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41. NUCLEAR CRITICALITY ASSESSMENT OF LEU AND HEU FUEL ELEMENT STORAGE*

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ABSTRACT

Criticality aspects of storing LEU (20%) and HEU (93%) fuel elements have been evaluated as a function of ^{235}U loading, element geometry, and fuel type. Silicide, oxide, and aluminide fuel types have been evaluated ranging in ^{235}U loading from 180 to 620 g per element and from 16 to 23 plates per element. Storage geometry considerations have been evaluated for fuel element separations ranging from closely packed formations to spacings of several centimeters between elements. Data are presented in a form in which interpolations may be made to estimate the eigenvalue of any fuel element storage configuration that is within the range of the data.

INTRODUCTION

Criticality aspects of storing fuel elements is of concern to all reactor operators. Any change to the types of fuel elements approved for storage may require that the subcriticality of a storage rack be reconfirmed. As an insight into what might be expected, this report presents results of a study assessing the storage of HEU and LEU fuel elements with various fissile contents.

SCOPE

Fuel Element Storage Model

In assessing fuel element storage, the type of fuel element and the storage configuration must be defined. For purposes of this report, twenty fuel element types were considered and a generic storage rack was used.

The storage rack is defined as an unpoisoned aluminum framework within which partitions form individual fuel element storage compartments. The entire unit is immersed in a pool so that the fuel elements are moderated and reflected with water. An infinite-by-infinite array of fuel elements is assumed and the separation between storage compartments is adjusted to control the storage rack reactivity. On this basis, reactivity effects associated with various types of fuel elements in various storage rack configurations can be made.

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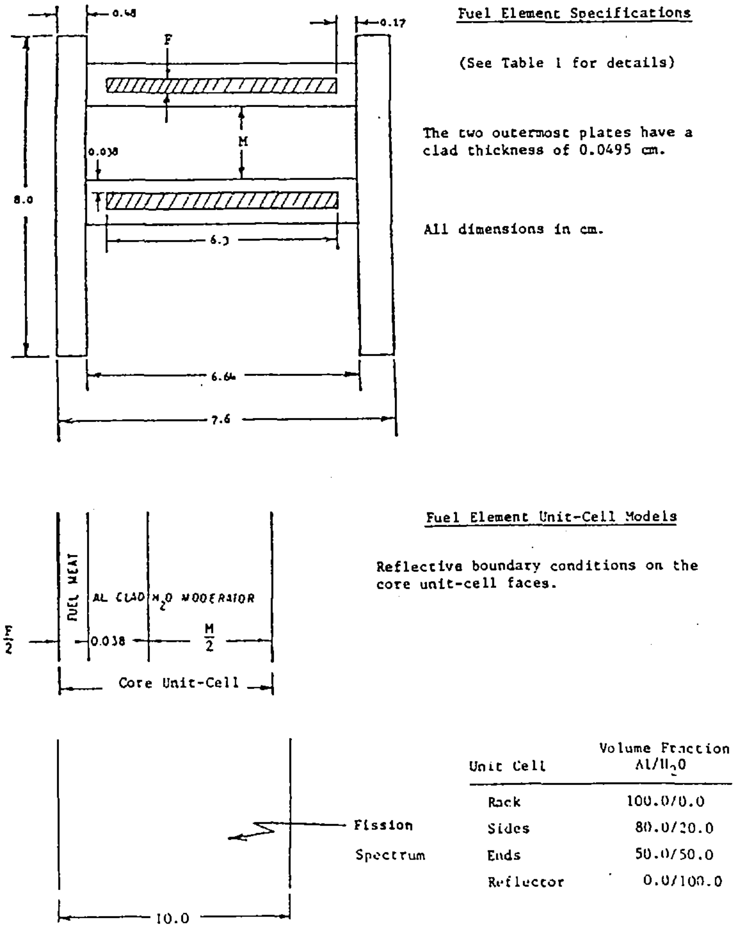
Calculation Model

Three-dimensional (XYZ) diffusion theory is used in the calculations in this report. In many of the calculations a simplified representation of the storage rack and the fuel elements are used. These simplifications included neglect of the aluminum storage compartments and the fuel element end-fittings. Sensitivity studies to assess the reactivity effects of these simplifications were,however, made and validation of the diffusion theory calculations were made using Monte Carlo techniques.

