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# CRITICALITY ANALYSIS OF BEAVER VALLEY UNIT 2 FUEL RACKS

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# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF ILLUSTRATIONS

# 1.0 INTRODUCTION

The Beaver Valley Unit 2 spent fuel rack (SFR) design described herein employs an array of racks, which will be considered as two separate spent fuel racks. Each of these fuel racks or arrays consists of existing Beaver Valley Unit 2 fuel racks. This analysis will reanalyze these fuel arrays. The smallest array referred to as Region 1 will be reanalyzed for criticality to show that 4.85 w/o fuel can be stored in the rack in three out of four storage locations. The largest 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 up to an enrichment of 4.85 w/o. The Regions 1 and 2 spent fuel rack design is a poisoned rack, previously analyzed for storage of 17x17 STD fuel assemblies with enrichments up to 3.6 w/o $U^{235}$ utilizing every storage location.

The Region 2 spent fuel rack reanalysis is based on maintaining $K_{eff} \leq 0.95$ for storage of Westinghouse 17x17 STD fuel at 4.85 w/o $U^{235}$ with an initial enrichment/burnup combination in the acceptable area of Figure 1 with utilization of every cell permitted for storage of the fuel assemblies.

## 1.1 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 spent fuel rack layout is shown in Figure 3. The fresh fuel rack storage cell design is depicted schematically in Figure 4 and the fresh fuel rack layout is shown in Figure 5.

## 1.2 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.

# 2.0 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[2, 3] system of codes for cross-section generation and KENO IV[4] for reactivity determination.

The 227 energy group cross-section library that is the common starting point for all cross-sections used for the benchmarks and the storage rack is generated from ENDF/B-V[2] data. The NITAWL[3] program 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[3] program which is a one-dimensional $S_n$ transport theory code. These multigroup cross-section sets are then used as input to KENO IV[4] 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 (B4C, steel, water, etc) that simulate LWR fuel shipping and storage conditions[5] to dry, harder spectrum uranium metal cylinder arrays with various interspersed materials[4] (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 $\Delta k$. 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 $\Delta k$.

# 3.0 CRITICALITY ANALYSIS OF REGION 1 SPENT FUEL RACKS

## 3.1 REACTIVITY CALCULATIONS

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

1. The W 17x17 STD 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 (See Table 2 for fuel parameters).

2. All fuel rods contain uranium dioxide at an enrichment of 4.85 w/o $U^{235}$ over the infinite length of each rod.

3. 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.

4. 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.

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

6. Fuel assemblies are loaded into three of every four cells in a checkerboard pattern in the storage cells as shown in Figure 6.

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

8. The minimum poison material loading of 0.017 grams B-10 per square centimeter is used throughout the array.

The KENO calculation for the nominal case resulted in a $K_{eff}$ of 0.9139 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0056.

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 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 racks this resulted in a reduction of the nominal 1.106" water gaps to their minimum values. Thus, the "worst case" KENO model of the Region 1 storage racks contains minimum water gaps of 1.007" 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 Unit 2 Region 1 spent fuel storage racks with three out of four storage:

$$K_{eff} = K_{worst} + B_{method} + B_{part} + \sqrt{[\ (ks)^2_{worst} + (ks)^2_{method}\ ]}$$

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

$B_{part}$ = bias to account for posion partical self-shielding

$kS_{worst}$ = 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:

$$K_{eff} = 0.9267 + 0.0083 + 0.0018 + \sqrt{[(0.0046)^2 + (0.0018)^2\ ]} = 0.9417$$

Since $K_{eff}$ is less than 0.95 including uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met with fuel enriched to 4.85 w/o.

## 3.2 POSTULATED ACCIDENTS

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 twelve 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., 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 $\Delta K$. 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.

## 3.3 SENSITIVITY ANALYSIS

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. Center-to-center spacing of storage cells.
3. Poison loading.

Results of the sensitivity analysis for the Region 3 storage cells are shown in Figures 7 through 9 for three of four storage.

# 4.0 CRITICALITY ANALYSIS OF REGION 2 SPENT FUEL RACK

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 2 spent fuel pool.

## 4.1 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 Unit 2 Region 2 racks. Note in Figure 1 the endpoint at 0 MWD/MTU where the enrichment is 3.6 w/o and at 8,200 MWD/MTU where the enrichment is 4.85 w/o. The interpretation of the endpoint data is as follows: the reactivity of the Region 2 racks containing fuel at 8,200 MWD/MTU burnup which had an initial enrichment of 4.85 w/o is equivalent to the reactivity of the Region 2 racks containing fresh fuel having an initial enrichment of 3.6 w/o. It is important to recognize that the curve in Figure 1 is based on a constant rack reactivity for that region 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.

## 4.2 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 associated with the burnup-dependent reactivities computed with PHOENIX is accounted for in the development of the Region 2 burnup requirements. A bias of 0.003 $\Delta k$ at 8,200 MWD/MTU is considered to be very conservative since comparison between PHOENIX results and the Yankee Core experiments and 81 benchmark experiments indicates closer agreement.

## 4.3 REACTIVITY CALCULATIO

The nominal and maximum $K_{eff}$ for storage of spent fuel in Region 2 is determined using the methods described in Section 2 for Region 1 in addition to the methods described in Section 4.2. 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 calculate the storage rack multiplication factor with an equivalent fresh fuel enrichment of 3.6 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:

1. The Westinghouse 17x17 STD fuel assembly was analyzed for Region 2.
2. The Westinghouse 17x17 STD spent fuel assembly contains uranium dioxide fuel at an equivalent "fresh fuel" enrichment of 3.6 w/o $U^{235}$.
3. 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.
4. No credit is taken for any spacer grids or spacer sleeves.
5. The array is infinite in lateral and axial extent which precludes any neutron leakage from the array.
6. The minimum poison material loading of 0.017 grams B-10 per square centimeter is used throughout the array.

The KENO calculation for the nominal case resulted in a $K_{eff}$ of 0.9246 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0046.

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 3). For the Region 2 racks, the water gaps are reduced from the nominal value of 1.106" to their minimum value. Thus, the "worst case" KENO model of the Region 2 storage racks contains minimum water gaps of 1.007" with symmetrically placed fuel assemblies. The uncertainty associated with the reactivity equivalence methodology was included in the development of the burnup requirements. This uncertainty was discussed in Section 4.2.

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 Unit 2 Region 2 spent fuel storage racks:

$$K_{eff} = K_{worst} + B_{method} + B_{part} + \sqrt{[(ks)^2_{worst} + (ks)^2_{method}]}$$

where:

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

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

$B_{part}$ = bias to account for poison partical self-shielding

$kS_{worst}$ = 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:

$$K_{eff} = 0.9336 + 0.0083 + 0.0018 + \sqrt{[(0.0046)^2 + (0.0018)^2]} = 0.9486$$

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 3.6 w/o $U^{235}$.

## 4.4 POSTULATED ACCIDENTS

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 twelve 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.

## 4.5 SENSITIVITY ANALYSIS

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 PHOENIX computer code.

Figures 10 through 12 illustrate the results of the sensitivity studies for spent fuel occupying every cell in the Region 2 fuel racks.

# 5.0 CRITICALITY ANALYSIS OF 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 2 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 soluble boron. The criticality method and cross-section library are the same as those discussed in Section 2 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:

1. 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.

2. All fuel rods contain uranium dioxide at an enrichment of 4.85 w/o $U^{235}$ over the infinite length of each rod.

3. 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.

