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RADIAL ZONING IN LARGE LMFBRs, PART I

by

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Applied Physics Division

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	ix
I. INTRODUCTION	1
II. STATIC ZONING: CARBIDE CORE	2
III. OPTIMUM ZONING FOR 300 DAY BURN CYCLE: CARBIDE CORE	3
IV. ZONING OF THE NITRIDE CORE	7
V. SUMMARY AND RECOMMENDATIONS	7
References	11

LIST OF FIGURES

	<u>Page</u>
Fig. 1a. Radial power peaking factor as a function of enrichment split for beginning-of-cycle conditions, carbide core. First and second legs of the "vees" correspond to the power peak occurring in the inner and outer core, respectively. Case 1: Fuel volume fraction = 0.33, $k_{eff} = 1.0078$.	19
Fig. 1b. Radial power peaking factor as a function of enrichment split for beginning-of-cycle conditions, carbide core. First and second legs of the "vees" correspond to the power peak occurring in the inner and outer core, respectively. Case 2: Fuel volume fraction = 0.45, $k_{eff} = 1.0078$.	20
Fig. 2a. Radial power peaking factors as a function of beginning-of-cycle enrichment split, before and after first-core burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core).	21
Fig. 2b. Radial power peaking factors as a function of beginning-of-cycle enrichment split, before and after first-core burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core).	22
Fig. 3a. Radial power peaking factors as a function of beginning-of-cycle enrichment split of unpoisoned fuel, before and after equilibrium burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core). Case 2: Fuel volume fraction = 0.33.	23
Fig. 3b. Radial power peaking factors as a function of beginning-of-cycle enrichment split of unpoisoned fuel, before and after equilibrium burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core). Case 2: Fuel volume fraction = 0.45.	24

LIST OF FIGURES (cont'd)

Fig. 4a.	Optimum radial power peaking factor as a function of outer core volume for static (beginning-of-cycle) conditions, and for first-core and equilibrium burn cycle of 300 days, carbide core. Case 1: Fuel volume fraction = 0.33.	25
Fig. 4b.	Optimum radial power peaking factor as a function of outer core volume for static (beginning-of-cycle) conditions and for first-core and equilibrium burn cycle of 300 days, carbide core. Case 2: Fuel volume fraction = 0.45.	26
Fig. 5.	Optimized enrichment split ϵ_2/ϵ_1 as a function of outer core volume for carbide core, static conditions.	27
Fig. 6.	Optimized beginning-of-cycle enrichment split ϵ_2/ϵ_1 as a function of outer core volume for 300 day burnup, carbide core, first-core loading.	28
Fig. 7.	Optimized beginning-of-cycle enrichment split ϵ_2/ϵ_1 of unpoisoned fuel as a function of outer core volume for 300 day equilibrium burnup, carbide core.	29
Fig. 8a.	Power density in carbide core at beginning and end of first-core cycle for outer core to total core volume $V_2/V = 0.4$ and optimized power for 300 day burnup. Power is normalized to a total power of 1 watt. ϵ_2/ϵ_1 (BOC) = beginning-of-cycle ratio of inner to outer core enrichment = 1.325, fuel volume fraction = 0.33.	30
Fig. 8b.	Power density in carbide core at beginning and end of first core cycle for outer core to total core volume $V_2/V = 0.4$ and optimized power for 300 day burnup. Power is normalized to a total power of 1 watt. ϵ_2/ϵ_1 (BOC) = beginning-of-cycle ratio of inner to outer core enrichment = 1.264, fuel volume fraction = 0.45.	31
Fig. 9.	Power density in carbide core at beginning and end of cycle for outer core to total core volume $V_2/V = 0.3$ and optimized beginning-of-cycle peak power. Fuel volume fraction = 0.45. Beginning-of-cycle ratio of outer core to inner core enrichment $\epsilon_2/\epsilon_1 = 1.335$.	32
Fig. 10.	Radial power peaking factor as a function of enrichment split for beginning-of-cycle conditions for nitride core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. Fuel volume fraction = 0.3207.	33

LIST OF FIGURES (cont'd)

Page

Fig. 11. Radial power peaking factors as functions of beginning-of-cycle enrichment split, before and after first core burn cycle for nitride core. V_2/V = ratio of outer core to total core volume. c_2/c_1 = ratio of outer core to inner core enrichment. Fuel volume fraction = 0.3207.

34

Fig. 12. Optimum radial power peaking factor as a function of outer core volume for static (beginning-of-cycle) conditions, and for first-core and equilibrium burn cycle of 300 days for nitride core.

