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DESIGN OF THE CLINCH RIVER BREEDER REACTOR PLANT HETEROGENEOUS CORE

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The paper is being patent cleared by the responsible DOE patent group. It incorporates the comments of the CRBRP Project Office set forth in its approval for release to TIC. The paper is to be presented at the IAEA International Conference on Nuclear Power in Vienna, Austria, in September 1982 and published in the proceedings thereof.

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DESIGN OF THE CLINCH RIVER BREEDER REACTOR PLANT HETEROGENEOUS CORE

ABSTRACT

The original core design for the Clinch River Breeder Reactor Plant (CRBRP) was a homogeneous core, as are essentially all of present day liquid metal fast breeder reactors. Except for control locations the centermost portion of the core was fuel, in two radial enrichment zones, surrounded radially and axially by uranium-238.

The homogeneous design met all imposed requirements, but it met its breeding ratio goal of 1.2 only with the initial core and LWR-recycle plutonium.

A study was undertaken to determine if a rearrangement of the core into a heterogeneous configuration, with fertile elements interspersed within the fueled zone, would improve the breeding ratio significantly without excessive adverse effects on other aspects of the design. The change had to be made without a change in control assembly positions or fuel assmbly pitch because of the advanced state of the design of the reactor head and internals structures at the time the change was contemplated.

The result of the study was that the heterogeneous concept improved not only the breeding ratio and doubling time, but also the control assembly worth, core restraint response, and the fuel cycle cost. In fact, the savings in fuel cost for the first core alone was more than enough to justify the additional engineering effort required to make the change.

After further, more definitizing studies, the Clinch River Breeder Reactor Plant Project adopted the heterogeneous core as its reference design.

This paper describes the design evolution and the major effects of the change from a homogeneous to a heterogeneous core in the Clinch River Breeder Reactor Plant.

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1. INTRODUCTION

The Clinch River Breeder Reactor Plant (CRBRP) orginally contained a homogeneous core. For reasons described below a design change was made to a heterogeneous core in January 1979. Because the CRBRP was in an advanced stage of design and fabrication, the possible changes were strictly limited. This paper summarizes the reasons for the design change and the results of the change.

1.1 Homogeneous Core Design

Figure 1 shows the prior homogeneous core. It contained 198 fuel assemblies in two enrichment zones, 150 blanket assemblies, 15 primary control assemblies, and 4 secondary control assemblies.

The CRBRP fuel assembly dimensions are 11.3 cm across flats by 4.26 m long. The assembly contains 217 fuel rods. Each rod is 5.84 mm in diameter and has a cladding thickness of 0.38 mm. The rods are spaced by wire wrap to a 1.26 pitch/diameter ratio. The core region is 91.5 cm high, and is bounded by axial blankets 35.6 cm long. The fission gas plenum is 121.9 cm long.

The blanket assembly has only 61 rods. The rods are 12.9 mm in diameter and contain 162.6 cm of depleted uranium dioxide in 0.38-mm thick cladding. In other respects the blanket assembly is similar to the fuel assembly.

The fuel had a two-year life in this core. Thus, replacement of one-half of the fuel assemblies was planned each year. It was hoped that advances in fuel technology would permit a three-year life, so the physics and thermal-hydraulics accounted for either a one-half or one-third scatter refueling pattern. The blankets were shuffled outwardly on a two-, three-, or six-year interval, all achieving a six-year in-core residence time.

With these core assembly designs in the homogeneous configuration, the CRBRP could achieve the breeding ratio goal of 1.2 in the first cycle. This is based on the use of Pu having an isotopic content equivalent to the isotopic content of Pu discharged from light water reactors (LWRs). However, the breeding ratio decreased for later cycles. In addition, the Pu to be used in the

CRBRP for the initial cores is not the LWR-recycle Pu intended for ultimate use in breeders. It is an available fuel of a different isotopic mix than LWR-recycle Pu, which reduces the breeding ratio by about 0.06. Throughout this paper that fuel is referred to as low Pu-240 fuel.

