored assemblies which precludes interaction).

However, accidents can be postulated which would increase reactivity. Examples are, not maintaining the proper checker board (2 of 4, or 3 of 4) loading when fuel is placed in the racks, or dropping a fuel assembly between the rack and pool wall. For these accident conditions, the double contingency principle of ANSI N16.1-1975 is applied. This states that one is not required to assume two unlikely, independent, concurrent events to ensure protection against a criticality accident. Thus, for accident conditions, the presence of soluble boron in the storage pool water can be assumed as a realistic initial condition since not assuming its presence would be a second unlikely event.

The presence of approximately 1000 ppm boron in the pool water will decrease reactivity by about 15 percent ΔK. Thus, for postulated accidents, should there be a reactivity increase, K_{eff} would be less than or equal to 0.95 due to the effect of the dissolved boron.

8. Sensitivity Analyses - Spent Fuel Rack Region 1

To show the dependence of K_{eff} on fuel and storage cells parameters as requested by the NRC, the variation of the K_{eff} with respect to the following parameters was developed using the KENO computer code:

1. Fuel enrichment
2. Stainless steel thickness
3. Center-to-center spacing of storage cells.

Results of the sensitivity analysis for the Region 1 storage cells are shown in Figures 7 through 9 for two of four storage and Figures 10 through 12 for three of four storage. All error bars shown on the figures are one sigma uncertainties.

9. Criticality Analysis - Spent Fuel Rack Region 2 - Spent Fuel Storage

This section develops and describes the analytical techniques and models employed to perform the criticality analyses for storage of spent fuel in Region 2 of the Beaver Valley Unit 1 spent fuel pool.

9.1 Reactivity Equivalencing

Spent fuel storage, in the Region 2 spent fuel storage racks, is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. A series of reactivity calculations are performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield the equivalent K_{eff} when the fuel is stored in the Region 2 racks.

Figure 1 shows the constant K_{eff} contour generated for the Beaver Valley Region 2 racks. Note the endpoint at 0 MWD/MTU where the enrichment is 3.10 w/o and at 9,700 MWD/MTU where the enrichment is 4.5 w/o. The interpretation of the endpoint data is as follows: the reactivity of the Region 2 racks containing fuel at 9,700 MWD/MTU burnup which had an initial enrichment of 4.5 w/o is equivalent to the reactivity of the Region 2 racks containing fresh fuel having an initial enrichment of 3.10 w/o. It is important to recognize that the curve in Figure 1 is based on a constant Region 2 rack reactivity and not on a constant fuel assembly reactivity. The data in Figure 1 is also provided as Table 3. Linear interpolation between two data points on this table will yield conservative results.

9.2 Analytical Methods

The data points on the reactivity equivalence curve were generated with a transport theory computer code, PHOENIX[7]. PHOENIX is a depletable, two-dimensional, multigroup, discrete ordinates, transport theory code. A 25 energy group nuclear data library based on a modified version of the British WIMS[8] library is used with PHOENIX.

A study was done to examine fuel reactivity as a function of time following discharge from the reactor. Fission product decay was accounted for using CINDER[9]. CINDER is a point-depletion computer code used to determine fission product activities. The fission products were permitted to decay for 30 years after discharge. The fuel reactivity was found to reach a maximum at approximately 100 hours after discharge. At this point in time, the major fission product poison, Xe^{135}, has nearly completely decayed away. Furthermore, the fuel reactivity was found to decrease continuously from 100 hours to 30 years following discharge. Therefore, the most reactive point in time for a fuel assembly after discharge from the reactor can be conservatively approximated by removing the Xe^{135}.

The PHOENIX code has been validated by comparisons with experiments where isotopic fuel composition has been examined following discharge from a reactor. In addition, an extensive set of benchmark critical experiments has been analyzed with PHOENIX. Comparisons between measured and predicted uranium and plutonium isotopic fuel compositions are shown in Table 4. The measurements were made on fuel discharged from Yankee Core 5[10]. The data in Table 4 shows that the agreement between PHOENIX predictions and measured isotopic compositions is good.

The agreement between reactivities computed with PHOENIX and the results of 81 critical benchmark experiments is summarized in Table 5. Key parameters describing each of the 81 experiments are given in Table 6. These reactivity comparisons again show good agreement between experiment and PHOENIX calculations.

An uncertainty associatea with the burnup-dependent reactivities computed with PHOENIX is accounted for in the development of the maximum Region 2 multiplication factor. An uncertainty of 0.01 Δk is considered to be very conservative since comparison between PHOENIX results and the Yankee Core experiments and 81 benchmark experiments indicates closer agreement.

9.3 <u>Reactivity Calculations - Spent Fuel Rack Region 2 - Spent Fuel</u>

The nominal and maximum K_{eff} for storage of spent fuel in Region 2 is determined using the methods described in Section 4 for Region 1 in addition to the methods described in Section 9.2. The actual conditions for this determination are defined by the zero burnup intercept point in Figure 1. The KENO-IV computer code is used to calculated the storage rack multiplication factor with an equivalent fresh fuel enrichment of 3.10 w/o. Combinations of fuel enrichment and discharge burnup yielding the same rack multiplication factor as at the zero burnup intercept are determined with PHOENIX.

The following assumptions were used to develop the nominal case KENO model for the Region 2 storage of spent fuel:

a. Historically, calculations for spent fuel racks similar to the Region 2 racks analyzed herein have shown that the Westinghouse 17x17 OFA fuel assembly yields a larger K_{eff} than does the Westinghouse 17x17 standard fuel assembly when both fuel assemblies have the same U^{235} enrichment. Thus, only the Westinghouse 17x17 OFA fuel assembly was analyzed for Region 2.

b. The Westinghouse 17x17 OFA spent fuel assembly contains uranium dioxide fuel at an equivalent "fresh fuel" enrichment of 3.10 w/o U^{235}.

c. The moderator is pure water at a temperature of 68°F. A conservative value of 1.0 gm/cm^3 is used for the density of water.

d. No credit is taken for any spacer grids or spacer sleeves.

e. The array is infinite in lateral and axial extent which precludes any neutron leakage from the array.

The KENO calculation for the nominal case resulted in a K_{eff} of 0.9245 with a 95 percent probability/95 percent confidence level uncertainty of $\pm$ 0.0054.

The maximum K_{eff} under normal conditions was determined with a "worst case" KENO model, in the same manner as for the Region 1 storage racks (see Section 5). An uncertainty associated with the reactivity equivalence methodology was considered in the development of the maximum K_{eff}. This uncertainty was discussed in Section 9.

Based on the analysis described above, the following equation is used to develop the maximum K_{eff} for the storage of spent fuel in the Beaver Valley Region 2 spent fuel storage racks:

$$K_{eff} = K_{worst} + B_{method} + [(ks_{worst})^2 + (ks_{method})^2 + (ks_{re})^2]^{1/2}$$

where:

K_{worst} = worst case KENO K_{eff} that includes centered fuel assembly position, material tolerances, and mechanical tolerances which can result in spacings between assemblies less than nominal

B_{method} = method bias determined from benchmark critical comparisons

ks_{worst} = 95/95 uncertainty in the worst case KENO K_{eff}

ks_{method} = 95/95 uncertainty in the method bias

ks_{re} = uncertainty in the reactivity equivalence methodology

Substituting calculated values in the order listed above, the result is:

$$K_{eff} = 0.9262 + 0.0083 + [(0.0059)^2 + (0.0018)^2 + (0.01)^2]^{1/2} = 0.9462$$

The maximum K_{eff} for Region 2 for this configuration is less than 0.95, including all uncertainties at a 95/95 probability/confidence level. Therefore, the acceptance criteria for criticality are met for storage of spent fuel at an equivalent "fresh fuel" enrichment of 3.10 w/o U^{235}.

10. Postulated Accidents - Region 2

Most accident conditions will not result in an increase in K_{eff} of the rack. Examples are the loss of cooling systems (reactivity decreases with decreasing water density) and dropping a fuel assembly on top of the rack (the rack structure pertinent for criticality is not excessively deformed and the dropped assembly has more than eight inches of water separating it from the active fuel height of stored assemblies which precludes interaction).

However, accidents can be postulated which would increase reactivity (i.e., misloading an assembly with a burnup and enrichment combination outside of the acceptable area in Figure 1, or dropping a fuel assembly between the rack and pool wall). For these accident conditions, the double contingency principle of ANSI N16.1-1975 is applied. This states that one is not required to assume two unlikely, independent, concurrent events to ensure protection against a criticality accident. Thus, for accident conditions, the presence of soluble boron in the storage pool water can be assumed as a realistic initial condition since not assuming its presence would be a second unlikely event.

The presence of approximately 1000 ppm boron in the pool water will decrease reactivity by about 15 percent ΔK. Thus, for postulated accidents, should there be a reactivity increase, K_{eff} would be less than or equal to 0.95 due to the effect of the dissolved boron.

11. Sensitivity Analysis - Region 2

To show the dependence of K_{eff} on fuel and storage cell parameters as requested by the NRC, sensitivity studies were performed in which the poison loading, the fuel enrichment, and the storage cell center-to-center spacing were varied, using the KENO computer code.

Figures 13 through 15 illustrate the results of the sensitivity studies for spent fuel (3.10 w/o U^{235} equivalent "fresh fuel" enrichment) occupying every cell in the Region 2 racks.

12. Criticality Analysis - Fresh Fuel Racks

This section describes the analytical techniques and models employed to perform the criticality analysis for storage of fresh fuel in the Beaver Valley Unit 1 fresh fuel racks.

Since the fresh fuel racks are maintained in a dry condition, the criticality analysis will show that the rack K_{eff} is less than 0.95 for the full density and low density optimum moderation conditions. The low density optimum moderation scenario is an accident situation in which no credit can be taken for soluable boron. The criticality method and cross-section library are the same as those discussed in Section 4 of this report.

The following assumptions were used to develop the nominal case KENO model for the storage of fresh fuel in the fresh fuel racks under full density and low density optimum moderation conditions:

a. The fuel assembly contains the highest enrichment authorized, is at its most reactive point in life, and no credit is taken for any burnable poison in the fuel rods. Historically, calculations for similar racks have shown that the W 17x17 OFA fuel assembly yields a larger K_{eff} than does the W 17x17 Standard fuel assembly when both fuel assemblies have the same U^{235} enrichment. Thus, only the W 17x17 OFA fuel assembly was analyzed. (See Table 2 for fuel parameters).

b. All fuel rods contain uranium dioxide at an enrichment of 4.5 w/o U^{235} over the infinite length of each rod.

c. No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken for the buildup of fission product poison material.

d. No credit is taken for any spacer grids or spacer sleeves.

12.1 Full Density Moderation Analysis

In the nominal case KENO model for the full density moderation analysis, the moderator is pure water at a temperature of 68°F. A conservative value of 1.0 gm/cm^3 is used for the density of water. The fuel array is infinite in lateral and axial extent which precludes any neutron leakage from the array.

The KENO calculation for the nominal case resulted in a K_{eff} of 0.8959 with a 95 percent probability/95 percent confidence level uncertainty of $\pm$0.0079.

The maximum K_{eff} under normal conditions arises from consideration of mechanical and material thickness tolerances resulting from the manufacturing process in addition to asymmetric positioning of fuel assemblies within the storage cells. Studies of asymmetric positioning of fuel assemblies within the storage cells has shown that symmetrically placed fuel assemblies yield conservative results in rack K_{eff}. The manufacturing tolerances are stacked in such a manner to minimize the water gap between adjacent cells, thereby causing an increase in reactivity. The sheet metal tolerances are considered along with construction tolerances related to the cell I.D. and cell center-to-center spacing. For the fresh fuel storage racks, the water gap is reduced from a nominal value of 11.75" to a minimum of 11.72". Thus, the most conservative, or "worst case", KENO model of the fresh fuel storage racks contains a minimum water gap of 11.72" with symmetrically placed fuel assemblies.

