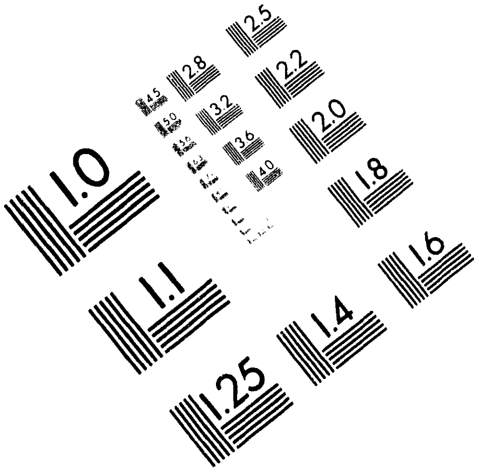

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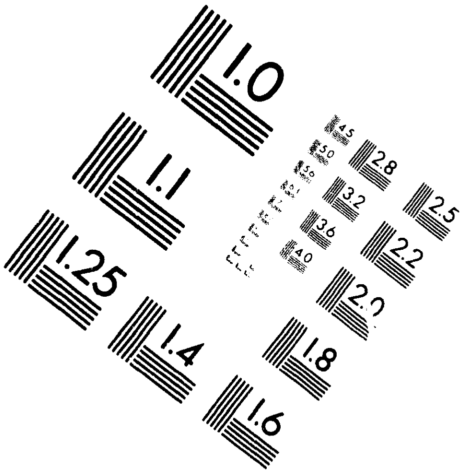

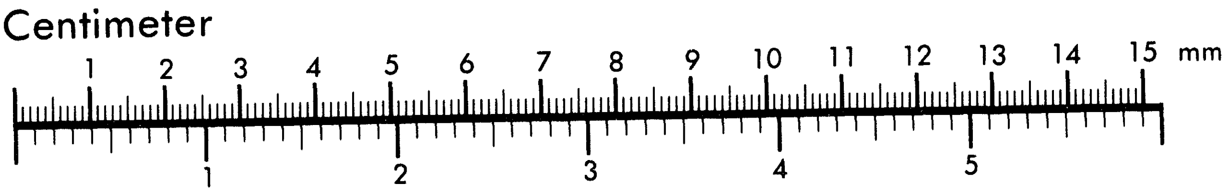

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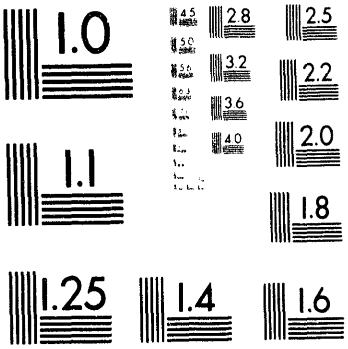

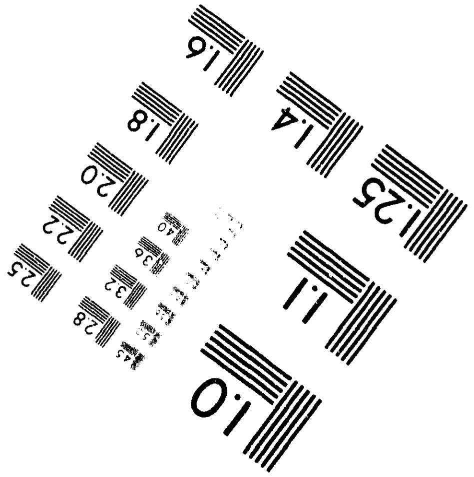

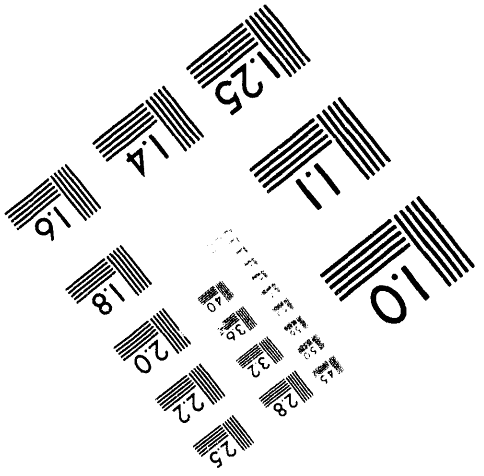

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RELOCATION OF RADIAL ENRICHMENT AT THE K REACTORS TO DECREASE ENRICHMENT INVENTORY

