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HIGH-²⁴⁰Pu FTR/EMC EXPERIMENTS

AND ANALYSIS:

CARBIDE FUEL AND UO₂ BLANKET

SUBASSEMBLY WORTHS

HANFORD ENGINEERING DEVELOPMENT LABORATORY
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P. A. Ombrellaro

June 1977

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HIGH-²⁴⁰Pu FTR/RMC EXPERIMENTS AND ANALYSIS:
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P. A. Ombrellaro

ABSTRACT

Carbide-plutonium fuel and UO₂ blanket subassembly worth measurements performed at ANL in the EMC/LWR were analyzed. Composition exchange worth calculations were performed for:

- a) the replacement of high-²⁴⁰Pu fuel composition for low-²⁴⁰Pu fuel composition and carbide-plutonium fuel composition, successively, in the center subassembly of the core,*
- b) the replacement of low-²⁴⁰Pu fuel composition for carbide-plutonium fuel composition in one outer driver subassembly, and*
- c) the replacement of the radial reflector composition with UO₂ blanket composition in one subassembly of the radial reflector.*

The composition exchange worth calculations were performed in two-dimensional x,y geometry, using diffusion theory and perturbation theory. Each method produces about the same calculated-to-experimental bias factors.

For the large carbide fuel and UO₂ blanket exchange worths, the C/E values are considered typical for the methods employed in the calculation. For the much smaller low-²⁴⁰Pu fuel exchange worth, the C/E values are poor as a result of large uncertainties in the measured exchange worths and inherent uncertainties in the calculations.

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HIGH-²⁴⁰Pu FTR/EMC EXPERIMENTS AND ANALYSIS
CARBIDE FUELS AND UO₂ BLANKET SUBASSEMBLY WORTHS

I. INTRODUCTION

In order to investigate the reactivity effect of carbide-plutonium fuel and UO₂ blanket subassemblies in the Fast Test Reactor (FTR), the reactivity worth of simulated subassemblies has been measured in the Engineering Mockup Critical (EMC) loaded with high-²⁴⁰Pu fuel. ⁽¹⁾ This high-²⁴⁰Pu fuel is referred to here as Light Water Reactor (LWR) plutonium fuel, even though it does not have the same isotopic composition as the LWR plutonium fuel intended for use in the FTR. The measurements were performed in a version of the BOL-REF-5S LWR-zone core configuration of the EMC/LWR that was developed by establishing a central zone of high-²⁴⁰Pu fuel in the EMC and inserting an additional Peripheral Shim Rod (PSR705) in the core.

The experiment consisted of measuring the exchange worths of subassemblies in different parts of the core. Subassembly worths were measured for:

- 1) the exchange of a high-²⁴⁰Pu fuel composition subassembly located in the center of the core for a low-²⁴⁰Pu fuel composition subassembly,
- 2) the exchange of a high-²⁴⁰Pu fuel composition subassembly in the center of the core for a carbide-plutonium fuel subassembly,
- 3) the exchange of a low-²⁴⁰Pu fuel subassembly located in the outer driver of the core for a carbide-plutonium fuel subassembly, and
- 4) the exchange of a reflector subassembly for a UO₂ blanket subassembly.

The purpose of these worth measurements in the EMC/LWR was to investigate the large reactivity effects resulting from the anticipated use of carbide-plutonium

fuel and UO_2 blanket subassemblies in the FTR, and to provide an experiment for establishing calculational bias factors.

A description of the experiment, the measured worths of carbide fuel and UO_2 blanket material, and the results of the calculational analysis of this experiment obtained by ANL are presented by R. B. Pond in Reference 1.

This report presents the calculational results obtained by HEDL from the analysis of carbide fuels and UO_2 blanket subassembly worth experiments. The analysis was performed using the two-dimensional diffusion theory code 2DBS⁽²⁾ and the two-dimensional perturbation Code PERT-V.⁽³⁾ The two computer codes were used with a new set of resonance and spatially self-shielded cross sections in a 42-energy group scheme, recently developed⁽⁴⁾ for the analysis of experiments performed in the EMC/LWR. The analysis provides: (1) a measure of how well the cross sections and standard methods at HEDL can reproduce the experimental results, and (2) an indication of the calculational uncertainty in estimating the large reactivity changes caused by the insertion of carbide fuel and UO_2 blanket subassemblies in the FTR.