35

LIST OF TABLES

	<u>Page</u>
Table I. Model of Carbide-Fueled Reactor	12
Table II. Optimum Volume and Enrichment Parameters for Carbide Model and Resulting Power Peaking Factors	13
Table III. Performance Characteristics of Case 1 of the Carbide Model Reactor (Fuel Volume Fraction = 0.33) with Fixed Radial Zoning, $V_2/V = .4$, and Optimum Power Peaking Factor	14
Table IV. Performance Characteristics of Case 2 of the Carbide Model Reactor (Fuel Volume Fraction = 0.45) with Fixed Radial Zoning, $V_2/V = .4$, and Optimum Power Peaking Factor	15
Table V. Breeding Ratio, Power Peaking Factor, and Fissile Inventories for Different Core Zoning and Enrichment Ratios of the Carbide Core, Case 2 (First Core)	16
Table VI. Model of Nitride-Fueled Reactor	17
Table VII. Optimum Volume and Enrichment Parameters for Nitride Core Model and Resulting Power Peaking Factor	18

ABSTRACT

The effect of radial zoning on optimization of the nuclear power peaking factor is considered for large LMFBRs of the 5000 MWt class. The dependence of the power peaking factor on the ratios of outer-to-inner core volumes and enrichments was investigated for static conditions and burn cycles corresponding to first core loadings and equilibrium cores. Carbide and nitride fuels were considered.

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I. INTRODUCTION

An important consideration for optimum performance of large LMFBRs is the minimization of the nuclear power peaking factor, defined as the peak-to-average power ratio in the reactor core. Although this factor is a function of many parameters and of geometry, its general dependence on design parameters can be determined without going into highly detailed analyses. Here, we have limited the study to the effect of radial zoning in a finite-cylinder uncontrolled core. The dependence of the power peaking factor on the ratios of outer-to-inner core volumes and enrichments was investigated. For more realistic results, calculations should be performed in the hex-z geometry.

The radially zoned cores are characterized by outer and inner zones of different plutonium enrichments. In order to correspond to actual reactors in the 5000 MWt class, the core was assumed to have a power of 4500 MWt; that is, 10% of the power is assumed to come from the axial and radial blankets. Two types of fuel were considered: (1) mixed uranium and plutonium carbide and (2) mixed uranium and plutonium nitride (N-14). In the case of the carbide fuel, two separate studies were made, based on two different fuel volume fractions.

In all three models of the reactor, the optimum volume and enrichment splits between outer and inner core were determined first for static, or beginning-of-cycle, conditions. Subsequently, the study was extended to

burn cycles corresponding to first core loadings and equilibrium burn cycles based on a 600 fpd and 1200 fpd residence time for core and radial blanket fuel, respectively (300 day burn cycles were used in all burnup calculations). It was found that the optimum zoning parameters differ according to core conditions.

Neutronic calculations were based on the ARC System One-dimensional Diffusion Theory Capacity, DARCID.⁽¹⁾ The REBUS-2⁽²⁾ code was used for burnup calculations.

The results for static radial zoning of the carbide core models are discussed in Section II. In Section III, the optimum radial zoning parameters for the first core and equilibrium core of the same carbide models with a 300 day burn cycle are given. The corresponding static and burnup results for the nitride core models are described in Section IV. Section V contains a summary and discussion of the results, and recommendations.

II. STATIC ZONING: CARBIDE CORE

The assumptions for the model carbide reactor are summarized in Table I. Two cases, corresponding to fuel volume fractions 0.33 and 0.45 respectively, are considered. The lack of an axial blanket is a reflection of the one-dimensional calculations. The core is assumed to be uncontrolled and unpoisoned and its fuel composition corresponds to beginning-of-cycle conditions.

For a fixed ratio of the outer core volume to total core volume, denoted by V_2/V , the ratio of outer to inner core enrichment, denoted by ϵ_2/ϵ_1 , was varied to determine the minimum radial power peaking factor. The resulting curves, shown in Figures 1a and 1b, take the form of "vees"; the first leg of each "vee" corresponds to the peak power occurring at the center of the

core, while the second leg corresponds to peaking in the outer core. The optimum parameters for the model reactor are given in Table II.

