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Central Fuel Worth in the Fast Test Reactor (FTR) Engineering Mockup

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1.0 INTRODUCTION

One of the primary purposes for making neutronics measurements in a critical assembly is to provide data to use for testing calculational tools. Experimental data from the engineering mockup critical (EMC)[1,2] of the Fast Test Reactor (FTR) have been used in many cases to "calibrate" analytical results by providing the bases for obtaining calculation versus experiment bias factors. These bias factors can then be used to adjust calculated parameters for the FTR.

An experiment was performed in the FTR-EMC to measure the total reactivity worth and the axial worth profile of withdrawing the central subassembly into the axial regions above the core. Calculations using three-dimensional X-Y-Z and two-dimensionsl R-Z models have been made to obtain reactivity worths for comparison with the experimental results. This comparison can be used to improve the accuracy of calculated worths of inner driver fuel motion in the FTR, such as the removal or addition of fuel subassemblies in reloading operations or fuel slumping or expulsion under accident conditions.

Another experiment measured the reactivity worth of replacing the fueled section of the central subassembly with sodium channel composition. The purposes of the analysis of this experiment are: (1) to determine if the C/E values obtained in the earlier three-dimensional calculations could be reproduced using another experiment from the FTR engineering mockup for comparison, (2) to determine what type of axial buckling adjustments are required to give the same calculated central fuel worths with a two-dimensional X-Y model that were obtained using the three-dimensional model, and (3) to obtain C/E values for the worths of an inner driver subassembly and an outer driver subassembly relative to sodium channel composition at the center of the EMC.

This report gives a brief description of the experiments, a detailed explanation of the analytical methods, the measured and calculated results, and a comparison of these results.

2.0 EXPERIMENTS

The FTR-EMC was assembled in the ZPR-9 critical facility at Argonne National Laboratory (ANL). The program of experiments performed in the EMC was divided into two phases. The first phase, designated Phase C of the FFTF critical experiments program[3], was composed of experiments related to core and shielding design and to safety problems having direct impact on the design. The second phase of experiments, designated Phase D, consisted of measurements related to FFTF operations and safety.

2.1 Phase D Experiment

The first experiment described in this report, was the initial step of Phase D[4]. The purpose of the experiment was to measure the total reactivity worth and the axial worth profile of the central fuel subassembly and thus provide a basis for a calculation to experiment comparison.

This experiment was performed in a beginning-of-life configuration of the EMC, designated BOL-REF-3[5]. Figure 1 is a cross sectional view of the EMC as viewed facing the front face of the stationary half. The BOL-REF-3 configuration had six peripheral shim rods (PSR), three fully withdrawn safety rods (SR), three fully withdrawn control rods (CR-506, CR-514 and CR-522), and three control rods (CR-508, CR-516 and CR-524) which were fully inserted. The four-matrix tube array at matrix positions 22-22*, 23-22, 22-23 and 23-23 was used to represent the central fuel subassembly. The reactivity worth for the movement of the central subassembly from the fully inserted condition to a condition representing six inches withdrawn was obtained by measuring the reactivity of the BOL-REF-3 configuration, reloading the materials in the central subassembly to simulate the six-inch withdrawal, and remeasuring the reactivity of the assembly. This procedure was continued with the central subassembly withdrawn in six-inch increments until a total withdrawal of 36 inches was achieved. As the inner driver composition was removed from the assembly, it was replaced with sodium channel composition.

The reference configuration for the experiment, BOL-REF-3, had an excess reactivity of 29.2 inhours, determined from the position of a calibrated ZPR-9 control rod. The withdrawal of the central fuel subassembly resulted in a reactivity loss so that all other configurations in the experiment were subcritical. The reactivity of each subcritical configuration was determined by

*Matrix positions are located by using the row numbers and column numbers in that order from Figure 1.