II. EXPERIMENT

A. Reference Core Configuration

The core configuration in which measurements of the worths of the carbide fuel and UO_2 blanket subassemblies were performed is the BOL-REF-5S LWR-zone core configuration⁽¹⁾ of the EMC/LWR with PSR-705 inserted, shown in Figure II-1.

In this core configuration of the EMC/LWR, control rods CR-506, CR-514, CR-522 and safety rods SR-304, SR-308, SR-312 are withdrawn, while control rods CR-508, CR-516, CR-524 and PSR-702, PSR-714, PSR-726 are inserted. The core has a fissile plutonium ($^{239}\text{Pu} + ^{241}\text{Pu}$) loading of 536.4 Kg and is 461.301 lk subcritical.

The inner driver and outer driver zones of the core each consist of type A and B tubes. In Figure II-1, type A tubes are located in odd-numbered matrix columns and type B tubes are in even-numbered columns.

The cross-hatched area within the inner driver in Figure II-1 identifies the subassemblies loaded with the high- ^{240}Pu (approximately 26 w/o ^{240}Pu) fuel composition. All other areas of the inner driver and outer driver regions consist of subassemblies loaded with EMC, low- ^{240}Pu (approximately 12 w/o ^{240}Pu) fuel compositions.

B. Subassembly Configurations

Each subassembly is composed of small plates of fuel and moderator materials loaded in drawers that are grouped to form a four-drawer subassembly. Figure II-2 is a plate-by-plate representation of the A and B drawers loaded with high- ^{240}Pu -type fuel in a four-drawer inner driver subassembly. Similarly, Figures II-3 and II-4 show the plate arrangements for the low- ^{240}Pu -type fuel in the inner driver and outer driver subassemblies, respectively.

HEDL 7703-202.2

FIGURE II-1. BOL-REF-5S LWR-Zone Configuration with PSR-705 Inserted.

HEDL 7703-202.1

FIGURE II-2. Platelet Loading Pattern in High- ^{240}Pu Fuel Composition Subassembly of Inner Driver of EMC/LWR.

HEDL 7704-024.3

FIGURE II-3. Platelet Loading Pattern in Low- ^{240}Pu Fuel Composition Subassembly of Inner Driver of EMC/LWR.

HEDL 7603-17.2

FIGURE II-4. Platelet Loading Pattern of Low-²⁴⁰Pu Fuel Composition Subassembly of Outer Driver of EMC/LWR.

The subassemblies identified as 101 (matrix positions 22-22, 22-23, 23-22, 23-23), 512 (matrix positions 17-29, 17-30, 18-29, 18-30), and 722 (matrix positions 22-35, 22-36, 23-35, 23-36) in Figure II-1 are the locations chosen for measurement of the exchange worths of the inner driver fuel, outer driver fuel and radial reflector compositions, respectively. (Matrix positions are identified by row number and column number, in that order.)

C. Sequence of Worth Measurements

The sequence of measurements⁽¹⁾ was initiated by establishing the reference subcriticality of the configuration of Figure II-1. Steps performed after the establishment of the reference configuration are described below and in Table II-1. These were as follows:

- Step 1 - Exchange of high-²⁴⁰Pu fuel composition for low-²⁴⁰Pu fuel composition in subassembly 101. Specifically, subassembly 101 as shown in Figure II-2 was exchanged for subassembly 101 as shown in Figure II-3.
- Step 2 - Exchange of high-²⁴⁰Pu fuel composition for carbide fuel composition in subassembly 101. In this exchange, subassembly 101 given in Figure II-2 was exchanged for subassembly 101 given in Figure II-5.
- Step 3 - Exchange of low-²⁴⁰Pu fuel composition for carbide fuel composition in subassembly 512 of the outer driver. Here subassembly 512 given in Figure II-4 was exchanged for subassembly 512 as shown in Figure II-6.
- Step 4 - Exchange of radial reflector (RR) composition for UO₂ blanket composition in subassembly 722. In this exchange, subassembly 722, given in Figure II-7, was replaced with subassembly 722, shown in Figure II-8.

