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SOME PHYSICS ASPECTS OF THE PLUTONIUM EXPERIMENT IN EBWR

by

B. J. Toppel and R. Avery

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B. J. Toppel and R. Avery

Reactor Physics Division

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I. INTRODUCTION

In anticipation of completion of the previously planned EBWR⁽¹⁻⁵⁾ program, the Division of Reactor Development of the AEC early in 1962 requested Argonne to participate in the Plutonium Recycle Program with particular emphasis on the part of the work that would be appropriate using the EBWR facility. Research at Hanford had for some time been concerned with heavy-water-moderated plutonium-fueled reactors, but there was a general lack of information concerning the corresponding light-water-moderated system.

A joint Argonne-Hanford program has evolved which will make use of the EBWR facility and which is now under way for the purpose of obtaining information useful for the utilization of plutonium as a fuel in light-water thermal systems. Such utilization could be made in either an all-thermal plutonium recycle system, or as the thermal part of a mixed fast-thermal reactor complex.

The potential advantages of plutonium recycle have long been recognized. In the fast-reactor area, these advantages are primarily, if not exclusively, related to the possibility of achieving a fuel cycle with a substantial breeding gain. Argonne is pursuing a vigorous program in connection with the fast system. In the thermal area, the potential advantages are perhaps less clear-cut, though not necessarily less real. Probably plutonium recycle in thermal reactors is primarily motivated by the desire to achieve modes of operation not otherwise possible, either longer irradiations, or the use of a lower enrichment feed.

An example of the mixed fast-thermal system is the following. A normal fast power reactor is used. The blanket fuel elements are irradiated until the desired plutonium concentration is achieved. The blanket elements are then transferred without reprocessing to the thermal reactor where they are used as fuel. The fuel elements are irradiated in the thermal reactor to as high a burnup as is practical. The fuel, which contains a considerable amount of the higher plutonium isotopes, is reprocessed, and the plutonium is used as makeup material for the fast reactor core.

An encouraging facet to this cycle is that studies carried out on fast systems have indicated that the blanket may not be able to pay for itself in such systems. The above system would alleviate the charges against the blanket, since these costs would be the same as those required for fueling the thermal core. Also, it appears that plutonium containing much of the higher isotopes is advantageous, in terms of neutron economy, as fast-reactor feed material.

The physics information required for the development of either the all-thermal or the mixed fast-thermal concept is essentially the same. Since the main objective is the attainment of certain rather basic numbers, in particular, obtaining data on the isotopic behavior of plutonium as it is irradiated in a thermal reactor, the experiment should be made as simple as possible while still yielding this information so that it would be most amenable to analysis.

In specifying an EBWR experiment that would be useful in the plutonium recycle program, the following considerations were kept in mind. Modifications to EBWR should be kept to a minimum. It should remain a boiling H_2O system. EBWR should be used primarily as an irradiation facility rather than in support of an active reactor experimental program. In this sense, the exact reactor configuration is somewhat arbitrary.

Because of the general lack of information regarding plutonium-fueled, light-water-moderated reactors, and in order to design a useful experiment, it was necessary to embark first on a series of survey calculations. These would permit one to observe the effects of major parameter variations such as size of plutonium zone, plutonium zone enrichment, composition of driver zones (if any), etc. The results of such calculations could then be considered in the light of the limitations imposed by the use of the EBWR facility itself.

The major portion of this report is concerned with the above-mentioned survey calculations. To clarify the subsequent discussion, the experiment that has evolved from the survey calculation results given in this report will be briefly outlined.

In the planned experiment on EBWR, the 148-element core (Fig. 1) is divided into four zones; the central 6×6 square, the immediately adjacent 28-element row, the next 32-element row (excluding the fuel elements on the 45° symmetry lines), and the remaining 52 outside elements. One of the outside elements will be replaced with an antimony-beryllium neutron source.

Each fuel element consists of a 6×6 array of fuel-bearing Zircaloy tubes of 0.372-in. ID with 0.025-in. walls (0.945-cm ID with 0.064-cm walls). These elements are similar to those of the EBWR Core 2 reference design. (6)

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Fig. 1. Schematic Layout of
Plutonium Experiment
in EBWR

control rods will be boron-stainless steel rods as before, but the boron will be enriched to approximately 90% in B^{10} rather than containing natural boron.

The plutonium fuel elements are designed for a burnup of 0.025 (~25,000 MWd/tonne), although no definite duration has been set for the experiment. It will be continued as long as feasible, if useful information on isotopic change behavior can be obtained.

The fuel element boxes in the central region are somewhat different than those in the remainder of the core. They are of a "take-apart" design and allow the withdrawal and replacement of individual rods within the element. This feature permits isotopic analysis studies of the central region as the burnup proceeds, and is essential to the success of the experiment, since the comparison of the measured and calculated isotopic variation is the main objective of the experiment.

The program includes critical experiments to be performed before the start of irradiation. These experiments have been performed partly

The central zone represents the plutonium test region. It contains mixed plutonium-uranium oxides.

The two rows surrounding the plutonium region may be referred to as the enriched uranium shim zones, and these rows may have their reactivity periodically increased to restore the reactivity of the overall system. They will initially have the same composition and will contain europium and samarium oxide burnable poisons to minimize the reactivity variation with burnup.

The outer 52-element region will contain natural uranium and is not intended to be replaced during the experiment.

The system is fully reflected with light water.

One of the control rods, fabricated from hafnium, will be similar to that used previously in EBWR⁽⁴⁾ and will be used again for oscillator measurements. The remaining eight control

at Hanford on rods similar to those shipped to Argonne for assembly into the fuel elements. At Argonne, critical experiments will be performed within the EBWR vessel. In particular, clean (i.e., no control rods inserted) critical configurations on only the plutonium elements will be obtained. Boric acid will be inserted to achieve criticality. Various reactivity coefficients will be measured, and other standard measurements will also be made. In particular, transfer-function measurements to test the system stability will be made after loading the driver zones and during the approach to power.

The system will then be irradiated to an average level of the order of 2000 MWd/tonne, in the plutonium region. At an initial power of about 40 MW and with sustained operation, this would require about 4 months. Correspondingly longer times would be involved if only lower powers can be attained or if sustained operation is not achieved. At the end of this irradiation step, the irradiated system will be investigated. This will consist of removing some plutonium rods from the system. A selection of the order of 12 rods will be sufficient to map the plutonium region. The rods will then be shipped to Hanford for isotopic analysis. Further measurements will be made at this time on the reactivity of the system. It will again be highly desirable to come to a clean condition, that is, where the assembly contains only the plutonium elements and the system is made critical by the addition of the proper amount of boric acid. Further measurements of items related to various reactivity coefficients will also be made at this time.

After these measurements are made, the irradiation will proceed for the next major time step, perhaps again of the order of 2000 MWd/tonne in the plutonium region.

Because of burnup of the plutonium zone and redistribution of the power, this second step will require about 5 months, again assuming sustained operation at a power of 40 MW.

The observed reactivity and control rod worth variations during the course of the irradiation will determine the desirability of altering the enrichment or poison content of the shim zone. If such variation is desirable, it is expected that only the 28-element shim row immediately adjacent to the plutonium test region will be changed.

The program, outlined above, of irradiation and periodic sampling and analysis of the plutonium fuel will be continued as long as the useful information derived thereby is consistent with the interest in the experiment and the effort required to achieve the required irradiation.

Comparison of the isotopic analyses obtained for the plutonium fuel with calculational predictions during the irradiation will facilitate the setting up of a mathematical model that should serve as the basis for future calculations for prototype systems of either the all-thermal recycle type, or the fast-thermal complex.

Details of the EBWR plant, as well as engineering details of the experiment, are described in other reports.^(1-5,7) The calculational model and results derived thereby, which have evolved as a result of the survey work described here, are reported on generally in References 7 and 8. Following a description of the survey calculational procedure and results, several special topics pertinent to the final calculational model will be discussed. The reasons for the changes in the proposed experiment from the early conclusions of the survey calculations (Section III-C) to the experiment just outlined will be considered in Section V.

II. DESCRIPTION OF SURVEY CALCULATIONAL METHODS

A. General Comments

Since many problems would be involved in the survey work, it was desirable to economize on computing time. To this end, several compromises were made in the computational model. For example, most of the calculations were made using a one-dimensional cylindrical model of the actual geometry (Fig. 1). As will be pointed out later, composition-dependent, microscopic cross sections were not obtained specifically for each system examined, but were rather generated by linearly combining cross sections appropriate to two of the specific compositions to be considered. For the survey work, the regional void distribution versus power was not considered in great detail, but rather voids were estimated based on the earlier EBWR results.^(4,5) Finally, such items as resonance self-shielding of cross sections, Dancoff effects, thermal flux weighting considerations, and control rod epithermal self-shielding effects, were treated rather simply for these first studies.

The results to be presented here should be considered in the light of the assumptions made in the computational model. These results have served as a guide to specifying the experiment in EBWR, and as a base upon which to build the final computational model.^(7,8)

B. Geometrical and Compositional Considerations

Figure 2 shows the typical nine-element cell considered for the EBWR. The fuel element shown contains a 6 x 6 array of fuel rods similar to those of the EBWR Core 2 reference design.⁽⁶⁾ These rods have a 1.072-cm OD and are clad with 0.0635-cm-thick Zircaloy. A second design was also considered which consisted of a 5 x 5 square array of the same pins having a 1.828-cm pitch.

In generating composition volume fractions, two basic cells were considered.⁽³⁾ In the first, the cell had the dimensions 12.75 x 12.75 in. (Fig. 2), bounded by the center lines of the control rod channels, and included all reactor materials (control rod guides, spacers, control rod followers, and total water). This cell was used for unrodded cold or hot calculations and will be designated as the "large cell." Other than the fuel and water, all materials in the large cell are Zircaloy.