CROSS SECTIONS

Microscopic cross sections for the fuel elements and the storage rack were calculated using the EPRI-CELL code[1] with ENDF/B-IV cross section data. The integral transport calculations in EPRI-CELL are performed for 69-fast groups and 35-thermal groups (<1.855 eV), and then collapsed to 5-broad groups with upper energy boundaries of 10 MeV, 0.821 MeV, 5.53 keV, 1.855 eV, and 0.625 eV. The fuel element geometry and the unit-cell models used in the EPRI-CELL calculations are shown in Fig. 1.



Fuel Element Specifications

(See Table 1 for details)

The two outermost plates have a clad thickness of 0.0495 cm.

All dimensions in cm.

Fuel Element Unit-Cell Models

Reflective boundary conditions on the core unit-cell faces.

Unit Cell	Volume Fraction Al/H_2O
Rack	100.0/0.0
Sides	80.0/20.0
Ends	50.0/50.0
Reflector	0.0/100.0

Fig. 1. Fuel Element Specifications and Unit-Cell Models.

Broad group cross sections were generated for each fuel element type using the flux spectrum of the core portion of the fuel element. The core portion of a fuel element included the fuel, clad and water channel regions as shown in Fig. 1.

Separate microscopic cross sections for the fuel element sideplates were generated using a pure ^{235}U fission spectrum on a 80/20 volume percent mixture of aluminum and water. The sideplate portion of a fuel element included the portion of clad on the fuel plates between the fuel meat and sideplates plus the same corresponding part of water in the water channels. Macroscopic cross sections appropriate for the sideplates of each fuel element type were used in the neutronic calculations.

The same methodology as used for the sideplates was used in generating cross sections for the fuel element end-fittings, the aluminum rack and the storage rack water reflector.

FUEL ELEMENT DESCRIPTION

Thirteen LEU (20% enriched) and seven HEU (93% enriched) fuel element types are used in this study covering a wide range of fuel densities, fuel types, and fuel element geometries. The choice of fuel element types are made based upon types currently in use in plate-type research and test reactors, and types which might be expected to be available as fuel material technology develops. The fuel element geometries considered contain between 16 and 23 plates per element.

Detailed specifications of the twenty fuel element types are listed in Table 1. The range of fuel densities, fuel types, and fuel element geometries are summarized below.

Fuel Type	Plates per Element	Fuel Meat Thickness, mm	Uranium Density, g/cc	^{235}U Loading, g
LEU U_3Si-Al	19	0.51	3.1-5.3	225-390
	23	0.51	3.2-7.0	280-621
LEU U_3O_8-Al	23	0.51	3.1	278
	16-22	0.76	3.1	288-396
	20	1.00	3.1	473
HEU UAl_x-Al	19	0.51	0.5-1.2	180-405
	23	0.51	0.4-1.3	180-530

Table 1. Fuel Element Loadings.

Fuel Element Loading Number	Fuel Type	Plates/ Element	^{235}U/ Element, g	Uranium Density, g/cc	Fuel Meat (F) Thickness, mm	Water Channel (M) Thickness, mm	Sideplate Volume Fractions, % Al	Sideplate Volume Fractions, % H_2O
1	LEU U_3O_8-Al	23	278	3.130	0.51	2.188	81.11	18.89
2	LEU U_3O_8-Al	16	288	3.130	0.76	3.451	79.56	20.44
3	LEU U_3O_8-Al	18	324	3.130	0.76	2.899	80.56	19.44
4	LEU U_3O_8-Al	20	360	3.130	0.76	2.457	81.51	18.49
5	LEU U_3O_8-Al	22	396	3.130	0.76	2.095	82.43	17.57
6	LEU U_3O_8-Al	20	473	3.130	1.00	2.217	83.04	16.96
7	LEU U_3Si-Al	19	225	3.071	0.51	2.916	79.49	20.51
8	LEU U_3Si-Al	19	350	4.778	0.51	2.916	79.49	20.51
9	LEU U_3Si-Al	19	390	5.324	0.51	2.916	79.49	20.51
10	LEU U_3Si-Al	23	280	3.157	0.51	2.188	81.11	18.89
11	LEU U_3Si-Al	23	320	3.609	0.51	2.188	81.11	18.89
12	LEU U_3Si-Al	23	390	4.398	0.51	2.188	81.11	18.89
13	LEU U_3Si-Al	23	621	7.000	0.51	2.188	81.11	18.89
14	HEU UAl_x-Al	19	180	0.528	0.51	2.916	79.49	20.51
15	HEU UAl_x-Al	19	280	0.822	0.51	2.916	79.49	20.51
16	HEU UAl_x-Al	19	405	1.189	0.51	2.916	79.49	20.51
17	HEU UAl_x-Al	23	180	0.437	0.51	2.188	81.11	18.89
18	HEU UAl_x-Al	23	280	0.679	0.51	2.188	81.11	18.89
19	HEU UAl_x-Al	23	405	0.982	0.51	2.188	81.11	18.89
20	HEU UAl_x-Al	23	530	1.285	0.51	2.188	81.11	18.89