The power peaking factor is fairly sensitive to variation in the enrichment split ϵ_2/ϵ_1 for a given outer to total core volume ratio. For example, a variation of 2% in ϵ_2/ϵ_1 near its optimum value yields a change of 5% in the peak/average power in the core for $V_2/V = 0.3$. In contrast, a 33% variation in V_2/V about its optimum value effects only a 0.4% change in the optimum power peaking factor. In the actual reactor V_2/V cannot be changed continuously since it depends on the number of assemblies in each zone. Therefore, a choice of the V_2/V nearest the optimum value should be made, and then ϵ_2/ϵ_1 varied continuously to determine the optimum conditions for that design. It is worth emphasizing that although the optimum power peaking factor may change by only a fraction of a percent for two different values of V_2/V , the optimum ϵ_2/ϵ_1 changes significantly. For the 33% variation in V_2/V just cited, there is a 10% change in the optimum ϵ_2/ϵ_1 .

III. OPTIMUM ZONING FOR 300 DAY BURN CYCLE: CARBIDE CORE

The optimum power peaking ratio is not just dependent on the fuel volume fraction, outer/total core volume, and enrichment split, but also on the length and type of burn cycle for the models of the reactor chosen. The optimum reactor design should yield the same power peaking factor at beginning and end of cycle. The model reactors described in Section II were assumed to have a 300 fpd burn cycle. It was found that optimum power peaking corresponded to the peak power at beginning of cycle occurring in the outer core and at the end of cycle in the core center. In other words, the "vee" shaped curves in Figures 1a and 1b shift to the right (towards larger enrichment splits) with burnup. Figures 2a and 2b display beginning- and end-of-cycle

radial power peaking factors for the first core loading (no fission products) as functions of the beginning-of-cycle enrichment split. In Figs. 3a and 3b, the radial power peaking factors are plotted for the equilibrium core burn cycle. In this case, the abscissa is the enrichment split of the unpoisoned fuel at beginning of cycle. The intersection of the beginning-of-cycle (BOC) and end-of-cycle (EOC) curves yields the optimum power peaking factor and enrichment split for the given outer-to-total core volume. The burnup calculation for Case 1, fuel volume fraction = 0.33, involved an end-of-cycle search for $k_{\text{eff}} = 1$; for Case 2, fuel volume fraction = 0.45, the search was for a beginning-of-cycle $k_{\text{eff}} = 1.0078$.

As in the static study, the power peaking factor is sensitive to the enrichment split ϵ_2/ϵ_1 . A change of 6% in ϵ_2/ϵ_1 near its optimum value for $V_2/V = 0.4$ may correspond to a 10% change in the peak/average power ratio. The optimum power peaking factor remains insensitive to the relative sizes of the outer and inner cores: a 25% change in V_2/V causes less than a 0.2% variation in the power peaking factor. Figures 4a and 4b display the broad minima in the radial peak/average power ratio as a function of V_2/V . Plots of the optimum V_2/V versus optimum ϵ_2/ϵ_1 for the two fuel volume fractions considered appear in Figures 5, 6, and 7.

The dependence of the power peaking factor on the fuel volume fraction is not as easily determined. Note that although Case 1 (fuel volume fraction = 0.33) yields a better peak/average power ratio than Case 2 (fuel volume fraction = 0.45) in the static study, this advantage was lost over the 300 day burn cycle. Table II contains a summary of the optimum parameters for Cases 1 and 2 of the model carbide core.

Figures 4a and 4b indicate that for the burn cycle considered, one may consider a range roughly between $V_2/V = 0.3$ and 0.5 to be optimum for the

carbide core, corresponding to a range in the optimum radial power peaking factor of approximately 1.23 - 1.28. The outer and inner core enrichments must be chosen appropriately, of course. Tables III and IV give the performance characteristics of the two cases of the carbide model reactor with a fixed ratio of outer core to total core volume, $V_2/V = 0.4$. The optimum values of ϵ_2/ϵ_1 were selected to minimize the radial peak/average power ratio. The breeding ratios at the beginning and end of cycle are based on definitions inherent in REBUS-2. The beginning-of-cycle (BOC) breeding ratio is the average over one day of

$$\frac{\text{production of fissile material}}{\text{destruction of fissile material}}$$

The EOC breeding ratio is averaged by taking the production and destruction of fissile material over the last burn step of the calculation, which in these cases coincided with the 300 day burn cycle. In calculating the local conversion ratio appearing in the table, both the production and destruction of fissile material was taken over a region; for calculation of the breeding ratios, the numerator was taken over the region and the denominator applies to the full reactor. The enrichments in Tables III and IV are defined as the ratio of fissile plutonium to total heavy metal in the region.