Based on the analysis described above, the following equation is used to develop the maximum K_{eff} for the Beaver Valley fresh fuel storage racks:

$$K_{eff} = K_{worst} + B_{method} + [(ks)^2_{worst} + (ks)^2_{method}]^{1/2}$$

Where:

K_{worst} = worst case KENO K_{eff} that includes material tolerances, and mechanical tolerances which can result in spacings between assemblies less than nominal

B_{method} = method bias determined from benchmark critical comparisons

ks_{worst} = 95/95 uncertainty in the worst case KENO K_{eff}

ks_{method} = 95/95 uncertainty in the method bias

Substituting calculated values in the order listed above, the result is:

$$K_{eff} = 0.9009 + 0.0083 + [(0.0066)^2 + (0.0018)^2]^{1/2} = 0.9160$$

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/ confidence level, the acceptance criteria for criticality is met.

12.2 Low Density Optimum Moderation Analysis

In the low density optimum moderation analysis, the fuel array is infinite in only the axial extent which precludes any neutron leakage from the top or bottom of the array.

Analysis of fresh fuel racks similar to the Beaver Valley Unit 1 racks has shown that the maximum rack K_{eff} under low density moderation conditions occurs at 0.045 gm/cm^3 water density. The KENO calculation of the Beaver Valley Unit 1 fresh racks at 0.045 gm/cm^3 water density resulted in a peak K_{eff} of 0.9194 with a 95 percent probability and 95 percent confidence level uncertainty of $\pm$0.0129.

The nominal cell center-to-center spacing, rack module spacing and material tolerances have been included in the base case model and result in a storage cell separation distance of 11.75" and a rack module separation distance of 20.75 inches. Studies of asymmetric positioning of fuel assemblies within the storage cells has shown that symmetrically placed fuel assemblies yield conservative results in rack K_{eff}.

Since the Beaver Valley rack tolerances are small (0.06") consideration of minimum cell center-to-center spacing, rack module spacing and material tolerances will have an insignificant effect on the fuel rack k_{eff}. As a result the maximum k_{eff} will be 0.9194 with a 95 percent probability and 95 percent confidence level uncertainty of $\pm$ 0.0129.

Based on the analysis described above, the following equation is used to develop the maximum K_{eff} for the Beaver Valley fresh fuel storage racks under low density optimum moderation conditions:

$$K_{eff} = K_{base} + B_{method} + [(ks)^2_{base} + (ks)^2_{method}]^{1/2}$$

where:

K_{base}	=	base case KENO K_{eff} that includes nominal mechanical and material dimensions
B_{method}	=	method bias determined from benchmark critical comparisons
ks_{base}	=	95/95 uncertainty in the base case KENO K_{eff}
ks_{method}	=	95/95 uncertainty in the method bias

Substituting calculated values in the order listed above, the result is:

$$K_{eff} = 0.9194 + 0.0083 + [(0.0129)^2 + (0.0018)^2]^{1/2} = 0.9407$$

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met.

13. Sensitivity Analysis - Fresh Fuel Racks

To show the dependence of K_{eff} on fuel and storage parameters as requested by the NRC, sensitivity studies were performed in which the poison loading, the fuel enrichment, and the storage cell center-to-center spacing were varied, using the KENO computer code.

Figures 16 through 18 illustrate the results of the sensitivity studies for fresh fuel occupying every cell in the fresh fuel racks.

14. Acceptance Criterion For Criticality

The neutron multiplication factor in spent fuel pool and fresh fuel vault shall be less than or equal to 0.95, including all uncertainties, under all conditions.

The analytical methods employed herein conform with ANSI N18.2-1973, "Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants," Section 5.7, Fuel Handling System; ANSI 57.2-1983, "Design Objectives for LWR Spent Fuel Storage Facilities at Nuclear Power Stations," Section 6.4.2; ANSI N16.9-1975, "Validation of Calculational Methods for Nuclear Criticality Safety," NRC Standard Review Plan, Section 9.1.2, "Spent Fuel Storage"; and the NRC guidance, "NRC Position for Review and Acceptance of Spent Fuel Storage and Handling Applications," ANSI 57.3-1983, "Design Requirements for New Fuel Storage Facilities at Light Water Reactor Plants."

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Table 1

Benchmark Critical Experiments[5,6]

	General Description	Enrichment w/o U235	Reflector	Separating Material	Soluble B-10 ppm	K_{eff}
1.	UO_2 rod lattice	2.46	water	water	0	0.9857 ± .0028
2.	UO_2 rod lattice	2.46	water	water	1037	0.9906 ± .0018
3.	UO_2 rod lattice	2.46	water	water	764	0.9896 ± .0015
4.	UO_2 rod lattice	2.46	water	B4C pins	0	0.9914 ± .0025
5.	UO_2 rod lattice	2.46	water	B4C pins	0	0.9891 ± .0026
6.	UO_2 rod lattice	2.46	water	B4C pins	0	0.9955 ± .0020
7.	UO_2 rod lattice	2.46	water	B4C pins	0	0.9889 ± .0026
8.	UO_2 rod lattice	2.46	water	B4C pins	0	0.9983 ± .0025
9.	UO_2 rod lattice	2.46	water	water	0	0.9931 ± .0028
10.	UO_2 rod lattice	2.46	water	water	143	0.9928 ± .0025
11.	UO_2 rod lattice	2.46	water	stainless steel	514	0.9967 ± .0020
12.	UO_2 rod lattice	2.46	water	stainless steel	217	0.9943 ± .0019
13.	UO_2 rod lattice	2.46	water	borated aluminum	15	0.9892 ± .0023
14.	UO_2 rod lattice	2.46	water	borated aluminum	92	0.9884 ± .0023
15.	UO_2 rod lattice	2.46	water	borated aluminum	395	0.9832 ± .0021
16.	UO_2 rod lattice	2.46	water	borated aluminum	121	0.9848 ± .0024
17.	UO_2 rod lattice	2.46	water	borated aluminum	487	0.9895 ± .0020
18.	UO_2 rod lattice	2.46	water	borated aluminum	197	0.9885 ± .0022
19.	UO_2 rod lattice	2.46	water	borated aluminum	634	0.9921 ± .0019
20.	UO_2 rod lattice	2.46	water	borated aluminum	320	0.9920 ± .0020
21.	UO_2 rod lattice	2.46	water	borated aluminum	72	0.9939 ± .0020
22.	U metal cylinders	93.2	bare	air	0	0.9905 ± .0020
23.	U metal cylinders	93.2	bare	air	0	0.9976 ± .0020
24.	U metal cylinders	93.2	bare	air	0	0.9947 ± .0025
25.	U metal cylinders	93.2	bare	air	0	0.9928 ± .0019
26.	U metal cylinders	93.2	bare	air	0	0.9922 ± .0026
27.	U metal cylinders	93.2	bare	air	0	0.9950 ± .0027
28.	U metal cylinders	93.2	bare	plexiglass	0	0.9941 ± .0030
29.	U metal cylinders	93.2	paraffin	plexiglass	0	0.9928 ± .0041
30.	U metal cylinders	93.2	bare	plexiglass	0	0.9968 ± .0018
31.	U metal cylinders	93.2	paraffin	plexiglass	0	1.0042 ± .0019
32.	U metal cylinders	93.2	paraffin	plexiglass	0	0.9963 ± .0030
33.	U metal cylinders	93.2	paraffin	plexiglass	0	0.9919 ± .0032

Table 2

Fuel Parameters Employed in Criticality Analysis

Parameter	W 17X17 OFA	W 17X17 Standard
Number of Fuel Rods per Assembly	264	264
Rod Zirc-4 Clad O.D. (inch)	0.360	0.374
Clad Thickness (inch)	0.0225	0.0225
Fuel Pellet O.D. (inch)	0.3088	0.3225
Fuel Pellet Density (% of Theoretical)	96	96
Fuel Pellet Dishing Factor	1.0	1.0
Rod Pitch (inch)	0.496	0.496
Number of Zirc-4 Guide Tubes	24	24
Guide Tube O.D. (inch)	0.474	0.482
Guide Tube Thickness (inch)	0.016	0.016
Number of Instrument Tubes	1	1
Instrument Tube O.D. (inch)	0.474	0.482
Instrument Tube Thickness (inch)	0.016	0.016

Table 3

BEAVER VALLEY FUEL ASSEMBLY MINIMUM BURNUP VS. INITIAL U_{235} ENRICHMENT FOR STORAGE IN REGION 2 SPENT FUEL RACKS

Initial U_{235} Enrichment	Assembly Discharge Burnup (GWD/MTU)
3.1	0
3.3	1.6
3.5	3.0
3.7	4.4
3.9	5.8
4.1	7.2
4.3	8.5
4.5	9.7

Note: Linear interpolation yields conservative results.

Table 4

Comparison of PHOENIX Isotopic Prediction to Yankee Core 5 Measurements

Quantity (Atom Ratio)	% Difference
U235/U	-0.67
U236/U	-0.28
U238/U	-0.03
PU239/U	+3.27
PU240/U	+3.63
PU241/U	-7.01
PU242/U	-0.20
PU239/U238	+3.24
MASS(PU/U)	+1.41
FISS-PU/TOT-PU	-0.02

Percent difference is average difference of ten comparisons for each isotope.

Table 5

Benchmark Critical Experiments
PHOENIX Comparison

Description of Experiments	Number of Experiments	PHOENIX k_{eff} Using Experiment Bucklings
UO_2		
Al clad	14	.9947
SS clad	19	.9944
Borated H_2O	7	.9940
Subtotal	40	.9944
U-Metal		
Al clad	41	1.0012
TOTAL	81	.9978

Table 6

Data for U Metal and UO2 Critical Experiments

Case Number	Cell Type	A/O U-235	H2O/U Ratio	Fuel Density (G/CC)	Pellet Diameter (CM)	Material Clad	Clad OD (CM)	Clad Thickness (CM)	Lattice Pitch (CM)	B-10 PPM
1	Hexa	1.328	3.02	7.53	1.5265	Aluminum	1.6916	.07110	2.2050	0.0
2	Hexa	1.328	3.95	7.53	1.5265	Aluminum	1.6916	.07110	2.3590	0.0
3	Hexa	1.328	4.95	7.53	1.5265	Aluminum	1.6916	.07110	2.5120	0.0
4	Hexa	1.328	3.92	7.52	.9855	Aluminum	1.1506	.07110	1.5580	0.0
5	Hexa	1.328	4.89	7.52	.9855	Aluminum	1.1506	.07110	1.6520	0.0
6	Hexa	1.328	2.88	10.53	.9728	Aluminum	1.1506	.07110	1.5580	0.0
7	Hexa	1.328	3.58	10.53	.9728	Aluminum	1.1506	.07110	1.6520	0.0
8	Hexa	1.328	4.83	10.53	.9728	Aluminum	1.1506	.07110	1.8060	0.0
9	Square	2.734	2.18	10.18	.7620	SS-304	.8594	.04085	1.0287	0.0
10	Square	2.734	2.92	10.18	.7620	SS-304	.8594	.04085	1.1049	0.0
11	Square	2.734	3.86	10.18	.7620	SS-304	.8594	.04085	1.1938	0.0
12	Square	2.734	7.02	10.18	.7620	SS-304	.8594	.04085	1.4554	0.0
13	Square	2.734	8.49	10.18	.7620	SS-304	.8594	.04085	1.5621	0.0
14	Square	2.734	10.38	10.18	.7620	SS-304	.8594	.04085	1.6891	0.0
15	Square	2.734	2.50	10.18	.7620	SS-304	.8594	.04085	1.0617	0.0
16	Square	2.734	4.51	10.18	.7620	SS-304	.8594	.04085	1.2522	0.0
17	Square	3.745	2.50	10.27	.7544	SS-304	.8600	.04060	1.0617	0.0
18	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	0.0
19	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	0.0
20	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	456.0
21	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	709.0
22	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	1260.0
23	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	1334.0
24	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	1477.0
25	Square	4.069	2.55	9.46	1.1278	SS-304	1.2090	.04060	1.5113	0.0
26	Square	4.069	2.55	9.46	1.1278	SS-304	1.2090	.04060	1.5113	3392.0
27	Square	4.069	2.14	9.46	1.1278	SS-304	1.2090	.04060	1.4500	0.0
28	Square	2.490	2.84	10.24	1.0297	Aluminum	1.2060	.08130	1.5113	0.0
29	Square	3.037	2.64	9.28	1.1268	SS-304	1.1701	.07163	1.5550	0.0
30	Square	3.037	8.16	9.28	1.1268	SS-304	1.2701	.07163	2.1980	0.0
31	Square	4.069	2.59	9.45	1.1268	SS-304	1.2701	.07163	1.5550	0.0
32	Square	4.069	3.53	9.45	1.1268	SS-304	1.2701	.07163	1.6840	0.0
33	Square	4.069	8.02	9.45	1.1268	SS-304	1.2701	.07163	2.1980	0.0
34	Square	4.069	9.90	9.45	1.1268	SS-304	1.2701	.07163	2.3810	0.0
35	Square	2.490	2.84	10.24	1.0297	Aluminum	1.2060	.08130	1.5113	1677.0
36	Hexa	2.096	2.06	10.38	1.5240	Aluminum	1.6916	.07112	2.1737	0.0
37	Hexa	2.096	3.09	10.38	1.5240	Aluminum	1.6916	.07112	2.4052	0.0
38	Hexa	2.096	4.12	10.38	1.5240	Aluminum	1.6916	.07112	2.6162	0.0
39	Hexa	2.096	6.14	10.38	1.5240	Aluminum	1.6916	.07112	2.9891	0.0
40	Hexa	2.096	8.20	10.38	1.5240	Aluminum	1.6916	.07112	3.3255	0.0
41	Hexa	1.307	1.01	18.90	1.5240	Aluminum	1.6916	.07112	2.1742	0.0
42	Hexa	1.307	1.51	18.90	1.5240	Aluminum	1.6916	.07112	2.4054	0.0
43	Hexa	1.307	2.02	18.90	1.5240	Aluminum	1.6916	.07112	2.6162	0.0