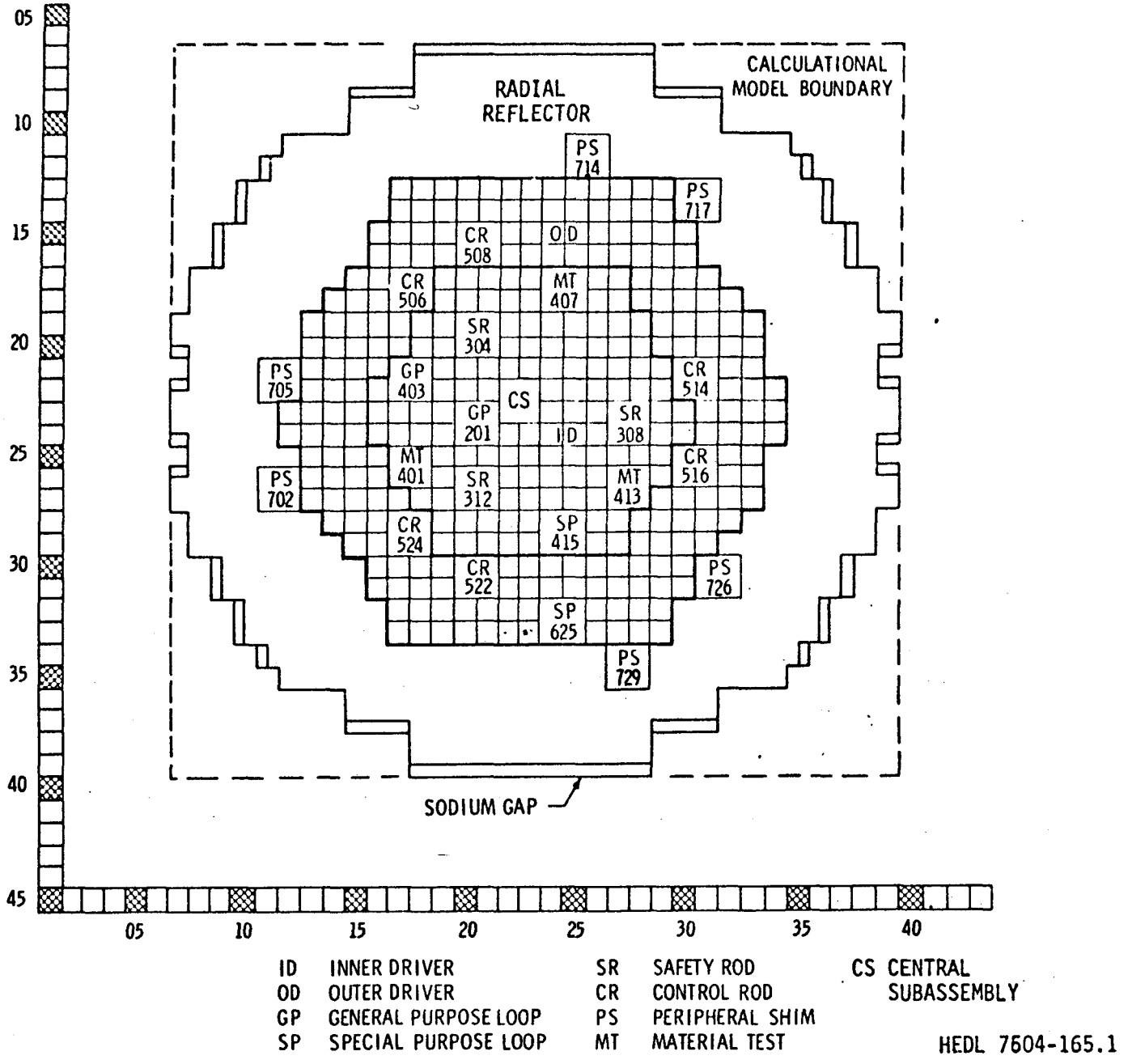


FIGURE 1. BOL-REF-3 Configuration of the FTR-EMC

the rod drop-inverse kinetics method.

2.2 Phase C Experiment

The purpose of the second experiment[6] described in this report was to measure the reactivity worth of an inner driver subassembly and an outer driver subassembly relative to sodium channel composition at the center of the EMC.

The experiment was performed in the BOL-REF-3 configuration except that matrix positions 19-33, 20-33, 18-32, and 15-16 contained radial reflector instead of outer driver composition. This modification compensated for the excess reactivity when the central subassembly is loaded with outer driver composition. The reactivity worth of removing the inner driver subassembly was determined by measuring the reactivity of the configuration with inner driver material in the central subassembly, then replacing the inner driver with sodium channel composition and remeasuring the reactivity. Measurement of the worth of removing the central subassembly loaded with outer driver composition was accomplished using the same procedure. The experimental results are included in Section 4.0 of this report.

3.0 ANALYTICAL METHODS

The purpose of the calculational work described in this report was to evaluate the analytical methods for computing fuel worth and worth profiles by comparing calculated worths with measured worths for the EMC. From this comparison, C/E bias factors were obtained for adjusting calculations of fuel worth in the FTR. The steps involved in the analysis were: (1) preparation of a twelve energy group cross section set, (2) development of a three-dimensional X-Y-Z model to compute the total worth of the central fuel subassembly in the FTR-EMC, (3) development of a two-dimensional R-Z model to calculate the axial worth profile and axial buckling adjustments, and (4) development of a two-dimensional X-Y model to calculate central subassembly worth and compare with the three-dimensional results.

3.1 Cross Section Preparation

A thirty-group set of cross sections for all regions of the EMC within 18 inches of the midplane (inner driver, outer driver, radial reflector, etc.) was available from an earlier study[7]. To reduce the computing time and cost for this study, the cross section set was collapsed to twelve groups over the appropriate fluxes for each zone, using the one-dimensional diffusion theory code, 1DX[8]. Cross sections for other regions of the EMC (axial reflector, axial shield, etc.) were generated from FTR Set 300[9] using 1DX. These cross sections were homogeneously resonance self-shielded and collapsed to twelve energy groups. The twelve-group

cross sections for all regions of the EMC were combined into a single set to be used in the reactor calculations.

3.1.1 Midplane Cross Sections

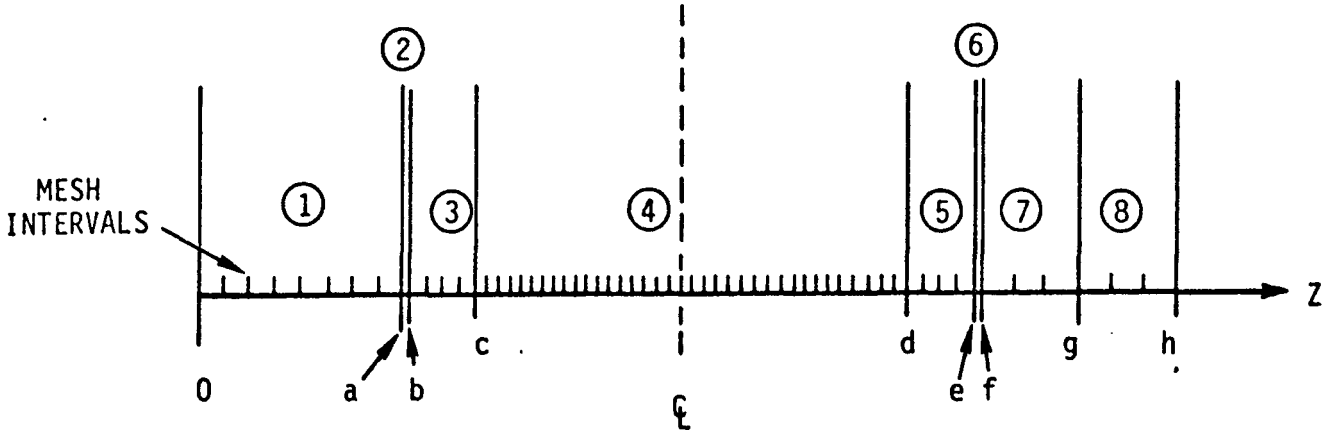
Cross sections for the materials in those zones of the EMC near the central midplane of the assembly were created using a one-dimensional radial model. The model was developed by homogenizing the materials in the EMC matrix tubes into annular rings of material conserving mass, volume, and approximate distance from the central axis of the assembly. A thirty energy group set of cross sections for these materials was prepared in an earlier study[7] in which the uranium and plutonium isotopes were heterogeneously resonance self-shielded and the cross sections were then adjusted to account for spatial flux depressions in the plutonium and uranium platelets used in the FTR-EMC. A homogeneous resonance self-shielding treatment was used for the remainder of the materials.