MASTER

INTRODUCTION

The enrichment inventory required in the Hanford reactors is greatly dependent on the location of the radial enrichment ring. Present and past philosophy has dictated that the radial enrichment be located as close to the periphery of the reactors as possible, consistent with total control criteria, to obtain maximum flattening efficiency. As long as individual tube power limits dictate total pile power this philosophy of maximum flattening is consistent with a goal of maximum production. For the past year the total pile power at the K reactors has been restricted by bulk outlet water temperature limit or administrative total power level limits. During this time fuel ruptures have been negligible due to improved metal quality and axial flux shaping. If present operating conditions continue the relocation of the enrichment ring could be desirable to decrease the enrichment inventory. Moving the radial enrichment toward the center of the reactor to decrease the inventory would result in lower flattening efficiency and require higher tube power limits for the same total pile power level.

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SUMMARY AND CONCLUSIONS

The Zilch modified one-group diffusion code for the IBM 7090 as programmed by G. F. Bailey was used to study the effect of relocating the radial enrichment ring. Results of this study are presented on Figure 1 as per cent variations from the values for the present radial enrichment locations. The plot of tube power variation is the variation required in maximum tube powers to maintain the same pile power as flattening efficiency is varied. The enrichment variation is broken down into the variations for spike and radial enrichment. **A graphic illustration of the parameters is presented in Figure I.**

For an example, the loading for KE Reactor in February, 1962, is given below. A comparison between the present situation and moving the radial enrichment in two lattice units is given.

	Present Situation (2/25/62) E-Ring in 5 L.U. from Edge	Radial Enrichment in 2 Lattice Units	% of Present Status
Radial Enrichment	304 Columns	245 Columns	81%
Spike Enrichment	198 Columns	167 Columns	84%
Reactor Power Level	4400 MW	4400 MW	-
Max. Tube Power	1731 KW	1847 KW	107%
ECT	2542	2381	94%

The radial enrichment inventory varies only slightly from one operating period to another. The amount of spike enrichment does vary as this is the primary tool in correcting for long-term reactivity changes. The example used is roughly an average inventory. **For this example the following approximate economic factors would apply:**

	Enriched Metal	Natural Metal	
Number of Tubes	90	90	
Tubes/Ton	8.35	7.22	
Tons of Metal	10.8T	12.5T	
Metal Cycle Time	3 Months	3 Months	
Tons of Metal/Year	43.2T	50T	
Cost per Ton	$4700	$2800	Savings:
Cost per Year	$203,040	$140,000	$63,000
Grams/MWD	0.77	.89	
MWD/Yr in these Tubes	40,000	40,000	
Gr/Yr in these Tubes	30,800	35,600	**Increase:**
% Pu-240	4.5	5.8	4,800 **grams**

The above values are not exact values and are definitely subject to closer evaluation. They do represent the magnitude of savings that can be accomplished through the reduction in the enrichment inventory.