All fuel elements are assumed to be fresh in accordance with standard practice for this type of criticality assessment. The presence of any burnable poison which might be required in many of the heavier loaded fuel elements is also neglected. These assumptions about fuel element poisoning effects are made in order that all calculated reactivities for the storage rack configurations will be conservative. The fuel elements are assumed to be 68 cm long with a 60 cm active fuel height and 4 cm above and below the fuel to simulate fuel element end-fittings.

STORAGE RACK CALCULATIONS

The first part of this section examines the reactivity trends that one fuel element type will have in various storage rack configurations. In the second part, the reactivity trends that one storage configuration will have with each of the twenty fuel element types are examined.

Overall, the results of this section are intended to provide the means of estimating eigenvalues for various fuel element types in various storage rack configurations. Based upon these data, a reactor operator will have a basis upon which to estimate the reactivity effect of substituting one fuel type for another in unpoisoned storage racks.

The storage rack model used in the calculations assumed an infinite-by-infinite array of fuel elements in which there are an infinite number of fuel elements in a row and an infinite number of rows. The spacing between fuel elements in a row and the separation between rows are specified to define the storage rack configuration. The calculational models used in this study are shown in Attachment 1.

Eigenvalues for a Given Fuel Element Type in Various Storage Rack Configurations

Table 2. Eigenvalue Calculations for an Infinite-by-Infinite Array of Number 13 Fuel Elements (LEU U_3Si 621 g ^{235}U) as a Function of Element Separation in a Row and Row Separation. (See Fig. D in Attachment 1.)

Element Separation in a Row, cm	Row Separation, cm						
	10	12	14	16	18	20	22
0.0	1.0419	0.9704	0.9206	0.8868	0.8643	0.8494	0.8398
0.25	1.0398	0.9691	0.9198	0.8865	0.8642	0.8496	0.8401
0.50	1.0360	0.9662	0.9176	0.8847	0.8628	0.8483	0.8390
0.75	1.0309	0.9620	0.9141	0.8816	0.8600	0.8458	0.8365
1.00	1.0245	0.9565	0.9092	0.8772	0.8559	0.8419	0.8327
1.50	1.0078	0.9417	0.8958	0.8647	0.8441	0.8305	0.8216
2.00	0.9868	0.9226	0.8782	0.8481	0.8281	0.8149	0.8064

Eigenvalue results are shown in Table 2 for an array of LEU U_3Si 621 g ^{235}U fuel elements with row separations of 10 to 22 cm, and element separations in a row of 0.0 to 2.0 cm. These data are plotted in Fig. 2 as a function of element separation for various row separations. In these calculations, both the aluminum of the storage rack and the fuel element end-fittings were neglected.