HEDL 7704-024.2

FIGURE II-5. Platelet Loading Pattern of Carbide-Plutonium Fuel Composition Subassembly of Inner Driver of EMC/LWR.

HEDL 7704-024.4

FIGURE II-6. Platelet Loading Pattern of Carbide-Plutonium Fuel Composition Subassembly of Outer Driver of EMC/LWR.

HEDL 7704-024.1

FIGURE II-7. Platelet Loading Pattern of Radial Reflector Composition Subassembly.

HEDL 7704-024.5

FIGURE II-8. Platelet Loading Pattern of UO_2 Blanket Subassembly.

TABLE II-1

COMPOSITION EXCHANGE STEP AND REACTIVITY VALUES MEASURED
DURING SUBASSEMBLY WORTH MEASUREMENTS

	<u>Step i</u>	<u>Subassembly</u>	<u>Excess Reactivity, ρ_i Corrected to 25°C 1h</u>
1.	Reference configuration BOL-REF-5S EMC core with PSR-705 inserted	-	-461.301 $\pm$ 2.185
2.	Exchange high- ²⁴⁰ Pu fuel for low- ²⁴⁰ Pu fuel	101	-460.655 $\pm$ 2.396
3.	Exchange high- ²⁴⁰ Pu fuel for carbide-plutonium fuel	101	-572.793 $\pm$ 3.422
4.	Exchange low- ²⁴⁰ Pu fuel for carbide-plutonium fuel	512	-514.066 $\pm$ 2.290
5.	Exchange radial reflector composition for UO ₂ blanket composition	722	-515.932 $\pm$ 1.299

The reactivity for each core configuration is designated ρ_i . Reactivity of the reference core configuration is designated ρ_0 . Quoted errors include statistically measured errors and table closure reactivity error.

During each step i , the subcriticality ρ_i of the core configuration was measured. The measured values of ρ_i reported in Reference 1 are presented in Table II-1.

D. Reactivity Corrections

The reactivity measurements were performed at different dates. Since the measured worth of a material change represents the reactivity change from the reactivity ρ_0 of the reference configuration to the reactivity ρ_i of the measured configuration, the reactivity data of Table II-1 had to be adjusted for the effects of ^{241}Pu decay.

The worths $\rho_i - \rho_0$ were adjusted for ^{241}Pu decay reactivity effects using a ^{241}Pu reactivity decay coefficient of -0.480 Ih/day .

The adjusted measured worths are presented in Table II-2. Worth uncertainties include the statistical reactivity uncertainties of each configuration and a $\pm 2.4\text{-Ih}$ table closure uncertainty.

TABLE II-2
MEASURED SUBASSEMBLY WORTH (Ih)

	<u>Composition Exchange</u>	<u>Subassembly</u>	<u>Measured $\rho_i - \rho_0$</u>
1)	High- ^{240}Pu for low- ^{240}Pu	101	$+1.126 \pm 4.694$
2)	High- ^{240}Pu for carbide fuel	101	-110.5 ± 5.3
3)	Low- ^{240}Pu for carbide fuel	512	-49.88 ± 4.64
4)	Radial reflector for UO_2 blanket	722	-51.27 ± 4.24

* ρ_0 represents reactivity of initial core configuration.

ρ_i represents reactivity of core configuration resulting from composition exchange i .

III. ANALYTIC MODEL

A. Description of Calculational Model

The composition exchange worths of low- ^{240}Pu fuel, carbide fuel and UO_2 blanket compositions were calculated using the two-dimensional diffusion theory code 2DBS⁽²⁾ and the two-dimensional perturbation code PERT-V.⁽³⁾ The calculations were performed in x,y geometry using a set of 42 energy-group resonance and spatially self-shielded cross sections that were developed specifically for analysis of experiments in the EMC/LWR.⁽⁴⁾ These cross sections were prepared from the FTR Set 300S⁽⁵⁾ cross section library.

The worth of each subassembly exchange was calculated as a reactivity change relative to that of the initial core configuration, BOL-REF-5S LWR-zone core configuration with PSR-705 inserted, Figure II-1.