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

The .. 17x17 STD fuel assembly was analyzed. (See Table 2 for fuel parameters)

## 5.1 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/cm³ 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 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 assembly center-to-center spacing and the total volume of steel 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 assembly center-to-center spacing is reduced from a nominal value of 21" to a minimum of 20.9375". 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 Unit 2 fresh fuel storage racks:

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

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:

$$K_{eff} = 0.9099 + 0.0083 + \sqrt{[(0.0080)^2 + (0.0018)^2]} = 0.9264$$

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

## 5.2 LOW DENSITY OPTIMUM MODERATION ANALYSIS

In the low density optimum moderation analysis, the fuel array is finite in the radial and axial extent.

Analysis of the Beaver Valley Unit 2 racks has shown that the maximum rack $K_{eff}$ under low density moderation conditions occurs at 0.076 gm/cm$^3$ water density. The KENO calculation of the Beaver Valley Unit 2 fresh racks at 0.076 gm/cm$^3$ water density resulted in a peak $K_{eff}$ of 0.9233 with a 95 percent probability and 95 percent confidence level uncertainty of ±0.0080. Figure 13 shows the fresh fuel rack reactivity as a function of the water density.

The minimum 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 11.72" and a rack module separation distance of 20.9375 inches.

Based on the analysis described above, the following equation is used to develop the maximum $K_{eff}$ for the Beaver Valley Unit 2 fresh fuel storage racks under low density optimum moderation conditions:

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

where:

$K_{base}$ = base case KENO $K_{eff}$ that includes nominal mechanical and material dimension

$B_{method}$ = 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:

$$K_{eff} = 0.9233 + 0.0083 + \sqrt{[(0.0080)^2 + (0.0018)^2]} = 0.9398$$

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

## 6.0 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."

## Table 1. Benchmark Critical Experiments [5,6]

| | General Description | Enrichment w/o U235 | Reflector | Separating Material | Soluble Boron 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 STANDARD |
|---|---|
| Number of Fuel Rods per Assembly | 264 |
| Rod Zirc-4 Clad O.D. (inch) | 0.374 |
| Clad Thickness (inch) | 0.0225 |
| Fuel Pellet O.D. (inch) | 0.3225 |
| Fuel Pellet Density (% of Theoretical) | 96 |
| Fuel Pellet Dishing Factor | 0.0 |
| Rod Pitch (inch) | 0.496 |
| Number of Zirc-4 Guide Tubes | 24 |
| Guide Tube O.D. (inch) | 0.482 |
| Guide Tube Thickness (inch) | 0.016 |
| Number of Instrument Tubes | 1 |
| Instrument Tube O.D. (inch) | 0.482 |
| Instrument Tube Thickness (inch) | 0.016 |

Table 3. Beaver Valley Unit 2 Fuel Assembly Minimum Burnup vs Initial $U^{235}$ Enrichment for Region 2 Spent Fuel Rack

| Initial $U^{235}$ Enrichment | Assembly Discharge Burnup (GWD/MTU) |
|---|---|
| Region 2 | |
| 3.6 | 0 |
| 4.0 | 2.6 |
| 4.4 | 5.3 |
| 4.85 | 8.2 |

Table 4. Comparison of PHOENIX Isotopics Predictions 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 |

Table 5. Benchmark Critical Experiments PHOENIX Comparison

| Description of Experiments | Number of Experiments | PHOENIX $K_{eff}$ Using Experiment Bucklings |
|---|---|---|
| $UO_2$ | | |
| Al clad | 14 | 0.9947 |
| SS clad | 19 | 0.9944 |
| Borated $H_2O$ | 7 | 0.9940 |
| Subtotal | 40 | 0.9944 |
| U-Metal | | |
| Al clad | 41 | 1.0012 |
| TOTAL | 81 | 0.9978 |

**Table 6. Data for U Metal and $UO_2$ Critical Experiments** (Part 1 of 2)

| 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) | Boron 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. Data for U Metal and $UO_2$ Critical Experiments (Part 2 of 2)

| Case Number | Cell Type | A/O U-235 | H20/U Ratio | Fuel Density (G/CC) | Pellet Diameter (CM) | Material Clad | Clad OD (CM) | Clad Thickness (CM) | Lattice Pitch (CM) | Boron 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 |

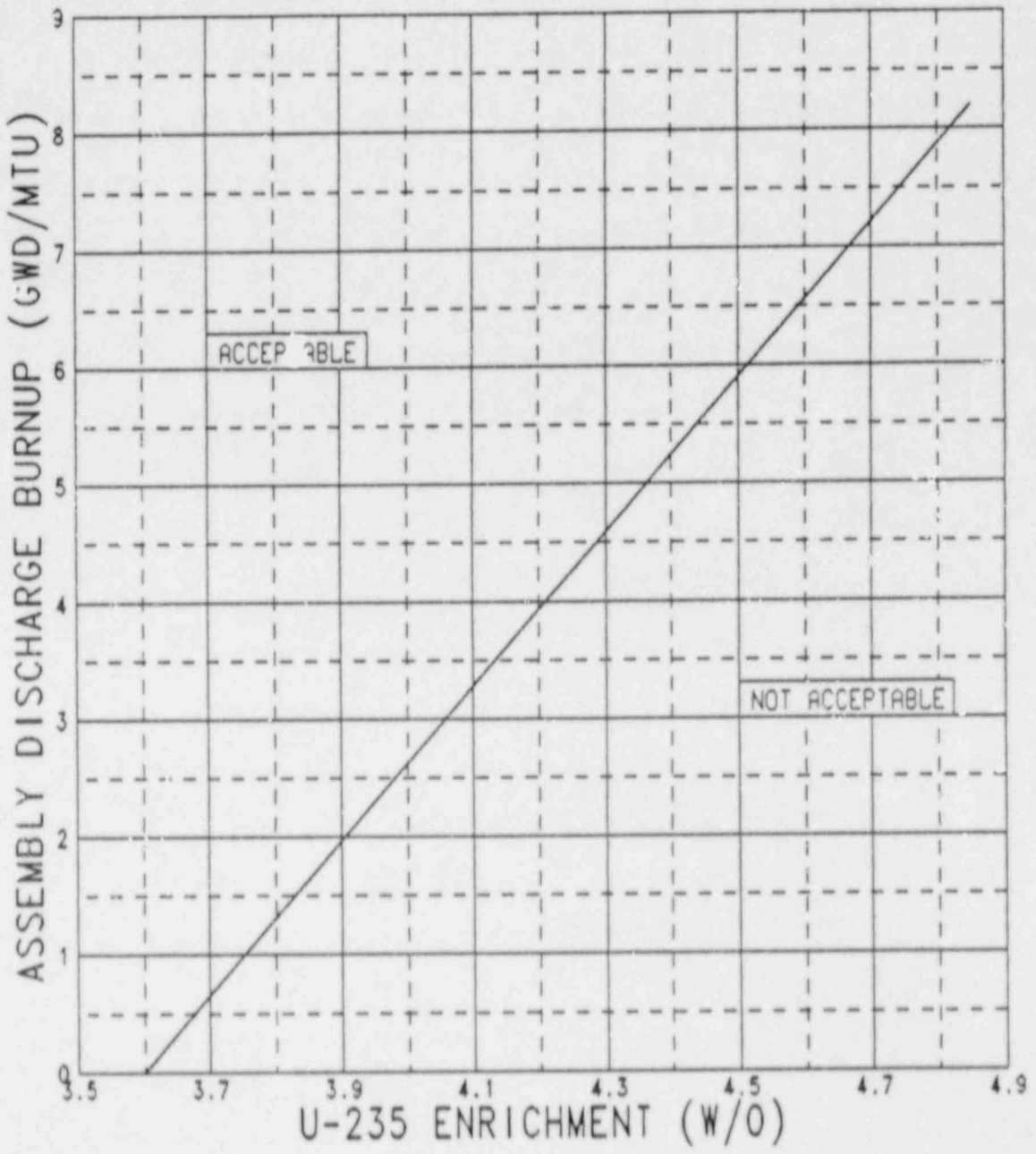


**Figure 1. Beaver Valley Unit 2 Fuel Assembly Minimum Burnup vs. Initial $U^{235}$ Enrichment for Storage in Region 2 Spent Fuel Racks**