These thirty-group cross sections were collapsed to twelve groups with the 1DX code using the radial model described in Ref. 10. Cross sections for the inner driver, outer driver, radial reflector, control rods, peripheral shims, sodium channels, test loops and material test assemblies were obtained by this procedure.

3.1.2 Axial Cross Sections

Cross sections for the axial regions of the EMC were prepared with the 1DX code using the one-dimensional plane (or slab) model illustrated in Fig. 2. The FTR Set 300 cross section library was used as input to the 1DX problem along with atom densities from Ref. 1. Atom densities for ^{241}Pu were adjusted to account for radioactive decay assuming a half-life of 14.8 years[11]. Cross sections were prepared for the axial shield, spring gaps, axial reflectors, core plenum and handling socket in thirty groups, using homogeneous resonance self-shielding. These cross sections were then collapsed to twelve groups using the appropriate fluxes for each axial zone.

The cross sections prepared for the axial regions were combined with the midplane cross sections, discussed in Section 3.1.1, to form a single set that could be used for all regions of a three-dimensional model of the FTR-EMC.



ZONE	NAME	THICKNESS (cm)
1	AXIAL SHIELD	58.42
2	SPRING GAP	0.7925
3	AXIAL REFLECTOR	15.24
4	INNER DRIVER	91.603
5	AXIAL REFLECTOR	15.24
6	SPRING GAP	0.7925
7	CORE PLENUM	30.48
8	HANDLING SOCKET	27.94

REGION BOUNDARIES (cm)
a = 58.42
b = 59.21
c = 74.45
d = 166.06
e = 181.30
f = 182.09
g = 212.57
h = 240.51

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FIGURE 2. Slab Model for Axial Cross Section Preparation

3.2 Three-Dimensional Calculations of the Phase D Experiment

The total reactivity worth due to the movement of the central fuel subassembly of the FTR-EMC from its normal position to a position 36-inches withdrawn into the movable half was computed using a three-dimensional model. The computations were done in twelve energy groups using the diffusion theory code 3DB[12]. The worth was obtained from two k-calculations. The calculational boundary in the X and Y directions is shown in Fig. 1. Figure 3 shows the axial structure of each region identified in Fig. 1 and the layer definition and mesh spacing used in the Z-direction in the three-dimensional model. The mesh spacing in the X and Y directions was 5.53 cm which was equivalent to the X and Y dimensions of the ZPR-9 matrix tubes. The mesh spacing in the Z-direction was approximately 5.1 cm in the core and axial reflector regions, but somewhat larger beyond the axial reflectors, as indicated in Fig. 3. Atom densities for each region were obtained from Ref. 1 with adjustments for ^{241}Pu decay.

The total reactivity worth, $\Delta\rho$, was obtained from the computed values of k_{eff}, as follows:

$$\Delta\rho = \frac{k_2 - 1}{k_2} - \frac{k_1 - 1}{k_1} = \frac{k_2 - k_1}{k_2\, k_1} \qquad (1)$$

where k_1 and k_2 are the computed effective multiplication constants for the subassembly inserted and withdrawn, respectively.

3.3 Two-Dimensional Calculations of the Phase D Experiment

A two-dimensional R-Z model was employed to compute the shape of the axial worth profile of the central fuel subassembly. This choice was made because the 2D R-Z model was expected to be adequate for this purpose and much less expensive than 3D calculations.

A cross sectional view of the 2D R-Z model is shown in Fig. 4. The model can be visualized by rotating the diagram around the Z-axis. The model was designed to represent the EMC as closely as possible with cylindrical symmetry while conserving the total volume of each region of the assembly, the total mass of each material and the approximate distance of the material from the axial centerline of the assembly. The type of material in each zone of Fig. 4 is listed in Table I.