The fuel design, except for 1) the addition of axial blankets, 2) a longer fission gas plenum, and 3) inlet and outlet hardware details, was made as nearly identical as possible to the design used in the Fast Flux Test Facility (FFTF) in order to take advantage of the extensive irradiation experience that will become available. The blanket design followed directly from the pitch imposed by the fuel assembly. Neither was optimized for breeding ratio or doubling time for use in a 975-MWth reactor.

2. HETEROGENEOUS DESIGN STUDY

The Clinch River Breeder Reactor Plant Project undertook redesign of the fuel and blanket assemblies as a means of achieving the desired breeding ratio. These advanced designs utilized larger diameter fuel rods and thinner fuel rod cladding.

The studies showed the desired goals could be attained. However, constraints imposed by the fuel development test program and the Project schedule tended to preclude changes in the fuel design for early reloads.

During this phase of the design, in 1975, a French study of the radial heterogeneous concept for liquid metal fast breeder reactor cores was published [1]. The stated merits of the concept were:

1. improved breeding ratio,
2. reduced doubling time,
3. decreased sodium void coefficient,
4. reduced core fluences,
5. flatter power distribution leading to improved average burnups with a single fuel enrichment.

This study was not the first heterogeneous design study. The initial core of Shippingport, a pressurized water reactor, used a "Seed and Blanket Concept" [2,3,4]. Breeding ratio and doubling time were, of course, not considered for these uranium fueled reactors, but conversion ratio, enrichment, and control worth and requirements were, and these are analogous concepts.

In the fast reactor field, versions of the concept were developed [5,6], and studies were ongoing [7]. However, not until the French paper [1] was there renewed interest in the concept by the CRBRP reactor design team.

A simple trial of the concept for the CRBRP core revealed that the claimed merits might be realized. Consequently, a design study was undertaken to develop a heterogeneous core design meeting all of the requirements of the homogeneous core and also achieving the breeding ratio goal of 1.2 with low Pu-240 fuel in the equilibrium cycle.

2.1 Ground Rules

The ground rules given below were adopted for the design study to minimize changes to reactor hardware that were in an advanced stage of design and procurement:

1. Overall safety characteristics must not be degraded.
2. Mechanical designs of fuel, blankets and control assemblies will not be changed except for their inlet hardware.
3. Blanket assembly shuffling will not be considered.
4. Control locations cannot be changed. The number of primary and secondary locations can be changed and/or transposed.
5. Fluence limits for permanent components must remain unchanged.
6. Power, refueling interval (one year), and availability of the reactor cannot be decreased.
7. Linear power limits on the fuel ($\sim$525 W/cm) and blankets ($\sim$660 W/cm) cannot be exceeded, based on calculations with three-sigma uncertainties on all nuclear, thermal-hydraulic, and engineering values when operating at 115% of rated power.

2.2 Selection of Core Arrangement

A variety of core arrangements were explored to select one which satisfies the goals of maximizing the fuel and blanket lifetime, achieving an equilibrium breeding ratio of 1.2 or greater with low Pu-240 fuel, and providing adequate control margin to accommodate minor perturbations from subsequent design changes and/or experimental biases.

One nearly optimum arrangement from a standpoint of flux and power shape, controllability, and fuel lifetime is shown in Figure 2. The design, called Concept 8, contained a total of 13 control locations. Seven were primary control locations, one in the center plus six in row 7 corner locations. Six were secondary control locations in row 4. This core arrangement had one major drawback. Due to the breeding gain, the inner blanket assemblies exceeded the linear power limitation at the end of two cycles of 275 full-power days (fpd) each.

Additional refuelings simply to replace internal blankets would decrease plant availability. The alternative of complete refueling on a shorter interval would increase fuel costs because fuel with significant life remaining would be removed.

A 91-rod blanket assembly would achieve the two-year life for the internal blankets but would violate ground rule two. This ground rule existed to avoid increased development costs. It would certainly not be cost effective to develop and irradiation-test a special blanket design for such a purpose. Nevertheless, from a purely core design standpoint, Concept 8 with a 91-rod internal blanket would probably have been the best performing core that could be designed.