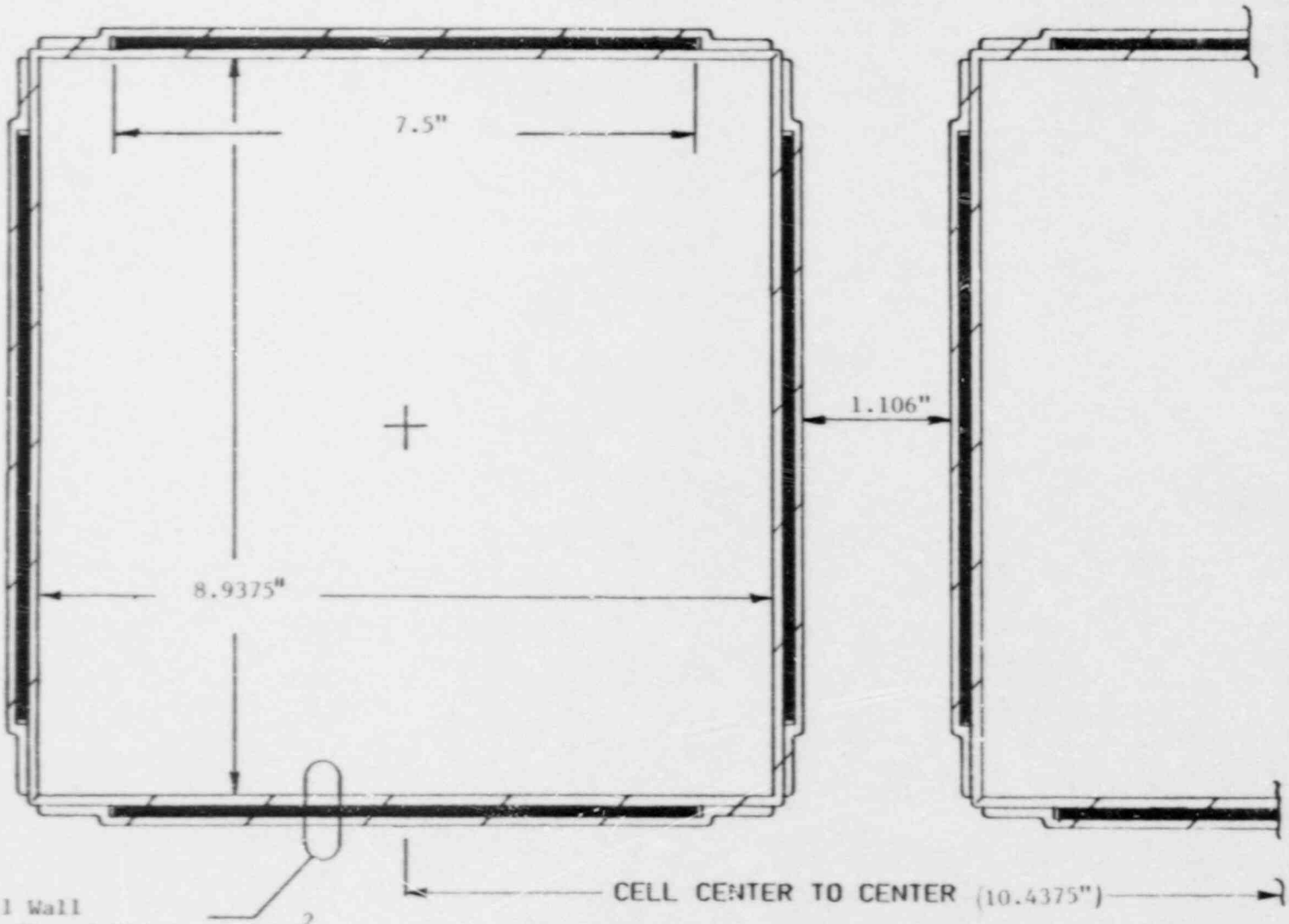


Figure 2. Beaver Valley Unit 2 Spent Fuel Storage Cell Nominal Dimensions

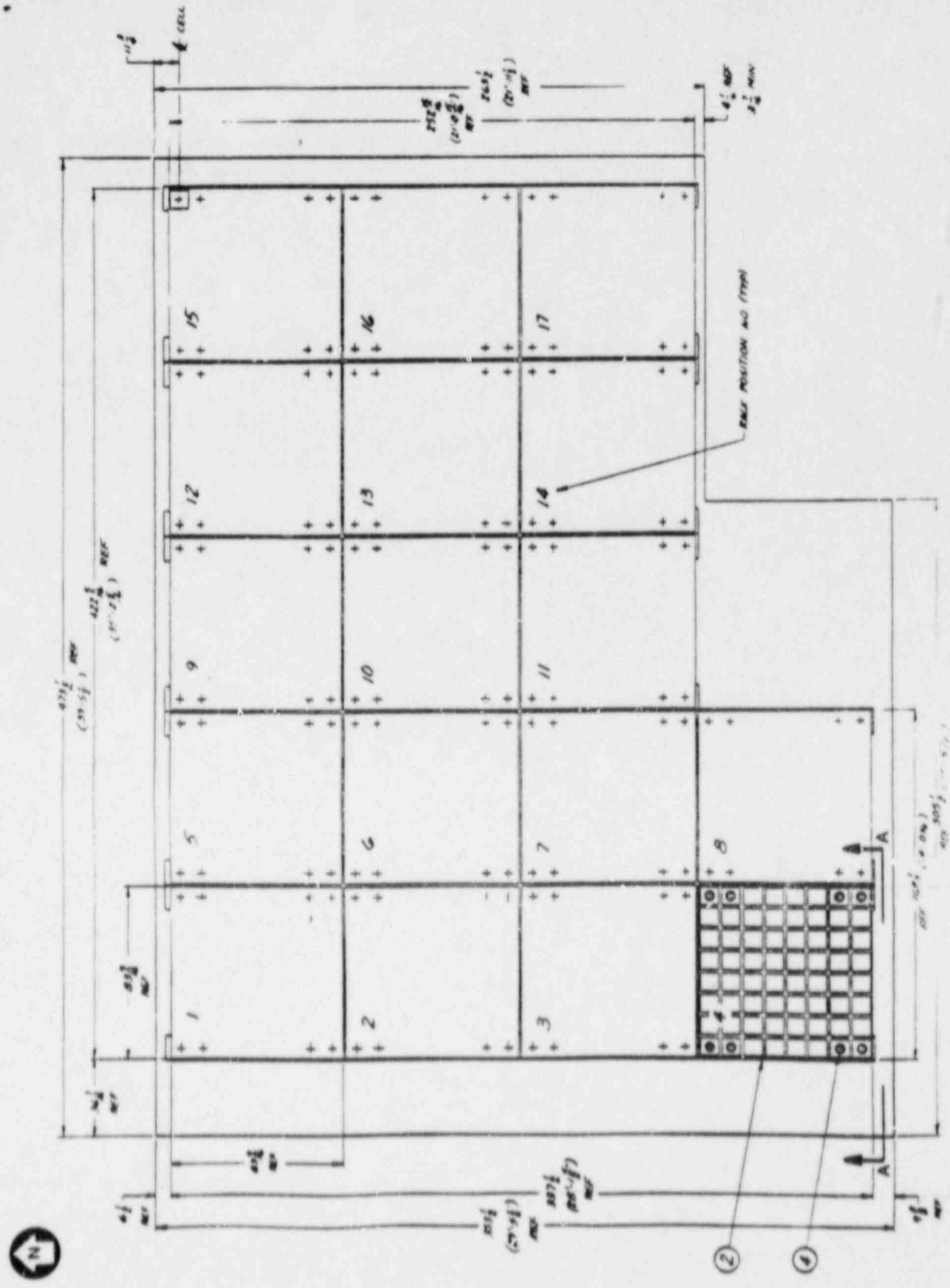


Figure 3. Beaver Valley Unit 2 Spent Fuel Rack Layout

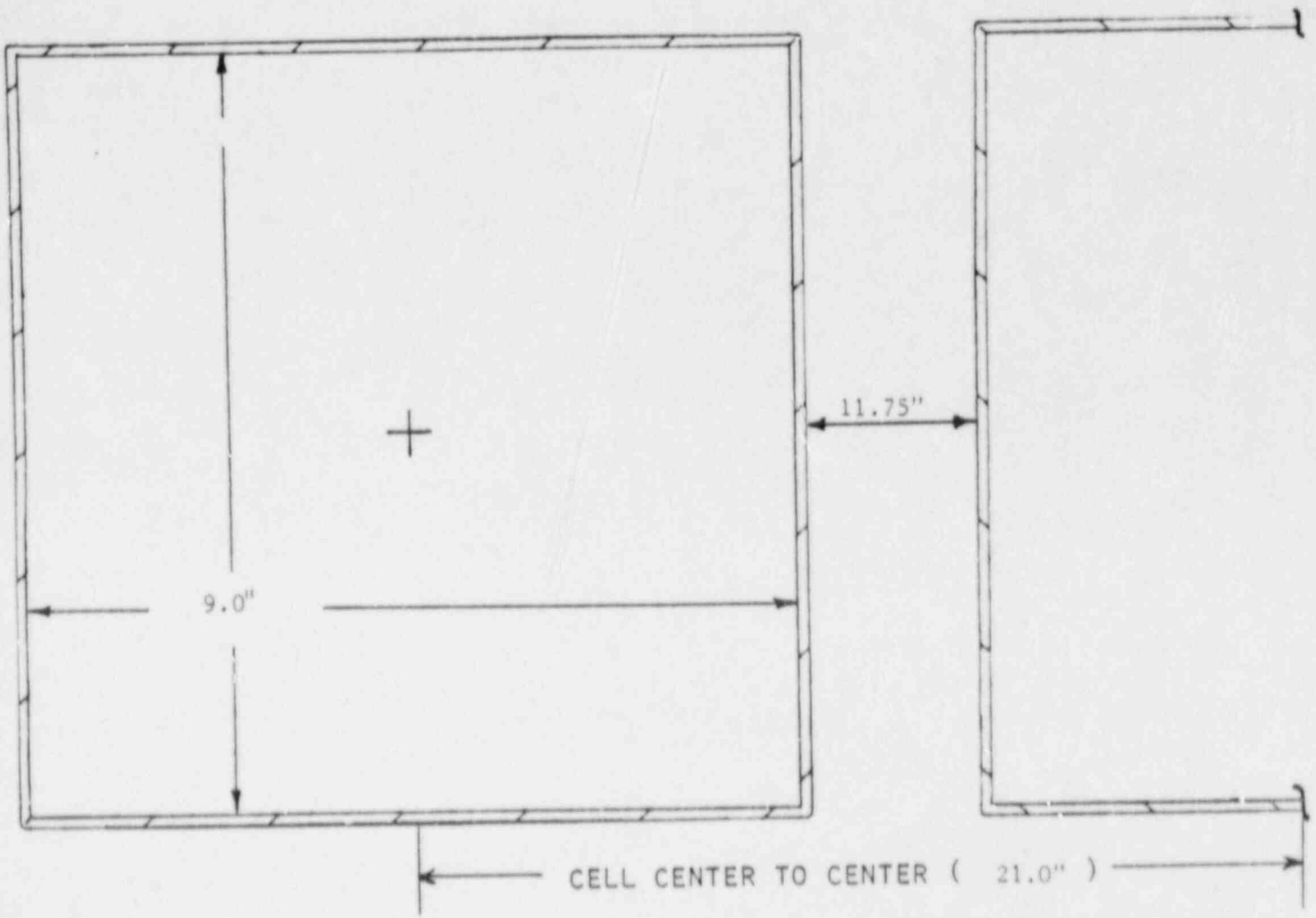