Table 6 (continued)

Data for U Metal and U02 Critical Experiments

Case Number	Cell Type	A/O U-235	H2O/U Ratio	Fuel Density (G/CC)	Pellet Diameter (CM)	Material Clad	Clad OD (CM)	Clad Thickness (CM)	Lattice Pitch (CM)	B-10 PPM
44	Hexa	1.307	3.01	18.90	1.5240	Aluminum	1.6916	.07112	2.9896	0.0
45	Hexa	1.307	4.02	18.90	1.5240	Aluminum	1.6916	.07112	3.3249	0.0
46	Hexa	1.160	1.01	18.90	1.5240	Aluminum	1.6916	.07112	2.1742	0.0
47	Hexa	1.160	1.51	18.90	1.5240	Aluminum	1.6916	.07112	2.4054	0.0
48	Hexa	1.160	2.02	18.90	1.5240	Aluminum	1.6916	.07112	2.6162	0.0
49	Hexa	1.160	3.01	18.90	1.5240	Aluminum	1.6916	.07112	2.9896	0.0
50	Hexa	1.160	4.02	18.90	1.5240	Aluminum	1.6916	.07112	3.3249	0.0
51	Hexa	1.040	1.01	18.90	1.5240	Aluminum	1.6916	.07112	2.1742	0.0
52	Hexa	1.040	1.51	18.90	1.5240	Aluminum	1.6916	.07112	2.4054	0.0
53	Hexa	1.040	2.02	18.90	1.5240	Aluminum	1.6916	.07112	2.6162	0.0
54	Hexa	1.040	3.01	18.90	1.5240	Aluminum	1.6916	.07112	2.9896	0.0
55	Hexa	1.040	4.02	18.90	1.5240	Aluminum	1.6916	.07112	3.3249	0.0
56	Hexa	1.307	1.00	18.90	.9830	Aluminum	1.1506	.07112	1.4412	0.0
57	Hexa	1.307	1.52	18.90	.9830	Aluminum	1.1506	.07112	1.5926	0.0
58	Hexa	1.307	2.02	18.90	.9830	Aluminum	1.1506	.07112	1.7247	0.0
59	Hexa	1.307	3.02	18.90	.9830	Aluminum	1.1506	.07112	1.9609	0.0
60	Hexa	1.307	4.02	18.90	.9830	Aluminum	1.1506	.07112	2.1742	0.0
61	Hexa	1.160	1.52	18.90	.9830	Aluminum	1.1506	.07112	1.5926	0.0
62	Hexa	1.160	2.02	18.90	.9830	Aluminum	1.1506	.07112	1.7247	0.0
63	Hexa	1.160	3.02	18.90	.9830	Aluminum	1.1506	.07112	1.9609	0.0
64	Hexa	1.160	4.02	18.90	.9830	Aluminum	1.1506	.07112	2.1742	0.0
65	Hexa	1.160	1.00	18.90	.9830	Aluminum	1.1506	.07112	1.4412	0.0
66	Hexa	1.160	1.52	18.90	.9830	Aluminum	1.1506	.07112	1.5926	0.0
67	Hexa	1.160	2.02	18.90	.9830	Aluminum	1.1506	.07112	1.7247	0.0
68	Hexa	1.160	3.02	18.90	.9830	Aluminum	1.1506	.07112	1.9609	0.0
69	Hexa	1.160	4.02	18.90	.9830	Aluminum	1.1506	.07112	2.1742	0.0
70	Hexa	1.040	1.33	18.90	19.050	Aluminum	2.0574	.07620	2.8687	0.0
71	Hexa	1.040	1.58	18.90	19.050	Aluminum	2.0574	.07620	3.0086	0.0
72	Hexa	1.040	1.83	18.90	19.050	Aluminum	2.0574	.07620	3.1425	0.0
73	Hexa	1.040	2.33	18.90	19.050	Aluminum	2.0574	.07620	3.3942	0.0
74	Hexa	1.040	2.83	18.90	19.050	Aluminum	2.0574	.07620	3.6284	0.0
75	Hexa	1.040	3.83	18.90	19.050	Aluminum	2.0574	.07620	4.0566	0.0
76	Hexa	1.310	2.02	18.88	1.5240	Aluminum	1.6916	.07112	2.6160	0.0
77	Hexa	1.310	3.01	18.88	1.5240	Aluminum	1.6916	.07112	2.9900	0.0
78	Hexa	1.159	2.02	18.88	1.5240	Aluminum	1.6916	.07112	2.6160	0.0
79	Hexa	1.159	3.01	18.88	1.5240	Aluminum	1.6916	.07112	2.9900	0.0
80	Hexa	1.312	2.03	18.88	.9830	Aluminum	1.1506	.07112	1.7250	0.0
81	Hexa	1.312	3.02	18.88	.9830	Aluminum	1.1506	.07112	1.9610	0.0