The zoning $V_2/V = 0.4$ appearing in Tables III and IV falls in the optimum range discussed earlier but is not equal to either of the actual optimum values given in Table II (the similar situation will hold for realistic core design since V_2/V varies discontinuously). However, they may be taken as representative of the optimum cases for the two fuel volume fractions since the other performance characteristics are not strongly dependent on V_2/V and ϵ_2/ϵ_1 . Table V contains first core burnup swings, power peaking factors,

breeding ratios, and fissile inventories for several core zonings and enrichment ratios for Case 2 of the carbide model reactor. Here, a 1.5% change in ϵ_2/ϵ_1 for fixed V_2/V causes changes of less than 0.1% in the burnup swing and less than 0.1% in the breeding ratios. The same change causes a 2.4% variation in the radial power peaking factor. Further, a 25% change in V_2/V corresponds to a 0.1% change in the burnup swing and less than 0.1% change in the breeding ratios.

The power densities at beginning and end of the first-core burn cycle versus core radius for the two cases of Tables III and IV are displayed in Figures 8a and 8b. Here it is shown explicitly that the beginning-of-cycle peak power occurs at the inner boundary of the second zone, while after 300 fpd, it has shifted to the center of the core.

Comparison of the results of the burnup zoning study with the results of the static study shows that static zoning, while straightforward, does not yield the optimum zoning parameters for the optimum peak power. For static zoning, the optimum beginning-of-cycle power distribution has equal maxima at the center of the core and in a ring at the inner boundary of the outer core. However, after the 300 day burn cycle, the peak power will occur in the inner core and the EOC power distribution results in a peak/average power ratio which is larger than for the BOC conditions. This is illustrated in Figure 9, where the power density at beginning and end of the first core cycle is plotted versus core radius for BOC optimum enrichment split $\epsilon_2/\epsilon_1 = 1.335$ corresponding to $V_2/V = 0.3$ and fuel volume fraction = 0.45. The radial peak/average power ratio in the core is 1.157 and 1.469 at the beginning and end of cycle, respectively.

IV. ZONING OF THE NITRIDE CORE

The zoning study also included a case of a 4500 MWt core fueled with mixed uranium and plutonium nitride (N-14). Assumptions for the nitride model appear in Table VI. Except for the different fuel, this model reactor closely resembles Case 1 of the carbide reactor, with approximately the same fuel volume fraction and core radius.

The static zoning study yielded the results depicted in Figure 10. It is interesting to compare these curves with the corresponding curves in Figure 1a for Case 1 of the carbide core. For the nitride core, the optimum static radial power peaking factor is 1.170 and occurs for $\epsilon_2/\epsilon_1 = 1.36$ and $V_2/V = 0.335$. For the carbide core, the optimum radial power peaking factor 1.168 corresponds to $\epsilon_2/\epsilon_1 = 1.40$ and $V_2/V = 0.32$.

Burnup zonings for a 300 day cycle are depicted in Figures 11 and 12. The optimum V_2/V shifted from 0.335 in the static study to the smaller values of approximately 0.26 for first core burnup and 0.20 to 0.25 for equilibrium burnup. This is in contrast to the shift to larger values of V_2/V in the carbide study. The nitride first core optimum power peaking factor 1.214 is obtained for the 300 day burn cycle with the BOC enrichment split $\epsilon_2/\epsilon_1 = 1.48$. This power peaking factor is approximately 3% less than the corresponding factor in Case 1 of the carbide core, indicating that the nitride fuel may yield the better performance in this regard.

The optimum parameters and radial power peaking factors for the nitride study are summarized in Table VII.

V. SUMMARY AND RECOMMENDATIONS

Three models of an uncontrolled reactor in the 5000 MWt class were investigated in order to determine optimum radial zoning parameters to minimize

the nuclear radial power peaking factor. The parameters chosen were the ratio of the outer core volume to the total core volume, denoted by V_2/V , and the ratio of the outer to inner core plutonium enrichment, ϵ_2/ϵ_1 . Although the results pertain specifically to the carbide and nitride models chosen, several general conclusions can be drawn for radial zoning of large LMFBRs.

For large reactors, the optimum radial power peaking factor can be expected to exhibit a broad minimum as a function of the ratio V_2/V . In the range $V_2/V = \text{"optimum value"} \pm 0.1$, the optimum radial power peaking factors of the models displayed variations in the range of 0.4% to 2.3%. Performance characteristics such as breeding ratios, burnup swings, and fissile inventories showed little dependence on V_2/V for ϵ_2/ϵ_1 near optimum.