**Figure 4. Beaver Valley Unit 2 Fresh Fuel Storage Cell Nominal Dimensions**

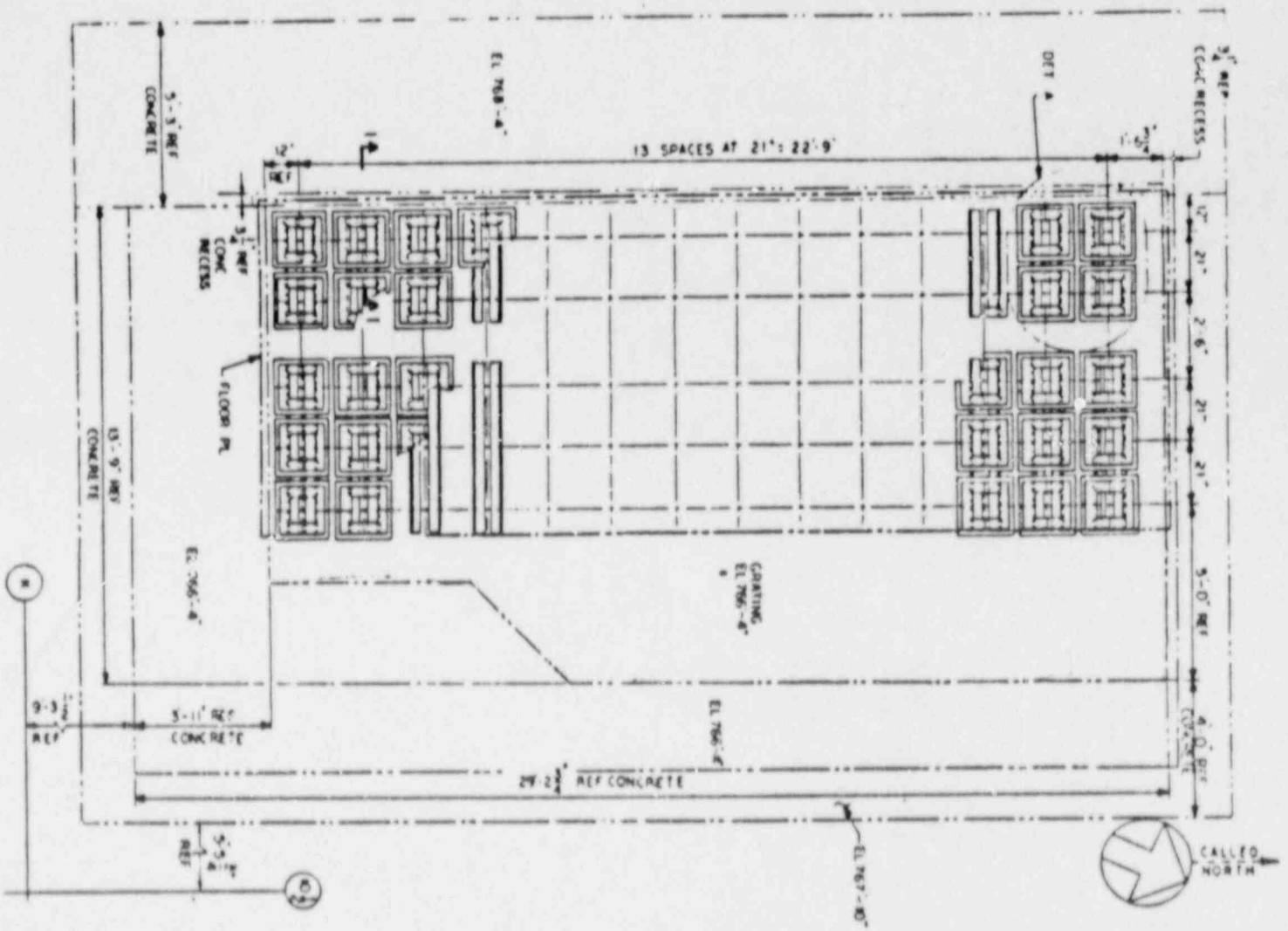


Figure 5. Beaver Valley Unit 2 Fresh Fuel Rack Layout

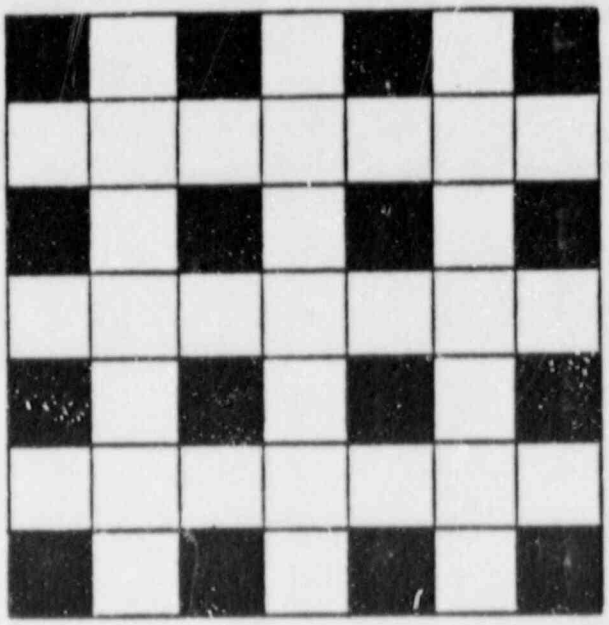