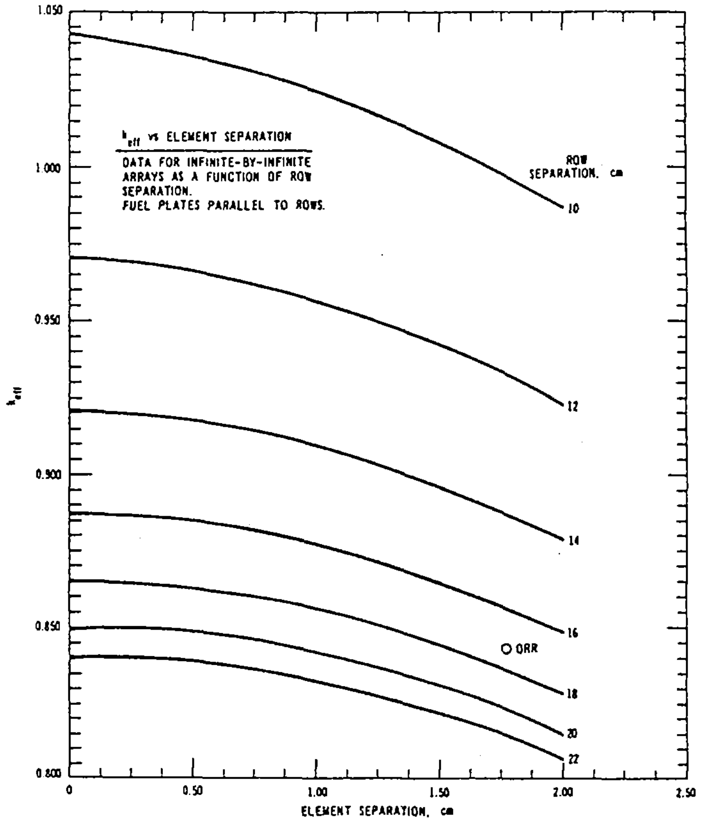


Fig. 2. Eigenvalues for Various Row Separations in Infinite-by-Infinite Arrays of LEU U_3Si 621 g ^{235}U Fuel Elements as a Function of the Separation Between Elements.

The results in Fig. 2 show the relative reactivity effects for this fuel element type as a function of various storage rack configurations. Interpolations to determine the eigenvalue for any specific configuration can also be readily made.

The Oak Ridge Research (ORR) reactor storage rack[2], for example, has a row separation of 17.2 cm and an element separation of 1.77 cm. According to Fig. 2 the eigenvalue for this configuration with the LEU U_3Si 621 g ^{235}U fuel elements would be 0.8431. This (calculated) eigenvalue is plotted in Fig. 2 and is identified "ORR".

Eigenvalues for a Given Storage Rack Configuration with Various Fuel Element Types

Table 3. Eigenvalue Calculations for Twenty Fuel Element Loadings, Each in an Infinite-by-Infinite Array and Assuming the ORR Fuel Storage Rack Spacing Specifications of 1.766 cm Element Separation and 17.24 cm Row Separation. (See Fig. E in Attachment 1.)

Fuel Element Loading Number	Fuel Type	Plates/ Element	^{235}U/ Element, g	k_{eff} Eigenvalue
1	LEU U_3O_8	23	278	0.7410
2	LEU U_3O_8	16	288	0.7587
3	LEU U_3O_8	18	324	0.7695
4	LEU U_3O_8	20	360	0.7765
5	LEU U_3O_8	22	396	0.7803
6	LEU U_3O_8	20	473	0.7967
7	LEU U_3Si	19	225	0.7154
8	LEU U_3Si	19	350	0.7889
9	LEU U_3Si	19	390	0.8044
10	LEU U_3Si	23	280	0.7402
11	LEU U_3Si	23	320	0.7613
12	LEU U_3Si	23	390	0.7899
13	LEU U_3Si	23	621	0.8453
14	HEU UAl_x	19	180	0.6903
15	HEU UAl_x	19	280	0.7772
16	HEU UAl_x	19	405	0.8377
17	HEU UAl_x	23	180	0.6783
18	HEU UAl_x	23	280	0.7635
19	HEU UAl_x	23	405	0.8229
20	HEU UAl_x	23	530	0.8594

Eigenvalue results are shown in Table 3 for infinite arrays of the twenty fuel element types in a storage configuration having the fuel element spacing specifications of the ORR storage rack. These data are plotted in Fig. 3 as a function of the ^{235}U loading in each fuel element type. In these calculations, 1/8 in. (0.32 cm)-thick aluminum storage compartments were included and the fuel element end-fittings were neglected.