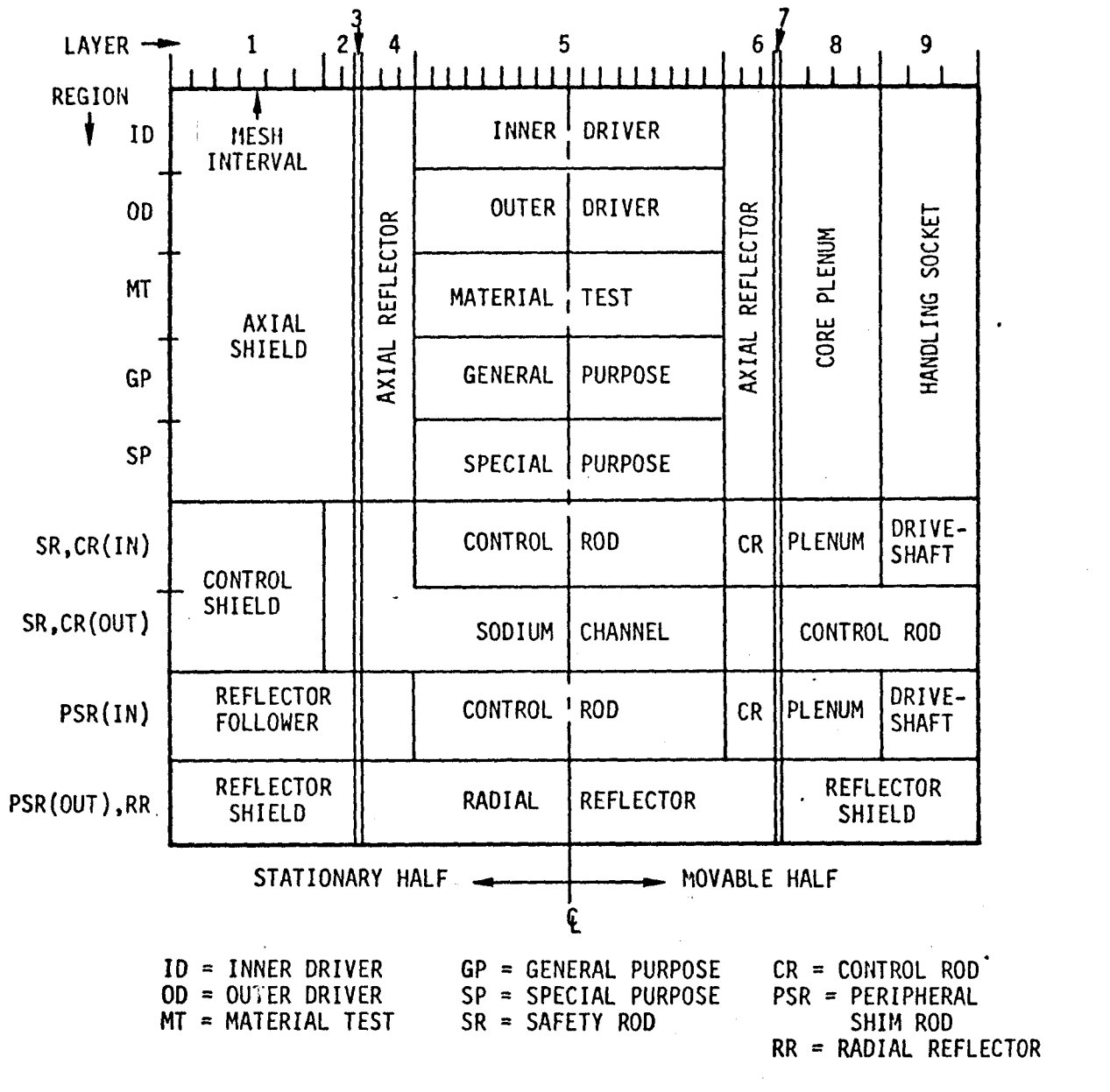
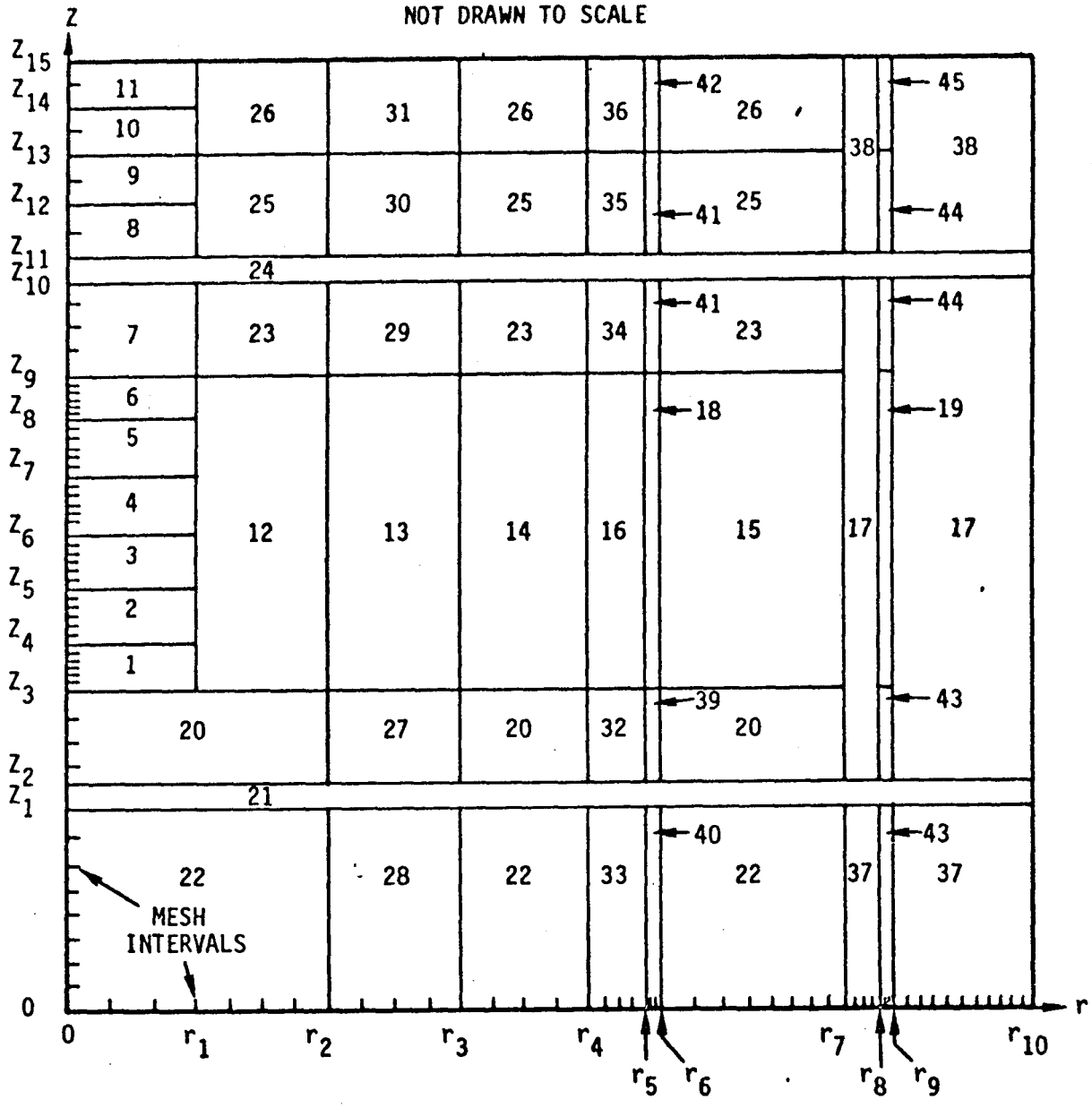