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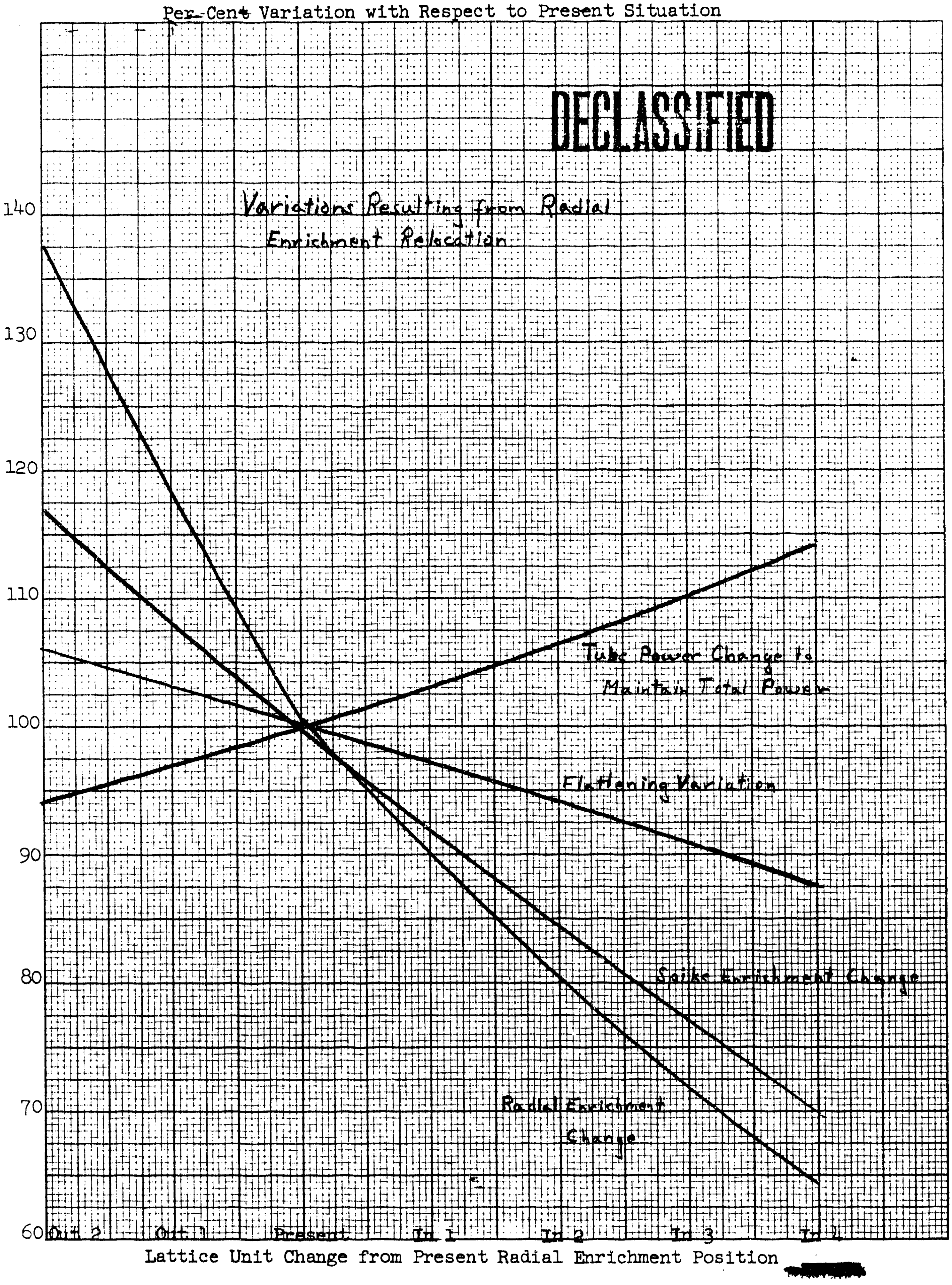
Figure I



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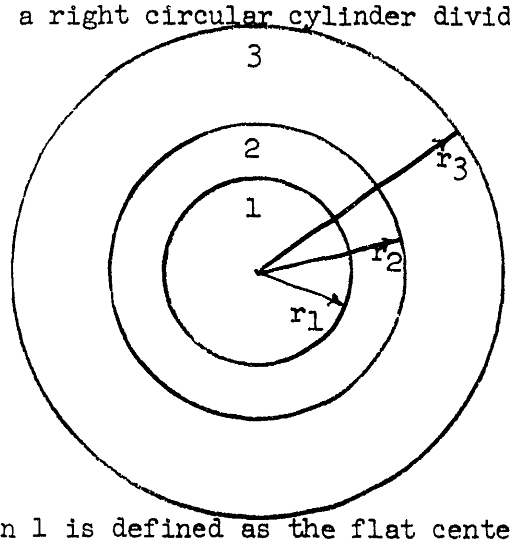
DISCUSSION

The only considerations made in this study are variations in tube power flattening change and enrichment inventory for a variation in radial enrichment position. The effects on conversion ratios, tube corrosion and graphite temperatures are not specified although these would definitely be affected.

Analytical Method

Radial Enrichment

The modified one-group one-dimensional diffusion theory can be used to determine the effect of relocating the radial enrichment region. The reactor is assumed to be a right circular cylinder divided into three regions.



Region 1 - Flat center zone

Region 2 - Radial Enrichment

Region 3 - Fringe Region

Region 1 is defined as the flat center zone, and region 3 is assumed to have some given material buckling, corrected for leakage and other reactivity losses. Using these assumptions and given the boundaries between the zones the buckling needed in the radial enrichment ring can be determined to make the pile critical. From this the number of tubes of enrichment needed can be determined.