The average atom densities for each composition in the core were obtained from Reference 1. In addition, the inner driver and outer driver compositions were corrected for decay of ^{241}Pu to ^{241}Am . The decay of ^{241}Pu to ^{241}Am was corrected to October 16, 1974 from the original date of analysis of each material composition using a 14.8-year ^{241}Pu half-life.

The inner and outer driver regions of the reference core configuration consist of approximately equal numbers of type A and type B drawers. The actual number of each type was accounted for in developing each zone of the core model used for the calculations.

Subassemblies 101 in the inner driver, 512 in the outer driver, and 722 in the reflector consist of two type A and two type B drawers. However, the UO_2 blanket subassembly consists of four drawers of one type.

From material content of each subassembly, a unit cell average composition was derived for each of the fuel and UO_2 blanket compositions. These atom densities are given in Table III-1.

TABLE III-1

UNIT CELL ATOM DENSITIES FOR FUEL AND REFLECTOR-BLANKET COMPOSITIONS
(x 10⁻²¹ atom/cc)

Isotope or Element	Unit Cell Inner Driver Fuel Compositions			Unit Cell Outer Driver fuel Compositions		Unit Cell Radial Reflector and Blanket Compositions	
	<u>tow-²⁴⁰Pu</u>	<u>High-²⁴⁰Pu</u>	<u>Carbide</u>	<u>tow-²⁴⁰Pu</u>	<u>Carbide</u>	<u>RR</u>	<u>UO₂</u>
²³⁹ Pu	1.329	1.255	1.329	1.624	1.624	-	-
²⁴⁰ Pu	0.176	0.482	0.176	0.204	0.204	-	-
²⁴¹ Pu	0.020	0.077	0.020	0.022	0.022	-	-
²⁴¹ Am	0.013	0.022	0.013	0.009	0.009	-	-
²³⁵ U	0.012	0.016	0.021	0.011	0.019	-	0.021
²³⁸ U	5.408	7.537	9.802	5.074	8.700	-	9.833
Fe	16.540	10.818	10.829	17.815	11.153	11.143	8.443
Ni	1.435	1.433	1.435	1.480	1.482	57.567	1.086
Cr	3.099	3.096	3.099	3.189	3.194	3.132	2.409
Mn	0.243	0.243	0.243	0.251	0.251	0.397	0.187
Mo	0.350	0.339	0.350	0.453	0.453	0.015	0.010
C	0.032	0.032	10.815	1.075	10.815	0.037	0.028
Si	0.192	0.192	0.192	0.197	0.198	0.198	0.153
Na	8.807	8.807	8.807	8.786	8.807	3.093	6.776
O	12.974	10.856	-	13.142	-	-	19.789

B. Method of Calculating Subassembly Worths

Two-dimensional direct and adjoint fluxes and a K_{eff} value were calculated for the reference configuration. In this configuration, subassembly 101 contained the high- ^{240}Pu fuel composition, subassembly 512 contained the low- ^{240}Pu fuel composition, and subassembly 722 contained the reflector material. Subsequent to this calculation, direct fluxes and K_{eff} values were calculated for the reference core, with each material composition exchange defined in steps 1 through 4 of Section II.

All calculations were performed using 2DBS with 33 mesh intervals in each of the x and y directions and a mesh spacing of 5.53 cm. An energy-independent buckling $B^2 = 566 \times 10^{-6} \text{ cm}^{-2}$ derived from an RZ-model calculation described in Appendix A was used for all the calculations.

The difference between the K_{eff} of the initial configuration and the K_{eff} for the configuration containing a material exchange provided the exchange worth of the material composition using the direct eigenvalue difference method.

The direct and adjoint fluxes calculated for the reference configuration were also used in first-order perturbation theory to calculate the worth of each of the exchanged materials. The first-order perturbation theory uses the direct flux and adjoint flux and the geometric configuration of the unperturbed system (reference core) in PERT-V to calculate the perturbation worth. The volume set in the numerator of the perturbation expression is chosen to match the perturbation volume.

In the calculations, outer driver cell-averaged cross sections for uranium and oxygen were used with radial reflector cell-averaged cross sections in the UO_2 blanket composition. Cell-averaged cross sections appropriate for the inner and outer driver compositions were used in the makeup of the compositions for subassemblies 101 and 512, respectively.