Figure 6. Beaver Valley Unit 2 Region 1 Three of Four Fuel Assembly Loading Schematic

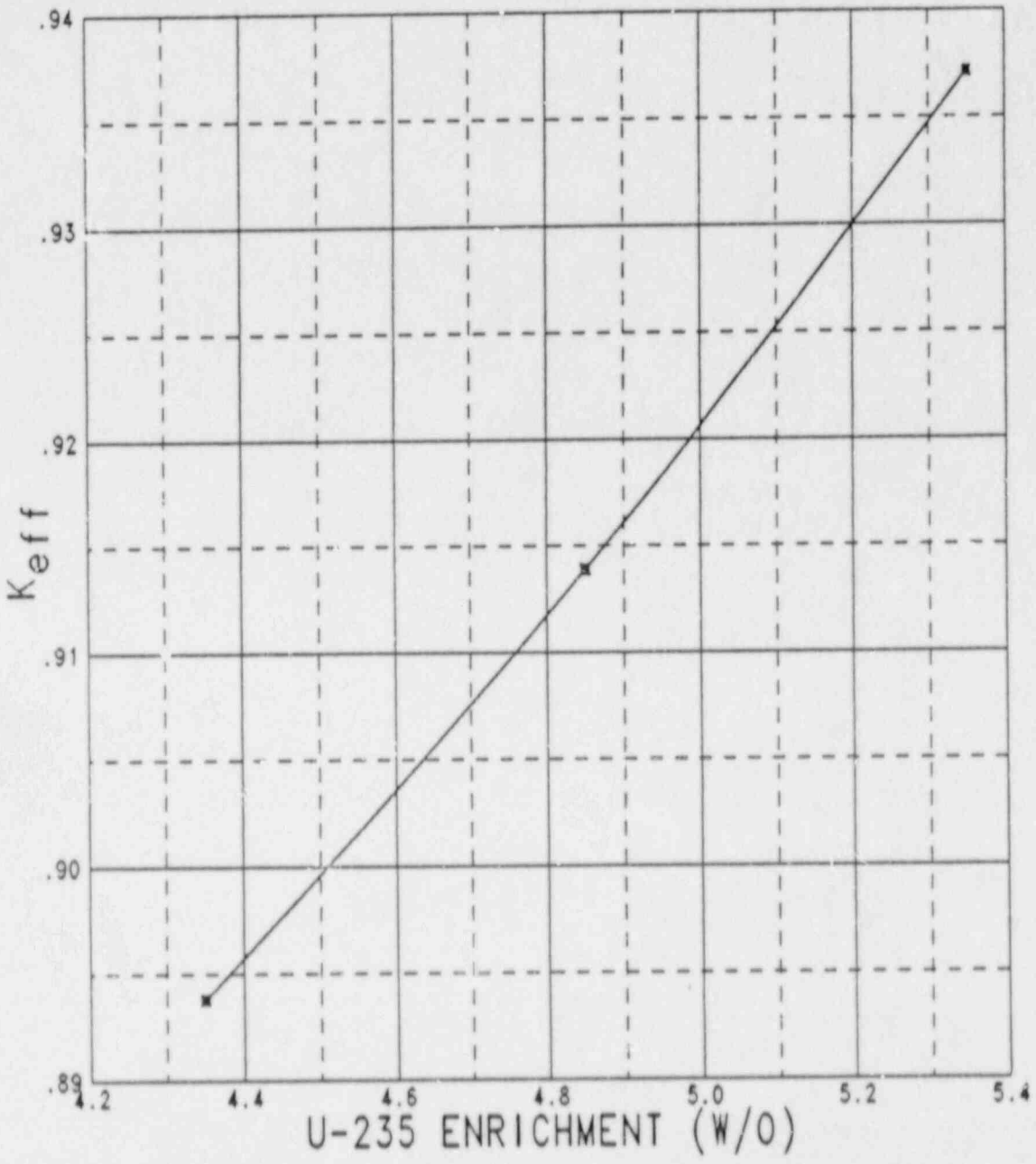


**Figure 7. Sensitivity of $K_{eff}$ to Enrichment in the Beaver Valley Unit 2 Region 1 Spent Fuel Storage Rack with Three of Four Storage**