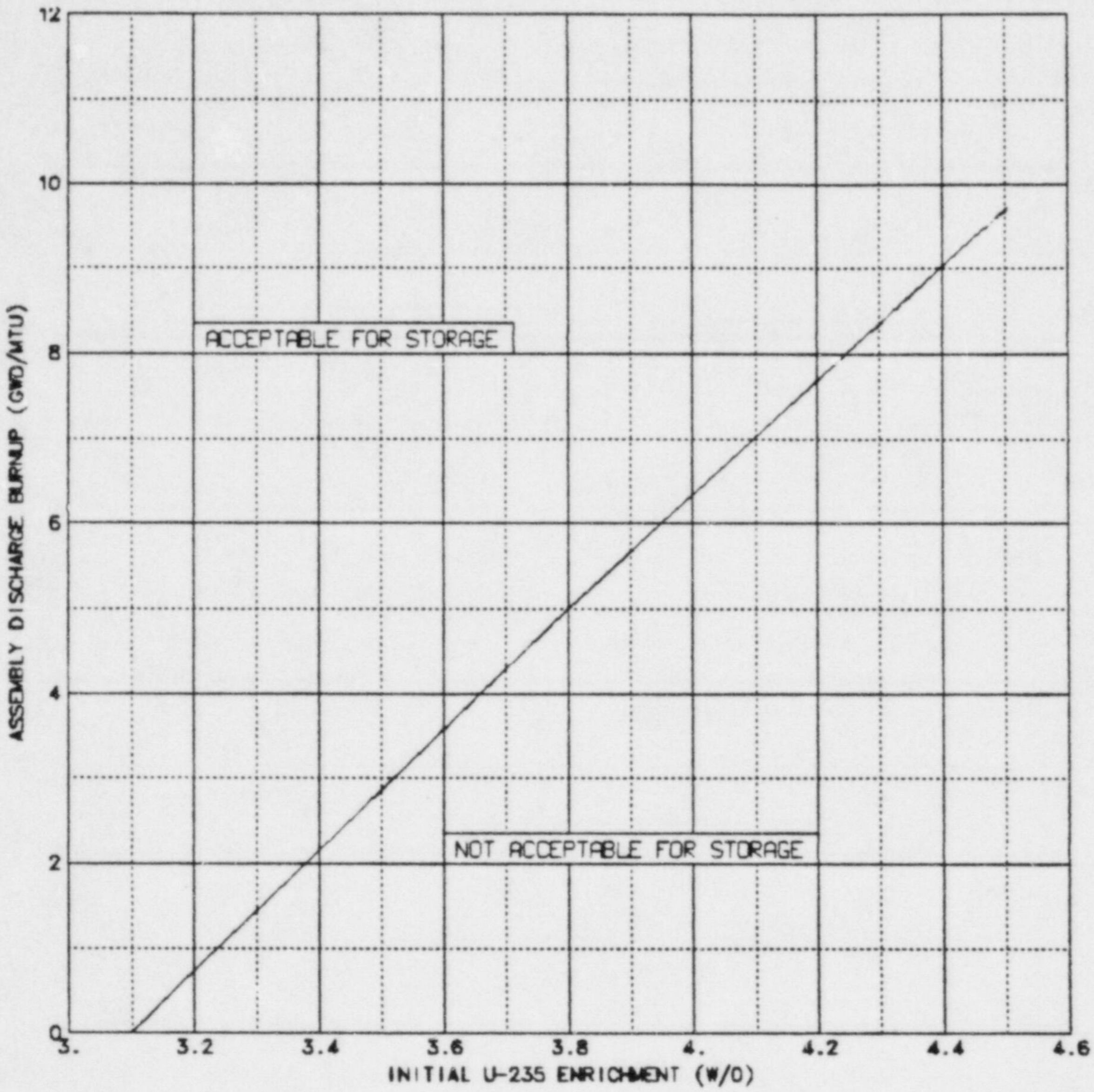


FIGURE 1

BEAVER VALLEY FUEL ASSEMBLY MINIMUM BURNUP VS. INITIAL U-235 ENRICHMENT FOR STORAGE IN REGION 2 SPENT FUEL RACKS

FIGURE 2

BEAVER VALLEY REGION 1 & 2 SPENT FUEL
STORAGE CELL NOMINAL DIMENSIONS

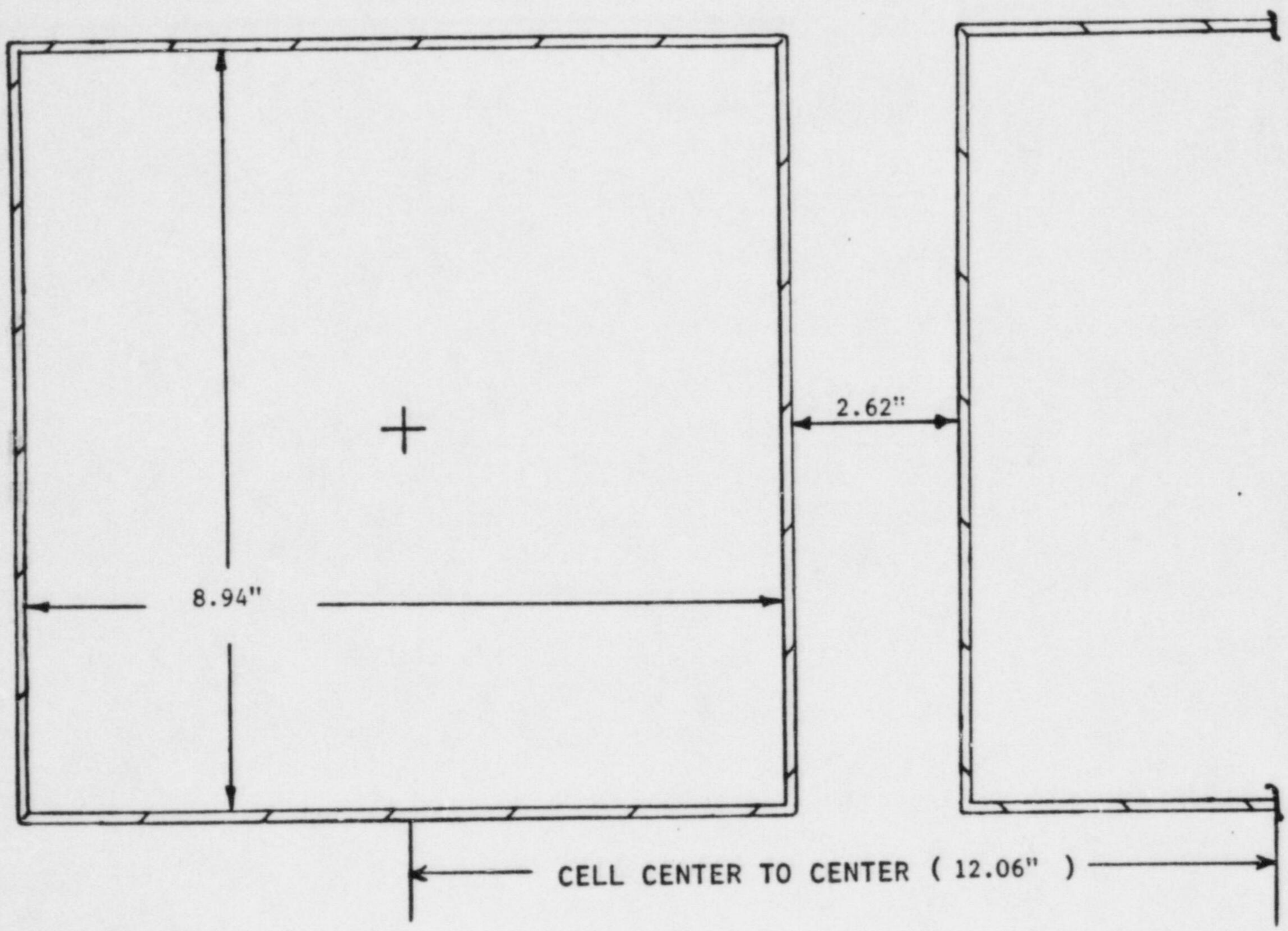


FIGURE 3

BEAVER VALLEY FRESH FUEL STORAGE CELL
NOMINAL DIMENSIONS

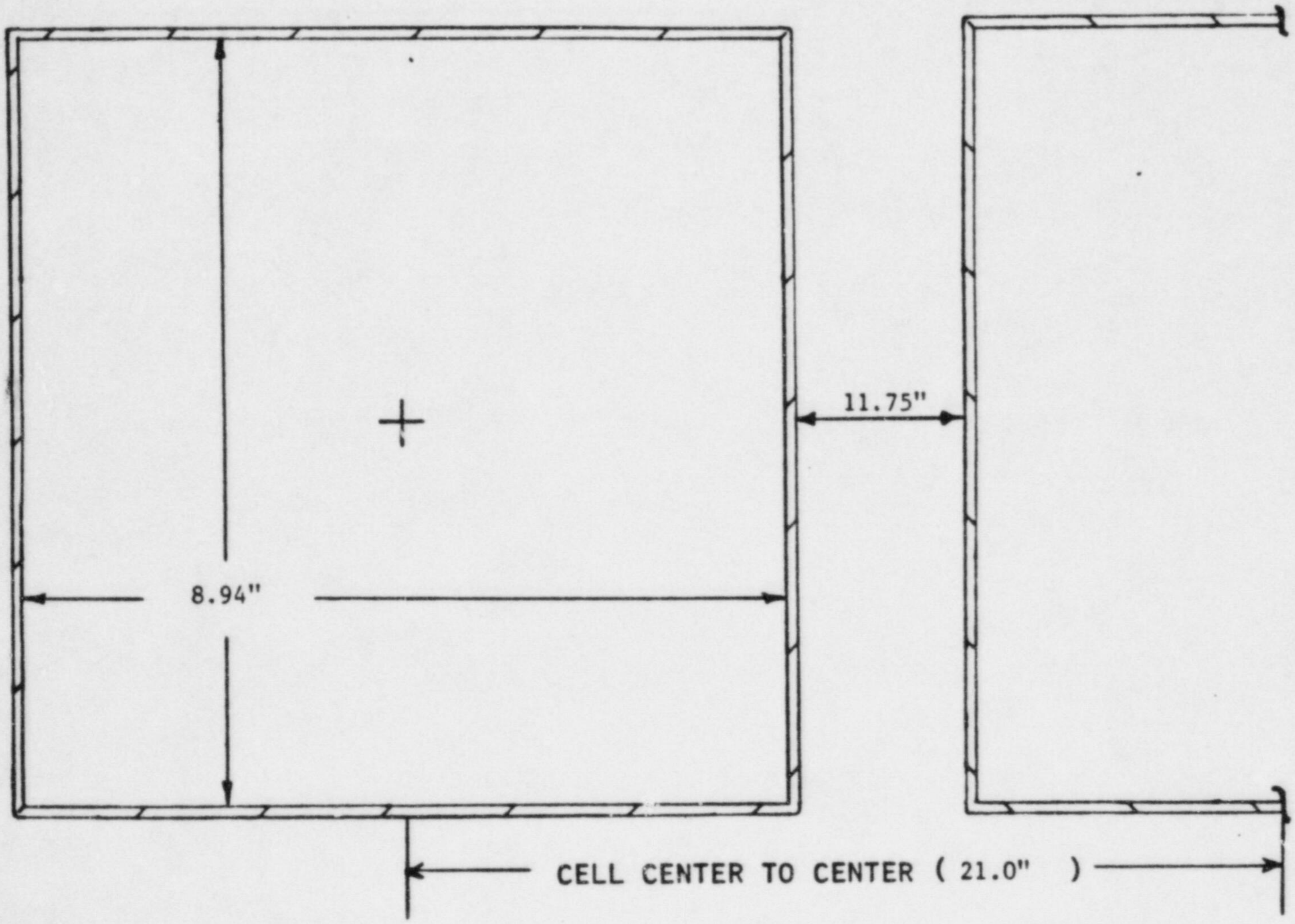


FIGURE 4

BEAVER VALLEY FRESH FUEL RACK LAYOUT

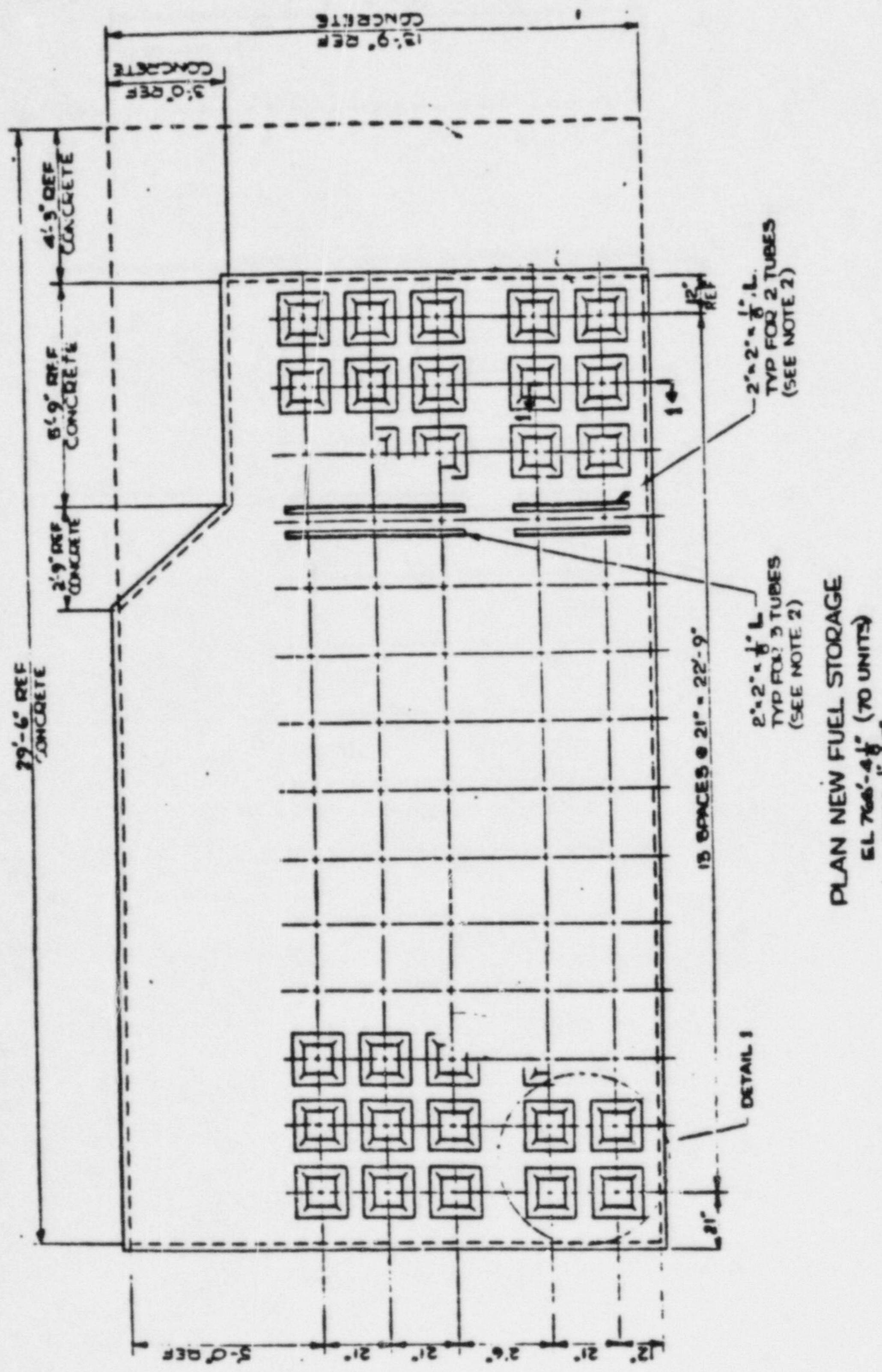


FIGURE 5

BEAVER VALLEY REGION 1 CHECKERBOARD
FUEL ASSEMBLY LOADING SCHEMATIC

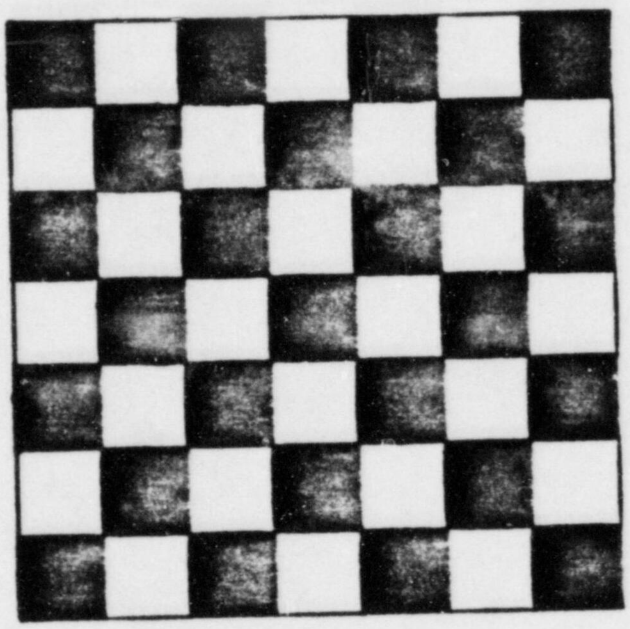
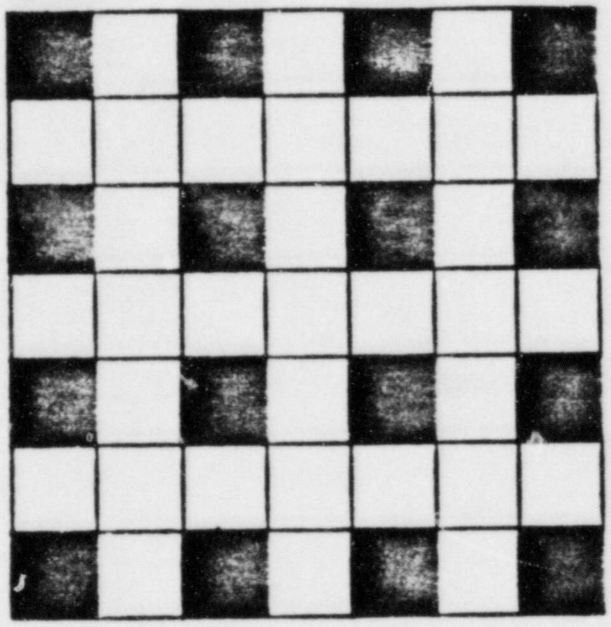