The actual magnitude of the optimum peaking factor and optimum V_2/V depend on many parameters. Burn cycle zoning resulted in an increase in the optimum peaking factor over the static zoning, and a shift in the optimum value of V_2/V . Optimum performance will depend on other parameters as well, such as the length and type of burn cycle, type of fuel, fuel volume fraction, fuel smear density, and control rods. Although not all these dependences were investigated in detail in the present analysis, the three models provided the information summarized below.

Under static conditions (beginning-of-cycle conditions), the carbide and nitride fuels yielded approximately equal optimum power peaking factors. Optimization for a 300 day burn cycle indicated the nitride fuel yielded a power peaking factor 3% less than for the carbide fuel. This indicates that the nitride fuel may give better performance in this regard, but more analysis is needed. For example, the smear densities of the fuel are expected to have an effect.

The results of the two carbide cores indicate that the dependence of the peaking factor on the fuel volume fraction is also a function of the length of the burn cycle. For static zoning, the fuel volume fractions 0.33 and 0.45 corresponded to optimum radial power peaking factors 1.168 and 1.154, respectively. However, zoning for a first core burn cycle of 300 fpd resulted in optimum radial peaking factors 1.250 and 1.276 for the two cases, respectively; that is, the optimum peaking factor is less for the smaller fuel volume fraction.

Minimization of the radial power peaking factor involved choosing the optimum value of the enrichment split ϵ_2/ϵ_1 , as well as for V_2/V . It was found that the power peaking factor is sensitive to variation in the enrichment split for fixed V_2/V . A change of 4% in ϵ_2/ϵ_1 from its optimum value can lead to a change of more than 10% in the radial power peaking factor. Although variation of ϵ_2/ϵ_1 near its optimum value was found to have little effect on performance characteristics such as breeding ratios, burnup swings, and fuel inventories, it can be regarded as important for the design of the reactor core. The present analysis has indicated that the more direct approach of static zoning, while perhaps adequate for determining an approximate V_2/V , does not yield a realistic value of ϵ_2/ϵ_1 .

A more realistic approach takes into account the burn cycle of the reactor. A 300 day burn cycle was chosen for the three model reactors investigated. The results indicated that the enrichments of the outer and inner cores should be chosen in general such that the peak power occurs in the outer core at the beginning of cycle. The precise value of the optimum ϵ_2/ϵ_1 will depend on many parameters. It was determined that it is sensitive to the choice of the core zoning parameter V_2/V , the type of fuel, fuel volume fraction, and length and type of burn cycle. It can also be expected

to be sensitive to the smear density of the fuel, and, more importantly, to the number and distribution of control rods and/or control rod positions. A systematic approach to these problems is needed.

Finally, based on the present results, the following analytical approach to radial zoning is suggested. The volumes of the outer and inner core, which vary discontinuously for actual reactors, should be chosen such that V_2/V lies close to its optimum value, roughly in the range 0.3 to 0.5. Then ϵ_2/ϵ_1 can be varied continuously until the optimum is reached for the chosen reactor conditions.

References

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2. L. C. Just, H. Henryson II, A. S. Kennedy, S. D. Sparck, B. J. Toppel, and P. M. Walker, "The System Aspects and Interface Data Sets of the Argonne Reactor Computation (ARC) System," ANL-7711 (1971).

Table I. Model of Carbide-Fueled Reactor

Power in core	4500 MWt
Fuel	Mixed Uranium-Plutonium Carbide
Coolant	Sodium
Structural Material	Stainless Steel SS316

Radius of Core	200 cm
Outer Radius of Radial Blanket	220 cm
Outer Radius of Radial Reflector	230 cm
Height of Core	91.44 cm

Isotope Fractions:

^{235}U	0.002
^{238}U	0.998
^{239}Pu	0.680
^{240}Pu	0.194
^{241}Pu	0.102
^{242}Pu	0.024

Smear Density

80% T.D.

	<u>Case 1</u>	<u>Case 2</u>
Fuel Volume Fraction	0.45	0.33
Coolant Volume Fraction	0.20	0.15
Structure Volume Fraction	0.35	0.52

Table II. Optimum Volume and Enrichment Parameters for Carbide Model and Resulting Power Peaking Factors

Fuel Volume Fraction	Study	$\frac{V_2}{V}$ (a)	$\frac{\epsilon_2}{\epsilon_1}$ (BOC) (b)	Radial Peak/Avg Power
0.33	Static	0.32	1.40	1.168
	First Core ^(c)	0.37	1.37	1.250
	Equilibrium Core	0.30-0.40	1.50-1.35	1.226
0.45	Static	0.31	1.32	1.154
	First Core	0.41	1.26	1.276
	Equilibrium Core	0.395	1.31	1.268

(a) $\frac{V_2}{V}$ = Ratio of outer core to total core volume.