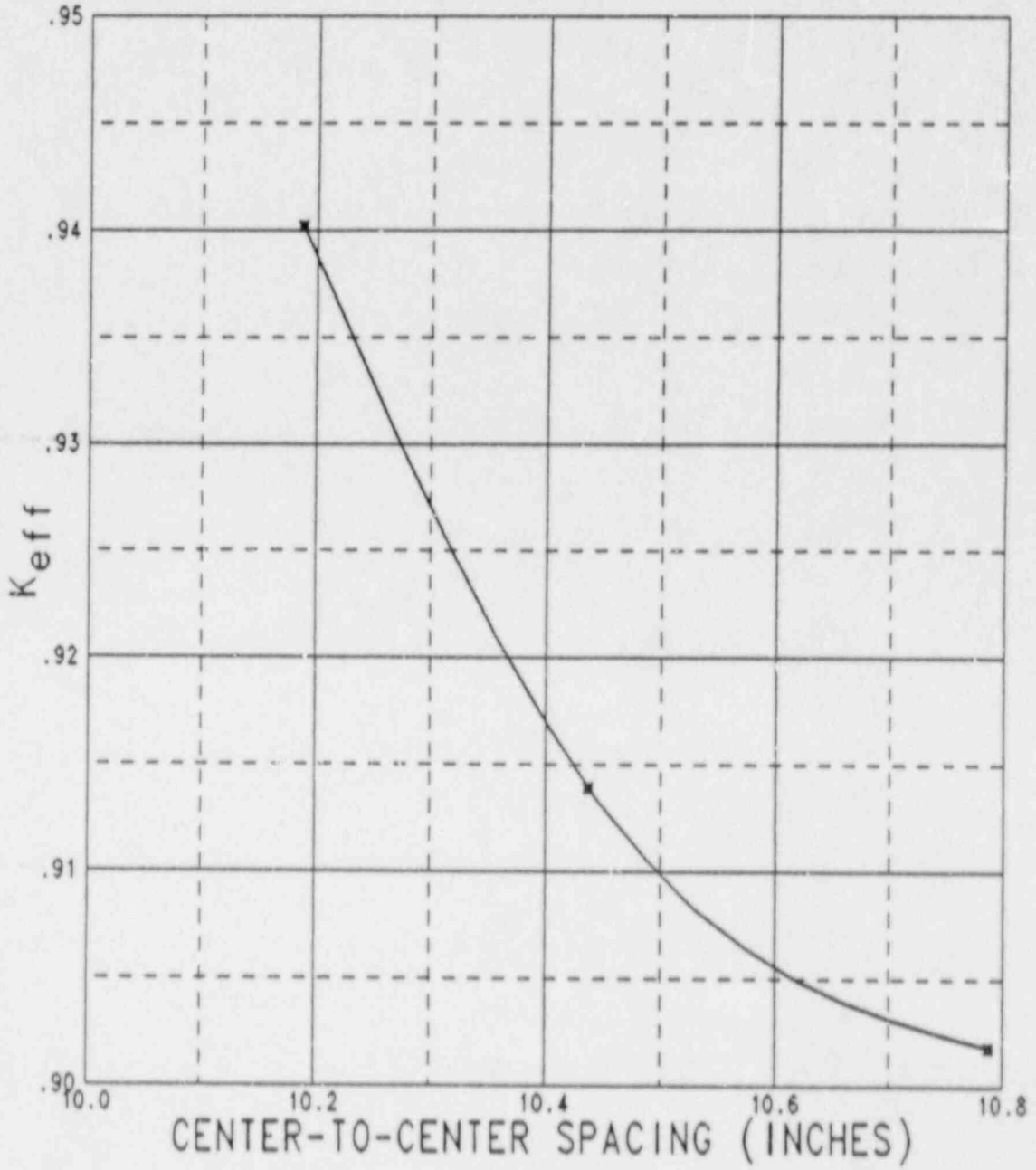


**Figure 8. Sensitivity of $K_{eff}$ to Center-to-Center Spacing in the Beaver Valley Unit 2 Region 1 Spent Fuel Storage Rack with Three of Four Storage**

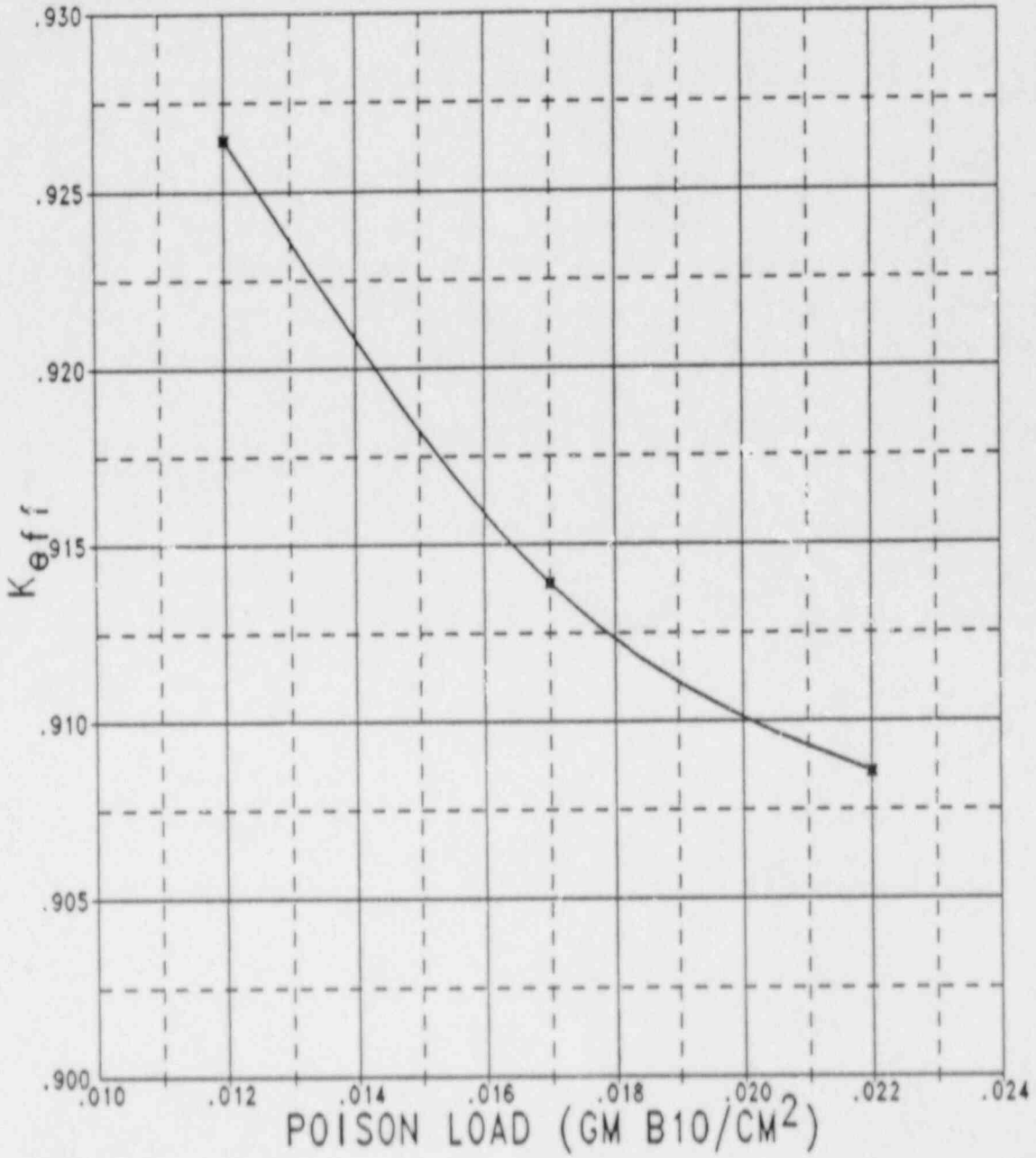


**Figure 9. Sensitivity of $K_{eff}$ to $B^{10}$ Loading in the Beaver Valley Unit 2 Region 1 Spent Fuel Storage Rack with Three of Four Storage**

