



Fuel Utilization in a Progressive Conversion Reactor (PCR)



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CONTENTS

	<u>Page</u>
Introduction	1
Basic PCR Concept	1
Basis for Preliminary Nuclear Performance Estimates	5
Parametric Study of LEU Once-Through Cycles	10
Comparisons of PCR to NASAP Reactors	16
Conclusions	21
References	23

TABLES

1. Basic Design Data for PCR Analysis	7
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FIGURES

1. Typical PCR and BWR Axial Power Distributions	3
2. Typical LEU-PCR BOC and EOC Axial Distributions (equilibrium cycles)	4
3. Typical Axial Distributions of Power, Quality, and CIIF Ratio	9
4. LEU-PCR Annual Uranium and Separative Work Versus Coolant/Fuel Ratio	11
5. LEU-PCR Annual Uranium and Separative Work Demands Versus Initial Fissile	12
6. LEU-PCR Annual Spent Fuel Fissile Amounts Versus Initial Fissile	14
7. LEU-PCR Exit Steam Quality Versus Initial Fissile	15
8. Relative U_3O_8 Requirements for Once-Through Fuel Cycles - NASAP Reactors and PCR	18

FIGURES (continued)

	<u>Page</u>
9. Relative U_{308} Requirements for LWRs With and Without Recycle - LEU-PCR and NASAP LWRs	19
10. Key Characteristics of LEU-PCRs and NASAP BWRs	20

Introduction

First, it is appropriate to note that the studies¹ supporting this paper were conducted when there was emphasis on improving the once-through fuel cycle because of a U. S. government policy against reprocessing and recycling of Light-Water-Reactor (LWR) fuel. While the government's policy has changed to deemphasize the once-through fuel cycle, we believe the results of our studies of the Progressive Conversion Reactor (PCR) concept remain of interest because of potential economic benefits without regard to the nonproliferation attributes. For example, our studies indicate that the uranium utilization might be improved about 50 percent over that of current LWRs. This contrasts with the recent Department of Energy (DOE) Nonproliferation Alternative Systems Assessment Program (NASAP) study² which concluded the following wide respect to the once-through fuel cycle:

"The fuel efficiency of light-water reactors might be improved by as much as 30 percent through fuel redesign, reoptimization of fuel-management practices, and plant design changes."

The Basic PCR Concept

The Progressive Conversion Reactor (PCR), an unconventional approach to the design and operation of boiling water reactors, is an old but little known concept, having been proposed to the Atomic Energy Commission by Internuclear Company in 1963. Internuclear Company proposed that the PCR concept could lead to low fuel costs through the beneficial effects of a higher conversion ratio and high fuel burnup. In our studies, emphasis was given to meeting nonproliferation objectives through improving the uranium utilization of once-through fuel cycles as well as through reducing the amount and quality of plutonium in spent fuel. It should be kept in mind that the PCR is not a specific concept, but rather a different approach to the design and operation of boiling water reactors. There are obviously many potential variations (e.g., fissile and fertile materials,

coolants, system size, operating pressure) to which the PCR concept can be applied - only several of the most obvious have been explored in our preliminary scoping studies¹. This paper presents some of the key results for the Low-Enriched-Uranium (LEU) once-through fuel cycle.

The PCR is a concept for depleting a boiling water reactor core from the bottom upwards. To explain the concept it is convenient to compare the axial power distributions at the beginning and end of a PCR equilibrium cycle to those of a conventional BWR. Figure 1 shows such typical axial power distributions. It is noted that the conventional BWR utilizes bottom entry control rods and burnable poisons to achieve a relatively flat axial power distribution that does not change greatly during a normal operating cycle. Elimination of these measures and use of a higher core exit steam quality in a typical PCR, results in a highly peaked axial power distribution that moves up the reactor core during a normal operating cycle as the fuel is preferentially depleted in the lower part of the core. With radial shuffling of fuel, approximately uniform burnup is achieved in the fuel in the lower portion of the core - which is considered the discharge fuel for a typical fuel cycle. The highly peaked axial power distribution has disadvantages from the standpoint of core thermal/hydraulics and requires a larger number of fuel rods per unit of reactor power. However, the highly peaked axial power distribution and the manner in which it moves up the core yield significant advantages in the potential for achievement of improved utilization of uranium and improved proliferation resistance attributes in the once-through LWR fuel cycle. The nuclear performance improvements indicated for the PCR result primarily from three factors: approximately uniform burnup in the discharged fuel, higher burnup in the discharged fuel, and higher average conversion ratios during the fuel cycle.

Typical operating characteristics of a PCR are indicated by Figure 2, which shows axial distributions of several key parameters for a simulated PCR equilibrium cycle. The analysis is for a reactor core with 3.3 percent LEU, a coolant/fuel ratio of three, and physical size and thermal power output (3580 Mwt) corresponding to a General Electric Company BWR-6³.