The second cell considered had the dimensions of 12.25 x 12.25 in. including nine fuel elements and bounded by the control rod guide structure. This cell was used mainly for cold control rod calculations in which the fuel elements were to be considered separately from the control rod channels. This cell is designated as the "small cell." For these survey calculations, the control rods were, as in earlier EBWR work,^(3,4) assumed to be 2 w/o natural boron in stainless steel.

Fig. 2. Typical Nine-element Cell

Table I lists the fuel, Zircaloy, and water-volume fractions in the small and large cell cases, and for the 6 x 6 and 5 x 5 fuel-pin geometries. The average volume fractions as determined above were also used in the uranium regions of the reactor even though they are most appropriate for the plutonium zone (because of the different control rod guide structure). Only the 6 x 6 pin array was considered in the uranium regions.

TABLE I CELL VOLUME FRACTIONS

Materials	Large Cell		Small Cell	
	6 x 6 Pins	5 x 5 Pins	6 x 6 Pins	5 x 5 Pins
Fuel	0.21663	0.15044	0.23468	0.16297
Zr	0.18854	0.16955	0.16301	0.14244
H ₂ O	0.59483	0.68001	0.60231	0.69459

For the one-dimensional calculations, the actual geometry was approximated by an equivalent-area cylindrical representation. The cylindrical region boundaries are listed in Table II. The breakdown given there corresponds, in Fig. 1, to the plutonium zone, the first shim zone, the second shim plus natural uranium zones, and the water reflector. At the time of performing the survey calculations, one shim zone plus an outer uranium region was considered.

TABLE II CYLINDRICAL REGION DIMENSIONS

Region	Fuel	Outer Radius, cm	Number of Fuel Elements	Assumed Void Fraction for Hot Calculations
Pu	PuO ₂ -UO ₂	36.55	36	0.3
U1 ^a	UO ₂	48.73	28	0.2
U2 ^a	UO ₂	74.10	84	0.16
H ₂ O Reflector	-	104.10	-	0

^aSee text for discussion of the arrangement of the driver uranium regions U1 and U2.

For the two-dimensional x-y geometry calculations used in calculating control rod worths, the detailed heterogeneous geometry in Fig. 2 was considered with the fuel elements assumed to be homogeneous units. Typical geometrical representations used are shown in Figs. 2 and 3 in Reference 3.

For all of the axially bare calculations, the assumed bare height was 140 cm.

C. Cross-section Prescription and Codes Utilized

Seven- and four-group cross sections were derived using the GAM-1⁽⁹⁾ and MUFT-4⁽¹⁰⁾ codes to generate nonthermal cross sections, and the SOFOCATE⁽¹¹⁾ code for thermal cross sections. The group structures utilized are given in Table III. The large, 1-eV, Pu²⁴⁰ resonance was put into group 6 of the seven-group set and group 3 of the four-group sets, and was calculated using MUFT-4. Since MUFT-4 is a homogeneous composition code, only energy self-shielding in the Pu²⁴⁰ resonance was accounted for. Resonance capture and fission energy self-shielding factors for Pu²³⁹ and U²³⁵ were obtained from two MUFT-4 calculations, one having normal compositions, and the other having very dilute amounts of the

self-shielding isotopes. The self-shielding factors so obtained were applied to the GAM-1 results for group 4 of the seven-group set and group 2 of the four-group sets. The use of MUFT-4 was required since the early GAM-1 library used contained resonance parameters only for U^{238} and Th^{232} .

TABLE III GROUP STRUCTURES FOR SEVEN- AND FOUR-GROUP CROSS-SECTION SETS

Seven-group Set		Four-group Set	
Group	Lower Energy, eV	Group	Lower Energy, eV
1	1.83×10^5	1	5.53×10^3
2	5.53×10^3	2	1.44
3	275	3	0.532
4	6.48	4	0
5	1.44		
6	0.532		
7	0		

The Dancoff factor, which was used to correct the fuel mean chord length for GAM-1 calculations of the U^{238} resonance integrals, was obtained by considering nearest and second-nearest neighboring pins, and ignoring the presence of the zirconium clad. The hot GAM-1 calculations assumed a fuel temperature of 1473°K.

All fuel was oxide, and a pure material nuclear density of 0.022×10^{24} molecules/cc was assumed for all of the heavy oxide isotopes. A zirconium atom density of 0.0425×10^{24} nuclei/cc was used, and the water nuclear density was taken to be 0.0334×10^{24} molecules/cc, multiplied by the product of the water density and one minus the regional average water void fraction due to steam formation.

SOFOCATE was used to generate thermal group cross sections, and for these survey calculations, thermal disadvantage factors were not included. A moderator temperature of 527°K was assumed for the hot cross sections, and 293°K for the cold values. The "bound hydrogen scattering" option in SOFOCATE was assumed for water.

To correct for errors in the then current SOFOCATE library, and to include more recent data, several revisions were made to the SOFOCATE derived values. The Pu^{240} in the SOFOCATE library was multiplied by a factor of 2.5. Also, Pu^{241} fission cross sections were multiplied by 0.43 (assumed for α^{41}) to obtain Pu^{241} capture, since the library values for this quantity were completely in error. In general, the GAM-1 epithermal values for ν were used in the thermal group rather than the SOFOCATE library values. In particular, the thermal values used for ν were 2.91, 3.05, and 2.43 for Pu^{239} , Pu^{241} , and U^{235} , respectively.

Xenon and samarium poisoning effects on reactivity were accounted for by dividing all values of ν by 1.05 for the hot, operating cross sections. This factor overestimated the reactivity effect and provided about a 2% margin of error in the reactivity predictions. This margin of error was desirable because of the uncertainty in the hydrodynamic information regarding void effects. For the cold cross sections, used primarily to calculate the adequacy of shutdown in the cold clean condition, the uncorrected values of ν were used. Nonsaturated fission products in the thermal group were assumed to behave as $1/\nu$ absorbers and to have an absorption cross section of 50 barns per fission at 0.0253 eV.

The calculated thermal cross section for boron was based on its $1/\nu$ behavior and a 755-barn cross section at 0.0253 eV. The B^{10} absorption cross section was $1/0.198$ as large as that of natural boron.

A series of MUFT-4, GAM-1, and SOFOCATE calculations was run to generate cross sections appropriate to the plutonium-zone spectra for plutonium enrichments of 2.5 and 5.0%, for voids ranging from 0 to 0.4, and for the 6 x 6 and 5 x 5 fuel-pin arrays. Table IV indicates the types of problems run and categorizes these according to plutonium enrichment, void, pin array, and temperature. The hot problems were run as seven- and four-group versions and were large-cell problems. The cold problems were four-group small-cell problems.

With reference to Table IV, fuel isotope microscopic cross sections obtained from problems 1 and 6 were used for hot operating calculations, while fuel cross sections from problems 11 and 13 were used in room-temperature calculations. Cross sections at enrichments other than 0.025 or 0.05 were obtained by linearly combining the 0.025 and 0.05 values in amounts appropriate to the enrichment required. Thus, for example, cross sections for an enrichment of 0.01 were approximated by combining 1.6 times the 0.025 values and minus 0.6 times the 0.05 values.

The same microscopic values were used for fuel cross sections for the 6 x 6 or 5 x 5 pin arrays. Also, all the fuel materials were assigned zero transport and zero group-scattering cross sections. These cross sections were accounted for in the so-called "base" materials, which also included the contribution of the zirconium and H_2O in the cell considered. For hot, 6 x 6 pin-array problems, the base cross sections were obtained by combining the results of problems 2, 3, 7, and 8 in Table IV to achieve the appropriate enrichment and void content desired. Similarly, for the 5 x 5 pin array, problems 4, 5, 9, and 10 were utilized. For the cold cross sections, problems 11 and 13 or 12 and 14 were combined according to whether a 6 x 6 or 5 x 5 array was being considered.

Problems 15 and 16 were water-only problems and generated cross sections appropriate for the reflector.

TABLE IV PARAMETERS FOR CROSS-SECTION
GENERATING PROBLEMS

Pu Enrichment	Pin Array	Void	Temperature	Problem
0.025	6 x 6	0.3	Hot	1
0.025	6 x 6	0	Hot	2
0.025	6 x 6	0.4	Hot	3
0.025	5 x 5	0	Hot	4
0.025	5 x 5	0.4	Hot	5
0.05	6 x 6	0.3	Hot	6
0.05	6 x 6	0	Hot	7
0.05	6 x 6	0.4	Hot	8
0.05	5 x 5	0	Hot	9
0.05	5 x 5	0.4	Hot	10
0.025	6 x 6	0	Cold	11
0.025	5 x 5	0	Cold	12
0.05	6 x 6	0	Cold	13
0.05	5 x 5	0	Cold	14
-	-	0	Hot	15
-	-	0	Cold	16

By the device indicated above, of linearly combining cross sections and utilizing the concept of a base material, a wide range of problems can be calculated with reasonable accuracy without becoming overwhelmed by an excessive number of cross-section calculations.

The compositions used for the GAM-1, MUFT-4, and SOFOCATE calculations were appropriate to the plutonium-zone large or small cell described above. The resulting cross sections were used also in the uranium regions of the problems considered. This approach was adopted for the survey work since the region of greatest importance is the plutonium zone. The use of cross sections appropriate for each region, though ultimately desirable for refined calculations, was felt not to be essential for the present purposes.

The macroscopic compositions were always correct for each region, even though the microscopic cross sections used were really most appropriate for the plutonium zone.