IV. CALCULATED RESULTS

The exchange worth of each of the low-²⁴⁰Pu fuel, carbide fuel, and UO₂ blanket compositions has been calculated using diffusion theory and first-order perturbation theory. The purpose of these calculations was to investigate the relative merits of each method in obtaining good agreement between the calculated and experimentally measured composition exchange worths. The details of each type of calculation and the computational results are given below.

A. Two-Dimensional Diffusion Theory

Two-dimensional diffusion theory calculations using 2DBS provided the results for the calculation of the exchange worth using a direct eigenvalue difference method. K_{eff} values and two-dimensional fluxes in 42 energy groups were calculated for each composition exchange in the basic core configuration of Figure II-1. The calculations were performed first for the reference configuration, and then again for the reference configuration with each replacement of the material compositions of subassemblies 101, 512, and 722, as defined by steps 1 through 4 of Section II.

Since the measured composition exchange worths are given as reactivity expressed in In-hours (Ih), Table II-2, it was necessary to convert the eigenvalue data to reactivity in In-hours by using a conversion factor of 978.4 In-hours per percent reactivity. This factor was calculated by the method described in Appendix B.

The reactivity change between the calculated reactivity of the initial configuration ρ_0^C and the reactivity ρ_i^C for each material exchange provided the calculated worths ($\rho_0^C - \rho_i^C$) of the low-²⁴⁰Pu fuel, carbide fuel, and UO₂ blanket subassemblies for direct comparison with the measured values.

Table IV-1 shows the measured composition exchange worths ($\rho_0^M - \rho_i^M$) and the calculated worths ($\rho_0^C - \rho_i^C$) obtained from the eigenvalue difference method and the corresponding calculated-to-experimental ratio, C/E, for each case.

TABLE IV-1

MEASURED AND CALCULATED COMPOSITION EXCHANGE WORTHS (Ih) AND
CALCULATED VALUE-TO-EXPERIMENTAL VALUE RATIOS

Step No.	Composition Exchange	Sub- assembly	Measured Worths	Direct Eigenvalue Difference		First-Order Perturbations	
			$\rho_0^M(Ih) - \rho_j^M(Ih)$	$\rho_0^C(Ih) - \rho_j^C(Ih)$	C/E	$\rho_0^{FOP}(Ih) - \rho_j^{FOP}(Ih)$	C/E
1	High- ²⁴⁰ Pu fuel composition for low- ²⁴⁰ Pu fuel composition	101	+1.126 ± 4.694	+43.3	38.41	+37.15	32.99
2	High- ²⁴⁰ Pu fuel composition for carbide fuel composition	101	-110.5 ± 5.3	-131.01	1.19	-137.62	1.25
3	Low- ²⁴⁰ Pu fuel composition for carbide fuel composition	512	-49.88 ± 4.64	-74.16	1.49	-74.51	1.49
4	Radial reflector composition for UO ₂ blanket composition	722	-51.27 ± 4.24	-53.62	1.05	-50.8	0.99

$\rho_0(Ih)$ = reactivity of initial core configuration (In-hours).

$\rho_j(Ih)$ = reactivity of core configuration with composition exchanged (In-hours).

B. Perturbation Method

Two-dimensional calculations using PERT-V provided the composition exchange worths using first-order perturbation theory.

In these calculations the direct flux, adjoint flux and geometry of the reference core configuration were used in PERT-V to calculate the reactivity coefficient for each isotope present in a material composition. This coefficient is calculated from the perturbation expression, in which the volume set in the numerator of the perturbation expression was chosen to match the perturbation volume (volume of subassembly).

The sum of the reactivity coefficient for each isotope summed over all isotopes in the exchange composition provided the reactivity worth ρ_i^{FOP} of the material composition. The difference between the reactivity worth of the exchange composition ρ_i^{FOP} and the reactivity worth of the initial core composition within the same subassembly volume ρ_0^{FOP} provided the worth of the material exchange.

Table IV-1 shows the worths $(\rho_0^{FOP} - \rho_i^{FOP})$ for each composition change calculated by first-order perturbation theory. Also given in the table are the calculated-to-experimental ratios.