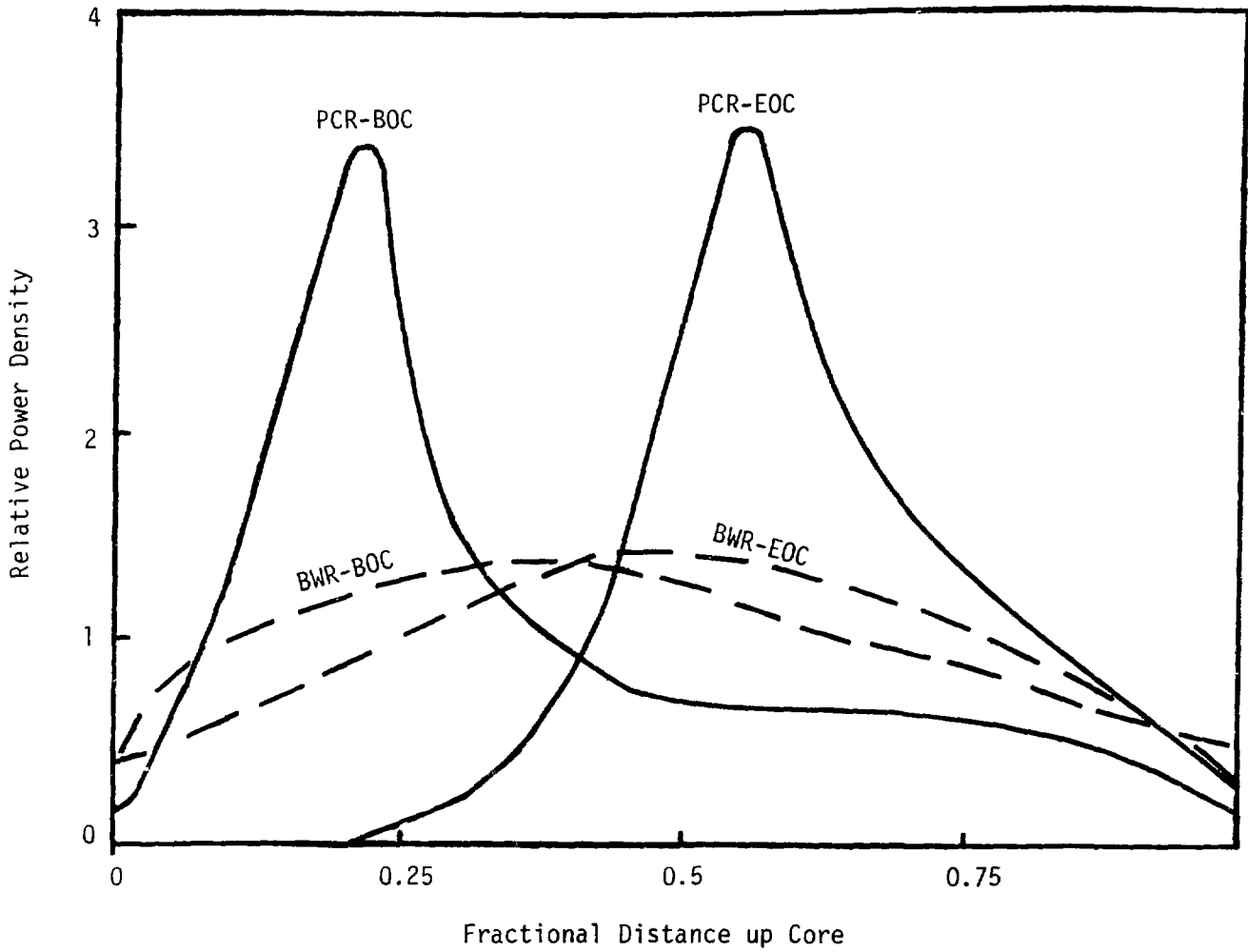


Figure 1. Typical PCR and BWR Axial Power Distributions

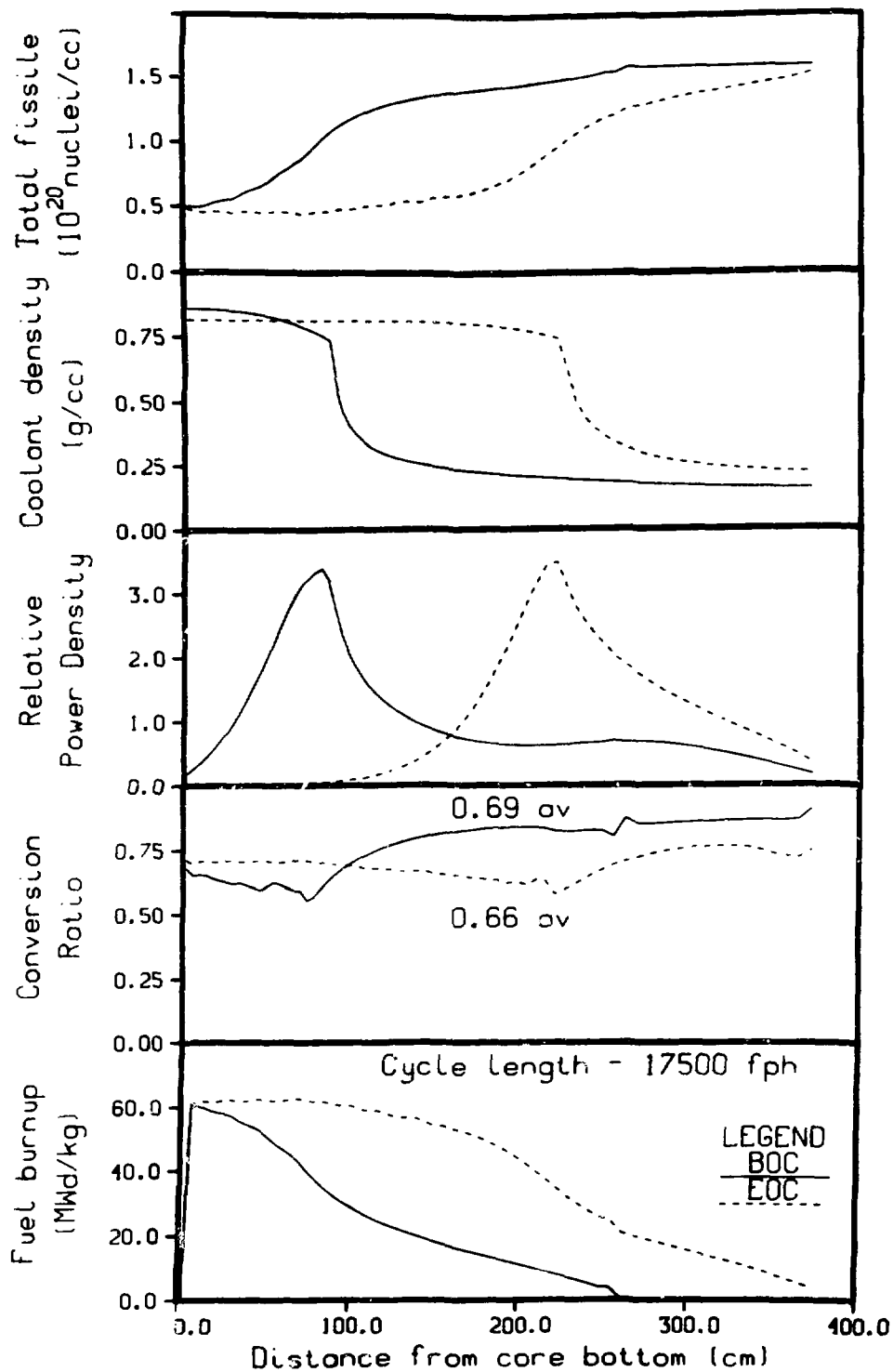


Figure 2. Typical LEU-PCR BOC and EOC axial distributions. (equilibrium cycle)

The reactor core is assumed to consist of three equal length sections in the vertical direction. For the Beginning-of-Cycle (BOC) the spent fuel in the lowest third at the end of the previous cycle has been discharged, the upper two sections have been moved downward one position and fresh uniformly loaded fuel has been added to the top section of the core (see top BOC curve). As noted previously, it is assumed that radial shuffling of fuel occurs during the cycle in order to maintain a relatively uniform radial distribution of fuel burnup. The middle set of curves shows how the power peak has moved up the core during the operating cycle. At the End-of-Cycle (EOC) the peak is slightly above the axial midpoint and there is essentially no power generated in the lower one-third of the core, indicating it is again time for refueling. The lowest curve shows the approximately uniform fuel burnup that is achieved in the lowest one-third of the core at the EOC. The discharge burnup is indicated to be about 60 Mwdt/KgHM for this equilibrium cycle, which has a life of 17,500 full power hours (fph) or more than 2.5 years at 0.75 capacity factor.