FIGURE 6

BEAVER VALLEY REGION ONE 3 OF 4 FUEL
ASSEMBLY LOADING SCHEMATIC



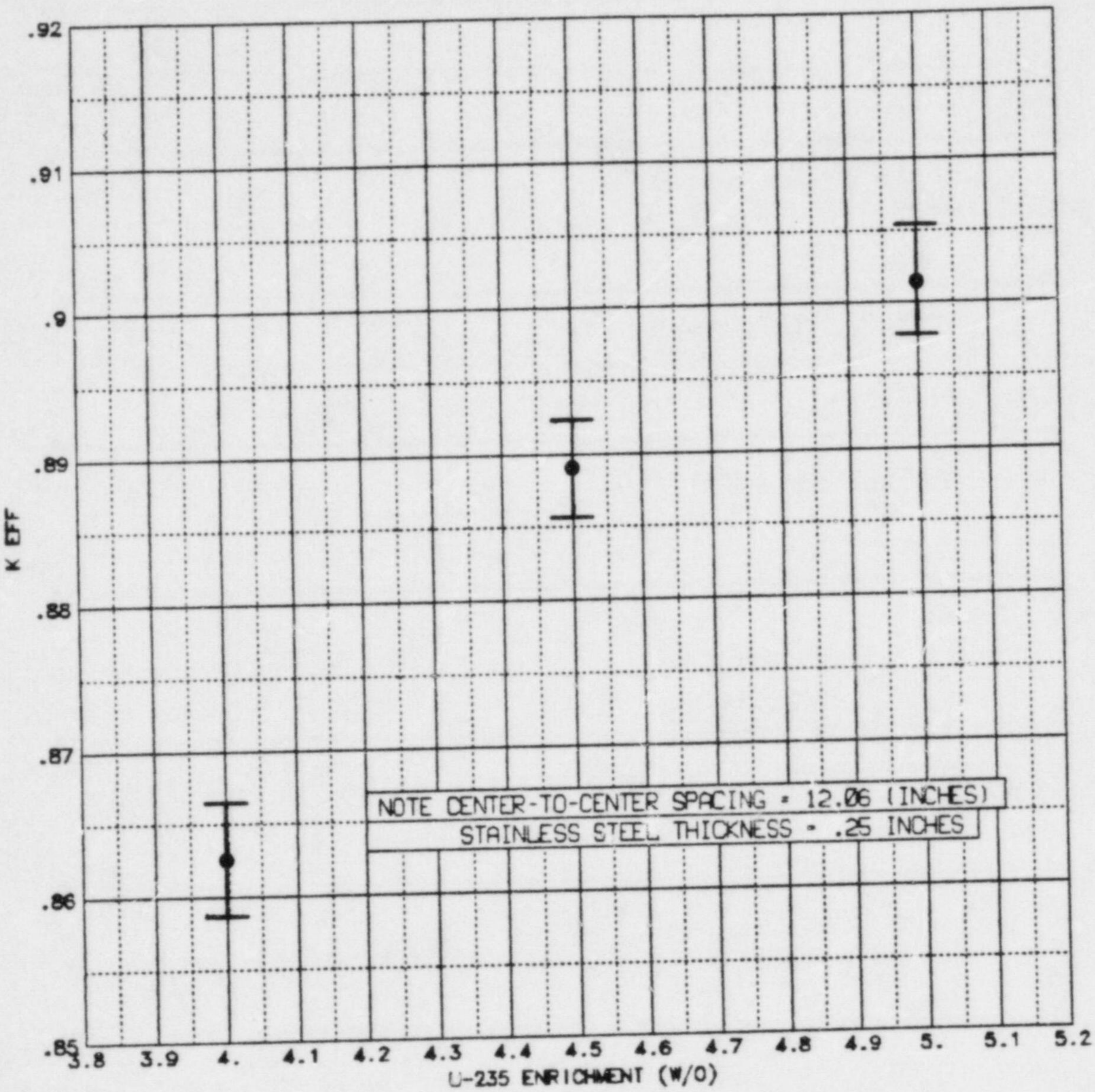


FIGURE 7

SENSITIVITY OF K-EFF TO ENRICHMENT IN THE BEAVER VALLEY REGION 1
SPENT FUEL STORAGE RACKS WITH TWO OF FOUR STORAGE

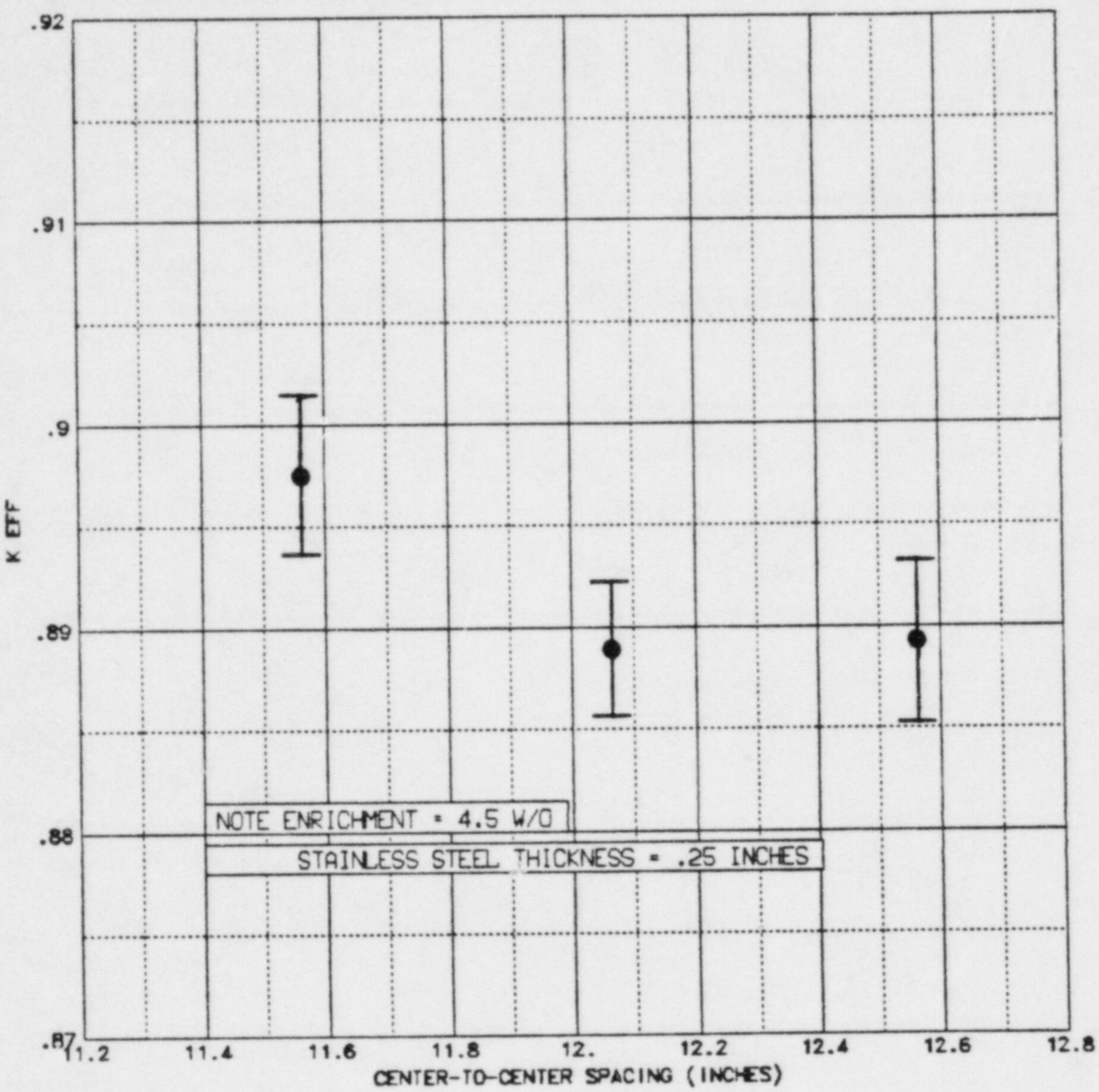


FIGURE 8

SENSITIVITY OF K-EFF TO CENTER-TO-CENTER SPACING IN THE BEAVER VALLEY REGION 1 SPENT FUEL STORAGE RACKS WITH TWO OF FOUR STORAGE

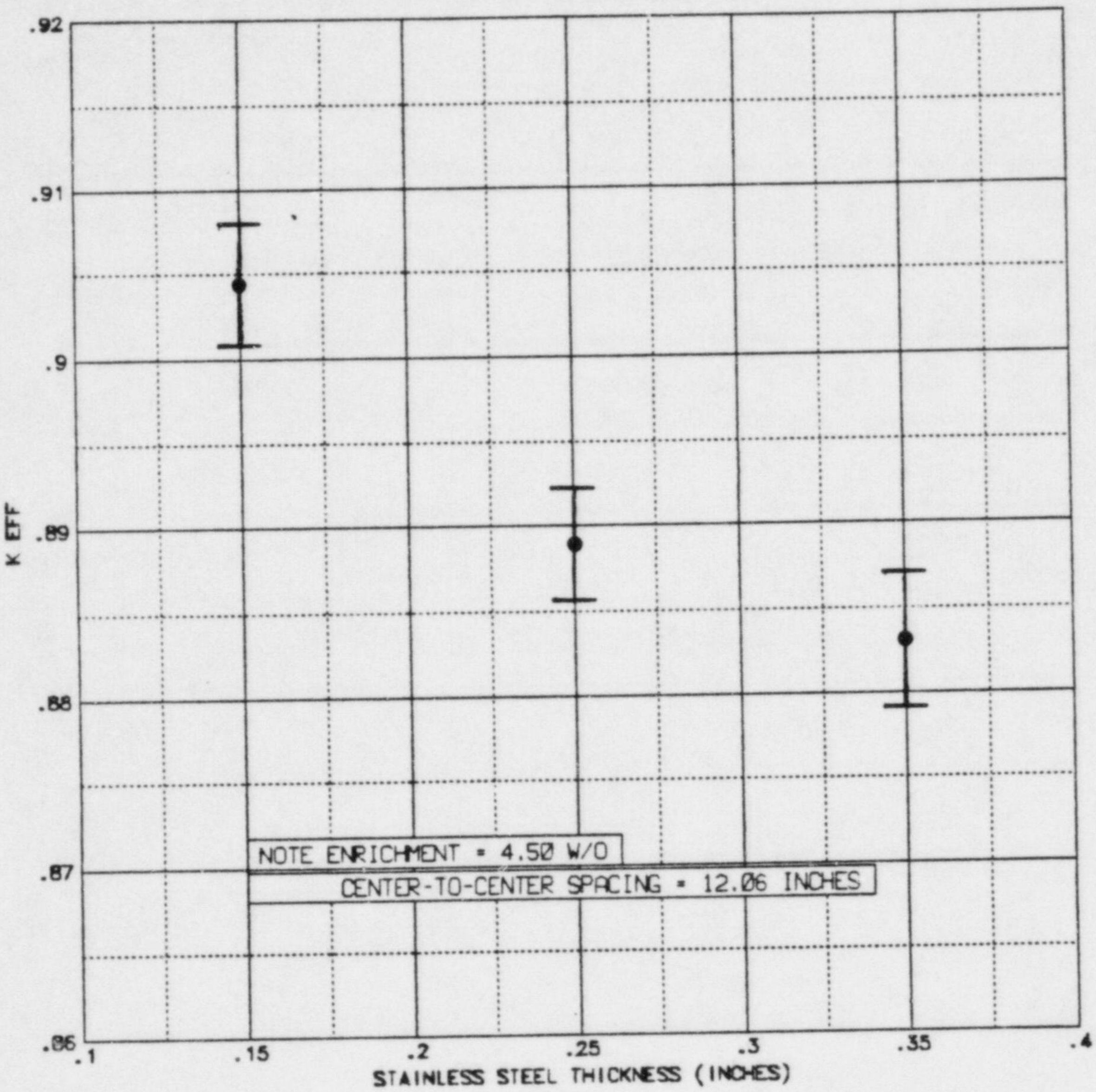


FIGURE 9

SENSITIVITY OF K-EFF TO STEEL CAN THICKNESS IN THE BEAVER VALLEY REGION 1 SPENT FUEL STORAGE RACKS WITH TWO OF FOUR STORAGE