The one-dimensional diffusion theory calculations were made using the REX code,⁽¹²⁾ which is an IBM-704 version of the code written for the UNIVAC.⁽¹³⁾

The seven-group, hot cross sections were used with the CYCLE code⁽¹⁴⁾ in performing burnup calculations. For the survey work, variations of microscopic cross sections with burnup were ignored. This

neglect will at first result in an underestimate of the reactivity of the system as burnup proceeds, since the increased self-shielding of the strong, 1-eV, Pu^{240} capture resonance is being ignored.

Two-dimensional diffusion theory problems were run using the PDQ codes.^(15,16) These problems were concerned mainly with control rod worth calculations. As in the physics calculations for the EBWR core 1A,⁽³⁾ a logarithmic boundary condition was assumed for the thermal group such that $(Dd\phi/dx)/\phi = -C$. Here, D is the thermal diffusion coefficient of the medium bordering the rod and as before,⁽³⁾ C was set equal to 0.46948, which corresponds to a black slab bordering core water. Since control rod, epithermal, self-shielding effects have not been included in the survey calculations, the control rod worths to be presented below are overestimates of the true worths.

Since the PDQ codes used allow group-transfer cross sections only between neighboring groups, some assumption was required in generating the four-group cross sections for use with PDQ. It was decided to include all of the actual transfer cross section from a group in the transfer to only the next group for the PDQ calculations. Thus, for example, whereas for REX calculations, group 2 would send neutrons into both groups 3 and 4 with cross sections $\Sigma_{2 \rightarrow 3}$ and $\Sigma_{2 \rightarrow 4}$, for PDQ, $\Sigma_{2 \rightarrow 3}$ was set equal to $\Sigma_{2 \rightarrow 3} + \Sigma_{2 \rightarrow 4}$. This approximation will result in smaller reactivities being calculated by PDQ than by REX since, for example, some neutrons that actually would skip over the epithermal group containing the large Pu^{240} capture resonance, are in PDQ being sent into this group. Estimates of the influence of this approximation were obtained by running REX calculations using both the correct four-group cross sections having the full scattering matrix, and PDQ type cross sections having only $\Sigma_{j \rightarrow j+1}$. The resulting correction factors were applied in the interpretation of the 2D results.

III. SURVEY CALCULATIONS

A. Scope

Various loadings were considered, and the properties of each system were determined. The loadings were of three different types: one, two, or three core zones. In all cases, the system was water-reflected. The one-zone system corresponds to an initially uniform $\text{PuO}_2\text{-UO}_2$ core; the two-zone system corresponds to a central 36-element plutonium region surrounded by a driver uranium region (U1) of a single enrichment; the three-zone system corresponds to a central 36-element plutonium region surrounded by a one-row region (28 elements) with uranium of one enrichment (U1), which in turn is surrounded by a uranium region of a second (lower) enrichment (U2). For the two- and three-zone cases, the U1 and U2 regions always utilized the 6 x 6 fuel-pin array element even when the 5 x 5 array element was considered for the plutonium zone.

Various initial plutonium enrichments in the range of 0.005 to 0.05 were considered for the central plutonium region. An enrichment in the range of 0.015 to 0.025 is of most interest to modern-day technology. In all cases, the plutonium was assumed to initially contain 92 a/o Pu^{239} and 8 a/o Pu^{240} , and was mixed with uranium depleted to 0.2 a/o U^{235} .

The results of these survey calculations are presented in Section B below in Tables V-X.

B. Results

Table V gives initial criticality and power distributions for the various loadings considered. The results are for the hot voided system and were obtained from the seven-group REX calculations. The two-zone loading refers to a central 36-element plutonium zone surrounded by a uniform 112-element uranium zone. The three-zone case again has a central 36-element central plutonium zone, but the outer uranium region is split into a 28-element zone (U1) and an outer 84-element zone (U2). The dimensions are given in Table II.

For the two-zone systems, the enrichment of the uranium region was varied for criticality. For the three-zone systems, the enrichment of the U2 region was specified and the U1 enrichment was varied for criticality.

Uniform plutonium or uranium cores were also considered and are denoted as one-zone systems. For these cases, all 148 elements had the same composition, and the enrichment of either plutonium or uranium needed for criticality was calculated. Power splits are given for the three zones indicated in Table II, even if the one- or two-zone cases are being calculated.

The results given are based on an assumed total power of 40 MW. Table V also gives examples of the effect of using cross sections derived for a 0.025 plutonium-enriched composition in problems having a 0.05 plutonium enrichment. The use of the incorrect cross sections is seen to slightly underestimate the reactivity of the system. One reason for this is the underestimation of the Pu^{240} self-shielding, as compared with cross sections derived at the correct concentration.

Table VI gives initial reactivity coefficients and control rod effects for the various loadings considered. The PDQ-3 code⁽¹⁶⁾ was used for the control rod studies. Comparison between the seven-group results and four-group REX results shows that these are generally in good agreement when the full scattering matrix is used (denoted by full $\Sigma_{j \rightarrow k}$ in the four-group set). The four-group calculations involving transfer only to the next lower group (Σ_{j+1} only) generally underestimate the reactivity by several percent.

Perhaps the most important conclusion that can be drawn from Table VI is that the void coefficient of reactivity increases for the systems having the higher plutonium enrichments. This increased void coefficient results in a larger reactivity swing from cold to hot voided conditions and complicates the control problem as compared to the lower enrichment cores. It may also be noted that the control rod worth is not a very sensitive function of the plutonium-zone enrichment.

Table VII gives the results of a general study on isotopic density and reactivity changes with burnup, as determined by the CYCLE code, for various initial plutonium compositions. Various one- and two-zone systems were examined. For this table, in the case of the single-zone uniform systems, spherical rather than cylindrical geometry was utilized.

The results of Table VII give insight to the desirable duration of the experiment, intended mainly to develop a computational model for predicting the isotopic behavior as irradiation proceeds. Experimental information from such an irradiation will be most useful in a range for which the various plutonium isotopic ratios show significant variation with burnup.

Figure 3 shows various isotopic ratios as a function of plutonium-zone burnup for the 6 x 6 pin-array two-zone system having an initial plutonium zone enrichment of 0.015 and a uranium zone enrichment of 0.01667. As seen in Fig. 3, the isotopic ratios show little variation at burnups well above 0.02 (~20,000 MWd/tonne). The corresponding isotopic densities are plotted against burnup for the same system in Fig. 4.

Table VIII gives the time behavior of the reactivity and of the power distribution for the various loadings under a possible, realistic mode of operation. In the mode chosen, plutonium-zone burnup steps of about 3000 MWd/tonne were chosen, and at the end of each burnup step, the shim was reloaded to restore the system to criticality. In the two-zone cases,

TABLE V INITIAL CRITICALITY AND POWER DISTRIBUTION FOR VARIOUS EBWR LOADINGS

	TWO ZONE											THREE ZONE						ONE ZONE, U OR Pu				
	6 x 6 PIN ARRAY						5 x 5 PIN ARRAY					6 x 6 PIN ARRAY					5 x 5 PIN ARRAY	6 x 6 PIN ARRAY		5 x 5 PIN ARRAY		
	Pu ^a	0.005	0.01	0.015	0.025	0.05	0.05 ^b	0.005	0.01	0.015	0.025	0.05	0.015	0.025	0.025	0.05 ^b	0.01	0.015	U ^a	Pu ^a	U ^a	Pu ^a
	U1 ^a	0.02041	-0.01712	0.01490	0.01258	0.01070	0.01176	0.02018	0.01520	0.01056	0.00334	<0 ^c	0.02095	0.01824	0.01515	0.01642	0.03369	0.01073	0.01684	0.01017	0.01803	0.00862
U2 ^a	----	----	----	----	----	----	----	----	----	----	----	0.01	0.0072	0.01	0.0072	0.0072	0.01					
k _{eff} at 1% U1 Enrichment		0.858	0.927	0.957	0.980	0.994	0.988	0.857	0.951	0.995	1.035	1.060	0.957	0.972	0.980	0.980	0.916	0.995	----	----	----	----
Power Fraction for Regions: 1		0.1792	0.3077	0.4064	0.5012	----	0.5432	0.1761	0.3683	0.5560	0.8537	----	0.4522	0.5572	0.5259	0.5921	----	0.5655	0.3419	0.3176	0.3591	0.3416
2		0.2470	0.2299	0.2101	0.1866	----	0.1703	0.2561	0.2307	0.1898	0.0778	----	0.2809	0.2569	0.2208	0.2267	----	0.1938	0.2305	0.2275	0.2330	0.2317
3		0.5738	0.4624	0.3835	0.3123	----	0.2865	0.5678	0.4010	0.2542	0.0685	----	0.2669	0.1859	0.2533	0.1812	----	0.2407	0.4276	0.4549	0.4079	0.4267
Megawatts per Assembly for 40 MW Total Power for Regions: 1		0.1991	0.3419	0.4515	0.5569	----	0.6035	0.1957	0.4092	0.6178	0.9485	----	0.5025	0.6191	0.5843	0.6579	----	0.6283	0.3799	0.3529	0.3990	0.3795
2		0.3529	0.3284	0.3001	0.2665	----	0.2433	0.3659	0.3296	0.2711	0.1111	----	0.4013	0.3670	0.3154	0.3239	----	0.2769	0.3293	0.3250	0.3329	0.3310
3		0.2733	0.2202	0.1826	0.1487	----	0.1364	0.2704	0.1909	0.1211	0.0326	----	0.1271	0.0885	0.1206	0.0863	----	0.1146	0.2036	0.2166	0.1943	0.2032
Pu per Assembly, kg		0.1339	0.2679	0.4018	0.6696	----	1.3393	0.0930	0.1860	0.2790	0.4650	0.9300	0.4018	0.6696	0.6696	1.3393	----	0.2790	----	0.2724	----	0.1603
Megawatts per Kilogram of Pu in Pu Zone		1.407	1.276	1.124	0.8313	----	0.4507	2.104	2.200	2.215	2.040	----	1.251	0.9247	0.8727	0.4912	----	2.252	----	1.295	----	2.367
aHot voided critical enrichments. bUsed microscopic cross sections derived in a 0.025 enriched Pu composition. c k _{eff} > 1.0 for 0 U1 enrichment.																						