An effective means of reducing the peak end-of-life internal blanket power is to lower the central core flux levels and thereby lower the plutonium accumulation. This was accomplished by removing selected fuel assemblies and substituting internal blanket assemblies near the center of the core, thereby shifting the flux from the core center toward the outer fuel regions. Ultimately, Concept 9' was selected for detailed design and experimental verification. It contained 156 fuel assemblies and 76 internal blanket assemblies as shown in Figure 3. In addition, six positions contained internal blanket assemblies and fuel assemblies on alternate cycles for reactivity burnup compensation.

In order to maximize the radial blanket assembly lifetime, while maintaining the peak linear power at less than 660 W/cm, the inner row radial blanket assemblies were burned in-place for four consecutive years and the outer row blanket assemblies were burned in-place for five consecutive years.

Complete refueling of fuel and inner blanket assemblies was performed every two years, at the end of even cycles. A partial refueling (six assemblies) was required at the end of each odd cycle to provide reactivity enhancement.

2.2.1 Relocation of Control Assemblies

A consequence of this core layout was an unacceptable reduction in the row 4 secondary control assembly worths in the lower flux environment at beginning-of-cycle. The six secondary control locations were therefore moved from row 4 out into the higher flux region in the row 7 flats. At the same time, the low worth central primary control location was eliminated and three primary control locations were added symmetrically in row 4. The net result was a 15-control-location system consisting of nine primary control locations and six secondary control locations. The primary control assemblies in row 4, as well as all secondary control assemblies, are fully withdrawn during all power operation.

2.3 One Final Iteration

Concept 9' was modelled on the Zero Power Plutonium Reactor (ZPPR) at the Argonne National Laboratory facilities in Idaho, as the ZPPR-7 series [8,9]. These experiments, performed from July 1976 through April 1978, confirmed the physics design calculations.

One final design iteration was made during the course of the experiments. The replacement of the radial blanket assemblies at the beginning of cycles 5 and 6 increased the burnup reactivity requirement on the fuel, but the primary control margin available at the beginning of cycle 5 was not sufficient to guarantee, with allowances for all uncertainties, the 550-fpd burnup requirement with low Pu-240 fuel.

LWR-recycle Pu should be available for cycle 5. The use of recycle Pu would guarantee the full 550 fpd with all uncertainties taken into account. Furthermore, in all likelihood the reduction in the magnitude of the end-of-cycle criticality uncertainties based on operating information obtained in the first four cycles would probably have eliminated the potential problem of a shortened cycle life even with low Pu-240 fuel.

Fortunately, however, control worth enhancement was explored. This led to a better understanding of heterogeneous cores and an improved final configuration for the CRBRP core design. The change from Concept 9' was apparently small but had dramatic effects. The six refueling locations in row 5 were interchanged with the adjacent blanket locations in row 6, and each row 8 blanket location adjacent to a control location was interchanged with its nearest row 9 fuel location on a factor of 12 symmetry. The final configuration, which has a refueling schedule identical to Concept 9', is shown in Figure 4.

This minor rearrangement of fuel locations adjacent to control locations results in a larger increase in control system worths than might be expected. The flux shifted inward somewhat reducing peripheral flux leakage and increasing fuel worth which permitted a slight decrease, approximately 0.5%, in enrichment. The combination of these effects reduced the burnup reactivity loss by approximately 10% and increased the breeding ratio by 0.03. Table I shows these effects for both cores using the same cross-section set and calculation techniques.

3. NEUTRONIC COMPARISON OF THE HOMOGENEOUS AND HETEROGENEOUS CRBRP CONFIGURATION

The differences between the heterogeneous and homogeneous configuration are partly an intrinsic characteristic of the heterogeneous arrangement of the fuel and inner blankets and partly a function of the different effective heavy metal mass of the two arrangements. The major differences may be categorized into 1) breeding ratio and doubling time characteristics, and 2) differences in reactivity coefficients and kinetic characteristics and their impact on the reactor dynamic behavior.