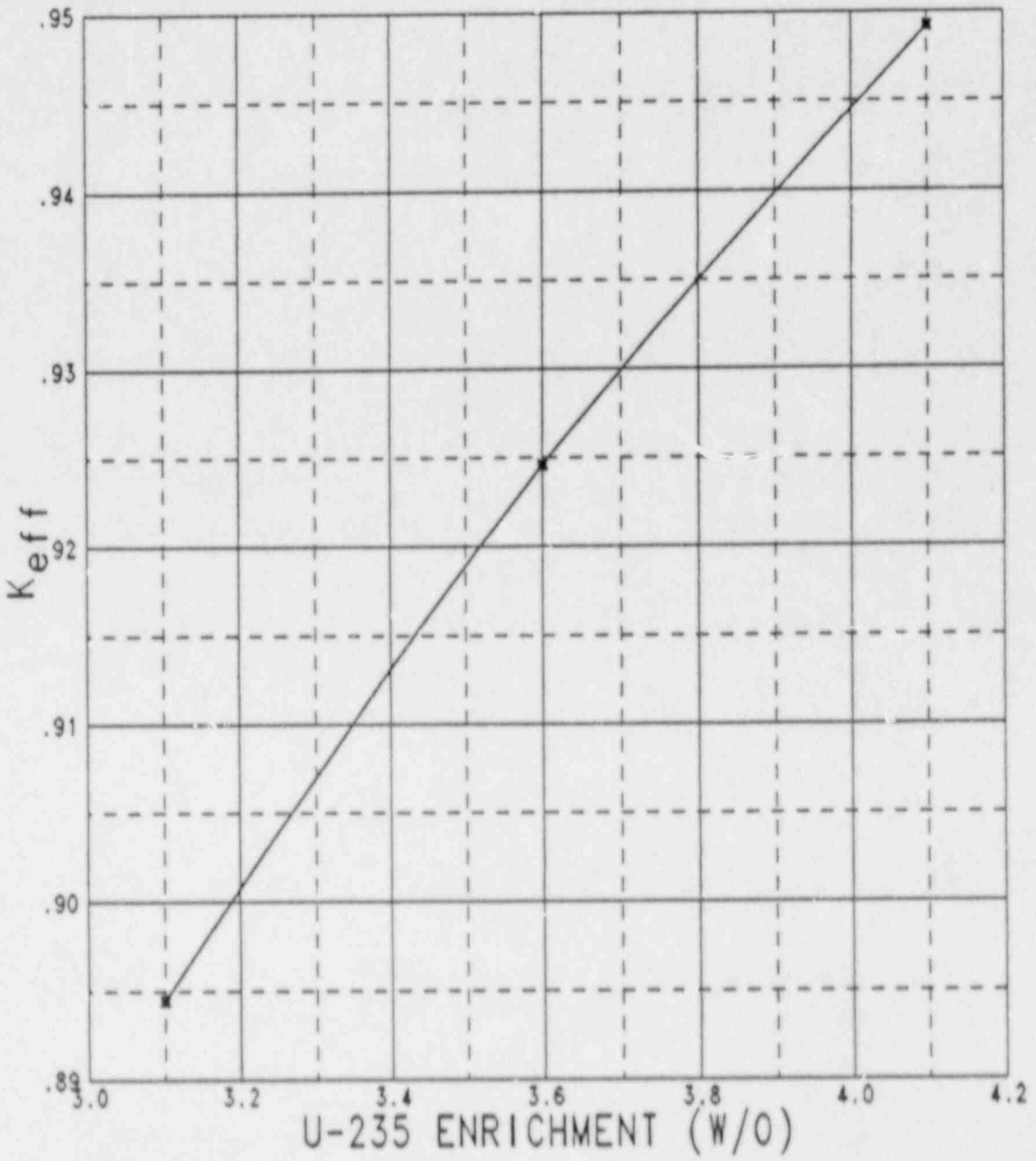


**Figure 10. Sensitivity of $K_{eff}$ to Enrichment in the Beaver Valley Unit 2 Region 2 Spent Fuel Storage Rack**

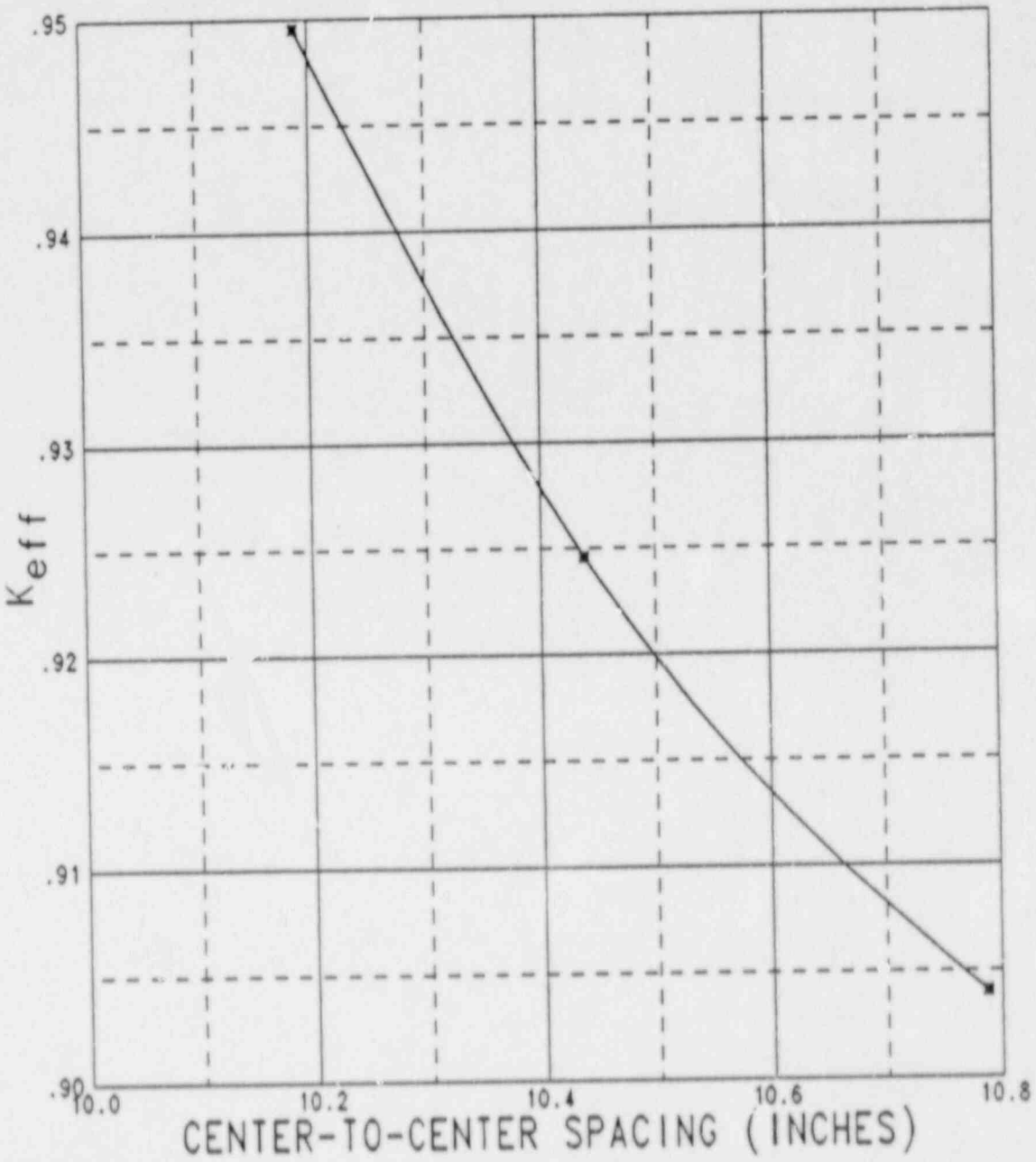


**Figure 11. Sensitivity of $K_{eff}$ to Center-to-Center Spacing in the Beaver Valley Unit 2 Region 2 Spent Fuel Storage Rack**