^aHot voided critical enrichments. ^bUsed microscopic cross sections derived in a 0.025 enriched Pu composition. ^ck_{eff} > 1.0 for 0 U1 enrichment.

TABLE VI INITIAL REACTIVITY COEFFICIENTS AND ROD WORTHS

						Two Zone						Three Zone			One Zone, U or Pu					
						6x6 Pin Array				5x5 Pin Array		6x6 Pin Array								
No. of Groups (RP-122)	Downscattering	Steam Voids	H ₂ O Density	H ₂ O Temperature	Control Rod Position	Pu ^C	0.01	0.015	0.025	0.05	0.01	0.015	0.025	0.015	0.025	0.01	6x6 Pin Array		5x5 Pin Array	
					U1 ^C	0.01712	0.01490	0.01258	0.01078	0.01520	0.01056	0.00334	0.02095	0.01824	0.03369	U ^C	Pu ^C	U ^C	Pu ^C	
					U2 ^C	---	---	---	---	---	---	---	---	0.01	0.0072	0.0072	0.01684	0.01017	0.01803	0.00862
k _{eff}																				
7	Complete ^a	Operating	Operating	Operating	Out	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	
4	Approximate ^b	Operating	Operating	Operating	Out	---	0.9812	0.9677	---	---	0.9834	0.9723	0.9801	0.9662	---	0.9973	0.9764	0.9994	0.9868	
4	Complete ^a	Operating	Operating	Operating	Out	---	1.0005	0.9994	---	---	1.0018	1.0934	1.0012	1.0000	---	0.9994	0.9976	1.0013	0.9999	
7	Complete ^a	75% Operating	Operating	Operating	Out	1.0138	---	1.0240	1.0280	1.0105	---	1.0314	---	---	---	---	---	---	---	
7	Complete ^a	50% Operating	Operating	Operating	Out	1.0263	---	1.0465	1.0535	1.0199	---	1.0580	---	---	---	---	---	---	---	
7	Complete ^a	25% Operating	Operating	Operating	Out	1.0370	---	1.0670	1.0769	1.0270	---	1.0807	---	---	---	---	---	---	---	
7	Complete ^a	None	Operating	Operating	Out	1.0462	1.0651	1.0853	1.0983	1.0322	1.0635	1.1000	1.0711	1.0902	---	1.0304	1.0552	1.0004	1.0240	
4	Complete ^a	None	Operating	Operating	Out	---	1.0681	1.0878	---	---	1.0662	1.1035	1.0744	1.0929	---	1.0324	1.0556	1.0029	1.0257	
4	Complete ^a	None	Operating	Operating	Out	---	1.1215 ^d	1.1422 ^d	---	---	1.1195 ^d	1.1587 ^d	1.1281 ^d	1.1475 ^d	---	1.0840 ^d	1.1084 ^d	1.0530 ^d	1.0770 ^d	
4	Complete ^a	None	Operating	Ambient	Out	---	1.1339	1.1575	---	---	1.1370	1.1591	1.1409	1.1634	---	1.1167	1.1068	1.0770	1.0523	
4	Complete ^a	None	Ambient	Ambient	Out	---	1.1729	1.2141	---	---	1.1668	1.2137	1.1829	1.2216	---	1.1305	1.1406	1.0661	1.0561	
4	Approximate ^b	None	Ambient	Ambient	Out	---	1.1514	1.1781	---	---	1.1501	1.1868	1.1615	1.1860	---	1.1287	1.1226	1.0647	1.0462	
4 (PDQ-3)	Approximate ^b	None	Ambient	Ambient	Out	1.0795 ^e	1.1494	1.1749	---	1.0920 ^e	1.1468	1.1751 ^f	---	1.1819	1.0977 ^g	1.0833 ^h	---	---	---	
4 (PDQ-3)	Approximate ^b	None	Ambient	Ambient	In	0.9093 ^e	0.9812	1.0156	---	0.9131 ^e	0.9724	1.0050 ^f	---	1.0187	0.9094 ^g	0.9355 ^h	---	---	---	

^aScattering to all lower groups. ^bScattering to next lower group only. ^cHot voided critical enrichments. For the three zone - 5x5 pin array, Pu = 0.015, U1 = 0.01073, U2 = 0.01. ^dk_{eff} × 1.05 to allow for xenon removal and uncertainties. ^eFor U1 Enrichment of 0.01228.

^fFor U1 enrichment of 0.00754. ^gFor U1 enrichment of 0.02. ^hFor U1 enrichment of 0.01503.