Table II summarizes the major neutronic differences between the homogeneous and the heterogeneous configurations. The heterogeneous configuration breeding ratio (on a consistent physical assembly design and operating history basis) substantially exceeds that of the homogeneous configuration. The heterogeneous design achieves the 1.2 breeding ratio goal with some margin utilizing the FFTF derived fuel assembly design with low Pu-240 plutonium fuel, a single fuel enrichment, and no blanket shuffling. The higher core-average heavy metal content, combined with the effect of concentrating the fuel near the outer core periphery, increased the required core fissile inventory in the heterogeneous design. Nevertheless, the heterogeneous design has a considerably shorter doubling time.

The peak fuel linear power is increased relative to the homogeneous design. This higher fuel linear power is not a necessary condition of a heterogeneous core configuration. For the CRBRP this increase was desirable because the homogeneous design had excess margin in its fresh fuel linear power rating. As a result of eliminating this excess margin, fuel costs were reduced by several million dollars over the first five years of operation even after subtracting the cost of additional blankets.

The heterogeneous power distribution is relatively flat. The peak internal blanket linear power is approximately the same as the peak equilibrium radial blanket power in the homogeneous design. The lower peak total and fast (> 0.11 MeV) flux levels in the heterogeneous design afford a beneficial effect on fuel assembly lifetime because CRBRP fuel lifetime is fluence limited. The peak fuel burnup in the heterogeneous design is slightly greater than that in the homogeneous design during early cycles.

The maximum positive sodium void worth in the fuel is reduced in the heterogeneous design. The lower sodium void worth reduces the already trivial potential for energetics from a hypothetical core disruptive accident. The sodium voiding sequence is also changed in the direction to further reduce the potential due to thermal response incoherencies between fuel and blanket assemblies. This sodium voiding behavior is an intrinsic characteristic of a heterogeneous configuration.

Accompanying this reduction in the sodium void worth is a reduction in the fast-acting fuel Doppler feedback, although the overall reactor Doppler coefficient is comparable to that of the homogeneous design. This reduced fuel Doppler coefficient introduces some changes in the design transient conditions, but does not adversely affect the overall safety of the plant.

4. OTHER EFFECTS OF A CHANGE TO A HETEROGENEOUS CORE

The other effects of a change to a heterogeneous design on other reactor components and characteristics were not major. Briefly:

1. Radial shielding requirements increased.
2. Axial shielding requirements decreased.
3. Core restraint performance improved.
4. Hot leg component transients changed insignificantly.
5. Control assembly costs decreased and lifetime improved.
6. Margin to generating energetics in a hypothetical core disruptive accident increased.
7. Refueling error potential decreased.

Other effects which were primarily the result of the change to batch refueling, but were also influenced by the use of the heterogeneous configuration, were:

8. Thermal striping protection requirements of the upper internals structure increased.

9. Criticality control requirements of the spent fuel storage tank increased.

A detailed discussion of these effects is provided in Reference [10].

5. GENERAL OBSERVATIONS ON THE DESIGN OF THE HETEROGENEOUS CORE

The analytical effort required in the design of a heterogeneous core is significantly increased as compared with a homogeneous core. One of the reasons is the sensitivity of heterogeneous cores to small azimuthal/radial variations which require explicit spatial calculations to observe. For example, the change from Concept 9' to the CRBRP design is a significant change, although it would be virtually unnoticed in an RZ calculation.

Thus, it is difficult to perform simple parametric analyses and derive definitive con-conclusions about heterogeneous designs. Another risk is that it is very easy to waste considerable time developing a poor heterogeneous design and blaming the concept instead of the designer. On the other hand, heterogeneous cores allow a designer to achieve azimuthal zoning as well as radial zoning, thus enhancing overall performance. In particular, clustering fuel around control locations enhances control assembly worth, avoids excess power in the cluster at beginning-of-cycle, but enhances burnup compensation during a cycle as the control assemblies move out.