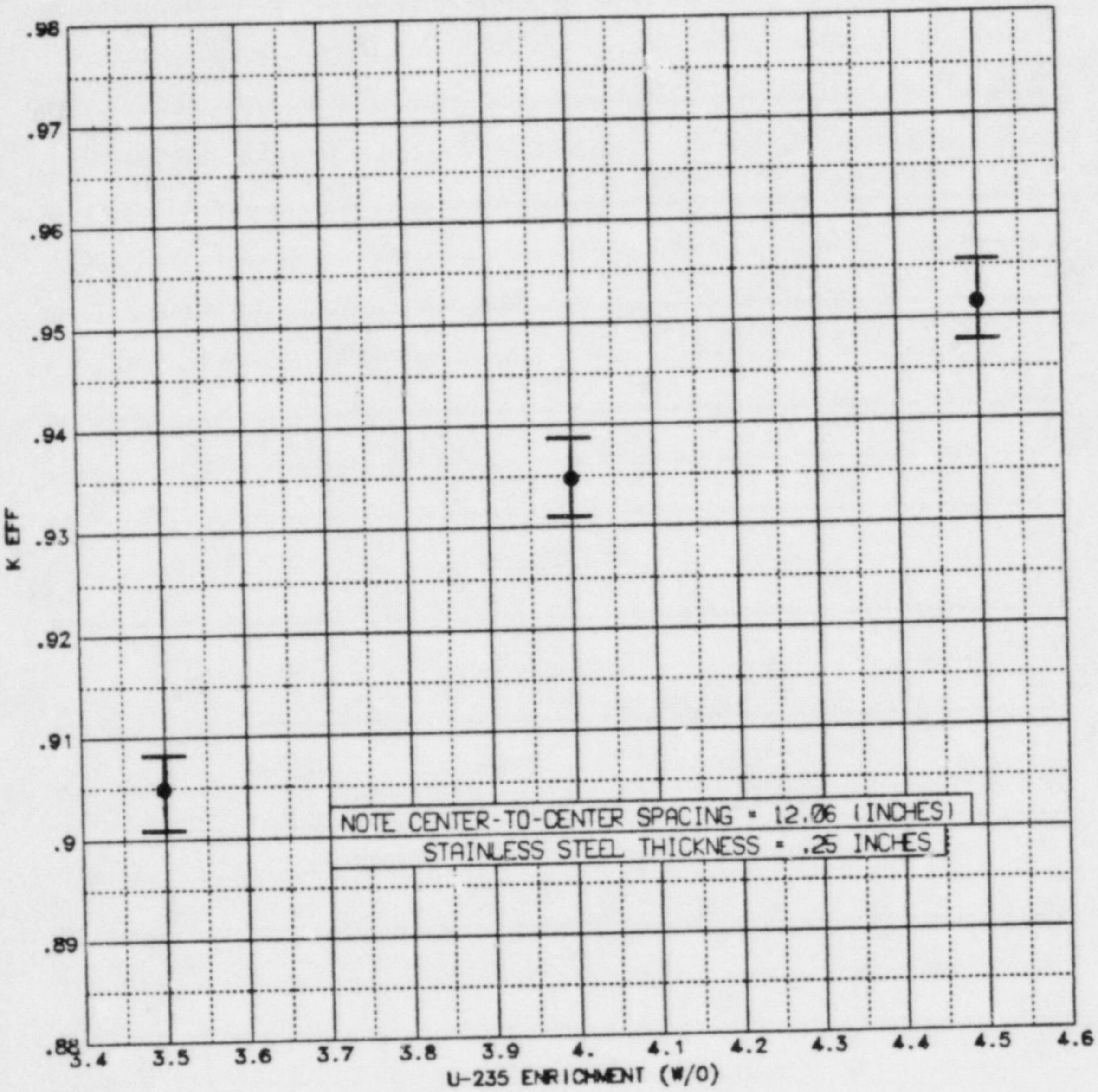


FIGURE 10

SENSITIVITY OF K-EFF TO ENRICHMENT IN THE BEAVER VALLEY REGION 1 SPENT FUEL STORAGE RACKS WITH THREE OF FOUR STORAGE

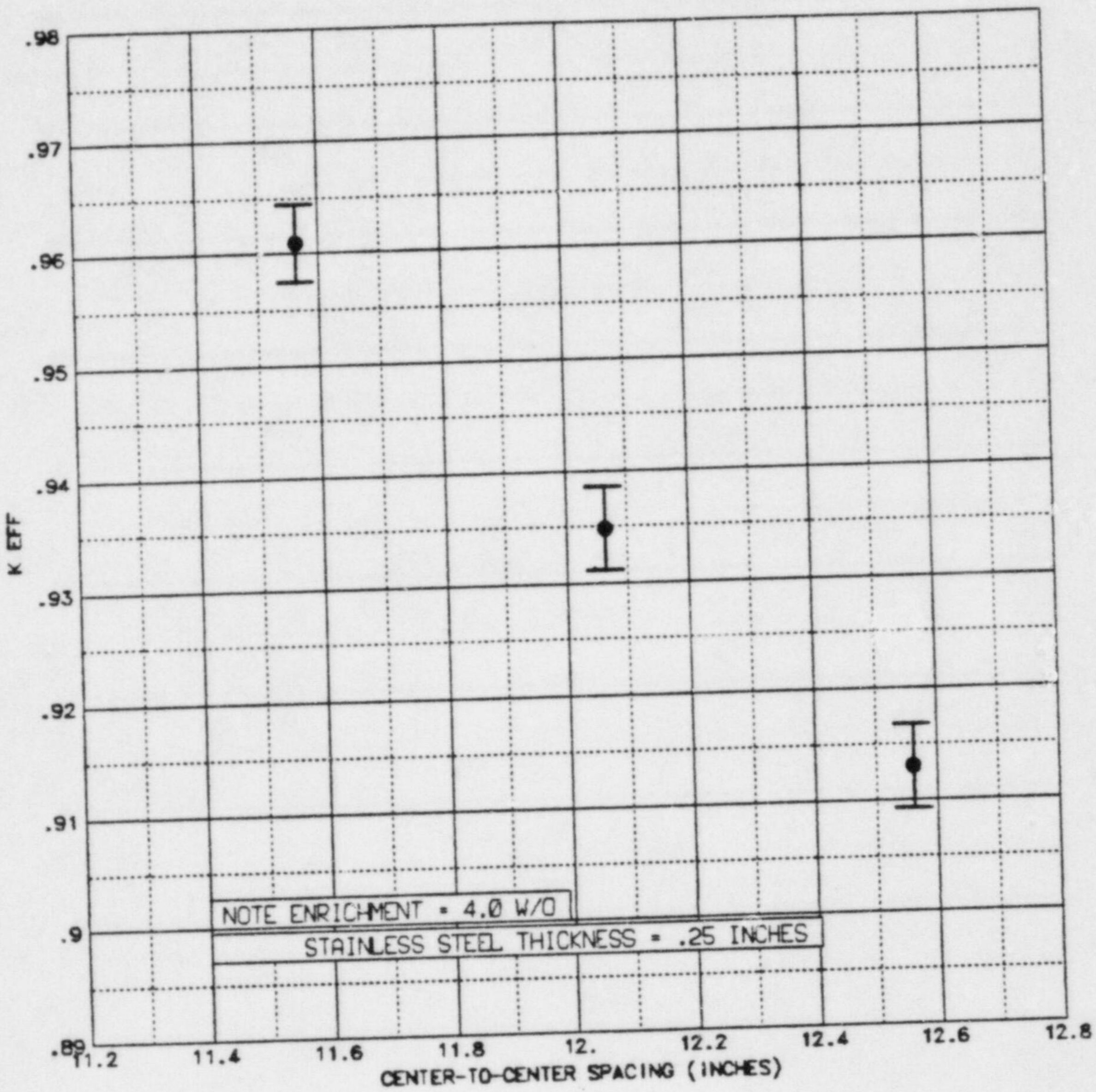


FIGURE 11

SENSITIVITY OF K-EFF TO CENTER-TO-CENTER SPACING IN THE BEAVER VALLEY
RETION 1 SPENT FUEL STORAGE RACKS WITH THREE OF FOUR STORAGE

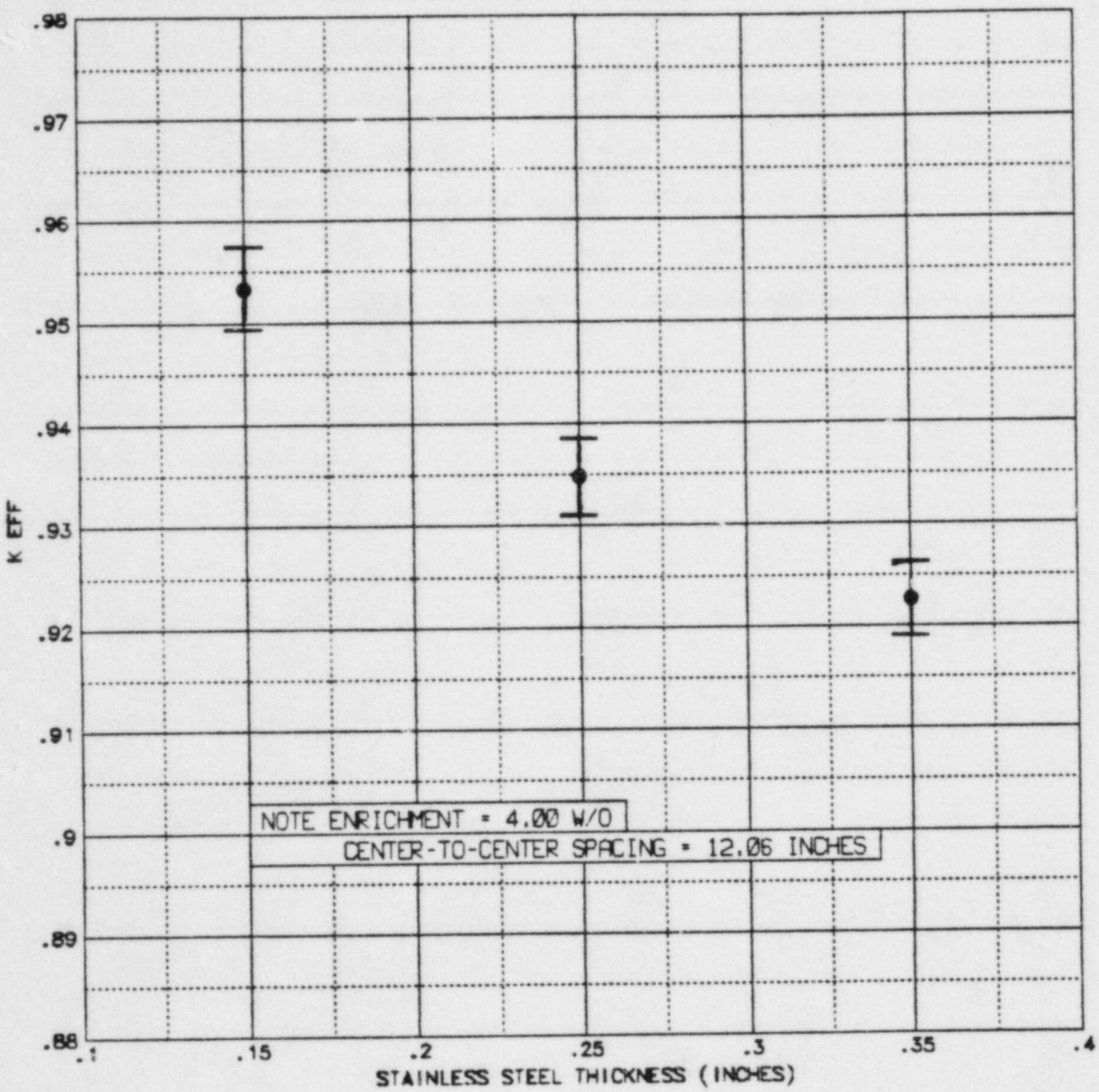


FIGURE 12

SENSITIVITY OF K-EFF TO STEEL CAN THICKNESS IN THE BEAVER VALLEY REGION 1 SPENT FUEL STORAGE RACKS WITH THREE OF FOUR STORAGE