TABLE VII GENERAL ISOTOPIC DENSITY AND REACTIVITY CHANGES WITH BURNUP

		Two Zone								One Zone (sphere)							
		6 × 6 Pin Array				5 × 5 Pin Array				6 × 6 Pin Array				5 × 5 Pin Array			
		Pu ^a												Pu Enrichment ^a			
		0.01	0.015	0.025	0.05	0.01	0.015	0.025	0.05	0.01	0.015	0.025	0.05	0.01	0.015	0.025	0.05
U ^a		0.01228	0.01667	0.00754	0.00455	0.01228	0.01667	0.00754	0.00455	0.01	0.015	0.025	0.05	0.01	0.015	0.025	0.05
0 Plutonium Zone Burnup																	
k _{eff}		0.9504	0.9638	0.9645	0.5564	0.9709	0.9993	1.0193	1.0254	1.0773	1.1193	1.1473	1.1476	1.1045	1.1689	1.2194	1.2387
Pu Region Composition for Isotope:	28	0.214030	0.212950	0.210790	0.205390	0.148600	0.147890	0.146380	0.142630	0.214030	0.212950	0.210790	0.205390	0.148640	0.147890	0.146380	0.142630
	49	0.001993	0.002980	0.004982	0.009966	0.001364	0.002076	0.003460	0.006920	0.001993	0.002989	0.004980	0.009965	0.001384	0.002076	0.003460	0.006920
	40	0.000173	0.000260	0.000433	0.000867	0.000150	0.000182	0.000310	0.000602	0.000173	0.000260	0.000433	0.000866	0.000120	0.000180	0.000301	0.000602
	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	25	0.000429	0.000427	0.000422	0.000412	0.000258	0.000297	0.000293	0.000286	0.000429	0.000427	0.000422	0.000412	0.000298	0.000297	0.000293	0.000286
	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.01 Plutonium Zone Burnup																	
k _{eff}		0.8551	0.8545	0.8586	0.8818	0.8483	0.8515	0.8838	0.9341	0.9109	0.9785	1.0409	1.0817	0.8902	0.9941	1.0952	1.1625
Pu Region Composition for Isotope:	28	0.212230	0.211420	0.209540	0.204400	0.147570	0.147040	0.145740	0.142160	0.212290	0.211480	0.209590	0.204430	0.147600	0.147080	0.145770	0.142180
	49	0.000973	0.001547	0.003092	0.007678	0.000582	0.000854	0.001887	0.005077	0.000921	0.001187	0.003038	0.007641	0.000815	0.001848	0.005049	0.001993
	40	0.000530	0.000666	0.000895	0.001334	0.000367	0.000508	0.000703	0.001033	0.000531	0.000569	0.000898	0.001325	0.000389	0.000515	0.000712	0.001038
	41	0.000342	0.000424	0.000519	0.000640	0.000213	0.000266	0.000319	0.000385	0.000338	0.000422	0.000521	0.000654	0.000208	0.000262	0.000315	0.000384
	42	0.000098	0.000081	0.000060	0.000049	0.000072	0.000056	0.000037	0.000023	0.000101	0.000085	0.000061	0.000043	0.000073	0.000056	0.000037	0.000023
	25	0.000236	0.000280	0.000325	0.000353	0.000154	0.000190	0.000225	0.000249	0.000233	0.000279	0.000323	0.000353	0.000151	0.000189	0.000225	0.000249
	26	0.000035	0.000029	0.000021	0.000015	0.000025	0.000019	0.000013	0.000008	0.000036	0.000029	0.000021	0.000015	0.000025	0.000019	0.000013	0.000008
0.02 Plutonium Zone Burnup																	
k _{eff}		0.8267	0.8116	0.8062	0.8399	0.8195	0.7952	0.8003	0.8780	0.7786	0.8557	0.9511	1.0281	0.6644	0.7700	0.9470	1.0900
Pu Region Composition for Isotope:	28	0.210180	0.209640	0.208113	0.203320	0.146200	0.145910	0.144940	0.141630	0.210250	0.209730	0.208200	0.203380	0.146230	0.145960	0.145000	0.141670
	49	0.000715	0.000965	0.001915	0.005802	0.000346	0.000316	0.000346	0.003521	0.000668	0.000903	0.001832	0.005740	0.000322	0.000403	0.000867	0.003467
	40	0.000502	0.000621	0.000915	0.001486	0.000331	0.000422	0.000694	0.001194	0.000492	0.000508	0.000900	0.001458	0.000327	0.000416	0.000695	0.001197
	41	0.000354	0.000505	0.000795	0.001173	0.000186	0.000266	0.000492	0.000748	0.000337	0.000490	0.000795	0.001197	0.000173	0.000264	0.000485	0.000750
	42	0.000305	0.000293	0.000244	0.000160	0.000252	0.000225	0.000176	0.000105	0.000312	0.000299	0.000249	0.000174	0.000234	0.000230	0.000180	0.000105
	25	0.000108	0.000159	0.000239	0.000297	0.000056	0.000092	0.000153	0.000211	0.000103	0.000155	0.000229	0.000353	0.000051	0.000088	0.000151	0.000211
	26	0.000056	0.000049	0.000039	0.000028	0.000030	0.000036	0.000026	0.000016	0.000056	0.000049	0.000039	0.000028	0.000040	0.000035	0.000026	0.000016
0.03 Plutonium Zone Burnup																	
k _{eff}		0.8116	0.7837	0.7599	0.8087	0.8082	0.7701	0.7269	0.8338	0.6937	0.7619	0.8E50	0.9904	0.5766	0.6199	0.8149	1.0339
Pu Region Composition for Isotope:	28	0.207940	0.207630	0.206514	0.202170	0.144633	0.144510	0.143930	0.141040	0.208000	0.207720	0.206620	0.202260	0.144640	0.144550	0.144010	0.141100
	49	0.000644	0.000764	0.001282	0.004317	0.000314	0.000345	0.000516	0.002299	0.000609	0.000715	0.001200	0.004237	0.000297	0.000322	0.000470	0.002226
	40	0.000464	0.000524	0.000762	0.001443	0.000299	0.000328	0.000507	0.001157	0.000454	0.000507	0.000738	0.001397	0.000297	0.000321	0.000494	0.001153
	41	0.000305	0.000406	0.000751	0.001482	0.000151	0.000187	0.000395	0.000958	0.000288	0.000381	0.000737	0.001503	0.000142	0.000173	0.000372	0.000959
	42	0.000469	0.000489	0.000476	0.000363	0.000351	0.000360	0.000369	0.000248	0.000474	0.000496	0.000486	0.000372	0.000354	0.000375	0.000378	0.000251
	25	0.000043	0.000077	0.000144	0.000244	0.000015	0.000033	0.000086	0.000172	0.000039	0.000072	0.000146	0.000244	0.000013	0.000029	0.000082	0.000172
	26	0.000062	0.000061	0.000055	0.000030	0.000044	0.000043	0.000037	0.000024	0.000062	0.000061	0.000053	0.000039	0.000043	0.000043	0.000037	0.000024
0.04 Plutonium Zone Burnup																	
k _{eff}		0.8030	0.7675	0.7136	0.7783	0.8027	0.7599	0.6767	0.7856	0.6348	0.6659	0.8061	0.9584	0.5369	0.5424	0.6303	0.9816
Pu Region Composition for Isotope:	28	0.205590	0.205420	0.204700	0.200940	0.142973	0.142920	0.142650	0.140370	0.205630	0.205490	0.204810	0.201060	0.142970	0.142940	0.142720	0.140460
	49	0.000618	0.000679	0.000964	0.003176	0.000305	0.000316	0.000384	0.001420	0.000596	0.000546	0.000997	0.003086	0.000294	0.000302	0.000354	0.001341
	40	0.000447	0.000473	0.000612	0.001291	0.000289	0.000296	0.000361	0.000985	0.000440	0.000459	0.000583	0.001237	0.000288	0.000293	0.000347	0.000972
	41	0.000282	0.000329	0.000574	0.001554	0.000142	0.000151	0.000237	0.000961	0.000271	0.000310	0.000542	0.001560	0.000136	0.000143	0.000215	0.000950
	42	0.000577	0.000613	0.000666	0.000580	0.000429	0.000454	0.000509	0.000435	0.000579	0.000515	0.000675	0.000602	0.000433	0.000457	0.000517	0.000443
	25	0.000016	0.000033	0.000084	0.000194	0.000001	0.000009	0.000036	0.000132	0.000014	0.000029	0.000082	0.000194	0.000003	0.000008	0.000032	0.000131
	26	0.000062	0.000064	0.000062	0.000049	0.000044	0.000043	0.000031	0.000031	0.000062	0.000064	0.000062	0.000048	0.000042	0.000044	0.000043	0.000031
0.05 Plutonium Zone Burnup																	
k _{eff}		0.7978	0.7586	0.6798	0.7419	0.7991	0.7550	0.5573	0.7180	0.5956	0.6003	0.6807	0.9242	0.5116	0.5093	0.5135	0.9142
Pu Region Composition for Isotope:	28	0.203180	0.203090	0.202664	0.199620	0.141294	0.141260	0.141130	0.139590	0.203200	0.203130	0.202750	0.199760	0.141280	0.141270	0.141170	0.139700
	49	0.000614	0.000642	0.000802	0.002329	0.000302	0.000308	0.000334	0.000861	0.000604	0.000526	0.000750	0.002231	0.000297	0.000300	0.000316	0.000788
	40	0.000439	0.000451	0.000514	0.001091	0.000282	0.000287	0.000305	0.000747	0.000434	0.000442	0.000494	0.001034	0.000284	0.000286	0.000298	0.000724
	41	0.000276	0.000295	0.000421	0.001426	0.00014	0.000143	0.000167	0.000773	0.000270	0.000285	0.000392	0.001407	0.000136	0.000138	0.000155	0.000741
	42	0.000647	0.000684	0.000774	0.000814	0.000482	0.000503	0.000570	0.000633	0.000646	0.000580	0.000778	0.000829	0.000486	0.000506	0.000572	0.000646
	25	0.000005	0.000013	0.000042	0.000056	0.000000	0.000002	0.000011	0.000093	0.000005	0.000011	0.000039	0.000147	0.000001	0.000002	0.000009	0.000091
	26	0.000059	0.000062	0.000061	0.000042	0.000041	0.000042	0.000044	0.000037	0.000058	0.000062	0.000065	0.000056	0.000039	0.000041	0.000044	0.000037

^a Hot voided critical enrichments.

Fig. 3
Isotopic Ratios vs Burnup for
Two-zone System with Plu-
tonium Enrichment of 0.015

Fig. 4
Isotopic Concentrations vs
Burnup for Two-zone System
with Plutonium Enrichment
of 0.015