Basis for Preliminary Nuclear Performance Estimates

Estimates of the performance of PCRs fueled with Low-Enriched-Uranium (LEU) are provided to permit a direct comparison to the fuel utilization currently achieved in and projected for the once-through LEU fuel cycle in PWRs and BWRs. The studies address the nuclear performance of once-through fuel cycles in terms of uranium resource and separative work requirements, the isotopic content of fresh and spent fuel, and the amounts of spent fuel. Considerations of core thermal/hydraulics were only the minimum needed to provide reasonable assurance that the nuclear performance estimates may be considered representative of practical PCRs. Many of the other aspects of boiling reactor design (e.g., boiling reactor stability, high burnup fuel integrity, reactor control) requiring thorough investigation to determine the feasibility of developing and commercializing the PCR have not been addressed in these studies.

Basic design data for the performance analyses are summarized in Table 1. In order that the PCR performance estimates be in appropriate perspective with respect to current BWRs, the General Electric BWR-6 No. 238-732³ was used as a basis for reactor thermal power, reactor core size, and system pressure. The net electrical power and net plant efficiency correspond to estimated equilibrium operating conditions and take into account the loss in efficiency that results from lowering the reactor feedwater temperature to 150°F. The fuel utilization of PCRs is generally favored by lower feedwater temperatures and the 150°F was selected as an appropriate minimum value for these studies. The conventional LWR rod/pellet type of UO₂ fuel element with 25 mils of zirconium cladding was also selected.

In order to limit the scope of the studies, but at the same time provide for somewhat equitable comparisons of results for various Coolant/Fuel (C/F) ratios, it was decided (on the basis of early results) to hold the core heat transfer area constant while the C/F ratio was varied. The heat transfer area for the normal active core height is about 156,000 ft² giving an average heat flux of about 78,000 but/hr-ft², a value that is about one-half the average heat flux in the BWR6-238-732³. The various coolant fuel ratios and their corresponding fuel rod diameters, average linear heat rates used in the study are indicated in Table 1. The relatively high C/F ratios (e.g., 2,3,4) are generally of interest in the LEU once-through fuel cycle where it is desired to have a low residual fissile content in the spent fuel. Lower C/F ratios would generally be of interest for fuel cycles in which the spent fuel would be reprocessed and higher residual fissile contents are of less concern.

The PCR nuclear performance is generally expected to be improved as the exit quality or superheat of the core coolant is increased. However, prior difficulties with fuel performance in superheat reactors as well as potential corrosion, erosion, deposition problems in the film dryout region at high exit qualities indicated that it would be appropriate to avoid these regimes in the preliminary studies. Therefore, early in the studies it was decided to direct the core burnup analyses primarily toward reactors that have core exit qualities of less than 70 percent at equilibrium burnup conditions.

TABLE 1

BASIC DESIGN DATA FOR PCR ANALYSIS

<u>Overall Plant</u>				
Reactor thermal power		3580		Mwt
Net plant efficiency		30		%
<u>Reactor Coolant Conditions</u>				
Reactor feedwater temperature		150		$^{\circ}\text{F}$
System pressure at core		1050		psia
<u>Reactor Core Size</u>				
Active diameter		183		in.
Active height		143		in.
<u>Fuel Elements</u>				
Type		rod/pellet		
Clad material		zirconium		
Clad thickness		0.025		in.
<u>Core Thermal/Hydraulics</u>				
Core heat transfer area		$\sim 156,000$		ft^2
Average core heat flux		$\sim 78,000$		Btu/hr-ft^2
<u>Core Geometry</u>				
Coolant/fuel ratio		2	3	4
Fuel rod o.d.	in.	0.30	0.25	0.218
Rod linear heat rate average	kw/ft	1.8	1.5	1.3

The nuclear performance associated with the progressive axial burnup in the PCR concept is generally enhanced by increasing the axial peak/average power density ratio. Preliminary heat transfer considerations indicated that reactors with axial peak/average power density ratios of about four to five would be acceptable. This is supported by Figure 3, which shows an estimate of the Critical Heat Flux (CHF) ratio for a typical power distribution with a 5/1 peak/average power and 70 percent exit core quality at 1050 psi. The CHF ratio is about two at the peak power location and decreases to about 1.3 in the low power density high quality region at the top of the core.

The nuclear performance estimates are based on axial one-dimensional neutronic analyses conducted with PDQ-7 which was modified with a flow-search option that determines the flow, core inlet temperature, and core exit quality that produce criticality with a specified reactor feedwater temperature. All the reactor cores analyzed in these studies rely solely on coolant flow-temperature control - there are no control rods in the cores. The burnup analyses assume there is radial shuffling of fuel assemblies at regular intervals to keep the radial distribution of burnup relatively uniform. Under this assumption the burnup estimates are expected to be representative of actual operations.

The burnup analyses were generally only carried to the point where the equilibrium values of the Net Fissile Consumption (NFC) and the fissile content of the spent fuel could be determined. The uranium and separative work requirements are based on a 75 percent plant capacity factor and 0.2 percent enrichment tails. No allowances are made for fabrication, conversion or ore processing losses. The fractions of the various uranium and plutonium isotopes in the spent fuel are based on the final burnup step, which in most cases has closely approached equilibrium burnup and is always within 10 percent of the estimated equilibrium burnup. A simulation of an equilibrium burnup cycle, indicated that the above approach provides reasonable estimates for the key operating parameters of interest in this study.