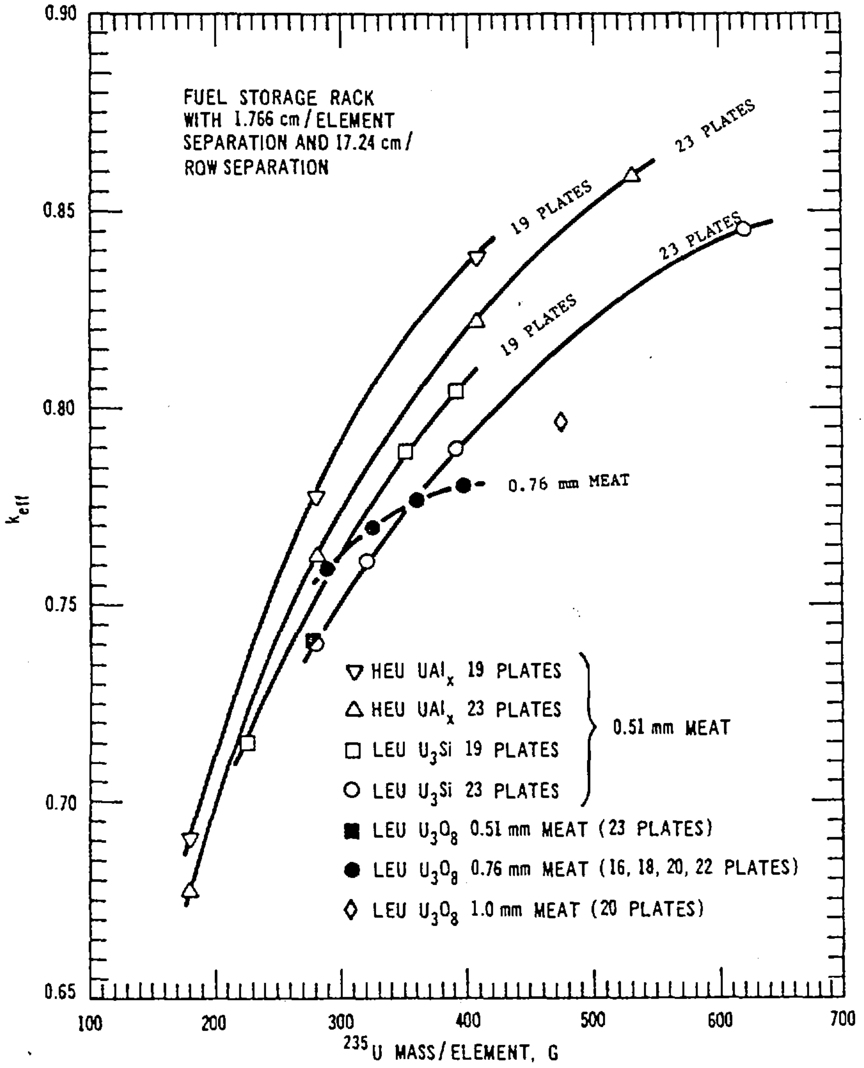


Fig. 3. Eigenvalues for Various LEU and HEU Elements in Infinite-by-Infinite Arrays With Separations of 1.766 cm Between Elements and 17.24 cm Between Rows as a Function of the ^{235}U Fuel Element Loading.

The results in Fig. 3 show the relative reactivity effects of fuel element storage in this configuration as a function of: (1) the number of plates per element, (2) the fuel meat thickness in an element, and (3) LEU vs. HEU fuel types. Interpolations to determine eigenvalues for other ^{235}U fuel element loadings can be readily made.

The data in Fig. 3 indicate that reactivity effects due to the fuel element geometry can be characterized as a function of the H/^{235}U atom ratio of the fuel element. For these fuel element geometries, the eigenvalues are inversely proportional to the number of plates per element and inversely proportional to the fuel meat thickness.

As would be expected, LEU fuel is less reactive than HEU fuel for a given fuel element geometry and ^{235}U loading. It is also evident that the eigenvalue results are not sensitive to the form of LEU fuel since the LEU U_3Si and LEU U_3O_8 results for 23-plate elements with 0.51 mm fuel meat are almost identical.

SENSITIVITY STUDIES

Configuration Model

The sensitivity of eigenvalue calculations to effects of the storage rack compartments, fuel element end-fittings, fuel element sideplates, and the diffusion theory model mesh have been evaluated. These results are listed in Table 4 for four storage rack configurations.

Table 4. Eigenvalue Sensitivity of an Infinite-by-Infinite Array of Number 13 Fuel Elements (LEU U_3Si 621 g ^{235}U) as a Function of Fuel Element and Storage Rack Representation, and the Calculational Model.

	k_{eff} Eigenvalue Assuming the ORR Fuel Storage Rack Geometry		k_{eff} Eigenvalue Assuming		
Configuration	17.24 cm/Row 1.766 cm/ Element	17.64 cm/Row 1.366 cm/ Element	14 cm/Row 0.25 cm/ Element	14 cm/Row 0.75 cm/ Element	Conclusion
1. As shown in Figs. G, H, I, and J in Attachment 1	0.8453	0.8366	0.9185	-	-
2. With Al replaced by H_2O in the 1/8 in.-thick Al frame region	0.8463	-	-	0.9169	Effect of frame is small
3. Without the Al frame region[a]	0.8431	0.8332	0.9198	0.9141	Effect of mesh is small
4. With an assumed 4 cm-long end-fitting (45.53/55.47-Al/H_2O)	0.8450	-	0.9182	0.9181	Effect of ends is very small
5. Fuel only - no sides, no frame, no ends - all replaced by H_2O	0.8558	-	0.9536	0.9391	Effect of sides is significant
6. Fuel and ends only - no sides, no frame - all replaced by H_2O	-	-	-	0.9392	Effect of ends is very small
7. Fuel and frame only - no sides, no ends - all replaced by H_2O	-	-	-	0.9436	Effect of frame is small

[a] This is the same as #2 but with a reduced number of X- and Y-mesh points in the water reflector. Without the Al frame region, the Y-mesh water reflector boundaries were, respectively: 12.62(9), 12.62(9), 11.0(7), and 11.0(7).