FIGURE 3. Axial Description of Each Region in the 3D Model of the EMC



ALL DIMENSIONS IN cm

Z_1 = 58.42	Z_9 = 166.06	r_1 = 6.24	r_6 = 45.35
Z_2 = 59.21	Z_{10}= 181.30	r_2 = 16.98	r_7 = 60.67
Z_3 = 74.45	Z_{11}= 182.09	r_3 = 27.73	r_8 = 64.78
Z_4 = 89.72	Z_{12}= 197.33	r_4 = 38.47	r_9 = 66.56
Z_5 =104.99	Z_{13}= 212.57	r_5 = 42.69	r_{10}= 89.25
Z_6 =120.26	Z_{14}= 227.80		
Z_7 =135.52	Z_{15}= 240.51		
Z_8 =150.79			

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FIGURE 4. Cross Sectional View of EMC 2D R-Z Model

TABLE I. Material Fractions Used in 2D R-Z Model

Zone No.	Fraction	Materials
1-6	0.5	Type A Inner Driver
	0.5	Type B Inner Driver
7	1.0	Axial Reflector
8,9	1.0	Core Plenum
10,11	1.0	Handling Socket
12	0.1561	Genl. Purpose Loop
	0.4292	Type A Inner Driver
	0.4147	Type B Inner Driver
13	0.2432	Sodium Channel
	0.3849	Type A Inner Driver
	0.3719	Type B Inner Driver
14	0.1643	Material Test Loop
	0.0548	Genl. Purpose Loop
	0.0548	Spec. Purpose Loop
	0.3693	Type A Inner Driver
	0.3568	Type B Inner Driver
15	0.0240	Spec. Purpose Loop
	0.4982	Type A Outer Driver
	0.4778	Type B Outer Driver
16	0.4234	Type A Outer Driver
	0.4061	Type B Outer Driver
	0.0568	Type A Op. Mat. O.D.
	0.1137	Type B Op. Mat. O.D.
17	0.5	Type A Radial Reflec.
	0.5	Type B Radial Reflec.
18	0.5	Control Rod
	0.5	Sodium Channel
19	1.0	Control Rod
20,23	1.0	Axial Reflector
21,24	1.0	Spring Gap
22	1.0	Axial Shield
25	1.0	Core Plenum
26	1.0	Handling Socket
27	0.2432	Sodium Channel
	0.7568	Axial Reflector
28	0.2432	Control Shield
	0.7568	Axial Shield
29	0.2432	Control Rod
	0.7568	Axial Reflector
30	0.2432	Control Rod
	0.7568	Core Plenum
31	0.2432	Control Rod
	0.7568	Handling Socket
32,34	0.0568	Type A Op.Mat.Ax.Refl.
	0.1137	Type B Op.Mat.Ax.Refl.
	0.8295	Axial Reflector
33	0.0568	Type A Op.Mat.Ax.Shld.
	0.1137	Type B Op.Mat.Ax.Shld.
	0.8295	Axial Shield
35	0.0568	Type A Op.Mat.Core Pl.
	0.1137	Type B Op.Mat.Core Pl.
	0.8295	Core Plenum
36	0.1705	Op.Mat.Handl. Socket
	0.8295	Handling Socket
37,38	1.0	Reflector Shield
39	1.0	Sodium Channel
40	1.0	Control Shield
41	0.5	Control Rod
	0.5	Control Rod Plenum
42	0.5	Control Rod
	0.5	Drive Shaft
43	1.0	Reflector Follower
44	1.0	Control Rod Plenum
45	1.0	Drive Shaft

The central subassembly was divided axially into six-inch segments with each segment assigned a separate zone number. With the central subassembly fully inserted, zones 1 through 6 contained inner driver composition. For a six-inch withdrawal of the central subassembly, zones 2 through 7 contained inner driver composition and zone 1 contained sodium channel composition. The eigenvalue, k_{eff}, for each configuration was computed using the two-dimensional diffusion theory code, 2DB[13].

The value of k_{eff} obtained using the R-Z model was much lower than that obtained from a 3D X-Y-Z calculation for the same EMC configuration. The basic problem is that of using a model with radial symmetry to describe the non-symmetric configuration shown in Fig. 1. The largest effect is the representation of the row 5 control rods and row 7 peripheral shims with cylindrical shells containing absorber composition. Spreading the ^{10}B in this fashion gives it a higher worth which results in a lower k_{eff} from the calculation.

To compensate for this effect, the atom density of the control rod composition was reduced in the cylindrical shells representing the control rods and peripheral shims so that the 2D R-Z k_{eff} was approximately the same as that obtained from the three-dimensional calculation. The atom densities of the control rod composition (B_4C, sodium and stainless steel) were reduced to 55.8 percent of their actual values to obtain the desired keff. Since the two-dimensional R-Z problem was used only to obtain the shape of the axial worth profile, it was not necessary that the k_{eff} be exactly the same as the three-dimensional value.