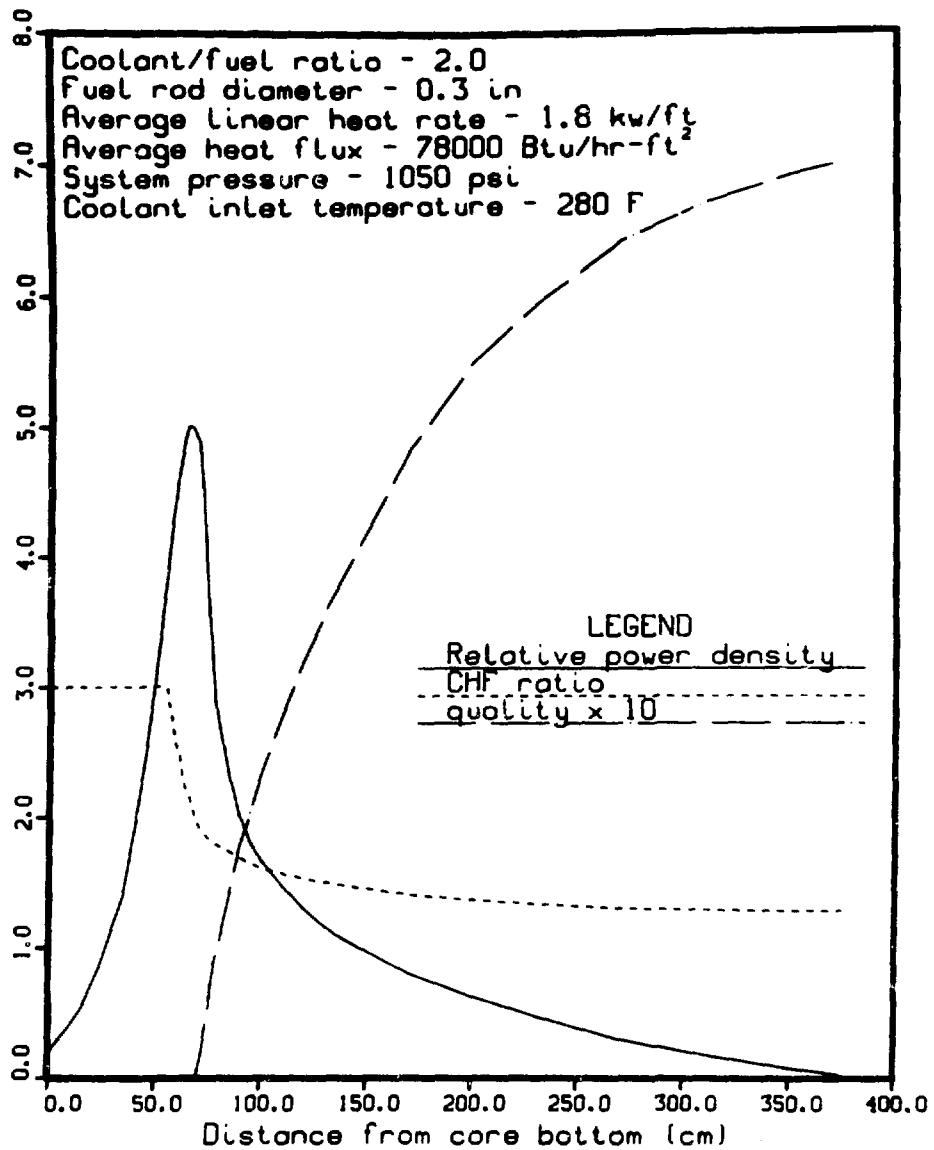


Figure 3. Typical axial distributions of power, quality, and CHF ratio.

Parametric Study of LEU Once-Through Cycles

With Coolant/Fuel (C/F) ratio and uranium enrichment as the two primary independent variables, a parametric study involving burnup analyses for the LEU once-through cycle was conducted to determine estimates of equilibrium cycle values for key operating parameters.

The effects of coolant/fuel ratio on several key parameters are indicated in Figure 4 for reactor cores loaded with LEU of 5 percent enrichment. These results indicate that with 5 percent enrichment, the annual U_3O_8 and separative work demands are minimized with Coolant/Fuel (C/F) ratios in the range of three to four. This is considerably above the 1.5-2 range typical of current LWRs primarily because of the relatively high steam content in the upper portion of the PCR core. The balance of the analysis results presented in this paper are for a coolant/fuel ratio of three, which, based on Figure 4, is reasonably close to the optimum with respect to U_3O_8 demand and separative work requirements.

The annual U_3O_8 demand and separative work requirements as a function of the enrichment of the equilibrium cycle makeup fuel are indicated in Figure 5, which also indicates equilibrium fuel burnup and conversion ratio estimates. The corresponding values for the NASAP² Reference BWR are noted on the figure. The minimum annual U_3O_8 demand of the PCR is indicated to be slightly above 100 ST/Gwe, which is almost a 50 percent reduction from the U_3O_8 demand of the NASAP Reference BWR. The minimum U_3O_8 demand occurs with fuel burnups above 100 Mwdt/kgHM, which is considerably above current LWR practice. However, extrapolation to the current LWR maximum burnup of about 45 Mwdt/kgHM indicates that the PCR could achieve more than a 30 percent reduction in annual U_3O_8 demand compared to the NASAP Reference BWR. The annual separative work demand of the PCR in the 45-120 Mwdt/kgHM burnup range is about 75-80 SWU/Gwe, about a 35-40 percent reduction from those of the NASAP Reference BWR.

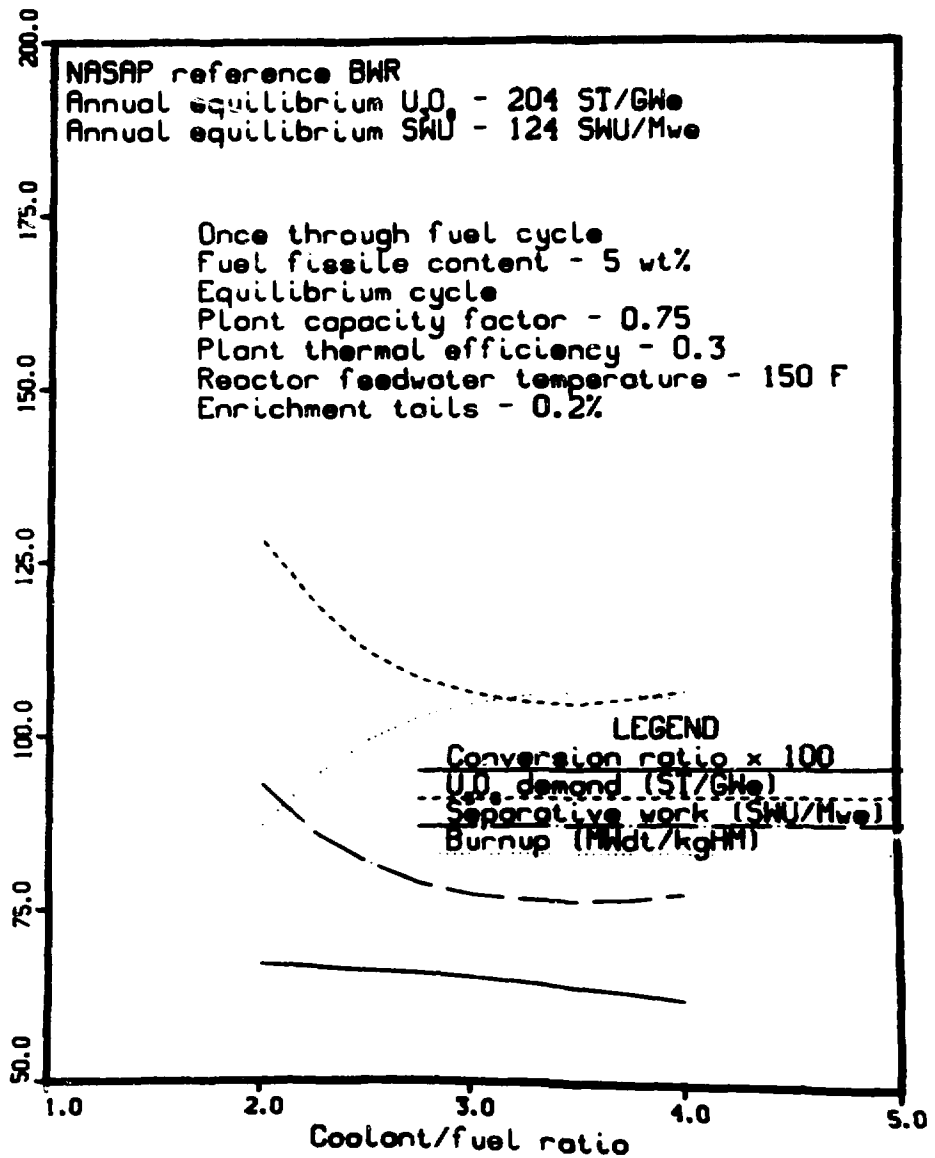


Figure 4. LEU-PCR annual uranium and separative work versus coolant/fuel ratio.