Even after a good design is selected, the effort required is significantly greater in doing the nuclear analysis, the thermal-hydraulic analysis, and the core restraint analysis.

A complete discussion of all aspects would fill another paper. However, some considerations worth noting are 1) the number and magnitude of flux gradients and the additional importance of gamma heating affect the nuclear analysis, 2) the greater amount of interassembly heat transfer affects the thermal-hydraulic analysis, and 3) the three-dimensional nonuniform assembly bowing affects the core restraint analysis.

6. SUMMARY

The adoption of the heterogeneous configuration for the Clinch River Breeder Reactor increased the breeding ratio to greater than 1.2 for all cycles with no change in fuel design and low Pu-240 fuel.

Although significantly increased analytical efforts were required in some areas, most of the effects were beneficial. Almost all engineering changes were straightforward and uncomplicated. The only significant change other than the core was the increase in the amount of thermal striping protection of the upper internals.

7. CONCLUSION

The extra degree of freedom afforded by a heterogeneous core allows for improved performance at the cost of significantly greater analytical effort.

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Table I

Effect of Minor Rearrangement of Fuel in a Heterogeneous Core

	Concept 9′ Figure 3	CRBRP Final Design Figure 4
Control Worth (%Δk):		
Primary System	6.58	7.29
Secondary System	2.65	4.16
Total	9.23	11.45
Burnup in 550 fpd (2 years) (%Δk)	5.22	4.66
Breeding Ratio with low Pu-240 fuel:		
Cycle 1 & 2	1.26	1.29
Eq. Cycle Avg.	1.21	1.24
Equilibrium Fuel Enrichment (w/%)	33.4	32.9
Peak Linear Power (W/cm):		
Fuel	522	525
Internal blanket	646	656

Table II

Summary Comparison of Major Neutronic Characteristics of the CRBRP Homogeneous and Heterogeneous Core

	Homogeneous	Heterogeneous
Breeding Ratio: (Initial Cycle, low Pu-240 fuel)	1.15	1.29
(Equilibrium Cycle, low Pu-240 fuel)	1.08	1.24
(Initial Cycle, LWR-Pu)	1.21	1.34
(Equilibrium Cycle, LWR-Pu)	1.14	1.29
Fissile Plutonium Inventory (Initial Core, Kg)	1230	1502
Fuel Enrichment (Initial Core, Low Pu-240 Fuel, w/%)	0.174 (IC) 0.252 (OC)	0.328
Peak Linear Power (3σ + 15% Overpower, W/cm):		
Fuel	469	525
Blankets	650	656
Peak Flux ($n/cm^2 \cdot sec$): Total	7.4×10^{15}	5.4×10^{15}
Fast (> 0.11 MeV)	4.2×10^{15}	3.4×10^{15}
Fuel Burnup (Cycles 1 + 2/3 + 4, MWd/Kg)	63/104	77/110
Sodium Void:		
(Maximum Positive, BOC Fuel Assemblies, $)	3.90	1.51
(Maximum Positive, EOC Fuel Assemblies, $)	4.00	2.31
Doppler Coefficient (Start-of-Life, $- T\, dk/dt \cdot 10^4$):		
Fuel	55.9	25.8
Internal Blankets	—	44.0
Radial Blankets	7.0	11.8
Axial Blankets	4.4	2.6