The following table summarizes the reactivity effects listed in Table 4 for one of these storage configurations; in general, all configurations show the same reactivity trends. The data are for the ORR storage rack configuration with LEU U_3Si 621 g ^{235}U fuel elements.

Change in Configuration	Reactivity Effect, % $\delta k/k$
Include fuel element end-fittings	-0.03
Include storage rack compartments	-0.10
Nominal (~10%) increase in mesh points*	+0.32

These reactivity effects indicate that the diffusion theory eigenvalue uncertainties of the storage rack configuration models are less than 1% $\delta k/k$.

Infinite Array Versus Finite Array of Fuel Elements

As an example of the conservatism implied by assuming an infinite-by-infinite array of fuel elements in a storage configuration vs. a finite array, the eigenvalue for the LEU U_3Si 621 g ^{235}U fuel elements in the ORR storage rack was calculated. A plan view of the ORR storage rack is shown in Fig. 4.

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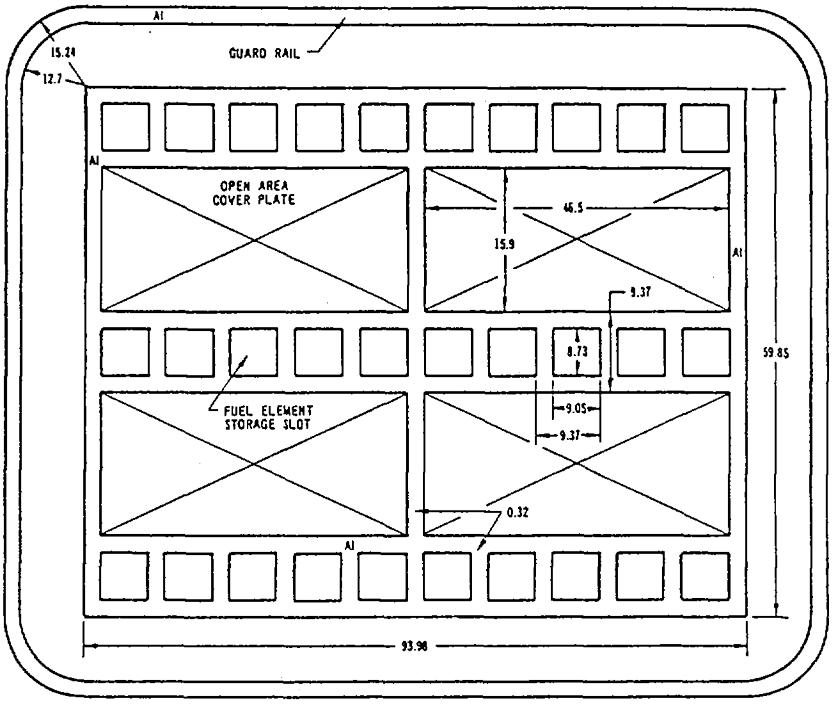
*Mesh sensitivities shown in the validation studies section indicates that the maximum mesh reactivity effect is about 0.9% $\delta k/k$ for a 100% increase in the number of mesh points. Further increases in the number of mesh points do not show a substantial additional reactivity increase.



ALL DIMENSIONS IN cm

Fig. 4. The ORR Fuel Storage Rack Configuration.

The rack has three rows of storage compartments and ten compartments per row. When fuel elements are centered in the compartments with the fuel element plates parallel to the rows, the spacing between elements in a row is 1.77 cm and the separation between rows is 17.2 cm.

The calculated eigenvalue for this configuration is 0.7985. This eigenvalue compares with a k_{eff} of 0.8453 (see Table 4) for an infinite-by-infinite array of fuel elements. The reactivity difference is about 5% δk/k. Calculations performed using infinite arrays are, therefore, clearly conservative.