TABLE VIII TIME BEHAVIOR FOR REALISTIC MODES OF OPERATION IN EBWR

		Two Zone						Three Zone						
		6x6 Pin Array			5x5 Pin Array			6x6 Pin Array			5x5 Pin Array			
		Pu ^a	0.015	0.025	0.05	0.015	0.025	0.05	0.015	0.025	0.05	0.015	0.025	0.05
		U2 ^a	----	----	----	----	----	----	0.01	0.0072	0.0072	0.01	0.0072	0.0072
Isotope		Region												
Initial Pu Region Isotopic Composition	28		0.212950	0.210790	0.205390	0.147890	0.146380	0.142630	0.212950	0.210790	0.205390	0.147890	0.146380	0.142630
	49		0.002989	0.004982	0.005965	0.002076	0.003460	0.006920	0.002989	0.004982	0.005965	0.002076	0.003460	0.006920
	40		0.000260	0.000433	0.000866	0.000180	0.000301	0.000602	0.000260	0.000433	0.000866	0.000180	0.000301	0.000602
	41		0	0	0	0	0	0	0	0	0	0	0	0
	42		0	0	0	0	0	0	0	0	0	0	0	0
	25		0.000427	0.000422	0.000412	0.000296	0.000293	0.000286	0.000427	0.000422	0.000412	0.000296	0.000293	0.000286
	26		0	0	0	0	0	----	----	0	0	0	0	0
0-0.003 Plutonium Zone Burnup Range														
Initial UI Enrichment			0.01490	0.01258	0.01176	0.01056	0.01258	0.01176	0.02095	0.01824	0.01642	0.01073	0.01824	0.01642
Initial k _{eff}			0.9991	0.9992	0.9997	0.9988	1.0491	1.0615	0.9995	0.9993	0.9994	0.9979	1.0530	1.0643
Final k _{eff}			0.9461	0.9573	0.9742	0.9317	1.0009	1.0313	0.9428	0.9542	0.9721	0.9301	1.0025	1.0328
Duration of Irradiation (Months)			5.940	4.674	4.224	2.994	2.996	2.676	5.271	4.160	3.855	2.937	2.752	2.517
Final Pu Region Isotopic Composition	28		0.212560	0.210460	0.205110	0.147690	0.146220	0.142500	0.212560	0.210450	0.205110	0.147690	0.146220	0.142490
	49		0.002412	0.004320	0.009228	0.001595	0.002922	0.006336	0.002418	0.004325	0.009232	0.001596	0.002924	0.006337
	40		0.000502	0.000668	0.001070	0.000370	0.000492	0.000776	0.000500	0.000666	0.001068	0.000370	0.000491	0.000775
	41		0.000106	0.000128	0.000172	0.000061	0.000071	0.000096	0.000108	0.000129	0.000173	0.000061	0.000072	0.000096
	42		0.000005	0.000004	0.000003	0.000003	0.000002	0.000002	0.000005	0.000004	0.000003	0.000003	0.000002	0.000002
	25		0.000383	0.000393	0.000394	0.000256	0.000274	0.000275	0.000383	0.000393	0.000394	0.000256	0.000274	0.000275
	26		0.000009	0.000006	0.000004	0.000006	0.000004	0.000002	0.000009	0.000006	0.000004	0.000006	0.000004	0.000002
Initial Regional Power Fraction	1		0.4064	0.5012	0.5432	0.5560	0.5411	----	0.4522	0.5572	0.5921	0.5655	0.5830	----
	2		0.2101	0.1866	0.1703	0.1898	0.1882	----	0.2809	0.2569	0.2267	0.1938	0.2564	----
	3		0.3835	0.3122	0.2865	0.2542	0.2706	----	0.2669	0.1859	0.1812	0.2407	0.1606	----
Final Regional Power Fraction	1		0.3396	0.4469	0.5092	0.4666	0.4857	----	0.3899	0.5110	0.5623	0.4780	0.5392	----
	2		0.2181	0.1977	0.1794	0.2120	0.2011	----	0.2880	0.2260	0.2318	0.2167	0.2708	----
	3		0.4423	0.3554	0.3114	0.3214	0.3132	----	0.2221	0.2230	0.2059	0.3053	0.1900	----
0.003-0.006 Plutonium Zone Burnup Range														
Initial UI Enrichment			0.01920	0.01705	0.01507	0.01500	0.01705	0.01507	0.03834	0.03374	0.02606	0.02000	0.03374	0.02606
Initial k _{eff}			0.9988	0.9993	0.9998	0.9776	1.0376	1.0524	1.0002	0.9995	0.9994	0.9740	1.0469	1.0582
Final k _{eff}			0.9516	0.9652	0.9778	0.9331	1.0015	1.0280	0.9543	0.9642	0.9756	0.9237	1.0074	1.0318
Duration of Irradiation (Months)			9.200	6.831	5.402	5.034	4.350	3.339	7.340	5.494	4.599	4.228	3.646	2.973
Final Pu Region Isotopic Composition	28		0.212130	0.210110	0.204830	0.147460	0.146040	0.142360	0.212120	0.210090	0.204810	0.147160	0.146040	0.142350
	49		0.001927	0.003715	0.008522	0.001182	0.002421	0.005771	0.001948	0.003733	0.008534	0.001185	0.002428	0.005775
	40		0.000650	0.000835	0.001232	0.000494	0.000634	0.000920	0.000643	0.000827	0.001225	0.000492	0.000631	0.000917
	41		0.000236	0.000277	0.000354	0.000141	0.000161	0.000203	0.000240	0.000281	0.000359	0.000142	0.000163	0.000206
	42		0.000025	0.000018	0.000014	0.000015	0.000010	0.000007	0.000025	0.000019	0.000014	0.000015	0.000010	0.000007
	25		0.000338	0.000363	0.000377	0.000234	0.000254	0.000264	0.000338	0.000333	0.000377	0.000234	0.000254	0.000264
	26		0.000018	0.000013	0.000009	0.000011	0.000008	0.000005	0.000018	0.000013	0.000009	0.000011	0.000008	0.000005
Initial Regional Power Fraction	1		0.2557	0.3398	0.4227	0.3389	0.3754	----	0.3172	0.4181	0.4930	0.3961	0.4416	----
	2		0.2276	0.2127	0.1930	0.2309	0.2197	----	0.3839	0.3629	0.2999	0.3062	0.3689	----
	3		0.5167	0.4475	0.3843	0.4302	0.4049	----	0.2989	0.2190	0.2071	0.2977	0.1895	----
Final Regional Power Fraction	1		0.2361	0.3169	0.4050	0.2738	0.3342	----	0.2946	0.3951	0.4776	0.3344	0.4078	----
	2		0.2271	0.2146	0.1965	0.2357	0.2241	----	0.3771	0.3582	0.2963	0.3130	0.3754	----
	3		0.5368	0.4685	0.3987	0.4835	0.4417	----	0.3283	0.2467	0.2261	0.3536	0.2168	----
0.006-0.009 Plutonium Zone Burnup Range														
Initial UI Enrichment			0.02107	0.01928	0.01738	0.01900	0.01928	0.01708	0.05300	0.04622	0.03430	0.03000	0.04622	0.03430
Initial k _{eff}			0.9990	1.0002	1.0006	0.9927	1.0297	1.0453	1.0009	1.0002	0.9999	0.9727	1.0414	1.0534
Final k _{eff}			0.9450	0.9642	0.9784	0.9474	0.9967	1.0240	0.9574	0.9678	0.9771	0.9277	1.0078	1.0303
Duration of Irradiation (Months)			11.724	3.606	6.418	8.138	5.680	3.958	3.828	6.562	5.223	5.760	4.476	3.387
Final Pu Region Isotopic Composition	28		0.211680	0.209740	0.204530	0.147210	0.145850	0.142220	0.211640	0.209710	0.204510	0.147190	0.145840	0.142210
	49		0.001544	0.003173	0.007849	0.000858	0.001967	0.005226	0.001586	0.003211	0.007874	0.000867	0.001981	0.005236
	40		0.000721	0.000942	0.001357	0.000550	0.000731	0.001037	0.000708	0.000927	0.001343	0.000547	0.000723	0.001030
	41		0.000351	0.000425	0.000538	0.000216	0.000254	0.000317	0.000360	0.000434	0.000548	0.000218	0.000260	0.000322
	42		0.000062	0.000045	0.000032	0.000041	0.000027	0.000017	0.000062	0.000046	0.000033	0.000041	0.000027	0.000017
	25		0.000293	0.000333	0.000360	0.000200	0.000233	0.000253	0.000294	0.000333	0.000359	0.000200	0.000233	0.000253
	26		0.000026	0.000019	0.000013	0.000017	0.000012	0.000007	0.000026	0.000019	0.000013	0.000017	0.000012	0.000007
Initial Regional Power Fraction	1		0.1951	0.2654	0.3531	0.2054	0.2863	----	0.2573	0.3459	0.4310	0.2867	0.3590	----
	2		0.2314	0.2202	0.2027	0.2428	0.2302	----	0.4387	0.4166	0.3452	0.3876	0.4305	----
	3		0.5735	0.5144	0.4442	0.5518	0.4835	----	0.3040	0.2375	0.2238	0.3257	0.2105	----
Final Regional Power Fraction	1		0.1960	0.2622	0.3481	0.1807	0.2617	----	0.2537	0.3382	0.4261	0.2549	0.3356	----
	2		0.2297	0.2198	0.2036	0.2418	0.2310	----	0.4290	0.4069	0.3373	0.3854	0.4317	----
	3		0.5743	0.5180	0.4483	0.5774	0.5073	----	0.3173	0.2549	0.2366	0.3598	0.2327	----
0.009-0.012 Plutonium Zone Burnup Range														
Initial UI Enrichment			----	0.02052	0.01829	----	0.02052	0.01829	----	0.05665	0.04169	----	0.05665	0.04169
Initial k _{eff}			----	1.0002	1.0001	----	1.0236	1.0389	----	0.9998	1.0000	----	1.0371	1.0500
Final k _{eff}														

the entire uranium zone was replaced, while in the perhaps more realistic three-zone systems, only the first 28-element shim region was altered. A total power of 40 MW was again assumed. The variation of shim enrichment and time duration of the burnup step as a function of burnup is also displayed in Table VIII. As burnup proceeds, the power fraction in the plutonium zone decreases, and consequently the time required for a given plutonium-zone burnup increases. Figure 5 illustrates this correlation and also gives the U1 enrichment needed for criticality at the beginning of each burnup step. The system considered in this figure is the 6 x 6 pin-array, three-zone system having a plutonium enrichment of 0.025 and a U2 enrichment of 0.0072.

Fig. 5

Burnup Step Duration, Plutonium Zone Power Fraction, and U1 Enrichment vs Burnup for Three-zone System with Plutonium Enrichment of 0.025

Table IX gives results that would be relevant to plutonium critical experiments as the burnup proceeds. For a complicated two- or three-zone configuration, it would be highly desirable to simplify the geometry in order to facilitate comparisons with theoretical results. In particular, a clean (that is, unrodded), plutonium-zone, critical configuration would be useful with the system being controlled with boric acid. Table IX indicates that such plutonium-zone criticals are in fact feasible, and depending upon the initial enrichment, that such criticals would be possible even after some burnup has occurred. The B^{10} content in the boric acid solution needed for criticality is given for each burnup. The influence of size may be inferred from Table IX where the results for a 64-element plutonium zone, rather than a 36-element plutonium zone, are shown (48.73-cm-radius, rather than 36.55-cm-radius plutonium zone).

Table X gives the influence of burnup on various reactivity coefficients and rod worths. Because of the preliminary nature of the calculations at this time, the results mainly pointed out that the specific results are sensitive to the configuration chosen and the initial plutonium enrichment. For example, the two-zone, 0.025 plutonium-enrichment case shows a decreasing rod worth with burnup, whereas the three-zone, 0.025 plutonium-enriched case has the opposite trend. The much more highly enriched U1 zone in the three-zone case, as compared with the uniform uranium zone in the two-zone core, concentrates the neutron importance at the position of the control rods. Although the results of Table X are rather sparse, they clearly indicate the importance of a careful examination of rod worth versus burnup for a realistic core design.

C. Conclusions

The survey results indicated that a satisfactory loading and mode of operation could be obtained that would permit a meaningful experiment to be set up in EBWR. Although further calculations were needed to specify precise properties, the following conclusions were drawn from the survey results.