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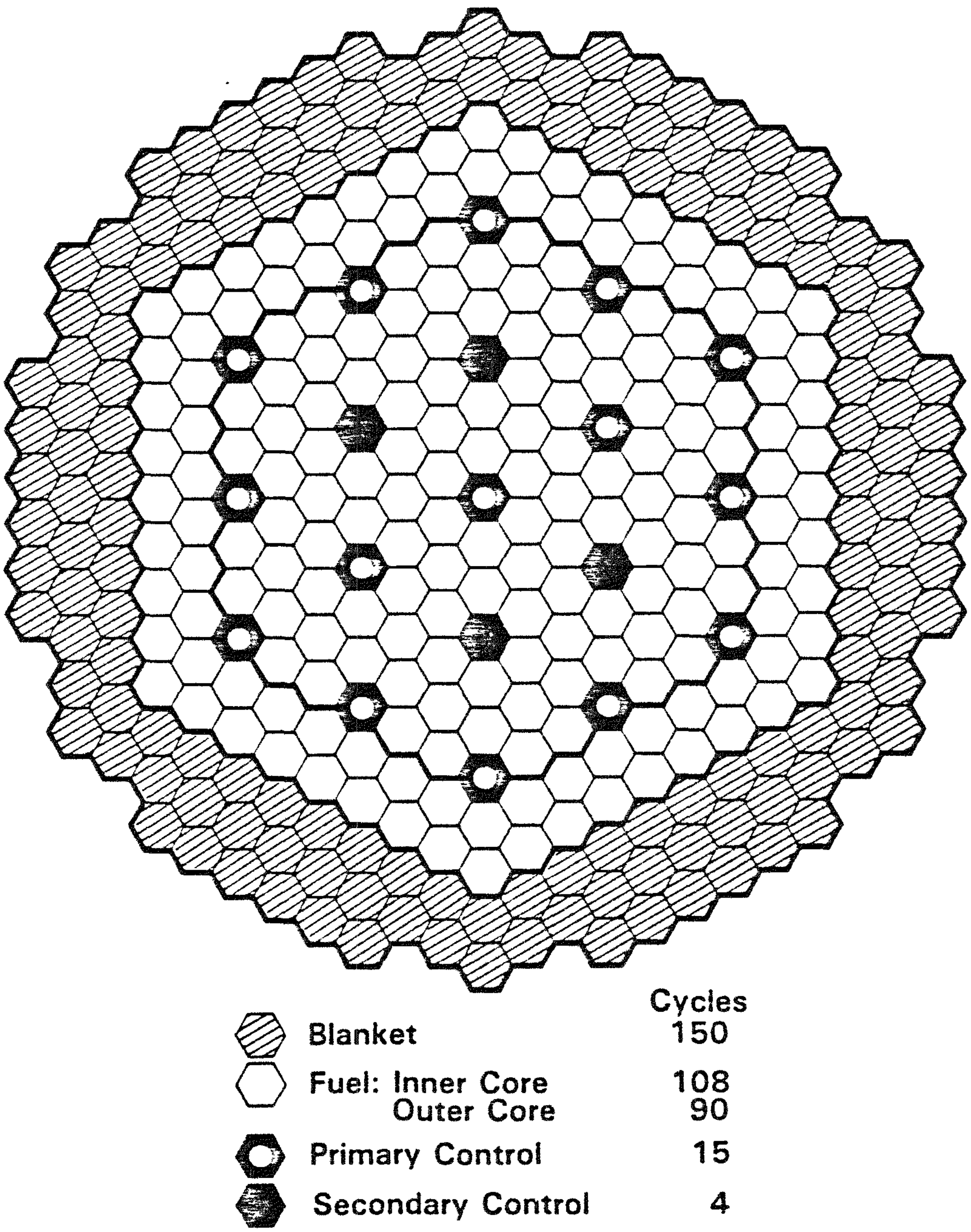