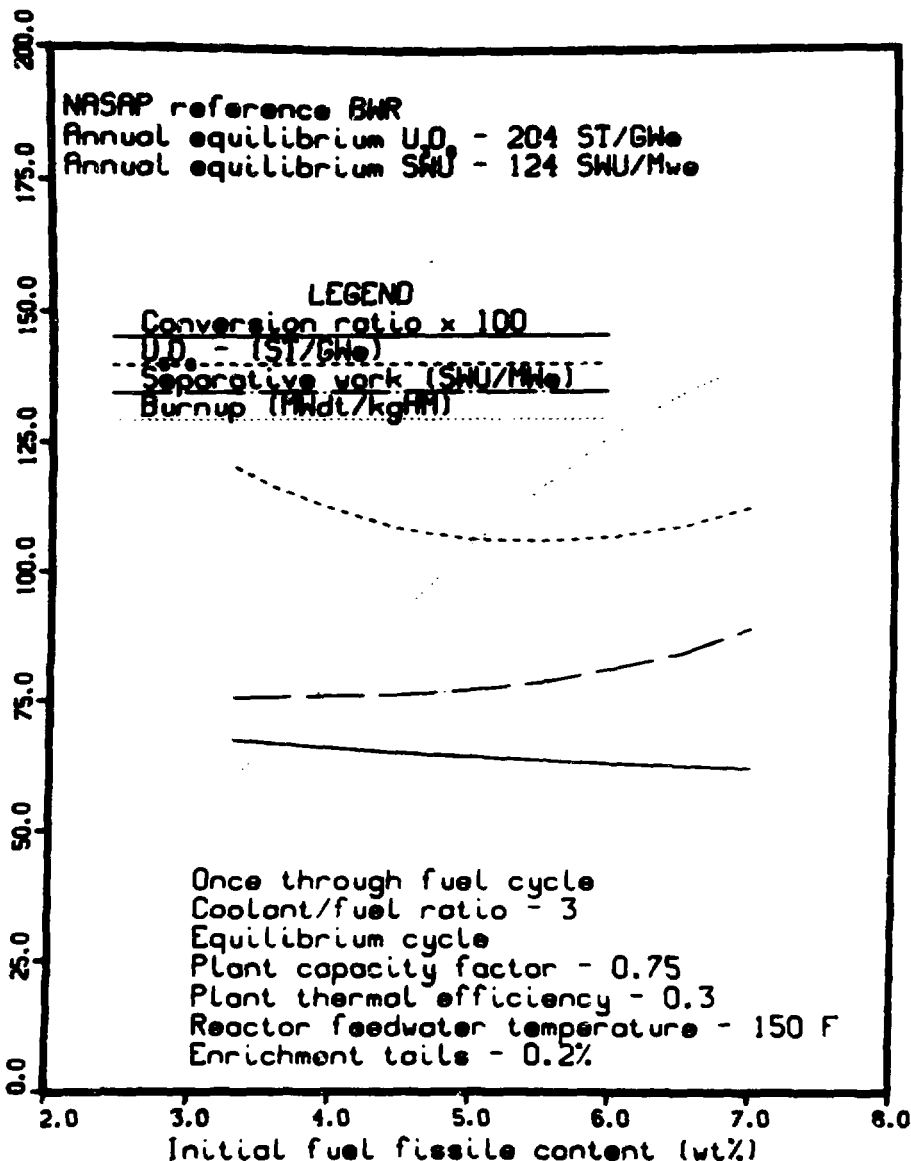


Figure 5. LEU-PCR annual uranium and separative work demands versus initial fissile.

The annual amounts of fissile in the spent fuel from the LEU-PCR are indicated in Figure 6 along with the weight percent of total fissile in the spent fuel. Corresponding values from the NASAP Reference BWR are noted on the figure. At 6 percent enrichment of makeup fuel, the total annual fissile discharged from the LEU-PCR reaches a minimum, which is less than one-tenth that of the NASAP Reference BWR. The corresponding weight percent of the total fissile in the LEU-PCR is less than one-third that of the NASAP Reference BWR. This reduction in the fissile content of spent fuel would likely make the LEU-PCR spent fuel even less economically attractive than current LWR fuel. It is also noted that at its minimum, the annual amount of Pu^{39,41} in the spent fuel, is only about one-fifth of the annual Pu^{39,41} discharge from the NASAP Reference BWR.

The LEU-PCR equilibrium cycle Beginning-of-Cycle (BOC) and End-of-Cycle (EOC) core exit coolant steam qualities versus makeup fuel enrichment are indicated in Figure 7. These values are based on replacing one-third of a 148-inch long core at reloading as previously described. The spread between the BOC and EOC exit steam qualities for a specific fissile content could be reduced, for example, by lengthening the core or reducing the fraction of core replaced at each refueling.

In reviewing the performance estimates contained herein, it must be kept in mind that the estimates are preliminary. Some of the simplifying assumptions (e.g., zero radial leakage of neutrons) used in the analyses result in fuel utilization characteristics that are slightly optimistic. On the other hand, the study has been very limited when considering all the design variables that affect PCR performance and, therefore, it is not unlikely that even better performance could be achieved with PCR-type reactors that are optimized for the various fissile/fertile combinations of interest.