V. DISCUSSION OF RESULTS

Table IV-1 shows that the agreement between the calculated and experimentally measured worths for the exchange of high- ^{240}Pu fuel composition for low- ^{240}Pu fuel composition is poor. The large uncertainty in the C/E values reflects the large (400%) uncertainty in the measured reactivity exchanged worths. Reference 1 states that designing the experiment such that the high- ^{240}Pu fuel composition and the low- ^{240}Pu fuel composition were closely matched in reactivity resulted in a large uncertainty (400%) in the small measured worth of the exchange of high- ^{240}Pu fuel composition for low- ^{240}Pu fuel composition in subassembly 101. This large uncertainty coupled with the inherent uncertainty of the calculations (which may be a few In-hours in low-worth calculations) leads to the poor C/E values shown in Table IV-1.

For the larger carbide and blanket exchange worths, the C/E values are considered typical for the approximate models and methods employed in the calculation. Worth calculations for exchange of the plutonium fuel composition for carbide-plutonium fuel composition ranges from 25% overprediction of the exchange worth in inner driver subassembly 101 to 49% overprediction of the exchanged worth in outer driver subassembly 512.

Replacement of the radial reflector with UO_2 blanket composition in subassembly 722 leads to C/E values ranging from 0.9% underprediction by first-order perturbation theory to 5% overprediction with the eigenvalue difference method.

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APPENDIX A

EMC/LWR CORE TRANSVERSE BUCKLING

An energy-independent buckling, $B^2 = 566 \times 10^6 \text{cm}^2$, was calculated for the BOL-REF-5S LWR-zone configuration, Figure II-1, with PSR-705 withdrawn. This buckling value was derived from a comparison of RZ model diffusion calculations for both the BOL-REF-5S LWR-zone core configuration and BOL-REF-5S configuration. The latter configuration differs from the first only in that the high- ^{240}Pu fuel compositions in the inner driver of the LWR-zone core configuration are replaced by low- ^{240}Pu inner driver fuel compositions.

Previous RZ calculations for the BOL-REF-5S core configuration show that the value of K_{eff} obtained using the RZ model is much lower than that obtained from three-dimensional calculations for the same core configuration.⁽⁶⁾

The problem arises in using a model with radial symmetry to describe the nonsymmetric configuration of the core. For example, with reference to Figure II-1, the primary effect of the low K_{eff} would result from the representation of the Row 5 control rods and the Row 7 peripheral shim rods as cylindrical shells containing the high-absorbing material boron. The distribution of the boron in such a manner gives the boron a higher worth, which in turn results in a lower K_{eff} . Previous calculations showed that this effect could be compensated for in the RZ model calculation by reducing the atom density of each material component of the control rod and peripheral shim rod compositions. The amount of reduction in the atom densities of these material compositions was chosen such that the K_{eff} obtained from the RZ calculation of the BOL-REF-5S core was approximately the same as the K_{eff} obtained from three-dimensional calculations of the same core.

Three-dimensional calculations for the BOL-REF-5S LWR-zone core configuration are not available for direct comparison with an RZ calculation. Therefore, it was necessary to derive a transverse buckling for the LWR-zone core configuration from a comparison of the BOL-REF-5S LWR-zone core with the

BOL-REF-5S core RZ calculations. In both calculations, the atom densities of the control rod and peripheral shim rod materials were reduced to 55.8 percent of their actual value on the basis of the calculations performed in Reference 6.

From previous evaluations of two- and three-dimensional calculations of the BOL-REF-5S core configuration,⁽⁷⁾ it was shown that a $B^2 = 565 \times 10^{-6} \text{ cm}^{-2}$ is required in an x,y calculation to obtain a K_{eff} in good agreement with three-dimensional K_{eff} . Using this value of B^2 and heterogeneous cross sections based on low-²⁴⁰Pu fuel compositions⁽⁴⁾ in an x,y calculation of BOL-REF-5S core configuration, a $K_{\text{eff}} = 0.9961$ is obtained. This K_{eff} value was used as a basis for calculating a transverse buckling from a one-dimensional radial calculation of the BOL-REF-5S configuration. The transverse buckling was calculated by choosing a buckling in a radial model representation of the core such that the radial calculation gave the same K_{eff} as an RZ calculation.