Figure 1. CRBRP Homogeneous Configuration

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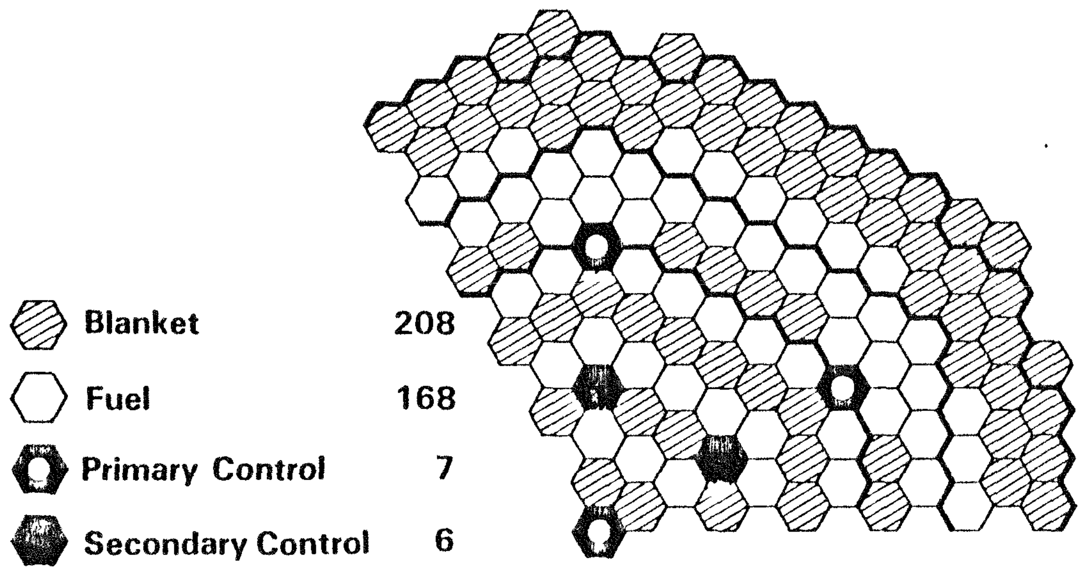

Figure 2. Nearly Optimum Heterogeneous Configuration, Concept 8

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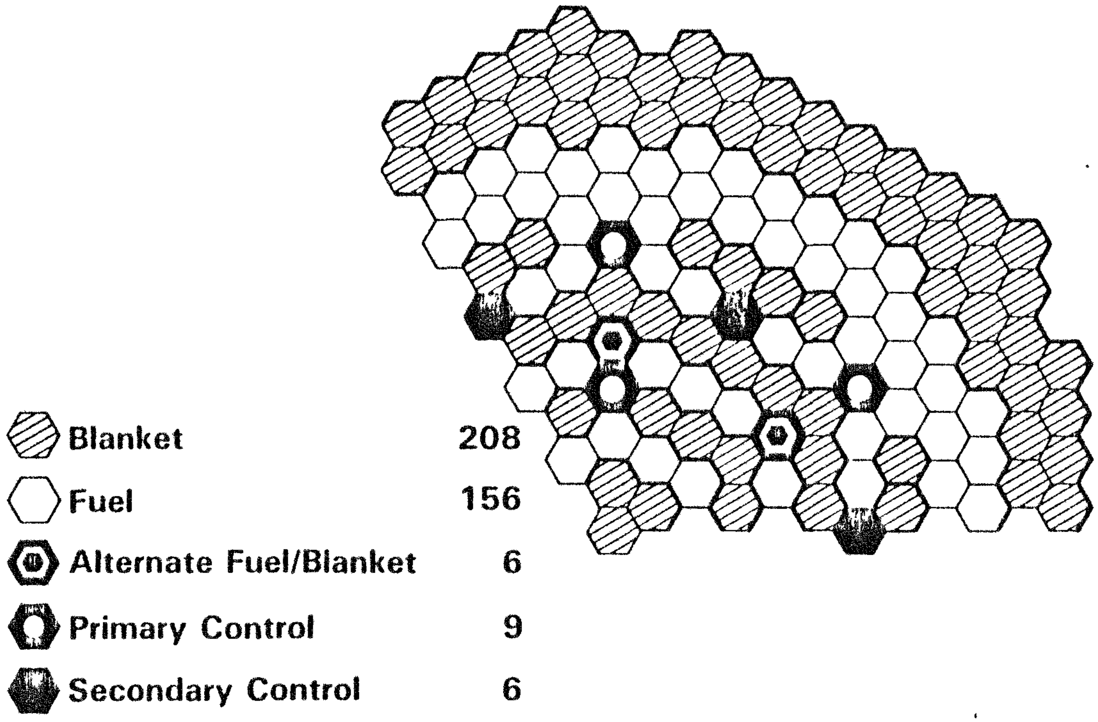