(b) $\frac{\epsilon_2}{\epsilon_1}$ (BOC) = Ratio of outer core to inner core enrichment of unpoisoned fuel at beginning of cycle.

(c) 300 day burn cycles are considered for both first and equilibrium cores.

Table III. Performance Characteristics of Case 1 of the Carbide Model Reactor (Fuel Volume Fraction=0.33) with Fixed Radial Zoning, $V_2/V=.4$, and Optimum Power Peaking Factor

	First Core		Equilibrium Core	
	BOC (a)	EOC	BOC	EOC
k_{eff}	1.0192	1.0000	1.0238	1.0000
Ratio of outer to total core volume, V_2/V (b)	0.4		0.4	
Ratio of outer to inner core enrichment, ϵ_2/ϵ_1 (c)	1.326	1.230	1.304	1.221
Radial peak/average power in core	1.252	1.249	1.228	1.229
Breeding ratio:				
Inner core	0.641	0.647	0.612	0.619
Outer core	0.291	0.272	0.278	0.269
Radial blanket	0.129	0.125	0.128	0.126
Reactor total	1.061	1.050	1.019	1.013
Local conversion ratio:				
Inner core	1.049	1.026	1.003	0.987
Outer core	0.748	0.765	0.716	0.744
Radial blanket	0.0	19.96	20.11	10.23
Enrichment, %:				
Inner core	10.11	10.61	10.55	10.92
Outer core	13.40	13.05	13.75	13.34
Core average	11.43	11.58	11.83	11.89
Radial blanket	0.0	1.093	0.54	1.58
Fissile inventory (kg):				
Inner core	2384	2408	2440	2430
Outer core	2106	1980	2125	1989
Radial blanket	0	173	86	250
Heavy metal inventory (kg):				
Total	55207	53761	54467	53025
Inner core	23588	22706	23129	22252
Outer core	15719	15176	15449	14913
Radial blanket	15900	15879	15889	15860
Peak power occurs in	outer core	inner core	outer core	inner core

(a) BOC and EOC refer to beginning-of-cycle and end-of-cycle conditions, respectively.

(b) The ratio $V_2/V=.4$ is near but not equal to the optimum values for both Cases 1 and 2 given in Table II. Fixing V_2/V simulates a reactor design with a fixed number of rows of assemblies in each zone. Similarly, in realistic calculations, it will not, in general, be possible to choose the optimum value of V_2/V since it varies discontinuously.

(c) ϵ_2/ϵ_1 in both cores was selected to yield the optimum power peaking factor for the given radial zoning. For the equilibrium core, the beginning-of-cycle ϵ_2/ϵ_1 for the unpoisoned fuel was 1.351.

Table IV. Performance Characteristics of Case 2 of the Carbide Model Reactor (Fuel Volume Fraction=0.45) with Fixed Radial Zoning, $V_2/V=.4$, and Optimum Power Peaking Factor

	First Core		Equilibrium Core	
	BOC ^(a)	EOC	BOC	EOC
k_{eff}	1.0078	1.0207	1.0078	1.0186
Ratio of outer to total core volume, V_2/V ^(b)	0.4		0.4	
Ratio of outer to inner core enrichment, ϵ_2/ϵ_1 ^(c)	1.264	1.171	1.249	1.164
Radial peak/average power in core	1.277	1.276	1.265	1.273
Breeding ratio:				
Inner core	0.769	0.771	0.749	0.751
Outer core	0.379	0.342	0.370	0.336
Radial blanket	0.109	0.100	0.111	0.101
Reactor total	1.257	1.213	1.229	1.189
Local conversion ratio:				
Inner core	1.269	1.201	1.238	1.182
Outer core	0.961	0.957	0.946	0.943
Radial blanket	0.0	25.5	25.4	12.90
Enrichment, %:				
Inner core	8.50	9.33	8.75	9.51
Outer core	10.75	10.93	10.92	11.07
Core average	9.40	9.97	9.61	10.13
Radial blanket	0.0	0.913	0.43	1.32
Fissile inventory (kg):				
Inner core	2734	2917	2771	2931
Outer core	2304	2281	2313	2283
Radial blanket	0	145	68	208
Heavy metal inventory (kg):				
Total	69514	68034	68789	67315
Inner core	32172	31272	31717	30824
Outer core	21442	20878	21180	20620
Radial blanket	15900	15884	15892	15871
Peak power occurs in	outer core	inner core	outer core	inner core

(a) BOC and EOC refer to beginning-of-cycle and end-of-cycle conditions, respectively.