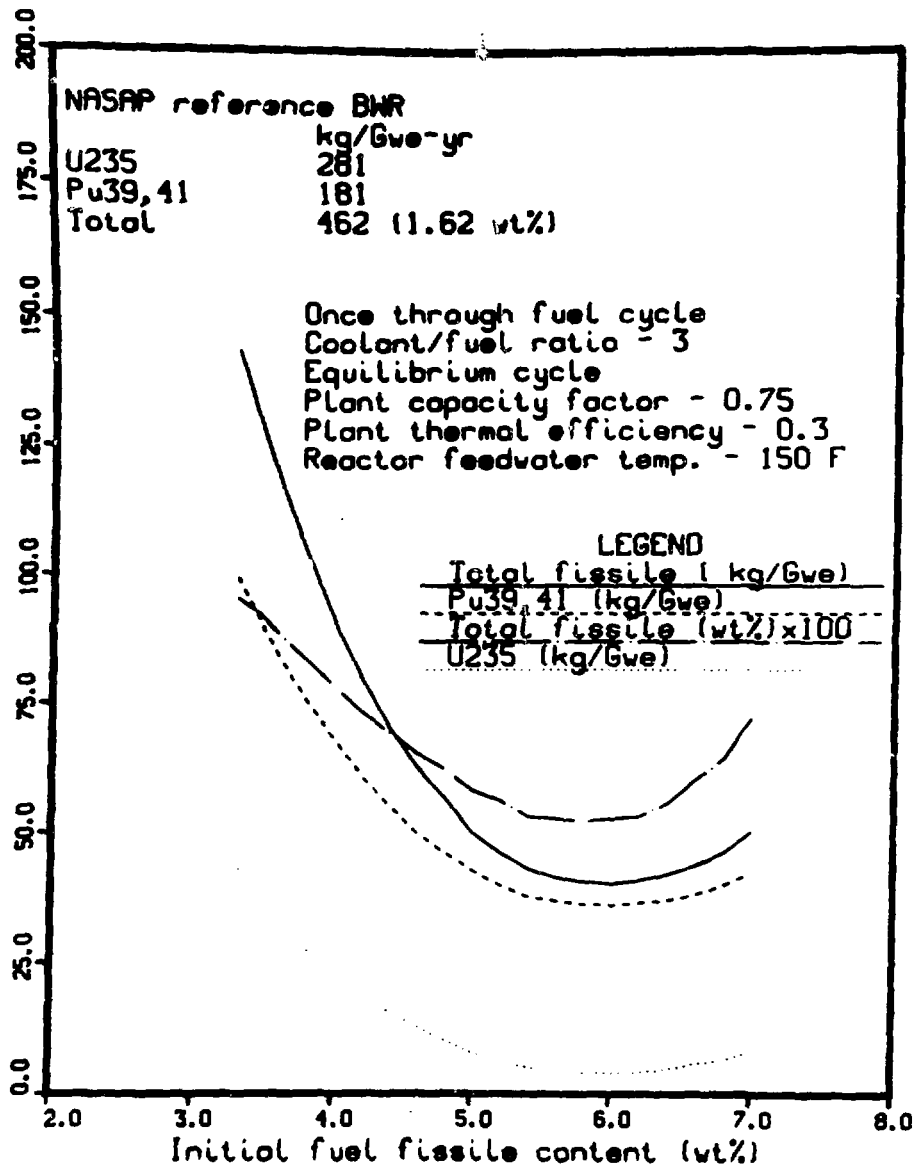


Figure 6. LEU-PCR annual spent fuel fissile amounts versus initial fissile.

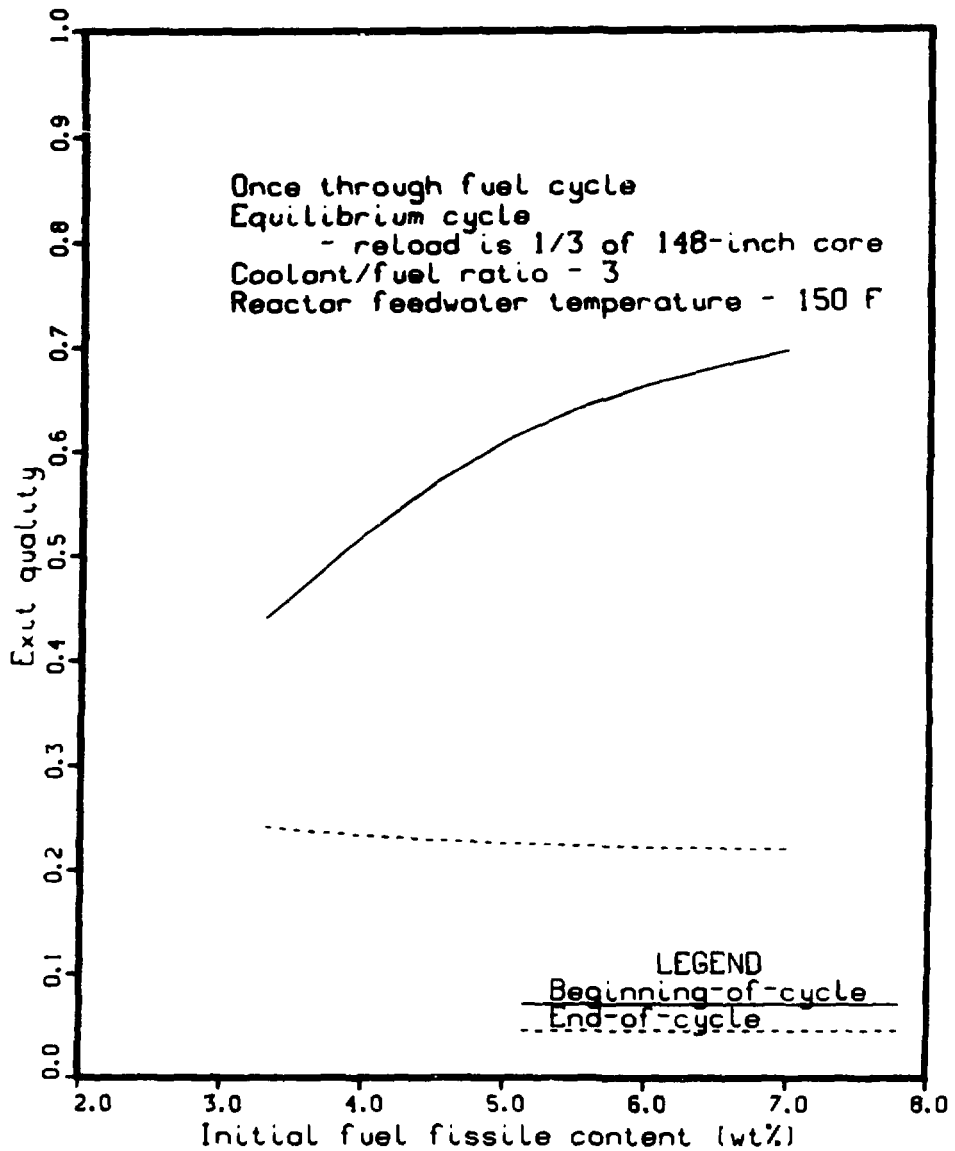


Figure 7. LEU-PCR exit steam quality versus initial fissile.

Comparisons of PCR to NASAP Reactors

The recent NASAP² studies involved an extensive investigation of the nonproliferation attributes of various reactor systems and their fuel cycles. Considerable emphasis was placed on studies for improving the uranium utilization of the once-through fuel cycle because of the potential impact on delaying the need for reprocessing and the breeder (LMFBR). The final three figures of this paper compare the results of our preliminary studies of the PCR concept to key results of the NASAP studies.

Figure 8 compares the uranium requirements of a PCR operating on a once-through Low-Enriched-Uranium (LEU) fuel cycle to the uranium requirements of once-through fuel cycles reported by the NASAP study. The relative requirements are for a 30-year reactor life without any credit for residual burnup capability. The indicated PCR uranium requirements (which are at a burnup of about 125 Mwdt/kgHM) are about the same as those for the Heavy Water Reactor (HWR), the most fuel efficient once-through fuel cycle reported by the NASAP studies. The PCR uranium requirements are indicated to be less than 60 percent of those of current LWRs and also appreciably less than the uranium requirements of the most improved LWRs expected on the basis of the NASAP studies.

Figure 9 extends the comparison of uranium requirements to cases involving recycle in LWR - values for once-through fuel cycles are included for reference. It is noted that the indicated uranium requirement of the PCR once-through fuel cycle is less than the lowest uranium requirements that NASAP projects for recycle in current or extended burnup LWR fuel cycles.