The k_{eff} calculations to obtain the shape of the axial worth profile were made with the reduced control rod atom densities. Equation (1) was used to obtain the worth of each six-inch increment of subassembly withdrawal.

3.4 Three-Dimensional Calculations of the Phase C Experiment

The reactivity worth of replacing the fuel portion of the central subassembly with sodium channel composition was computed using a three-dimensional model. As in the analysis of the Phase D experiment, these computations were done in twelve groups using the diffusion theory code 3DB. The calculational model is very similar to the three-dimensional model described above, except that radial reflector replaces outer driver composition in matrix positions 19-33, 20-33, 18-32, and 15-16. See Figure 1. The worth of replacing inner driver and outer driver fuel with sodium channel composition was obtained from two k-calculations for each replacement. Equation (1) was used to compute the worth.

3.5 Two-Dimensional Calculations of the Phase C Experiment

One of the purposes of analyzing the phase C central worth experiment was to develop a two-dimensional X-Y model to calculate fuel worth. This model used the central midplane of the three-dimensional model as the core map. Values of k_{eff} were computed using the computer code 2DB.

An axial buckling value was input to 2DB to account for neutron leakage in the axial dimension not treated in the 2D X-Y model. The calculations were done with the axial buckling unchanged. When the composition of the central subassembly is changed, however, the neutron leakage in the axial direction is different. So, to account for this difference, axial buckling adjustments were obtained from comparison of R-Z and R models for the various central subassembly compositions. Then the calculated worths were altered to account for the change in axial buckling. The results of the axial buckling studies, worths corresponding to the constant buckling approximation, and worths corrected using axial buckling adjustments, are given in Section 4.4 of this report.

4.0 RESULTS

4.1 Experimental Results of the Phase D Experiment

The measured worth of each increment of subassembly withdrawal and the total worth are given in Table II. The experimental results[4] were reported in units of inhours. These values were converted to $\%\Delta k/k$ using a conversion factor of 1047.71 $Ih/\%\Delta k/k$[14].

4.2 Calculated Results of the Phase D Experiment

4.2.1 Three-Dimensional Results

The values of k_{eff} obtained from the three-dimensional calculations for the central subassembly fully inserted and fully withdrawn are given in Table III.

Using these values of k_{eff} in Equation (1), the total calculated worth for the 36-inch withdrawal of the central fuel subassembly is $-0.964 \pm 0.005\%\Delta k/k$.

One of the objectives of this study was to obtain a C/E bias factor for the computation of inner driver fuel worth in the FTR. Using the three-dimensional calculated total worth of the central fuel subassembly given above ($-0.964 \pm 0.005\%\Delta k/k$) and the measured total worth from Table II ($-0.858 \pm 0.012\%\Delta k/k$), the C/E value is 1.12 ± 0.02. Based on this result, the reactivity worth of inner driver fuel near the center of the FTR, obtained from three-dimensional calculations, should be reduced by about twelve percent.

TABLE II. Measured Reactivity Worth of Central Fuel Subassembly

Subassembly Withdrawal Inches	Worth of Withdrawing Central Fuel Subassembly	
	Inhours[a]	%Δk/k[b]
From 0 to 6	- 72.8 ± 3.4	-0.0695 ± 0.0032
From 6 to 12	-158.6 ± 3.5	-0.1514 ± 0.0033
From 12 to 18	-203.0 ± 5.0	-0.1938 ± 0.0048
From 18 to 24	-192.8 ± 9.4	-0.1840 ± 0.0090
From 24 to 30	-166 ± 14	-0.158 ± 0.013
From 30 to 36	-106 ± 17	-0.101 ± 0.016
From 0 to 36	-899 ± 13	-0.858 ± 0.012

a From Ref. 4.

b 1%Δk/k = 1047.71 Inhours (Ref. 14).

TABLE III. Values of K_{eff} From Three-Dimensional Calculations

Central Subassembly Position	K_{eff}
Inserted	0.99582 ± .00003
Withdrawn	0.98635 ± .00004

4.2.2 Two-Dimensional Results

The values of k_{eff} obtained from the two-dimensional R-Z calculations for each position of the central subassembly are listed in Table IV. The worth of each increment of subassembly withdrawal and the total worth were obtained using Equation (1) and the values of k_{eff} in Table IV. These results are given in the first column of worth values in Table V. The second column of worths in Table V are the same numbers normalized so that the total worth is equal to that obtained from the three-dimensional calculations. The last column of Table V is again the same data but normalized so that the total worth is equal to the measured total worth.

The integral worth was determined from the k_{eff} for the fully inserted condition and the values of k_{eff} for each step of subassembly withdrawal using Equation (1). Table VI gives the integral worth values from the experimental data and from the two-dimensional R-Z calculations normalized to the experimental total worth. These results have been plotted in Fig. 5. When the calculations are normalized in this way, the agreement between calculation and experiment for the intermediate points on the curve is quite good. Note that the differences between the calculated and experimental values in Table VI are less than the experimental uncertainties.

4.3 3D Results of Phase C Experiment

Table VII gives the experimental results in units of inhours and also converted to $\%\Delta k/k$. Also given in Table VII is the calculated worth of the central fuel subassembly and the ratio, C/E, of calculated to experimental worth.

4.4 2D Results of the Phase C Experiment

4.4.1 Axial Buckling Studies

The reactivity worth of the substitution of fuel with sodium channel composition was also computed with a two-dimensional X-Y model using the 2DB computer code and the same twelve group cross sections. A constant axial buckling of 0.0005706 was used in the two k-calculations from which the worth was obtained. The worth by this method was $-1.1543 \pm 0.0004\%\Delta k/k$, approximately 10.5% higher than that obtained from the three-dimensional calculations. The C/E value using this calculated result was 1.266 ± 0.029.