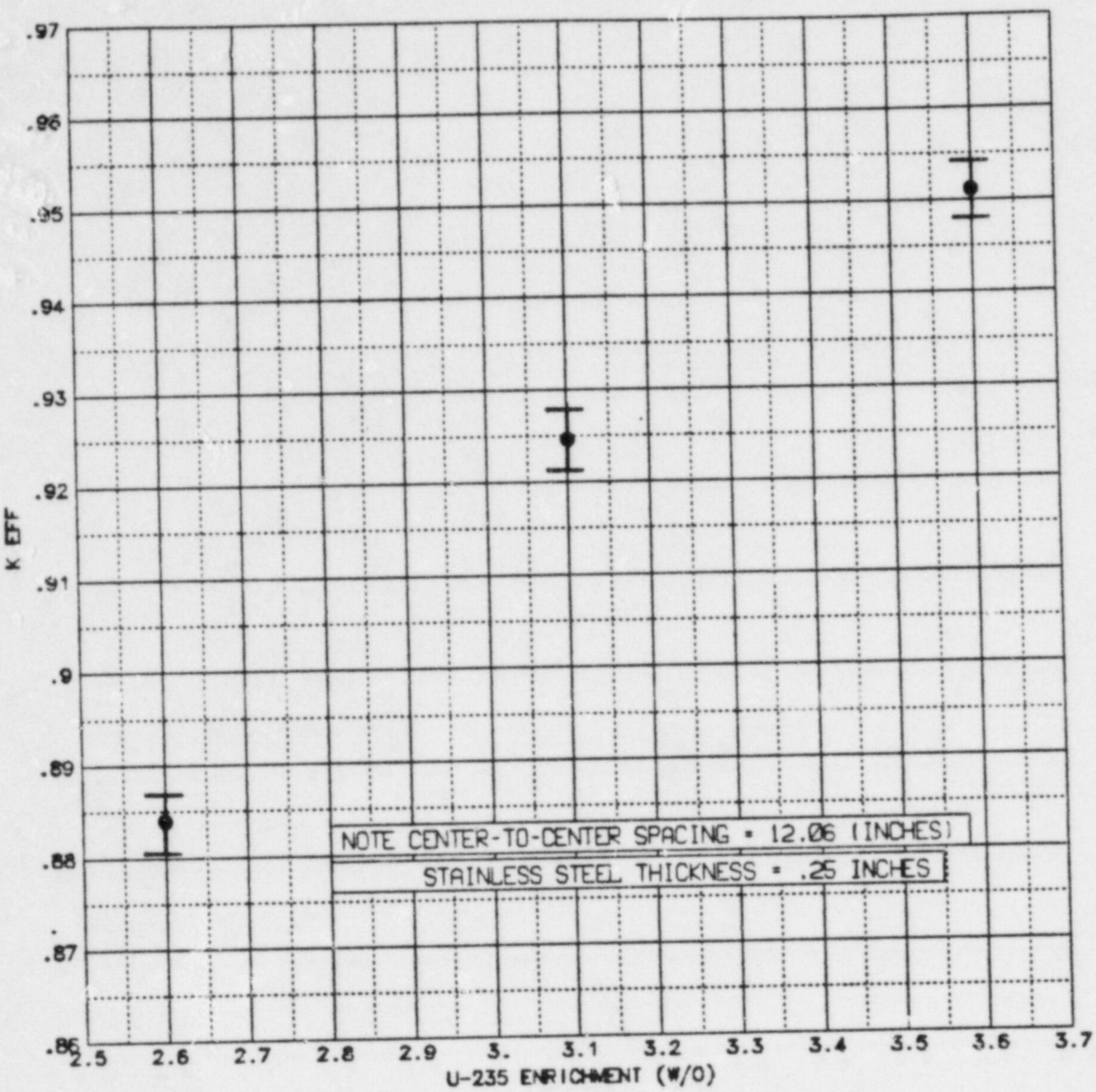


FIGURE 13

SENSITIVITY OF K-EFF TO ENRICHMENT IN THE BEAVER VALLEY
REGION 2 SPENT FUEL STORAGE RACKS

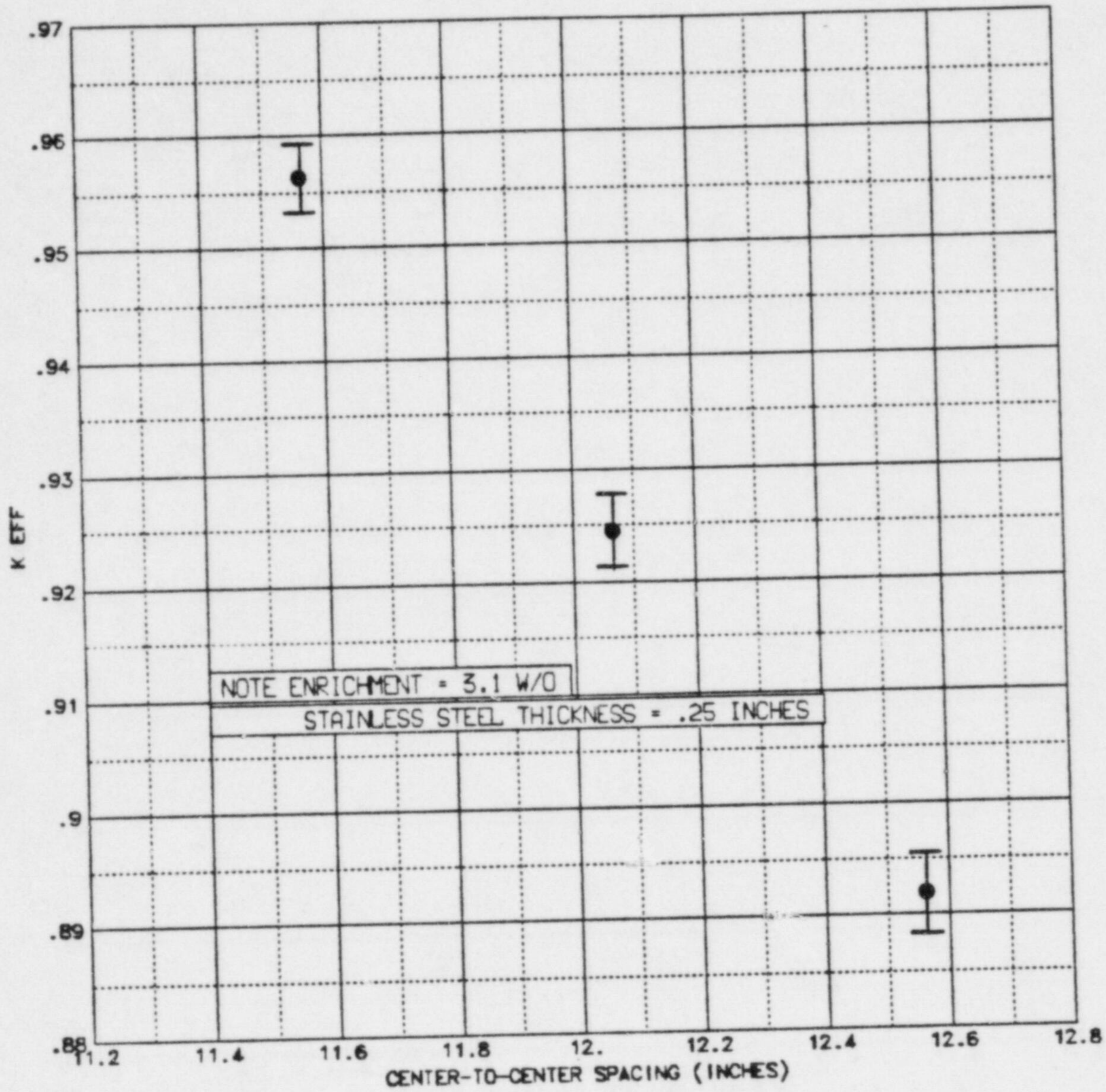


FIGURE 14

SENSITIVITY OF K-EFF TO CENTER-TO-CENTER SPACING IN THE BEAVER VALLEY REGION 2 SPENT FUEL STORAGE RACKS

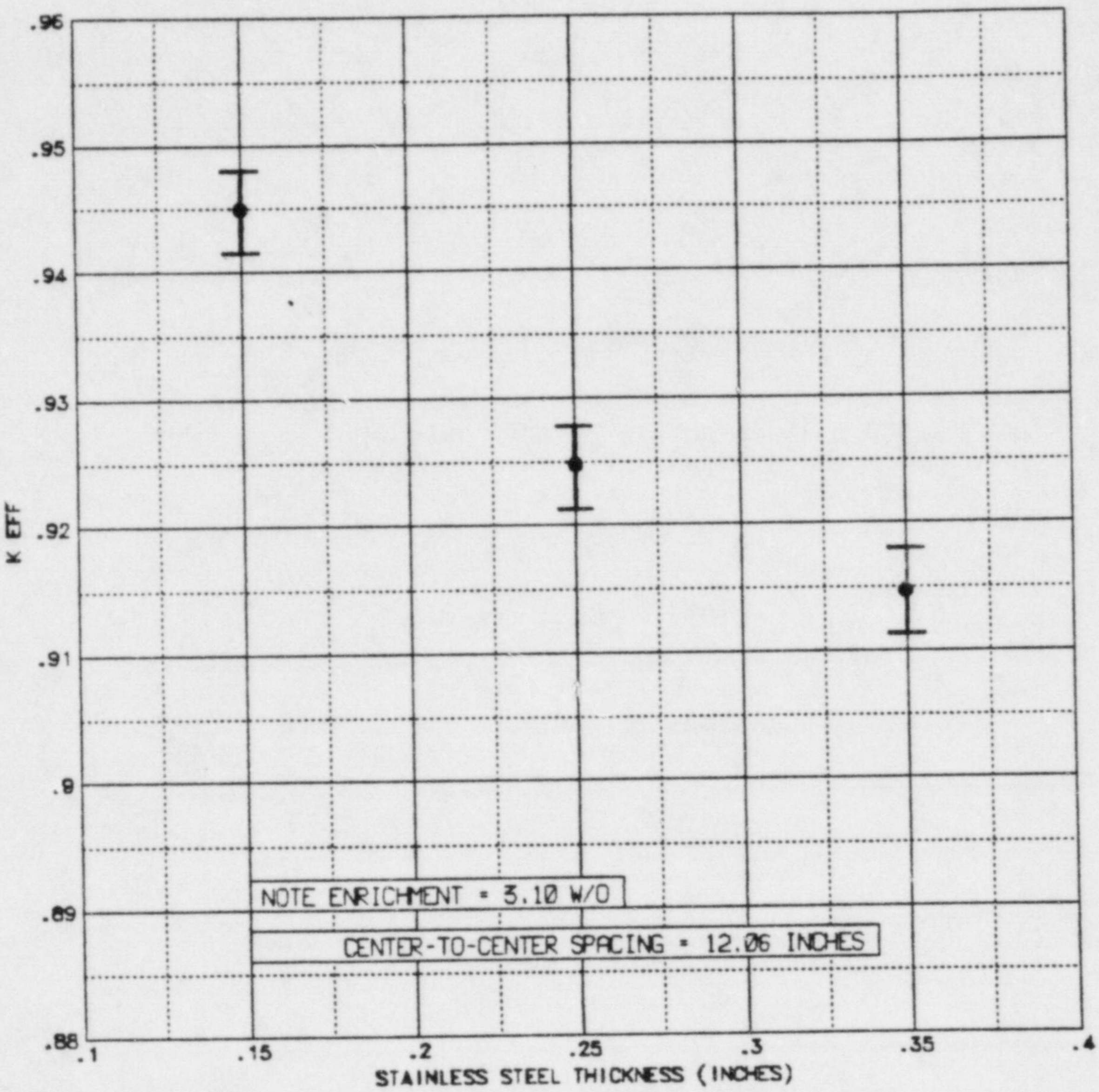


FIGURE 15

SENSITIVITY OF K-EFF TO STEEL CAN THICKNESS IN THE BEAVER VALLEY REGION 2 SPENT FUEL STORAGE RACKS