Figure 10 compares the LEU-PCR to NASAP BWRs with respect to several parameters pertinent to nonproliferation objectives. Values are indicated for three NASAP BWRs; the Reference BWR represents the current fuel cycle, the Improved BWR represents improvements expected to be implemented beginning in 1990, and the Composite Improved BWR represents improvements for 2000 and beyond. For the PCR two burnup levels are indicated - "current" corresponds to the approximate current maximum exposure of 45 Mwdt/kgHM and "extended +" corresponds to about 125 Mwdt/kgHM. All data are for once-through fuel cycles.

The top bar graph compares the U_3O_8 and separative work requirements - the PCR has the lowest requirements for both.

The middle bar graph indicates the annual discharges of fissile plutonium (Pu39,41) and total fissile. The extended burnup PCR has the lowest discharges - compared to the Reference BWR, the extended burnup PCR discharges only about one-fifth of the fissile plutonium and one-tenth of the total fissile.

The bottom bar graph indicates the levels of key constituents in the spent fuel. The weight percent of Pu-238 in the spent fuel is indicated by the shaded bars. A high Pu238 content may be desirable because this heat producing isotope can reduce the attractiveness of plutonium for weapons use. The extended burnup PCR indicates the highest Pu-238 content, which at 6-7 percent, is a level that may assist in deterring weapons use of the plutonium. The Pu239,241 contents of the plutonium, as well as the total fissile in the spent fuel are also indicated on the bottom bar graph. Low Pu239,241 levels are preferred since these two isotopes are the primary constituents of weapons. The extended burnup PCR is noted to have the lowest Pu39,41 contents. Low values of residual fissile in the spent fuel are also desirable for the once-through fuel cycle since in this case the residual fissile represents wasted energy. There is substantially less residual fissile in the spent fuel from the extended burnup PCR. The weight percent of fissile is about one-third that for the Reference BWR - thus if reprocessing and recycle for current LWRs is marginally economic (as indicated in the NASAP report), then the reduced fissile content in PCR spent fuel should make reprocessing of this fuel uneconomic for many years into the future.

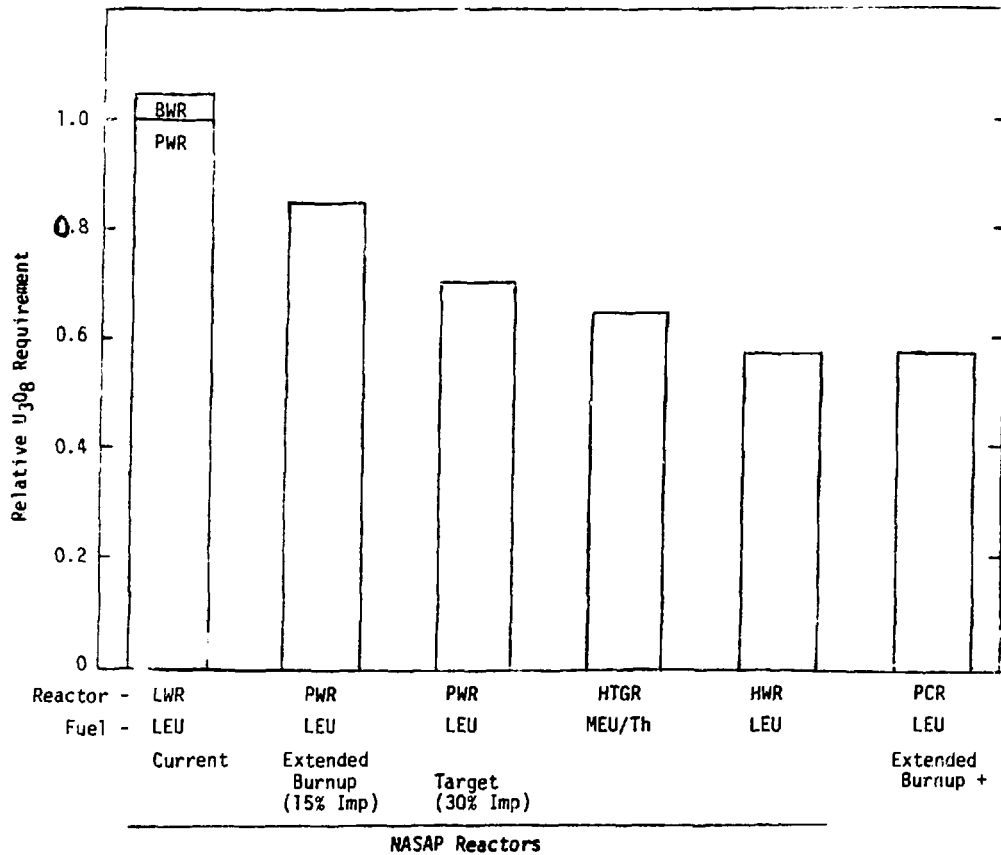


Figure 8. Relative U_{3O_8} Requirements for Once-through Fuel Cycles - NASAP Reactors and PCR

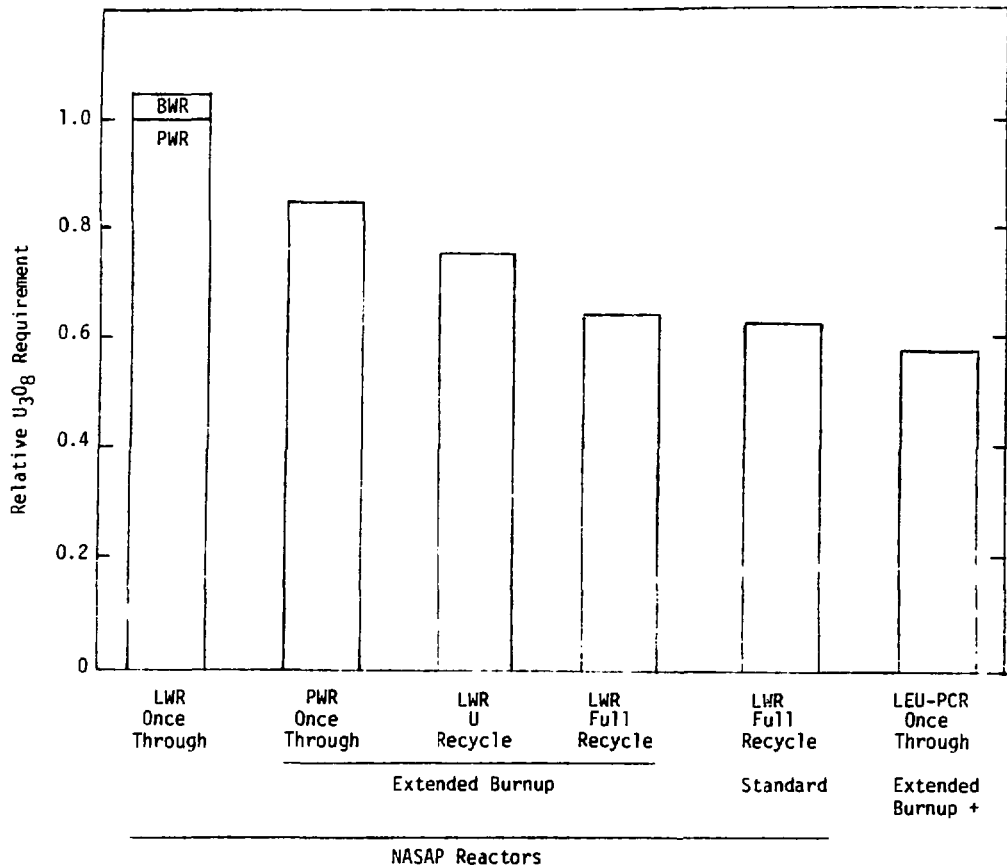


Figure 9. Relative U_{3O_8} Requirements for LWRs With and Without Recycle - LEU-PCR and NASAP LWRs