Table A-I shows the K_{eff} value obtained from an RZ calculation of the BOL-REF-5S core and its reasonably good agreement with a K_{eff} value obtained from an x,y calculation with $B^2 = 565 \times 10^{-6} \text{ cm}^{-2}$. Also given in the table is the buckling $B^2 = 578 \times 10^{-6} \text{ cm}^{-2}$ determined from the RZ and radial model calculations.

The RZ model representation of the BOL-REF-5S LWR-zone configuration is shown in Figure A-1. This model was designed to represent the LWR-zone core configuration with cylindrical symmetry while conserving the total volume of each region of the core, the total mass of each material composition, and the approximate distance of the material compositions from the axial centerline of the core. The volume fraction of materials comprising each zone of Figure A-1 is given in Table A-II. The eigenvalue for the $K_{\text{eff}} = 0.9999$ RZ model was calculated using the two-dimensional diffusion theory code 2DBS.⁽²⁾ By requiring that the K_{eff} obtained from a radial calculation of the LWR core model be the same as that of the RZ calculation, a buckling $B^2 = 579 \times 10^{-6} \text{ cm}^{-2}$ was determined.

Since the buckling values derived from the RZ calculations, specifically $B^2 = 578 \times 10^{-6} \text{cm}^{-2}$ for BOL-REF-5S core configuration and $B^2 = 579 \times 10^{-6} \text{cm}^{-2}$ for BOL-REF-5S LWR-zone core configuration, differ by $1 \times 10^{-6} \text{cm}^{-2}$, it is assumed that this same change is reflected in the B^2 value derived from the x,y calculation. Thus a value of $B^2 = 566 \times 10^{-6} \text{cm}^{-2}$ is chosen for all x,y calculations of the BOL-REF-5S LWR-zone core calculations.

TABLE A-I

K_{EFF} AND BUCKLING VALUES OBTAINED FOR THE
BOL-REF-5S CORE CONFIGURATION

	<u>x,y Model</u>	<u>RZ Model</u>
K_{eff}	0.9961	0.9965
B^2	0.00565	0.000578

TABLE A-II

VOLUME FRACTION OF MATERIALS USED IN EACH
ZONE OF THE RZ MODEL

<u>Zone No.</u>	<u>Fraction</u>	<u>Materials</u>
1	0.5	Type A Inner Driver High- ²⁴⁰ Pu
	0.5	Type B Inner Driver High- ²⁴⁰ Pu
2	0.36	Type A Inner Driver High- ²⁴⁰ Pu
	0.32	Type B Inner Driver High- ²⁴⁰ Pu
	0.16	Material Test Loop
	0.16	General Purpose Loop
3	0.3061	Type A Inner Driver High- ²⁴⁰ Pu
	0.4082	Type B Inner Driver High- ²⁴⁰ Pu
	0.0241	Type A Inner Driver Low- ²⁴⁰ Pu
	0.0241	Type B Inner Driver Low- ²⁴⁰ Pu
	0.2449	Sodium Channel
4	0.1757	Type A Inner Driver High- ²⁴⁰ Pu
	0.1351	Type B Inner Driver High- ²⁴⁰ Pu
	0.2297	Type A Inner Driver Low- ²⁴⁰ Pu
	0.1892	Type B Inner Driver Low- ²⁴⁰ Pu
	0.1622	Material Test Loop
	0.05405	General Purpose Loop
	0.05405	Special Purpose Loop
5	0.4706	Type A Outer Driver Low- ²⁴⁰ Pu
	0.3529	Type B Outer Driver Low- ²⁴⁰ Pu
	0.0588	Type A Outer Driver Operational Matrix
	0.1176	Type B Outer Driver Operational Matrix
6	0.5	Control Rod
	0.5	Sodium Channel
7	0.5854	Type A Outer Driver Low- ²⁴⁰ Pu
	0.4146	Type B Outer Driver Low- ²⁴⁰ Pu
8	0.5116	Type A Outer Driver Low- ²⁴⁰ Pu
	0.4574	Type B Outer Driver Low- ²⁴⁰ Pu
	0.03101	Special Purpose Loop
9,11	1.0	Radial Reflector
10	1.0	Peripheral Shim Rod