This large difference between the two- and three-dimensional results showed that the assumption of constant axial buckling was causing a significant error in the two-dimensional X-Y calculation of central fuel worth.

TABLE IV. Values of K_{eff} From Two-Dimensional R-Z Calculations

Central Subassembly Position (inches withdrawn)	K_{eff} [a]
0	0.995845
6	0.995065
12	0.993350
18	0.991174
24	0.988999
30	0.987254
36	0.986151

a Uncertainty in k_{eff} is 3×10^{-5}.

TABLE V. Calculated Reactivity Worth of Central Fuel Subassembly

Subassembly Withdrawal, Inches	Calculated Reactivity Worth, %Δk/k		
	From 2D R-Z Calculations	Normalized to[a] Total 3D Worth	Normalized to[b] Total Experimental Worth
0 to 6	-0.0787	-0.0769	-0.0684
6 to 12	-0.1735	-0.1695	-0.1508
12 to 18	-0.2210	-0.2158	-0.1921
18 to 24	-0.2219	-0.2167	-0.1929
24 to 30	-0.1787	-0.1745	-0.1554
30 to 36	-0.1133	-0.1107	-0.0985
0 to 36	-0.9871	-0.9641	-0.8581

a Normalization Factor = 1.0239 = ratio of 2D total worth to 3D total worth.

b Normalization Factor = 1.1503 = ratio of 2D total worth to experimental total worth.

TABLE VI. Integral Worth of Central Fuel Subassembly

Subassembly Withdrawal, Inches	Experimental Results	Calculated Worth[a] Normalized to Total Experimental Worth
0 to 6	-0.0695 ± 0.0032	-0.0684
0 to 12	-0.2209 ± 0.0034	-0.2192
0 to 18	-0.4147 ± 0.0047	-0.4113
0 to 24	-0.5987 ± 0.0083	-0.6042
0 to 30	-0.7570 ± 0.0109	-0.7596
0 to 36	-0.8581 ± 0.0124	-0.8581

a Uncertainty in calculated values is ± 0.0043.

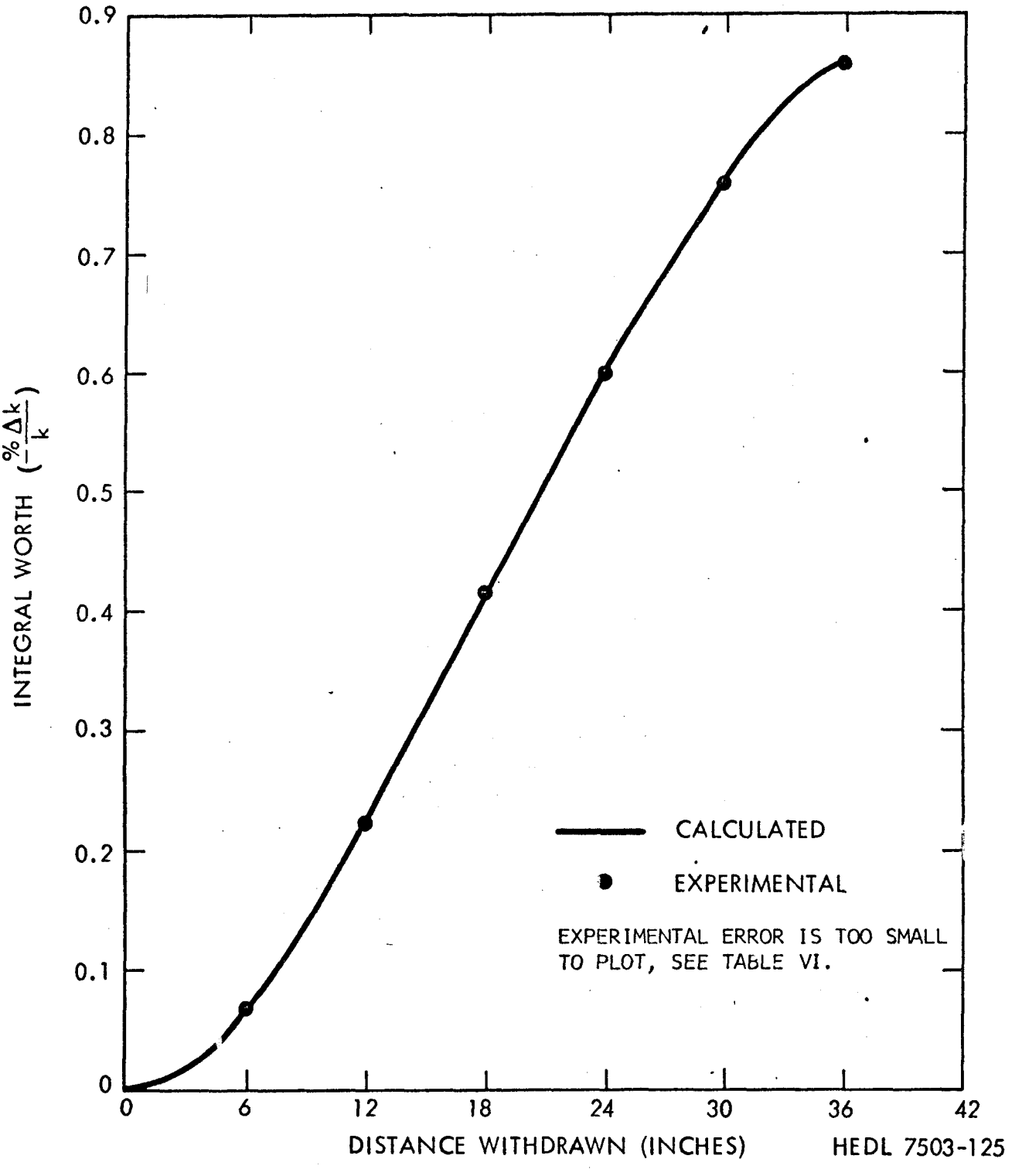

FIGURE 5. Integral Worth of Central Subassembly

Table VII

Measured and 3-D Calculation of Central Fuel Worth[a]

Measured		Calculated	
Inhours[b]	%Δk/k[c]	%Δk/k	C/E
-955±22	-0.912±0.021	-1.0446±0.0044	1.146±0.027

a Remove fuel portion of central subassembly and replace it with sodium channel composition.

b Ref. 6.

c 1047.71 Ih=1%Δk/k (Ref. 14).