The general modified one-group diffusion equation is:

$$\nabla^2 \phi + B^2 \phi = 0.$$

For cyclindrical geometry this can be stated as:

$$\frac{d^2\phi}{dr^2} + \frac{1}{r}\frac{d\phi}{dr} + B^2\phi = 0$$

This has the solutions:

1) $B^2 = 0$
$\phi = A + C \ln r$

2) $B^2 > 0$
$\phi = AJ_0 (Br) + C\, Y_0 \; (Br)$

3) $B^2 < 0$
$\phi = A\, I_0(Br) + C\, K_0 \; (Br)$

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Using these solutions the critical equations for the problem can be derived. The equations are found by applying the following boundary conditions:

$$\phi_1 \Big|_{R_1} = \phi_{1+i} \Big|_{R_1}$$

$$\frac{d\phi_1}{dr} \Big|_{R_1} = \frac{d\phi_{1+i}}{dr} \Big|_{R_1}$$

$$\phi_n \Big|_{R_n} = 0$$

For this three region problem the following equations are applicable:

Region 1 (Defined as flat or constant flux)

$$B_1^2 = 0$$

ϕ_1 = A constant which can be assumed equal to 1

$$\frac{d\phi_1}{dr} = 0$$

Region 2

$$\phi_2 = A_2 J_o (B_2 r) + C_2 Y_o (B_2 r)$$

$$\frac{d\phi_2}{dr} = A_2 B_2 J_1 (B_2 r) + C_2 B_2 Y_1 (B_2 r)$$

Region 3

$$\phi_3 = A_3 J_o (B_3 r) + C_3 Y_o (B_3 r)$$

$$\frac{d\phi_3}{dr} = A_3 B_3 J_1 (B_3 r) + C_3 B_3 Y_1 (B_3 r)$$

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Applying the boundary conditions:

At r_1:

$$\frac{d\phi_1}{dr} = \frac{d\phi_2}{dr} = A_2B_2J_1\,(B_2r_1) + C_2B_2Y_1\,(B_2r_1) = 0 \qquad (1)$$

$$\phi_1 = \phi_2 = A_2J_o(B_2r_1) + C_2Y_o\,(B_2r_1) = 1 \qquad (2)$$

At r_2:

$$\phi_2 = \phi_3$$

$$A_2J_o(B_2r_2) + C_2Y_o(B_2r_2) = A_3J_o(B_3r_2) + C_3Y_o(B_3r_2) \qquad (3)$$

$$\frac{d\phi_2}{dr} = \frac{d\phi_3}{dr}$$

$$A_2B_2J_1(B_2r_2) + C_2B_2Y_1(B_2r_2) = A_3B_3J_1(B_3r_2) + C_3B_3Y_1(B_3r_2) \qquad (4)$$

At r_3:

$$\phi_3 = 0 = A_2J_o(R_3r_3) + C_3Y_o(B_3r_3) \qquad (5)$$

For clarification the following symbols are used for the various bessel functions:

$J_o(B_2r_1) = X_1$

$Y_o(B_2r_1) = X_2$

$B_2J_1(B_2r_1) = X_3$

$B_2Y_1(B_2r_1) = X_4$

$J_o(B_2r_2) = X_5$

$Y_o(B_2r_2) = X_6$

$J_o(B_3r_2) = X_7$

$Y_o(B_3r_2) = X_8$

$B_2J_1(B_2r_2) = X_9$

$B_2Y_1(B_2r_2) = X_{10}$

$B_3J_1(B_3r_2) = X_{11}$

$B_3Y_1(B_3r_2) = X_{12}$

$J_o(B_3r_3) = X_{13}$

$Y_o(B_3r_3) = X_{14}$

Equations 1 - 5 may now be rewritten

1. $A_2X_3 + C_2X_4 = 0$
2. $A_2X_1 + C_2X_2 = 1$
3. $A_2X_5 + C_2X_6 = A_3X_7 + C_3X_8$
4. $A_2X_9 + C_2X_{10} = A_3X_{11} + C_3X_{12}$
5. $A_3X_{13} + C_3X_{14} = 0$

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By appropriate manipulation, the following solution is obtained:

$$\frac{X_{10}X_3 - X_4X_9}{X_6X_3 - X_4X_5} = \frac{X_{12}X_{13} - X_{14}X_{11}}{X_8X_{13} - X_{14}X_7}$$

Various values for B_2 can be substituted into the above equation until a solution is found. Luckily G. F. Bailey's Zilch program for the 7090 will supply the results for this equation.

The actual calculations were made using a fourth region for the extrapolation area. The three region derivation was made here for simplification.

The effective buckling in region one was assumed to be 0, in region three to be 5×10^{-6}, and in the extrapolation region 12×10^{-6}. The total radius of the 3220 lattice unit reactor is 619.5 cm. The extrapolation radius was assumed to be 671.5 cm. The radial enrichment region was assumed to be two lattice units wide. The following are the radii used for regions one and two..