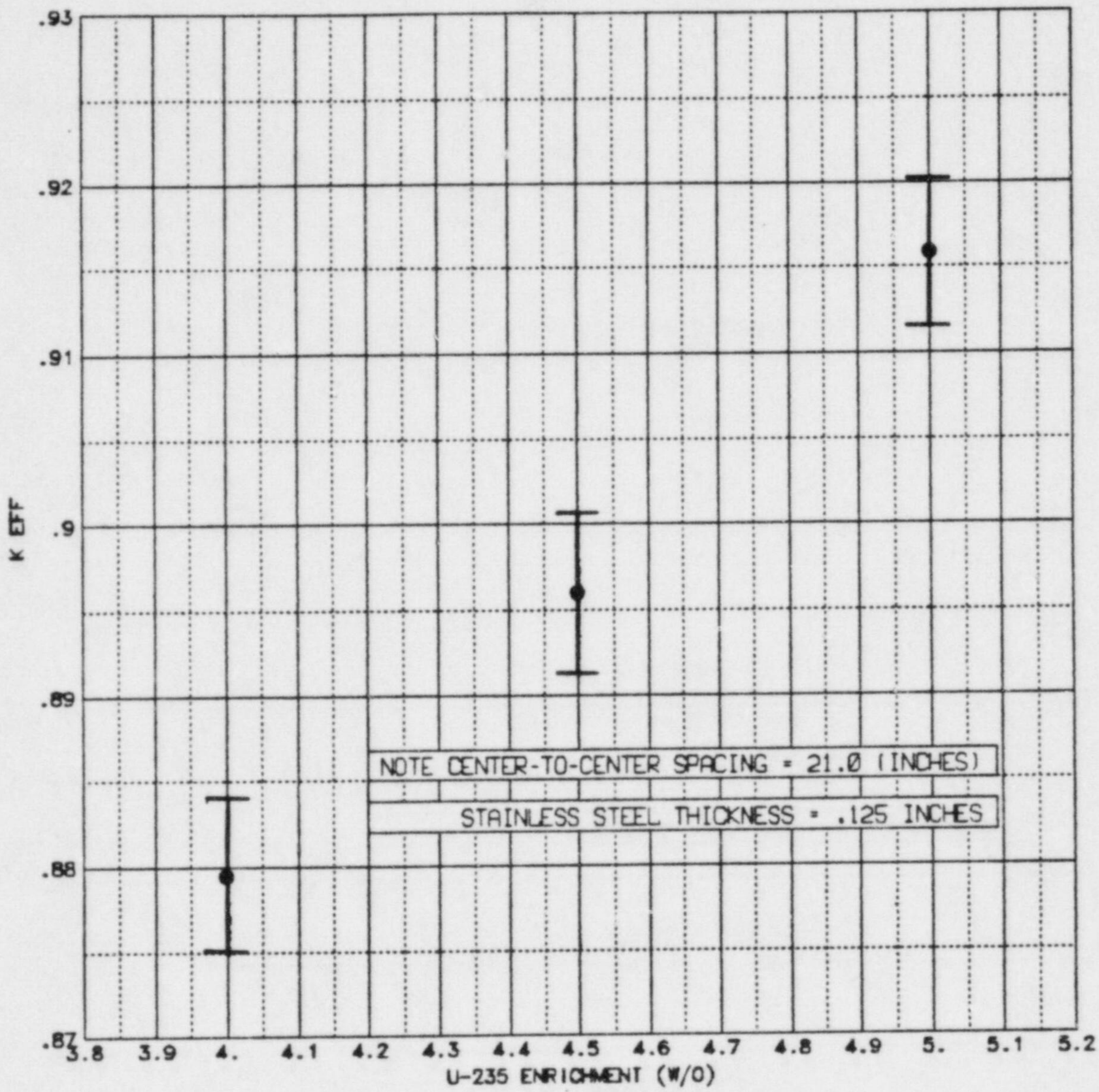


FIGURE 16

SENSITIVITY OF K-EFF TO ENRICHMENT IN THE BEAVER VALLEY FRESH FUEL STORAGE RACKS

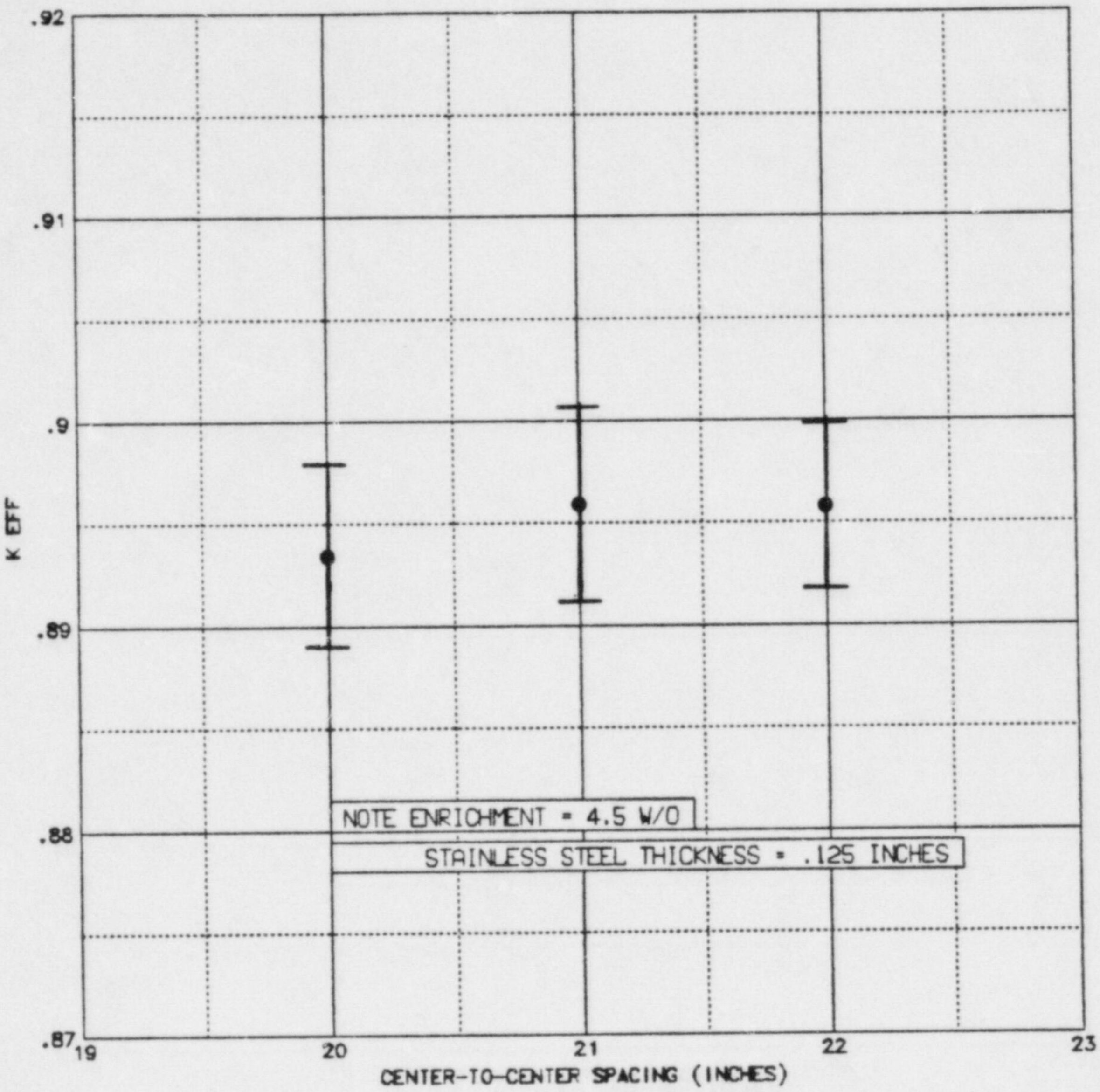


FIGURE 17

SENSITIVITY OF K-EFF TO CENTER-TO-CENTER SPACING IN THE BEAVER VALLEY FRESH FUEL STORAGE RACKS

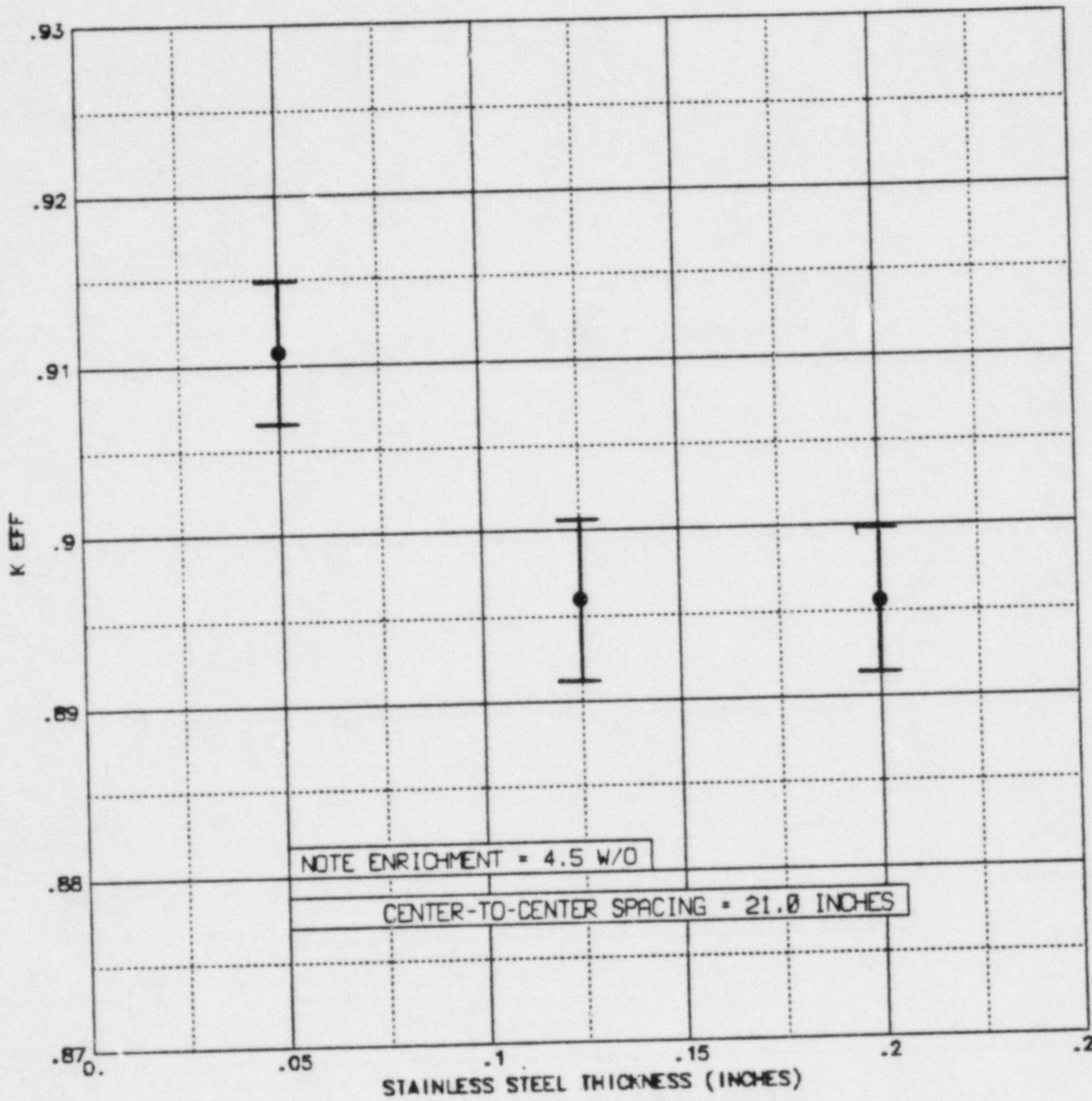


FIGURE 18

SENSITIVITY OF K-EFF TO STEEL CAN THICKNESS IN THE BEAVER VALLEY FRESH FUEL STORAGE RACKS