1. The fuel size of the reference design of the previously planned EBWR Core 2 appeared to be quite satisfactory and would therefore be selected.
2. The most favorable system of the proposed loadings appeared to be the three-zone system with an initial enrichment in the range of 0.025 for the plutonium region and probably of the 6 x 6 pin-array type. There is really no very strong difference between the 6 x 6 and the 5 x 5 systems. However, the 6 x 6 systems seem to be slightly more favorable. They have a reactivity swing during operation that is somewhat smaller, and they permit a somewhat higher initial enrichment for the reactivity required than do the 5 x 5 systems. Therefore, while an optimum plutonium system would probably have a somewhat looser lattice than the 6 x 6 system, for the purposes of the current experiment, the 6 x 6 system appears to be desirable.
3. The control problem in long-term reactivity swings might be a serious problem in the loading. The possibility of incorporating burnable poison in the fuel zone therefore required serious consideration. A satisfactory means of inserting the poison into the fuel allows the use of burnable poison and very much alleviates some of the reactivity problems. For example, fewer fuel-zone loadings are necessary, and the reactivity swing during each burnup step is reduced.
4. The power density split for the various loadings appeared not to introduce any very serious difficulties. It might, however, be restrictive on some of the loadings and might tend to rule against extremely-high-enrichment central plutonium regions because of excessive power in those

TABLE X
REACTIVITY COEFFICIENTS AND ROD WORTHS
AT VARIOUS BURNUPS

TABLE X REACTIVITY COEFFICIENTS AND ROD WORTHS AT VARIOUS BURNUPS						TWO-ZONE - 6x6 PIN ARRAY				THREE-ZONE - 6x6 PIN ARRAY				
						Pu ^c	0.015	0.015	0.025	0.025	0.015	0.015	0.025	0.025
						U1 ^c	0.01490	0.02107	0.01258	0.02052	0.02095	0.05300	0.01824	0.05665
						U2 ^c	—	—	—	—	0.01	0.01	0.0072	0.0072
						PLUTONIUM ZONE BURNUP								
NO. OF GROUPS (RP-122)	DOWN-SCATTERING	STEAM VOIDS	H ₂ O DENSITY	H ₂ O TEMP.	CONTROL ROD POSITION	0	0.006	0	0.009	0	0.006	0	0.009	
						k _{eff}								
7	Complete ^a	Operating	Operating	Operating	Out	Critical	Critical	Critical	Critical	Critical	Critical	Critical	Critical	
4	Approx. ^b	↓	↓	↓	↓	0.9812	—	0.9677	—	0.9801	—	0.9662	—	
4	Complete ^a	↓	↓	↓	↓	1.0005	—	0.9994	—	1.0012	—	1.0000	—	
7	↓	75% Operating	↓	↓	↓	—	—	1.0240	—	—	—	—	—	
7	↓	50% Operating	↓	↓	↓	—	—	1.0465	—	—	—	—	—	
7	↓	25% Operating	↓	↓	↓	—	—	1.0670	—	—	—	—	—	
7	↓	None	↓	↓	↓	1.0651	1.0405	1.0853	1.0484	1.0711	1.0602	1.0902	1.0709	
4	↓	↓	↓	↓	↓	1.0681	—	1.0878	—	1.0744	—	1.0929	—	
4	↓	↓	↓	↓	↓	1.1215 ^d	—	1.1422 ^d	—	1.1281 ^d	—	1.1475 ^d	—	
4	↓	↓	↓	Ambient	↓	1.1339	—	1.1575	—	1.1409	—	1.1634	—	
4	↓	↓	Ambient	↓	↓	1.1729	1.1480	1.2141	1.1561	1.1829	1.1834	1.2216	1.1999	
4	Approx. ^b	↓	↓	↓	↓	1.1514	1.1361	1.1781	1.1327	1.1615	1.1627	1.1860	1.1667	
4 (PDQ-3)	↓	↓	↓	↓	↓	1.1494	—	1.1749	1.1342	—	—	1.1819	1.1596	
4 (PDQ-3)	↓	↓	↓	↓	IN	0.9812	—	1.0156	1.0391	—	—	1.0187	0.9750	

^aScattering to all lower groups. ^bScattering to next lower group only. ^cHot voided critical enrichments.
^dk_{eff} x 1.05 to allow for Xenon removal and uncertainties.

regions. For the systems with high plutonium enrichments, the power split indicated that the bulk of the power is produced in that region, and if one assumed a total power of the order of 40 MW, this could lead to an excessively high power density in the plutonium region. However, there is no reason to then still insist on the same total power, since a lower total reactor power would still lead to the same power per plutonium element. It is this latter quantity that is really relevant in the experiment.

The physics considerations as concluded from the initial survey may be summarized as follows: The loading that appeared to be most probable was a three-zone system with a central 0.025 plutonium-enrichment region surrounded by a thin zone whose enrichment would vary as the experiment proceeded but would be expected to fall in the range of 2 to 5%. The outer region would probably be natural uranium. Higher plutonium enrichments in the central region are ruled against largely by control requirements. They would have too large a cold-to-hot void reactivity swing. Furthermore, they would involve a plutonium-enrichment that is not of greatest current interest. At future times, when higher burnups are envisaged, perhaps the enrichment of interest would go beyond 0.025.

The question of fuel-to-water-volume ratio as characterized by the question of 6 x 6 versus 5 x 5 pin arrays is rather difficult. However, the 6 x 6 pin array seemed to be somewhat more advantageous since it reduced the reactivity swing during operation.

In Section IV, refinements in the calculations will be discussed, and finally in Section V, arguments leading to the system described in the Introduction will be presented.

IV. TOPICS RELATED TO AN IMPROVED CALCULATIONAL MODEL

A. General Comments

Following the general survey calculations, the subsequent physics studies were of a somewhat different nature. The wide range of possible loadings was narrowed considerably, and more precise calculations were made to determine the required enrichments to greater accuracy.

The physics calculations were concerned with the following areas: (1) The rod worths and reactivity coefficients were studied as the burnup proceeds (Table X gives some preliminary results). (2) Power-void iterations were made with greater precision. (3) The effects of variation of the cross sections due to spectrum changes as the burnup proceeds were studied. (4) Precise thermal disadvantage calculations were made, and, in particular, the effect of burnup on this quantity was studied. (5) More precise control rod calculations were made. In particular, the absorption in the epithermal groups was studied with greater precision. (6) The influence of burnable poisons on reactivity behavior with burnup was studied. (7) Experimental checks, insofar as it was possible to find them, were made.⁽⁸⁾ This area, however, did not yield too many useful check points. It is just for this reason that the present experiment is important.

In this section, specific topics will be discussed that are pertinent to the calculational model and to results that have evolved from the physics studies.

In the present calculational model, the Pu^{240} resonance at 1.056 eV is calculated using GAM-1 rather than MUFT-4. Thus, heterogeneity effects, as well as energy self-shielding effects, are being accounted for. Also, the RIC code⁽¹⁷⁾ is now used to obtain the resonance self-shielding correction factors for Pu^{239} and U^{235} . RIC uses a method similar to that used in GAM-1 in calculating resonance integrals. The RIC-derived correction factors are applied to the GAM-1 results.

Examination of various experimental results indicated that SOFO-CATE calculations using the free gas model gave closer agreement than did the previously assumed "bound hydrogen scattering" model. Hence all subsequent calculations have used the free-gas approximation in calculations of the thermal cross sections.

The control rod, epithermal, self-shielding effects were studied by using the transport theory DTK code⁽¹⁸⁾ in a four-region slab geometry corresponding to the fuel region, control rod guides, water gap, and control rod (Fig. 2). A 21-group cross-section set was set up with the lower energy of groups 3, 18, 20, and 21 corresponding to those of groups 1-4 of the four-group set used for the PDQ-3 rod worth calculations.

The comparison of the results of the 21- and four-group DTK calculations provided correction factors for the four-group set to force agreement with the epithermal absorptions found from the 21-group calculations. For the natural boron control rods, the epithermal cross sections required about a 10% reduction to force agreement with the 21-group results. To provide some additional margin of control, it was decided to utilize 90% enriched boron in the control rods. For this case, the epithermal cross sections required about a 35% reduction, as compared with the 21-group results. The modified four-group set was used for all control rod worth studies.

Thermal disadvantage factors were evaluated using a series of one-group DSN-8⁽¹⁹⁾ calculations. First, a so-called "pin-cell" calculation was performed using cylindrical geometry corresponding to the fuel, clad, and water gap of the fuel pin. A purely scattering pseudo region, four mean free paths thick, was used outside the water region as suggested by Honeck⁽²⁰⁾ to avoid the problems of reflecting boundary conditions in small cylindrical cells. The results of the pin-cell calculations were used to homogenize the inside of the fuel element. Next, DSN-8 slab geometry problems were run corresponding to the fuel element contents, the zirconium can, and the interelement water gap. These results were used to homogenize the fuel elements of the small cell (Fig. 2) to provide input for the final DSN-8 slab calculations corresponding to the homogenized nine-element fuel region, the water gap, the zirconium guide structure, and the homogenized water, zirconium control rod follower, and zirconium spacer region (Fig. 2). The final flux weighting factors were used to correct all thermal cross sections. In this procedure, the influence of flux weighting is being neglected in the SOFOCATE calculations. In later calculations,⁽⁸⁾ the flux weighting was used to modify input to SOFOCATE itself. In this case, the derived thermal cross sections need no further corrections.

B. Burnable Poison Considerations

1. Introductory Comments

As indicated in Table VIII, the variation of k_{eff} with burnup depends upon the initial enrichment of the plutonium zone and the configuration of the system. For example, for the three-zone, 0.025 plutonium-zone case, k_{eff} falls by 3-4% for each 3000 MWd/tonne burnup interval. For the system considered, this would result in a substantial decrease in power over the burnup step and would necessitate rather frequent reloadings to restore the system reactivity.

To improve this situation, a dispersed burnable poison incorporated in the shim-zone fuel was considered. As a preliminary effort, the effect of varying amounts of dispersed B^{10} in the shim fuel was considered. The three-zone, 0.025 plutonium-zone system was assumed for the reference

case. With a shim-zone (U1) enrichment of 0.06 (U2 enrichment of 0.0072) and a B^{10} to uranium atom ratio of about 0.003, the shim zone needed to be refueled after an irradiation corresponding to approximately that received by the initial shim zone plus its first replacement if no B^{10} were used.