Radial ring position w/respect to present location	Number of L.U. in region one	r_1	Number of L.U. in region two	r_2
Present	1884	466.6 cm	320	504.7 cm
In one L.U.	1733	447.5	307	485.6
In two L.U.	1589	428.5	295	466.6
In three L.U.	1450	409.4	283	447.5
In four L.U.	1319	390.4	270	428.5
Out one L.U.	2040	485.7	334	523.8
Out two L.U.	2204	504.7	345	542.8

Using the above values of radii and buckling, the buckling required in the radial enrichment ring to attain a critical reactor was determined. It was then assumed that this buckling was a weighted average of corrected material bucklings of the natural and enriched metal charged in the radial ring.

	Material Buckling	Enriched corrected for short charge (Assume cosine axial flux)	Assume -47 µb loss for axial leakage and poisons
Natural metal	52 µb		5
Enriched metal	270 µb	266	219

These corrected bucklings were used to determine number of E-columns in the radial enrichment ring. Following is an example for the present situation:

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f = function of enriched columns
320 columns in radial ring
Calculated radial ring buckling is 166.9 μb

$219f + 5(1-f) = 166.9$

$f = \frac{161.9}{214} = .757$

Number of enriched columns = 320f = 320 x .757 = 242

The presently loaded reactor has 404 tubes in the radial enrichment ring rather than the 320 in the equivalent cylindrical reactor. This larger number is due to the greater neutron leakage in the square pile as compared to the equivalent cylindrical pile and increased enriched loading on the near side of the reactor to compensate for control rods going through this region. A ratio of actual to theoretical number of tubes is used to correct the previous calculated radial enrichment inventory.

Correction factor 404 ÷ 320 = 1.26

Required enrichment = 242 x 1.26 = 305 columns

Spike Enrichment

The calculations for determining spike enrichment were based on the present actual situation. To allow for adequate control in the central zone it is necessary to charge spike enrichment. Spike enrichment will vary from one operating period to the next since it is greatly dependent on the residual exposure of the metal in the reactor. An average value for the present loading was assumed to determine what spike enrichment inventory is necessary with the radial enrichment in the present location. From this information the percentage of central tubes charged with enrichment can be ascertained. Since the total number of tubes in the central zone will vary with the change in radial enrichment location the number of spike enriched columns will also vary if the required percentage of enriched columns is assumed a constant.

On February 25, 1962, a total of 198 spike enriched columns were charged in KE reactor. At this time the central zone of the reactor consisted of 1884 tubes. The percentage of enriched columns is therefore 10.5 per cent.

Flattening Efficiency

ECT or flattening efficiency for the Hanford reactors is defined as total pile power divided by the average tube power of the ten high power tubes in the central flat zone of the reactor. G. F. Bailey's Zilch program will supply flattening efficiency data. In the calculations for this problem the central flat zone was assumed to be perfectly flat so that results would be for ideal flattening conditions. In actual operation local high areas in the central zone will vary from the optimum program

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conditions. From past operating data the actual flattening efficiency averages 10 per cent below the maximum attainable flattening.

For the present loading conditions for the K reactors the maximum flattening efficiency is 2807 ECT. Average actual flattening efficiency is 2526 ECT.

Results

The effects of varying the location of the ring are listed in the following tables

Enrichment Inventory

Position of Radial Ring w/Respect to Present Location	Number of Tubes in E-Ring (Corrected)	Radial Ring Buckling (μb)	Radial Enrichment (column)	% Change from Present	Spike Enrichment (columns)	% Change from Present
Present	404	166.9	305	-	198	-
In one	387	152.7	275	90.2	182	91.9
In two	372	141.2	246	80.7	167	84.3
In three	357	131.5	219	71.8	152	76.8
In four	340	123.5	197	64.6	138	69.7
Out one	421	184.4	363	119.0	214	108.1
Out two	435	206.5	420	137.7	231	116.7

Flattening Efficiency and Tube Power Variation

Position of Radial Ring w/Respect to Present Location	Flat Zone Size	Maximum ECT	Average Operational ECT	% Change from Present	Tube Power for 4400 MW Power Level	% Change from Present
Present	1884	2807	2526	-	1742	-
In one	1733	2719	2447	96.9	1798	103.2
In two	1589	2631	2368	93.7	1858	106.7
In three	1450	2544	2290	90.7	1921	110.3
In four	1319	2457	2211	87.5	1990	114.2
Out one	2040	2895	2606	103.2	1688	96.9
Out two	2204	2982	2684	106.3	1639	94.1

A R Kosmata/

Pile Physics Unit
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