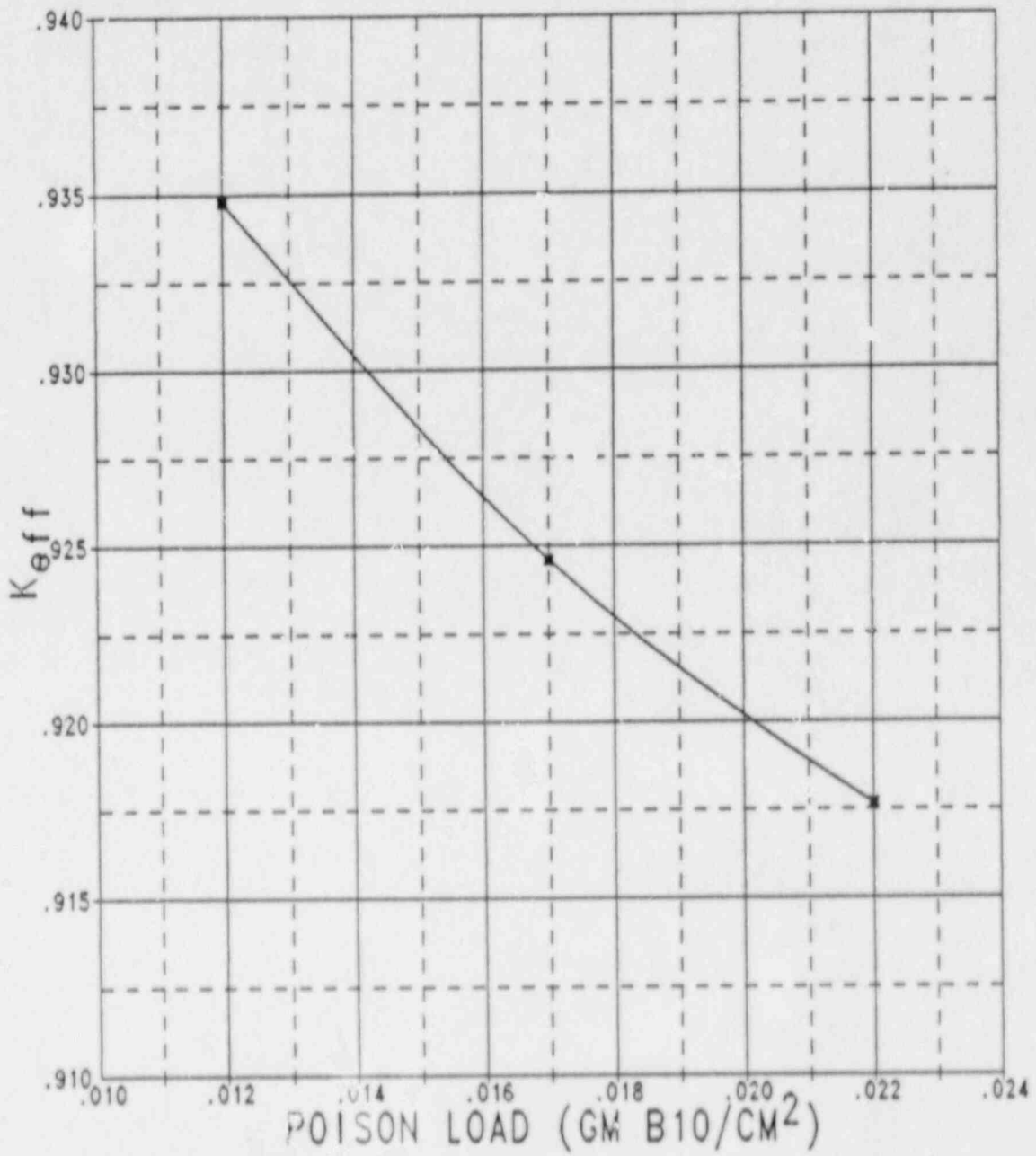


**Figure 12. Sensitivity of $K_{eff}$ to $B^{10}$ Loading in the Beaver Valley Unit 2 Region 2 Spent Fuel Storage Rack**

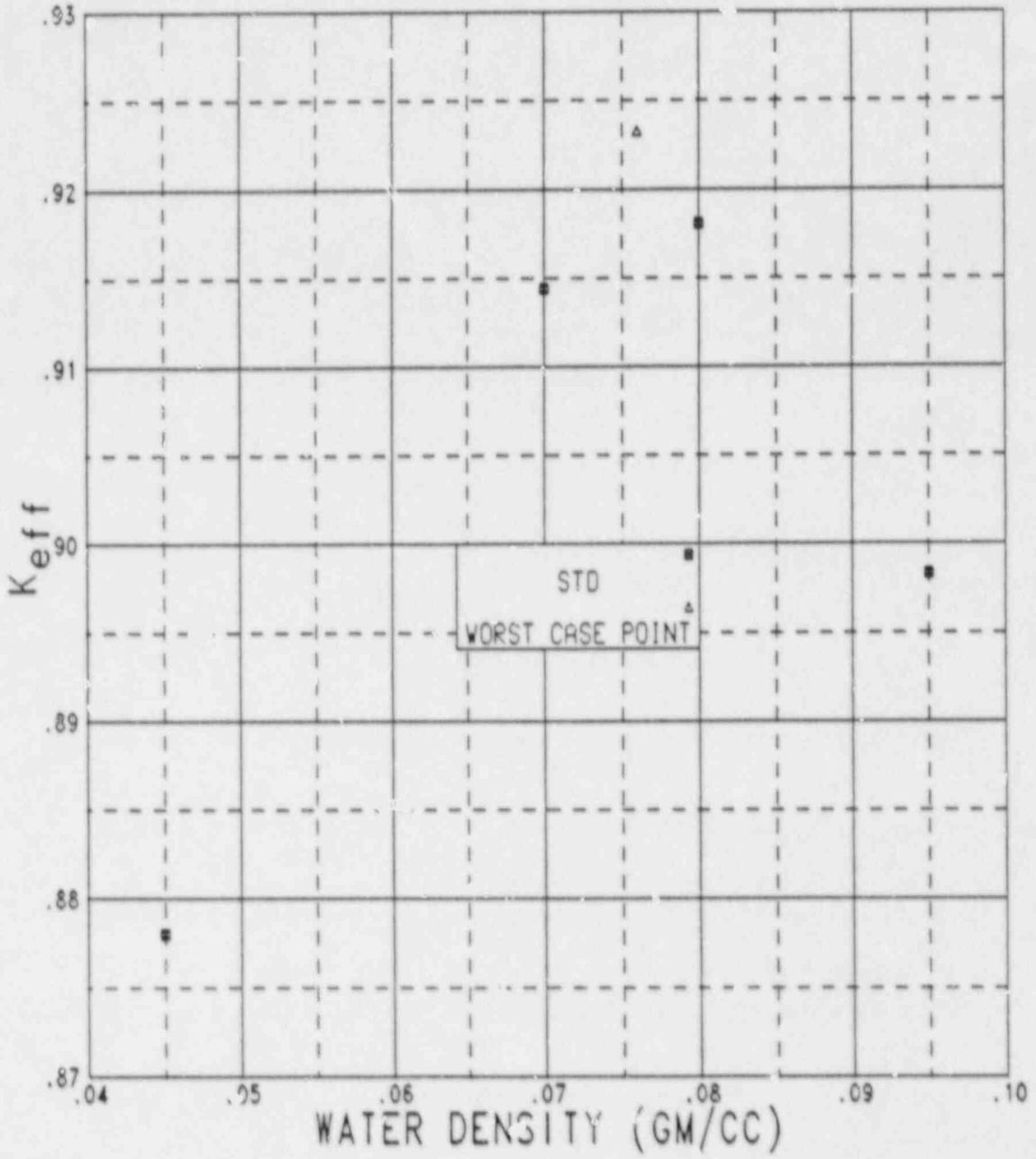


**Figure 13. Sensitivity of $K_{eff}$ to Water Density in the Beaver Valley Unit 2 Fresh Fuel Storage Racks**

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