(b) The ratio $V_2/V=.4$ is near but not equal to the optimum values for both Cases 1 and 2 given in Table II. Fixing V_2/V simulates a reactor design with a fixed number of rows of assemblies in each zone. Similarly, in realistic calculations, it will not, in general, be possible to choose the optimum value of V_2/V since it varies discontinuously.

(c) ϵ_2/ϵ_1 in both cores was selected to yield the optimum power peaking factor for the given radial zoning. For the equilibrium core, the beginning-of-cycle ϵ_2/ϵ_1 for the unpoisoned fuel was 1.307.

Table V. Breeding Ratio, Power Peaking Factor, and Fissile Inventories for Different Core Zoning and Enrichment Ratios of the Carbide Core, Case 2 (First Core)

$\frac{V_2}{V}$ (a)	Beginning-of-Cycle								End-of-Cycle (300 days)						
	$\frac{\epsilon_2}{\epsilon_1}$ (b)	k_{eff}	Radial Peak/Avg Power	Reactor Breeding Ratio (c)	Fissile Inventory (kg)			$\frac{\epsilon_2}{\epsilon_1}$	k_{eff}	Radial Peak/Avg Power	Reactor Breeding Ratio	Fissile Inventory (kg)			
					Inner Core	Outer Core	Total Core					Inner Core	Outer Core	Total Core	
0.5	1.19	1.019	1.21	1.061	2007	2394	4401	1.13	1.000	1.36	1.049	2020	2303	4323	
	1.23	1.020	1.26	1.061	1985	2442	4427	1.16	1.000	1.28	1.049	2007	2333	4340	
	1.25	1.020	1.28	1.060	1973	2467	4440	1.17	1.000	1.23	1.049	1999	2349	4348	
0.4	1.28	1.018	1.18	1.062	2409	2052	4461	1.20	1.000	1.33	1.049	2424	1946	4370	
	1.31	1.019	1.23	1.062	2392	2090	4482	1.22	1.000	1.27	1.050	2413	1970	4383	
	1.33	1.019	1.26	1.061	2382	2113	4495	1.23	1.000	1.24	1.050	2406	1983	4389	
0.3	1.42	1.018	1.17	1.063	2814	1716	4520	1.31	1.000	1.31	1.049	2829	1597	4426	
	1.45	1.018	1.22	1.063	4802	1743	4546	1.33	1.000	1.28	1.050	2822	1614	4436	
	1.47	1.018	1.25	1.062	2794	1761	4555	1.35	1.000	1.25	1.05	2816	1625	4441	

(a) $\frac{V_2}{V}$ = Ratio of outer core to total core volume.

(b) $\frac{\epsilon_2}{\epsilon_1}$ = Ratio of outer core to inner core enrichment.

(c) See text for definition of the reactor breeding ratio.

Table VI. Model of Nitride-Fueled Reactor

Power in Core	4500 Mw
Fuel	Mixed Uranium-Plutonium Nitride
Coolant	Liquid Sodium
Structural Material	Stainless Steel SS-316
Radius of Core	194.887 cm
Outer Radius of Radial Blanket	208.704 cm
Outer Radius of Radial Reflector	221.404 cm
Height of Core	91.44 cm
Isotope Fractions	
²³⁵ U	0.003
²³⁸ U	0.997
²³⁹ Pu	0.667
²⁴⁰ Pu	0.195
²⁴¹ Pu	0.103
²⁴² Pu	0.025
Fuel Volume Fraction	0.32071
Coolant Volume Fraction	0.19817
Structure Volume Fraction	0.48111
Fuel Smear Density	80% T.D.

Table VII. Optimum Volume and Enrichment Parameters for Nitride Core Model and Resulting Power Peaking Factor

	Fuel Volume Fraction	$\frac{V_2}{V}$ (a)	$\frac{\epsilon_2}{\epsilon_1}$ (b) (BOC)	Radial Peak/Avg. Power
Static Study	0.32	0.335	1.36	1.170
First Core ^(c)	0.32	~0.26	~1.48	1.214
Equilibrium Core	0.22	~0.20-0.25	~1.72-1.55	1.188

(a)
 $\frac{V_2}{V}$ = Ratio of outer core to total core volume.