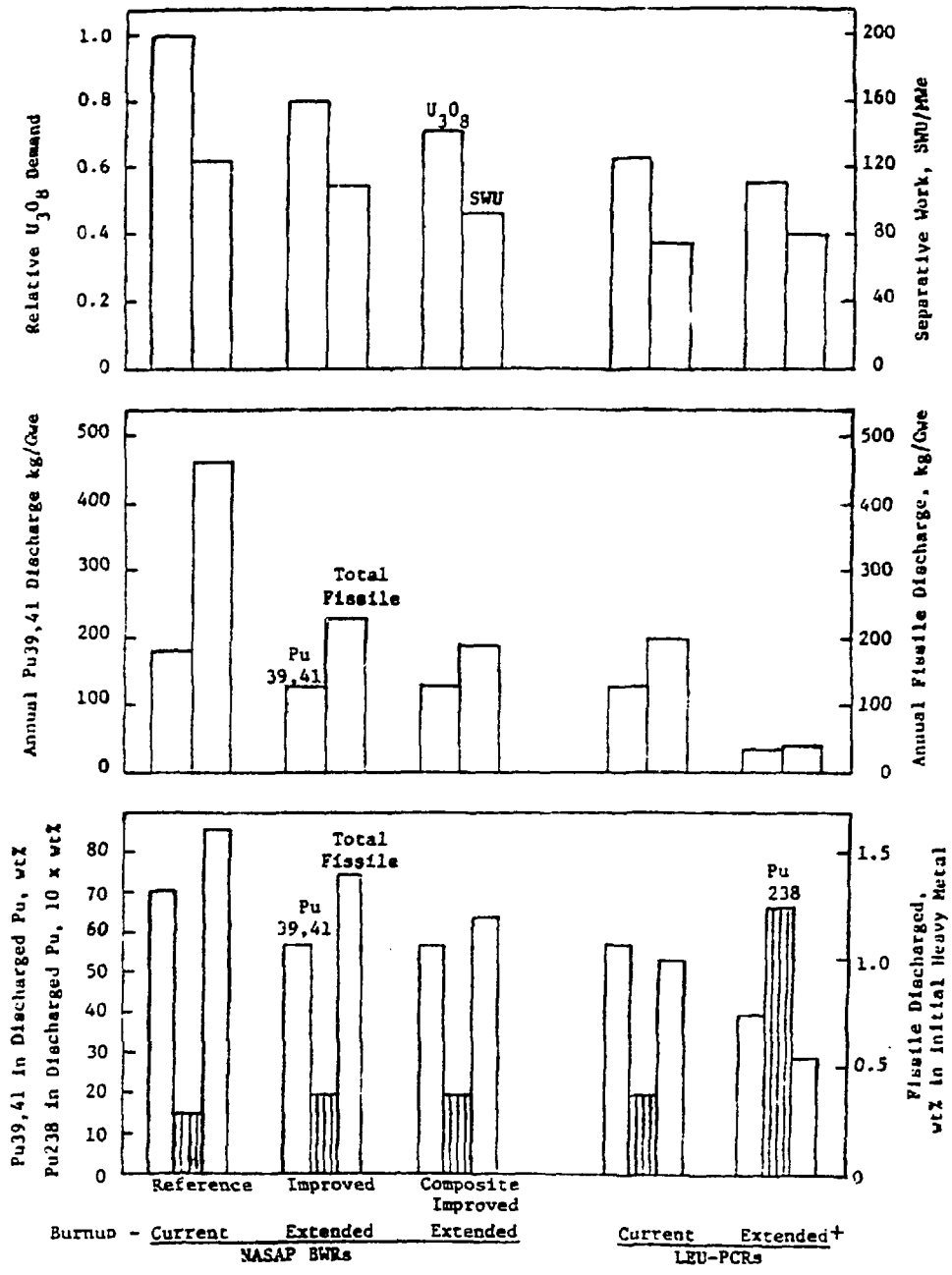


Figure 10. Key Characteristics of LEU-PCRs and NASAP BWRs

Conclusions

Our preliminary studies indicate that for once-through fuel cycles, the PCR offers potential improvements over current LWRs in the following major areas.

1. Improved uranium utilization (reduced uranium demand)
2. Degraded plutonium product in spent fuel
3. Reduced plutonium content of spent fuel
4. Reduced amount of spent fuel
5. Reduced fissile content of spent fuel
6. Reduced separative work

The potential significant improvements in uranium utilization in the PCR are associated with more marked departures from current LWR practices than those considered in the NASAP report. However, the departures are in reactor core design and operational features - the extensive U. S. LWR technology and industrial capabilities remain applicable. The progressive axial burnup technique employed to achieve higher conversion ratios and longer core life in a PCR may be applicable, to a limited degree, to current BWRs without major plant modifications. The extent of uranium utilization improvement that can be achieved in a PCR once-through fuel cycle depends largely on the ability to develop BWR nuclear fuel elements that can accommodate fuel exposures that are substantially higher than current practice. However, even with fuel exposures corresponding to current LWR maximums, the higher conversion ratios achievable in PCRs provide for potential improvements in fuel utilization. The uranium utilization efficiency achievable in a PCR once-through LEU fuel cycle is substantially greater than that achievable with recycle of current LWR discharge fuel and may approach that noted in the NASAP report² for fuel recycle in other nonbreeder reactors. Thus, commercialization of the PCR could eliminate the need for fuel reprocessing until required by introduction of a breeder and could substantially delay the need for a breeder. If reprocessing of LWR spent fuel is implemented to accommodate plutonium-recycle in LWRs, the PCR concept would provide for more efficient utilization of recycle fuels. Further, if high burnup BWR

fuels are developed, the amount of fissile material in the spent fuel can be made low enough to make the reprocessing of the spent fuel for LWR recycle uneconomic.

While the results of these preliminary studies are encouraging, it is anticipated that a thorough study and appraisal of the PCR concept would show even further potential gains in uranium utilization and identify substantial economic incentives for extending BWR technology to accommodate the PCR concept.

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