VALIDATION STUDIES

Because of the importance and often the necessity of relying upon calculations to determine safe fuel element storage configurations, some of the diffusion theory eigenvalues were compared with results using Monte Carlo techniques. These data are shown in Table 5. As shown in Table 5, calculations were performed for a critical configuration,[3] for an infinite row of fuel elements, and for an infinite-by-infinite array of fuel elements. The diffusion theory code used was DIF3D[4], and the Monte Carlo codes were VIM[5] and KENO[6].

Table 5. Validation of Calculational Methods.

Configuration	Diffusion Theory DIF3D ENDF/B-IV	Monte Carlo VIM ENDF/B-IV	Monte Carlo KENO ENDF/B-IV	Monte Carlo KENO Hansen Roach
1. Critical SPERT-D HEU UAl_x 306 g ^{235}U	0.9999	-	1.0217±0.0039[a]	0.9997±0.0048
2. One infinite row LEU U_3Si 621 g ^{235}U,				
0.25 cm/element, 8 cm reflector	0.8036[b]	0.8244±0.0049	0.8353±0.0052	0.8327±0.0052
1.77 cm/element, 8.62 cm reflector	0.7860	0.8113±0.0049	0.8144±0.0030	-
3. Infinite-by-infinite LEU U_3Si 621 g ^{235}U,				
1.77 cm/element, 17.2 cm/row	0.8431[c]	0.8642±0.0066	0.8617±0.0038	0.8899±0.0051

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[a] Data are for 54K histories. Five batches of 30K histories each were: 1.0255±0.0055, 1.0249±0.0052, 1.0229±0.0046, 1.0096±0.0056 and 1.0274±0.0056.

[b] Doubling the xy mesh gives a k_{eff} of 0.8092. Mesh effect is of the order of 0.6% δk/k.

[c] Doubling the xy mesh gives a k_{eff} of 0.8521. Mesh effect is of the order of 0.9% δk/k.

In general, the eigenvalues calculated with Monte Carlo are systematically larger than with diffusion theory. The uncertainties quoted for the Monte Carlo results are $\pm 1\sigma$ and in most cases, at least two standard deviations would be required to cover the diffusion theory results.

The 2 to 3% $\delta k/k$ difference between diffusion theory and Monte Carlo is somewhat accounted for by a mesh reactivity effect in diffusion theory. For the two subcritical configurations, this reactivity effect is worth between 0.6 to 0.9% $\delta k/k$. Based upon these comparisons, diffusion theory eigenvalues for this fuel element storage study could be underestimated by 1 to 2% $\delta k/k$.

RESULTS AND CONCLUSIONS

The results of this study have shown that replacement of HEU fuel elements with LEU fuel elements will not have a significant reactivity effect in most storage racks. The magnitude of any reactivity effect will depend upon the change in ^{235}U loading and differences in the fuel element geometry.

As an aid to assess fuel element storage, curves are developed (Figs. 2 and 3) for reactivity effects as functions of LEU and HEU fuel element types for various unpoisoned storage rack configurations. The curves cover LEU and HEU fuel element loadings between approximately 200 and 600 g ^{235}U per element with various fuel element geometries, and storage rack configurations with various row and fuel element separations.

Relative to HEU fuel elements, reactivity increases associated with larger ^{235}U loadings in LEU fuel elements tend to be compensated for, simply by the reduced enrichment. Increases of about 50 grams of ^{235}U per element result in no net reactivity change when the fuel element geometries are the same. Reactivity effects due to fuel element geometry differences are slowly varying functions of the number of plates per element, the fuel meat thickness, and the water channel thickness.

REFERENCES

1. B. A. Zolotar, et al., "EPRI-CELL Code Description," Advanced Recycle Methodology Program System Documentation, Part II, Chapter 5 (1975).

2. J. T. Thomas, "Nuclear Criticality Assessment of Oak Ridge Research Fuel Element Storage," ORNL/CSD/TM-58, Oak Ridge National Laboratory (1978).

3. E. B. Johnson and R. K. Reedy, Jr., "Critical Experiments with SPERT-D Fuel Elements," ORNL/TM-1207, Oak Ridge National Laboratory (1965).