The use of boron in the fuel, however, is metallurgically questionable because of the effects of helium generated in the $B^{10}(n, \alpha)$ reaction. Attention was therefore turned to the possible use of rare-earth burnable poisons, and it was decided to determine what influence various europium and samarium contents would have on the reactivity behavior.

2. Isotopic Chain Termination Prescription

The CYCLE code was originally set up to study the U^{238} -Pu and Th^{232} -U burnup chains and has room for two, unconnected, five-isotope chains, plus fission products and a single-isotope burnable poison. To accommodate the elaborate burnup chains of europium and samarium⁽²¹⁾ together with the U^{238} -Pu chain in CYCLE, it was necessary to abbreviate these chains.

The following specific example will illustrate the procedure utilized. Consider a four-isotope neutron-capture chain, where the isotopic concentrations N_i are associated as

$$N_1 \xrightarrow{C_1} N_2 \xrightarrow{C_2} N_3 \xrightarrow{C_3} N_4 \xrightarrow{C_4} \text{Dump},$$

and where initially $N_1 = N_0^1$ and $N_2 = N_3 = N_4 = 0$. "Dump" implies that when N_4 captures a neutron, the chain is broken. The C_i are the effective one-group neutron-capture cross sections for the isotopes i . Using the shorthand notation,

$$E_i = \exp(-C_i \tau),$$

$$E_{ij} = E_i - E_j,$$

$$C_{ij} = C_i - C_j,$$

and

$$\tau = \int_0^t \phi(t') dt',$$

where ϕ is the effective one-group flux, the solution of the above problem can be written in terms of the integrated flux-time τ as

$$\frac{N_1(\tau)}{N_0^1} = E_1,$$

$$\frac{N_2(\tau)}{N_0^1} = \frac{C_1 E_{12}}{C_{21}},$$

$$\frac{N_3(\tau)}{N_0^1} = \frac{C_1 C_2 E_{13}}{C_{21} C_{31}} + \frac{C_1 C_2}{C_{12} C_{32}} E_{23},$$

and

$$\frac{N_4(\tau)}{N_0^1} = \frac{C_1 C_2 C_3 E_{14}}{C_{21} C_{31} C_{41}} + \frac{C_1 C_2 C_3 E_{24}}{C_{12} C_{32} C_{42}} + \frac{C_1 C_2 C_3 E_{34}}{C_{13} C_{23} C_{43}}.$$

Also, considering events integrated over an interval $\tau_{21} = \tau_2 - \tau_1$, the above equations may be integrated to yield the average isotopic concentrations $\langle N_i \rangle_{\tau_{21}}$ for the interval such as

$$\langle N_1 \rangle_{\tau_{21}} (\tau_2 - \tau_1) = \frac{1}{N_0^1} \int_{\tau_1}^{\tau_2} N_1(\tau) d\tau = \frac{1}{C_1} [\exp(-C_1 \tau_1) - \exp(-C_1 \tau_2)],$$

and similar more-complicated expressions for

$$\langle N_2 \rangle_{\tau_{21}} \text{ through } \langle N_4 \rangle_{\tau_{21}}.$$

To terminate the chain after N_1 , the procedure adopted was to preserve the total number of absorptions by assigning an adjusted value to $C_1 = \langle C_1 \rangle_{\tau_{21}}$ such that

$$\langle C_1 \rangle_{\tau_{21}} \langle N_1 \rangle_{\tau_{21}} = \sum_{i=1}^4 \langle N_i \rangle_{\tau_{21}} C_i,$$

with the τ_{21} interval chosen to be appropriate for the burnups of interest to the present experiment.

The effective one-group cross sections were obtained by collapsing seven-group cross sections obtained from GAM-1 and SOFOCATE using an earlier-derived seven-group REX spectrum for the B^{10} poisoned U1 zone at 0.06 enrichment.

The above procedure is necessarily approximate, and the accuracy of the results depends upon: (a) the multigroup cross sections used to generate the effective one-group cross sections, (b) the collapsing spectrum

assumed, and, finally, (c) the estimate regarding the τ interval over which the results are to be appropriate.

Similar considerations were used for dividing the complex europium and samarium chains into several simplified chains that could be accommodated in CYCLE. The breakdown utilized is shown schematically in Fig. 6. The isomeric transition in Eu^{151} is indicated, as is the

fact that Eu^{153} is seen not to burn out. This approximates the effect of the higher europium isotopes after Eu^{153} .

^aDUMP IMPLIES NEUTRON CAPTURE BREAKS THE CHAIN

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Fig. 6. Simplified Neutron Burnup Chains Used for CYCLE Calculations

proportions of europium and samarium present. The large initial reactivity overshoots are due to the rapid burnout of the large cross-section isotope Sm^{149} . From the standpoint of practical design, a compromise is necessary between the desire to minimize long-term reactivity falloff, so as to sustain high-power operation, and to minimize the initial reactivity overshoot, so as to simplify the control requirements. In Fig. 7, the 1/3 case probably represents such a possible compromise. This case corresponds to about 12 grams of europium and 20 grams of samarium per U1 zone fuelelement.

The results presented in Fig. 7 do not account for buildup of fission product samarium, although the results for the final design⁽⁷⁾ do account for this effect. Also, as will be pointed out in the next section, the europium/samarium ratio has been altered in the present design, along with the plutonium-zone enrichment and the size of the U1 zone.

3. Results

Some typical results of reactivity versus plutonium-zone burnup are shown in Fig. 7. The case illustrated is the three-zone system with 0.025 enriched plutonium region, 0.06 enriched U1 zone, and 0.0072 enriched U2 zone. The relative amounts of europium and samarium are indicated by the parameters on the curves. The various europium and samarium isotopes being considered are present according to the natural abundances,⁽²¹⁾ and the absolute amount of poison was adjusted for criticality at zero burnup. Figure 7 illustrates the variations possible in burnup behavior according to the relative

Fig. 7. Reactivity Variation vs Burnup for Various Europium to Samarium Ratios in 0.06 Enriched U1 Zone with Plutonium Zone Enrichment of 0.025

V. ARGUMENTS LEADING TO THE PRESENT CONFIGURATION

The present configuration for the experiment, described briefly in the Introduction, represents a change from the system considered so far in the development of the physics. In particular,

1. The enrichment of the plutonium region, atoms plutonium/(atoms uranium + atoms plutonium), has been lowered from 0.025 to 0.015.
2. The shim zone has retained a uranium enrichment of 0.06 but has been increased in size from 28 to 60 elements.
3. The amount and composition of poison in the shim zone have been altered. Each element will now contain approximately 34 grams of europium and 6 grams of samarium (atoms europium/atoms uranium = 0.0020; atoms samarium/atoms uranium = 0.00037). The corresponding numbers were previously 12 grams of europium and 20 grams of samarium per element.

The changes were motivated entirely by operational considerations relating to the characteristics of the EBWR facility and not by any technical considerations relating to the objectives of the experiment. The considerations that led to these changes are concerned with the shutdown requirements of the facility and, in particular, with the use of boric acid for shutdown. It was the original intent not to be bound in the EBWR plutonium loading by the "nine-rod shutdown without boric acid" requirement; i.e., the system is sub-critical if all the rods are in, even if there is no boric acid in the system. It was, and still is, believed that this can be done safely. There is, for example, a precedent for it in the Yankee reactor. Furthermore, it probably will be progressively more widely used in future reactors so that operational experience with this mode of operation is valuable. After further reflection, however, the judgment of those operationally responsible for EBWR was that it would be advisable to adhere to the "nine-rod shutdown without boric acid" requirement unless it was necessary to abandon it to accomplish the objectives of the experiment. The objections were not to the use of boric acid for shutdown per se, but rather to doing so with the present system, which was not designed for that purpose.

Further studies led to the conclusion that the purposes of the experiment would not be compromised by the changes described above and that these changes would permit retaining the condition of nine-rod shutdown without boric acid.

The original decision to have a plutonium enrichment of the order of 2.5% was primarily made for reasons given in Section III-C. The range of interest is not narrow, and a strong case can be made for both lower and higher enrichments. Generally, one would predict that the enrichment of

most interest in plutonium recycle will initially be of the order of 1.5% and will gradually increase as higher-burnup systems are contemplated. Probably the only facet of the program that will be adversely affected, though not in a serious way, deals with plans to perform cold critical experiments on the plutonium region. With the lower enrichment, these criticals will probably require some additional reactivity from a driver zone for burnups greater than about 3000 MWd/tonne. This will somewhat complicate the analysis.

With the new loading configuration, the fraction of total power in the plutonium region drops from about 0.5 to about 0.4. This leads to an increased duration to achieve a specified burnup (MWd/tonne). However, if one takes the burnup per kilogram of fuel as a better yardstick of isotopic buildup, which it undoubtedly is, the time required to obtain information is not adversely affected.

The interdependence of the enrichment and the shutdown criterion comes about mostly in the following manner. The rod worth does not change significantly. However, the void coefficient increases significantly with plutonium enrichment (Table VI). This occurs because the core is effectively smaller as the enrichment increases since more of the system's reactivity is concentrated in the center. It also appears, from the latest void estimates based on recent EBWR experience,⁽⁵⁾ that voids are greater than previously believed. If one were to retain the "nine-rod shutdown without boric acid" criterion with a 2.5% plutonium region, the power that could be reached would be unreasonably low. Only if the void coefficient was decreased (by using a 1.5% plutonium region) could a reasonable power be reached. To compensate for the loss of system reactivity resulting from the lower plutonium enrichment, a compensating increase must be made. The wider shim zone appears to be the best way to accomplish this. If one alternatively reduced the poison concentration in the 28-element (narrow) shim zone, the long-term reactivity loss would become considerably greater.

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