Figure 3. Heterogeneous Configuration, Concept 9′

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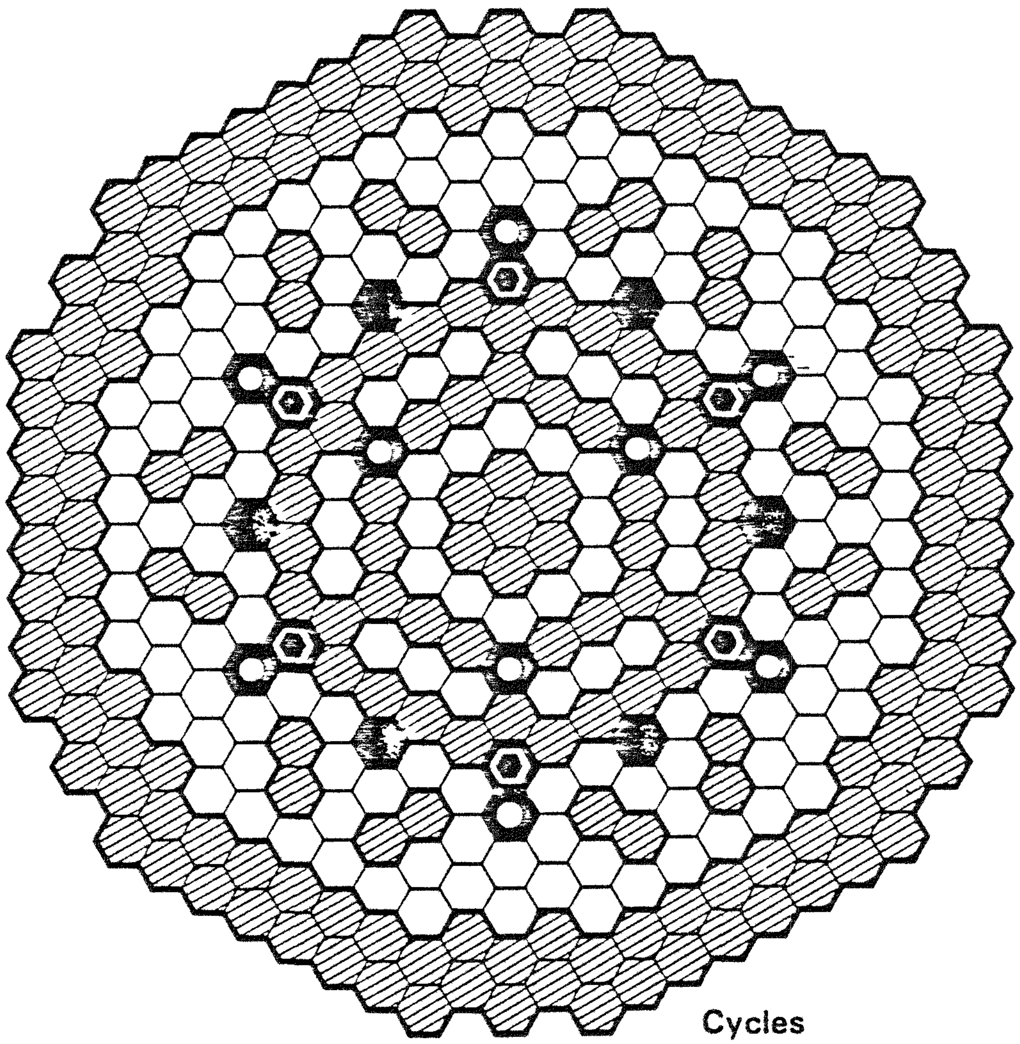

	Cycles Odd	Cycles Even
Blanket	208	202
Fuel	156	162
Alternate Fuel/Blanket	6	
Primary Control	9	
Secondary Control	6	

Figure 4. CRBRP Core

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