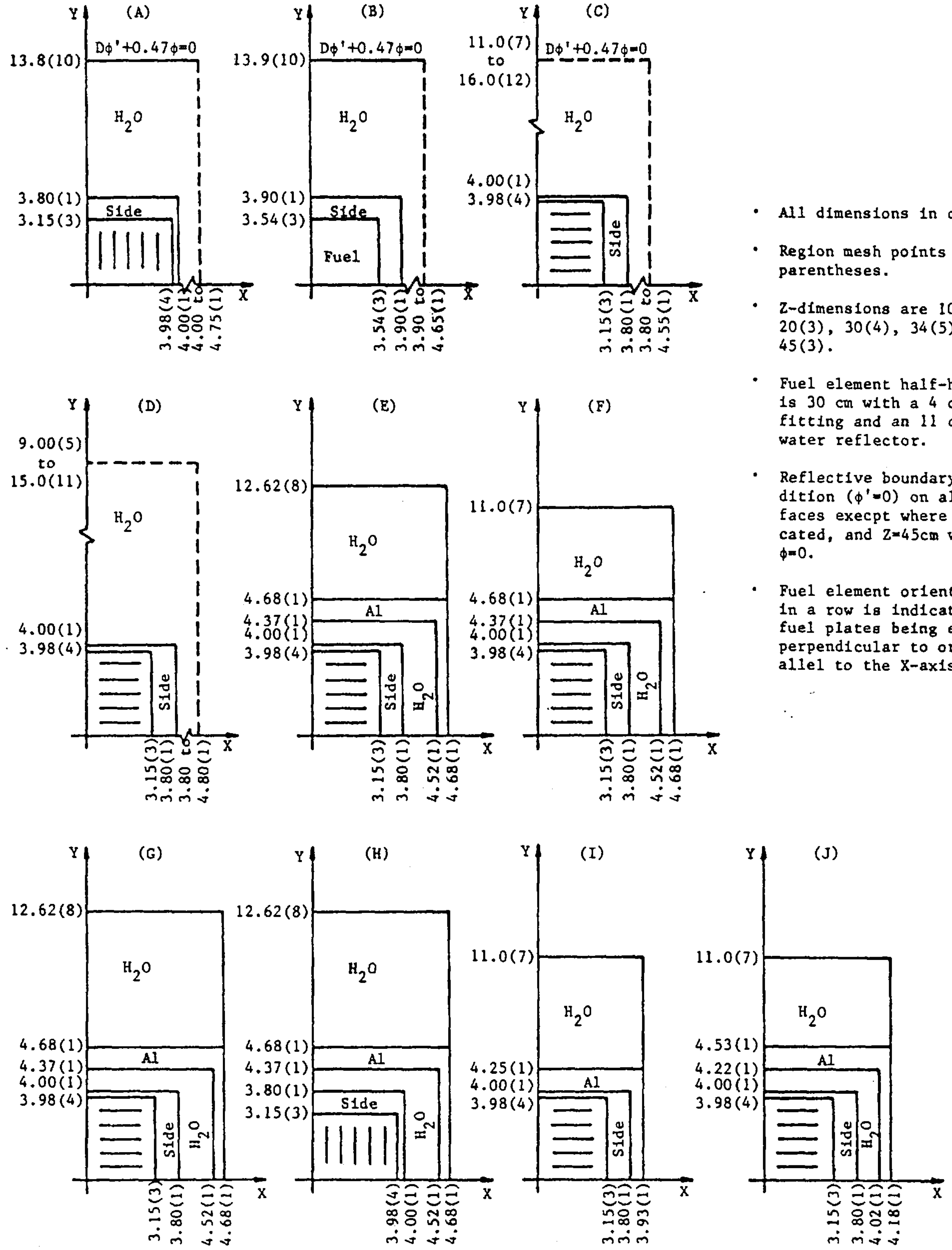
4. K. L. Derstine, "DIF3D: A Code to Solve One-, Two-, and Three-Dimensional Finite-Difference Diffusion Theory Problems," ANL-82-64, Argonne National Laboratory (to be published).

5. L. M. Petrie and N. F. Cross, "KENO-IV: An Improved Monte Carlo Criticality Program," ORNL-4938, Oak Ridge National Laboratory (1975).

6. R. N. Blomquist, et al., "VIM - A Continuous Energy Monte Carlo Code at ANL," ORNL/RSIC-44, Oak Ridge National Laboratory (1980).

Attachment 1

Three-Dimensional Diffusion Theory Calculational Models



- All dimensions in cm.
- Region mesh points in parentheses.
- Z-dimensions are 10(4), 20(3), 30(4), 34(5), 45(3).
- Fuel element half-height is 30 cm with a 4 cm end-fitting and an 11 cm axial water reflector.
- Reflective boundary condition ($\phi'=0$) on all faces execpt where indicated, and Z=45cm where $\phi=0$.
- Fuel element orientation in a row is indicated by fuel plates being either perpendicular to or parallel to the X-axis.