TABLE A-II (continued)

VOLUME FRACTION OF MATERIALS USED IN EACH
ZONE OF THE RZ MODEL

<u>Zone No.</u>	<u>Fraction</u>	<u>Materials</u>
12	1.0	Sodium Gap
13,25	1.0	Axial Reflector
14	0.24323 0.75677	Sodium Channel Axial Reflector
15,27	0.1705 0.8295	Operational Matrix Axial Reflector Axial Reflector
16	1.0	Sodium Channel
17,24	1.0	Reflector Follower
18,29	1.0	Spring Gap
19	1.0	Axial Shield
20	0.24323 0.75677	Control Shield Axial Shield
21	0.1705 0.8295	Operational Matrix Axial Shield Axial Shield
22	1.0	Control Shield
23,34,35	1.0	Reflector Shielding
26	0.24323 0.75677	Control Rod Axial Reflector
28	1.0	Control Rod Plenum
30	1.0	Core Plenum
31	0.24323 0.75677	Core Rod Core Plenum
32	0.1705 0.8295	Operational Matrix Core Plenum Core Plenum

TABLE A-II (continued)
VOLUME FRACTION OF MATERIALS USED IN EACH
ZONE OF THE RZ MODEL

<u>Zone No.</u>	<u>Fraction</u>	<u>Materials</u>
33	0.5 0.5	Control Rod Control Rod Plenum
36	1.0	Handling Socket
37	0.24323 0.75677	Control Rod Handling Socket
38	0.1705 0.8295	Operational Matrix Handling Socket Handling Socket
39	0.5 0.5	Control Rod Control Rod Shaft
40	1.0	Drive Shaft

APPENDIX B

KINETICS PARAMETERS FOR BOL-REF-5S LWR-ZONE CORE CONFIGURATION WITH PSR-705 INSERTED

This section describes the procedure used to compute the effective delayed neutron fraction, β_{eff} , and the inhour-to-percent $\Delta k/k$ conversion factor for the BOL-REF-5S LWR-zone core configuration with PSR-705 inserted. These parameters were computed following the procedure used in Reference 8.

Calculation of the kinetics parameters was performed using the two-dimensional perturbation code PERT-V. Direct and adjoint fluxes were calculated for the reference core configuration, Figure II-1, using 2DBS code in x,y geometry and 42 energy groups. The calculations used thirty-three mesh intervals in each direction and a mesh spacing of 5.53 cm. An energy-independent buckling $B^2 = 566 \times 10^{-6} \text{ cm}^{-2}$ was used. The 42 energy group cross sections used were the heterogeneous cross sections developed for the analysis of EMC/LWR experiments.⁽⁴⁾

Six precursor groups and the fissionable isotopes ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{235}U and ^{238}U were used in the calculations. The delayed neutron data for the isotopes were taken from those included in ENDF/B-IV and presented by S. A. Cox in Reference 9.

The results obtained from PERT-V include the effective delayed neutron fraction $\beta_{\text{eff}} = 3.175 \times 10^{-3}$ and the reactivity associated with a period of one hour, given as $\frac{\Delta k}{k} = 1.0221 \times 10^{-5}$. From these data the coefficients inhour per-dollar and inhour-to-d/o- $\Delta k/k$ were calculated. The kinetics parameters are summarized in Table B-I.

TABLE B-I
KINETICS PARAMETERS

β_{eff}^*	$\text{Inhours}(\Delta k/k)^*$	$\text{Inhours/dollar}^{**}$	$\text{Inhours}/\% \Delta k/k^{***}$
3.175×10^{-3}	1.0221×10^{-5}	310.6	978.4

* $\beta_{\text{eff}} = \sum_{i=1}^6 \beta_{\text{eff}_i} (\beta_{\text{eff}_i})$ = fraction-delayed neutrons in precursor group

** $\text{Inhours/dollar} = \beta_{\text{eff}}/\Delta k/k$

*** $\text{Inhours}/\% \Delta k/k = (100 \Delta k/k)^{-1}$

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