(b)
 $\frac{\epsilon_2}{\epsilon_1}$ (BOC) = Ratio of outer core to inner core enrichment of unpoisoned fuel at beginning of cycle.

(c)
Burn cycle is 300 fpd for both first core and equilibrium core.

Case 1: Fuel Vol. Fr. = 0.33; $k_{eff} = 1.0078$

Fig. 1a. Radial power peaking factor as a function of enrichment split for beginning-of-cycle conditions, carbide core. First and second legs of the "vees" correspond to the power peak occurring in the inner and outer core, respectively.

Case 2: Fuel Vol. Fr. = 0.45; $k_{eff} = 1.0078$

Fig. 1b. Radial power peaking factor as a function of enrichment split for beginning-of-cycle conditions, carbide core. First and second legs of the "vases" correspond to the power peak occurring in the inner and outer core, respectively.

Case 1: Fuel Volume Fraction = 0.33

Fig. 2a. Radial power peaking factors as a function of beginning-of-cycle enrichment split, before and after first core burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core).

Case 2: Fuel Volume Fraction = 0.45

Fig. 2b. Radial power peaking factors as a function of beginning-of-cycle enrichment split, before and after first core burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core).

Fig. 3a. Radial power peaking factors as a function of beginning-of-cycle enrichment split of unpoisoned fuel, before and after equilibrium burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core). Case 1: Fuel Volume Fraction = 0.33.

Fig. 3b. Radial power peaking factors as a function of beginning-of-cycle enrichment split of unpoisoned fuel, before and after equilibrium burn cycle for carbide core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. BOC curves: beginning-of-cycle power peaking factor (peak power in outer core). EOC curves: end-of-cycle (300 fpd) power peaking factor (peak power at center of core). Case 2: Fuel Volume Fraction = 0.45.

Fig. 4a. Optimum radial power peaking factor as a function of outer core volume for static (beginning-of-cycle) conditions, and for first-core and equilibrium burn cycle of 300 days, carbide core. Case 1: Fuel volume fraction = 0.33.

Fig. 4b. Optimum radial power peaking factor as a function of outer core volume for static (beginning-of-cycle) conditions and for first-core and equilibrium burn cycle of 300 days, carbide core. Case 2: Fuel volume fraction = 0.45.

Fig. 5. Optimized enrichment split ϵ_2/ϵ_1 as a function of outer core volume for carbide core, static conditions.

Fig. 6. Optimized beginning-of-cycle enrichment split ϵ_2/ϵ_1 as a function of outer core volume for 300 day burnup, carbide core, first-core loading.

Fig. 7. Optimized beginning-of-cycle enrichment split ϵ_2/ϵ_1 of unpoisoned fuel as a function of outer core volume for 300 day equilibrium burnup, carbide core.

Fig. 8a. Power density in carbide core at beginning and end of first-core cycle for outer core to total core volume $V_2/V = 0.4$ and optimized power for 300 day burnup. Power is normalized to a total power of 1 watt. ϵ_2/ϵ_1 (BOC) = beginning-of-cycle ratio of inner to outer core enrichment = 1.325, fuel volume fraction = 0.33.

Fig. 8b. Power density in carbide core at beginning and end of first core cycle for outer core to total core volume $V_2/V = 0.4$ and optimized power for 300 day burnup. Power is normalized to a total power of 1 watt. ϵ_2/ϵ_1 (BOC) = beginning-of-cycle ratio of inner to outer core enrichment = 1.264, fuel volume fraction = 0.45.

Fig. 9. Power density in carbide core at beginning and end of cycle for outer core to total core volume $V_2/V = 0.3$ and optimized beginning-of-cycle peak power. Fuel volume fraction = 0.45. Beginning-of-cycle ratio of outer core to inner core enrichment $e_2/e_1 = 1.335$.

Fig. 10. Radial power peaking factor as a function of enrichment split for beginning-of-cycle conditions for nitride core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. Fuel volume fraction = 0.3207.

Fig. 11. Radial power peaking factors as functions of beginning-of-cycle enrichment split, before and after first core burn cycle for nitride core. V_2/V = ratio of outer core to total core volume. ϵ_2/ϵ_1 = ratio of outer core to inner core enrichment. Fuel volume fraction = 0.3207.

Fig. 12. Optimum radial power peaking factor as a function of outer core volume for static (beginning-of-cycle) conditions, and for first-core and equilibrium burn cycle of 300 days for nitride core.