In order to investigate these axial buckling effects, three sets of two-dimensional, R-Z, and one-dimensional, R, diffusion theory problems were run to estimate the magnitude of axial buckling changes due to the substitution of inner driver (ID), outer driver (OD), and material test (MT) compositions for sodium channel composition. The results of these runs are summarized in Table VIII.

When the axial buckling adjustment from Table VIII is used in the two-dimensional X-Y calculation of the worth of inner driver composition relative to sodium channel composition, the calculated worth is 1.0402 ± 0.0004%Δk/k —— a value very close to that obtained from the three-dimensional calculations. This indicates that the axial buckling adjustments derived from R and R-Z calculations can be applied to X-Y calculations, at least for the central subassembly.

The last value shown in Table VIII was derived from the first and third. Comparing this with results given in a previous report[15] shows that the effect on the axial buckling of an MT-inner driver substitution is approximately a factor of two greater at the center of the core than it is in row 4.

4.4.2 Bias Factors for Central Fuel Worth

Additional calculations were made using the two-dimensional X-Y model with buckling adjustment to obtain the calculated worth of a simulated outer driver subassembly at the central subassembly location. A measurement of this worth was also obtained in Part IX of the ANL-FFTF Phase C experiments[6]. The measured worth was 1235 ± 22 inhours or 1.179 ± 0.021%Δk/k. The calculated worth is 1.353 ± 0.0004 %Δk/k for a C/E of 1.147 ± 0.020.

Table IX summarizes the experimental results, the two-dimensional X-Y calculated worths with and without buckling adjustments, and the C/E bias factors.

5.0 DISCUSSION AND CONCLUSIONS

Using a three-dimensional model, a C/E of 1.12 ± 0.02 was computed for the fuel withdrawal from the central subassembly. For the total removal of fuel, the three-dimensional computations produce a C/E of 1.15 ± 0.03. These bias factors have error bars which overlap indicating that the uncertainty in the C/E determination probably accounts for their difference. Although they are not in disagreement within the uncertainties, there are differences between the experimental configurations that could account for a small difference in C/E.

Table VIII

Buckling Adjustments for Central Subassembly Modifications

Composition Removed	Composition Added	Axial Buckling Change ΔB^2 (10^{-6} cm^{-2})
Sodium Channel	Inner Driver	+5.0
Sodium Channel	Outer Driver	+5.2
Sodium Channel	Material Test	+2.8
Material Test	Inner Driver	+2.2

Table IX

Measured and 2-D X-Y Calculations of Central Fuel Worths[a]

	Inner Driver	Outer Driver
Measured Worth[b], Inhours	955±22	1235±22
Measured Worth[c], %Δk/k	0.912 ±0.021	1.179 ±0.021
Calculated Worth, %Δk/k (Constant Buckling)	1.1543 ±0.0004	1.4715 ±0.0004
C/E (Constant Buckling)	1.266 ±0.029	1.248 ±0.022
Calculated Worth, %Δk/k with Buckling Adjustment	1.0402 ±0.0004	1.3528 ±0.0004
C/E (w/Buckling Adjustment)	1.141 ±0.026	1.147 ±0.020

a Relative to sodium channel composition.

b Ref. 6.

c 1%Δk/k = 1047.71 inhours (Ref. 14).

For example, core cross sections were used for the central subassembly fuel when it was withdrawn into the axial regions. These may not be the most appropriate cross sections for fuel surrounded by axial reflector and core plenum instead of fuel composition. It is recommended that for FTR calculations involving fuel movement into the axial regions, the 1.12 ± 0.02 value be used. If the fuel is totally removed, then the 1.15 ± 0.03 should be used.

The two-dimensional R-Z model computed a good worth profile of fuel withdrawal or insertion from the central subassembly. Since computer time for an R-Z model is less than that for an X-Y-Z, R-Z geometry is recommended for computing the worth profile of fuel movement into the axial regions of the core.

Using a 2D, X-Y model with constant buckling, C/E bias factors of 1.25 to 1.27 were computed. When axial buckling adjustments for composition changes were included, these values were reduced to 1.15, comparing favorably with the 3D results. It is very important that axial buckling changes due to material composition changes be taken into account in 2D, X-Y computations.

It should be noted that the C/E values reported are a function of the conversion factor of inhours to %Δk/k. For all the calculations in this study, 1047.71 In/%Δk/k was used. There is an uncertainty in this factor because it is computed with delayed neutron parameters which vary depending upon which literature reference is selected. A recent study of the sensitivity of the conversion factor to published delayed neutron data has shown that the factor could range from 980 Ih/%Δk/k to 1055 In/%Δk/k. The 1047.71 In/%Δk/k, which was used throughout this report, was computed by ANL to be consistent with the experiment. The 980 In/%Δk/k came from data recently published in ENDF/B Version IV. The C/E bias factor is directly proportional to the magnitude of this conversion factor. So, if a set of delayed neutron data which produces a differing conversion factor is found to be more accurate, then the C/Es reported here can be adjusted.

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