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Optimum Cycle Length and Discharge Burnup for Nuclear Fuel

Phase II: Results Achievable with Enrichments Greater than 5 w/o

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Technical Report

Optimum Cycle Length and Discharge Burnup for Nuclear Fuel

Phase II: Results Achievable with Enrichments Greater than 5.0 w/o

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Final Report, September 2002

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REPORT SUMMARY

Core reload design and economic analyses show that both PWRs and BWRs can derive significant benefits by increasing their discharge burnups above the currently licensed values. Phase I of this study demonstrated that achieving optimum economics requires fuel with enrichments greater than the current limit of 5 w/o. Results from the current Phase II study show that fuel with higher enrichments (up to 6 w/o) further reduces costs and increases burnups if the costs of enrichment, manufacturing, transportation, licensing, and storage/disposal of such fuel remains essentially the same.

Background

Increasing the level of burnup at which LWR fuel is discharged can present significant environmental—as well as economic advantages—by requiring fewer assemblies to be discharged for a given amount of produced energy. An earlier EPRI study quantified the benefits that Duke Power could derive for 2 of their PWRs operating on 18-month cycles by increasing their burnup (EPRI Report TR-112571). A second project—sponsored jointly by EPRI and the U.S. Department of Energy's Nuclear Energy Plant Optimization (NEPO) program—was initiated to estimate the industry-wide applicability of these findings. The study examined both BWRs and PWRs and cycle lengths of 12, 18, and 24 months. Phase I of this project was limited to fuel with enrichments of up to 5 w/o U^{235}. The study found that fuel costs decrease with increasing discharge burnups (EPRI Report 1003133). The current Phase II of this project extends the investigation for the most economical BWR and PWR cycle lengths to even higher batch average discharge burnups by using fuel enriched to greater than 5 w/o.

Objective

- To estimate the economic costs and benefits attainable by extending fuel discharge burnup levels under a realistic utility environment.
- To determine optimum burnup levels and cycle lengths achievable for both BWRs and PWRs when fuel with enrichments in excess of 5 w/o is utilized.
- To identify potential technical obstacles that need to be overcome to achieve the desired optimum burnup levels.

Approach

A team of investigators developed core reload designs for a 764 assembly GE BWR and a 193 assembly Westinghouse PWR. The cycle length for the BWR was 24 months while the cycle length for the PWR was 18 months. The designs conformed to all technical and safety limits except for peak burnup levels and fuel enrichments, which were allowed to exceed the currently licensed values. Investigators increased the batch average discharge burnups by gradually

reducing the number of fresh assemblies used in reload designs. Next, they compared the economics of all the reload scenarios to deduce trends in fuel cost.

Results

The analysis showed that use of greater than 5 w/o enriched fuel can result in additional decreases in fuel costs and further increases in discharge burnups for both BWRs and PWRs. For the BWR 24-month cycle, the fuel costs decline by $2.4 million, or 4.3% reduction in fuel cost per cycle, as the batch average discharge burnup increased from about 52,400 MWD/MTU to about 65,200 MWD/MTU. For the PWR 18-month cycle with Performance+ fuel, the fuel costs declined by $2.3 million, or 4.7% reduction in fuel cost per cycle, as the batch average discharge burnup increases from about 56,500 MWD/MTU to about 70,300 MWD/MTU. For the PWR 18-month cycle with RFA fuel, the fuel costs decline by $2.9 million, or 5.8% reduction in fuel cost per cycle, as the batch average discharge burnup increases from about 51,700 MWD/MTU to about 64,600 MWD/MTU.

EPRI Perspective

This project has demonstrated the extent of benefits that can be achieved by increasing discharge burnup levels up to the highest levels achievable within the 5 w/o enrichment limit (Phase I), and beyond (up to 6 w/o in Phase II). Above the current enrichment limit, reload cores can be designed without exceeding technical and safety limits and the economics continue to improve with burnup. However, the improvement must be significant enough to offset the large, one-time cost that will be associated with the licensing, fabrication, and transportation of such fuel.

The results of this study provide justification for the EPRI Robust Fuel Program objective of developing databases and processes to support licensing applications for an increase in maximum burnup levels. They also provide an incentive for closer investigation of the costs involved in upgrading fabrication, transport, and storage capabilities for greater than 5 w/o enriched fuel.

Keywords

LWR fuel
Fuel performance
Burnup economics
Optimum burnup
Robust fuel

ABSTRACT

EPRI has initiated the Robust Fuel Program (RFP) to address fuel performance and reliability issues associated with U.S. light-water nuclear reactors. This program is expected to foster the development of nuclear fuel assemblies that can achieve rod burnups of 75000 MWD/MTU or more with adequate operating margin. The RFP, jointly with the Department of Energy's NEPO program sponsored a study aimed at determining the optimum burnups and cycle lengths for LWR fuel. Phase I of this study showed decreasing trends in fuel costs as burnups were increased to the maximum levels achievable while constraining fuel enrichments to less than the current 5.0 w/o limit. The purpose of Phase II of this study has been to extend the burnup range by using fuel enriched in excess of 5.0 w/o and assess the technical difficulties that must be overcome in order to realize such burnups.

Results obtained under Phase II showed a continuing decline in fuel costs. No optimum was reached as discharge burnups were increased to the maximum values achievable with fuel enriched up to 6 w/o.

EXECUTIVE SUMMARY

This report summarizes the results of Phase II of the optimum cycle length and discharge burnup study for BWRs and PWRs. The Phase II study extended the range of BWR and PWR batch average discharge burnups considered in the Phase I study by using fuel enriched in excess of 5.0 w/o U^{235}. The BWR fuel management considered 24 month cycles while the PWR fuel management considered 18 month cycles. The BWR studies were performed for a large, 764 assembly core and used Westinghouse SVEA-96 Optima2 fuel. The PWR studies were performed with a 4 loop, 193 assembly Westinghouse NSSS and considered both Performance+ and RFA fuel. The BWR study extended the batch average discharge burnup range to 65000 MWD/MTU by considering maximum enrichments up to 6.0 w/o. The PWR study extended the batch average discharge burnup range to 70000 MWD/MTU for Performance+ fuel with enrichments near 5.9 w/o and to near 65000 MWD/MTU for RFA fuel with enrichments near 5.5 w/o. These studies were performed meeting all normal design criteria except for peak rod burnup and maximum enrichment limits.

For both the BWR and PWR, the fuel costs continued to decline with increasing batch average discharge burnup. For the BWR 24 month cycle, the fuel costs decline by $2.4 million, or 4.3% reduction in fuel cost per cycle as the batch average discharge burnup increases from about 52400 MWD/MTU to about 65200 MWD/MTU. For the PWR 18 month cycle with Performance+ fuel, the fuel costs decline by $2.3 million, or 4.7% reduction in fuel cost per cycle as the batch average discharge burnup increases from about 56500 MWD/MTU to about 70300 MWD/MTU. For the PWR 18 month cycle with RFA fuel, the fuel costs decline by $2.9 million, or 5.8% reduction in fuel cost per cycle as the batch average discharge burnup increases from about 51700 MWD/MTU to about 64600 MWD/MTU.

The Phase II study continues to show fuel costs declining with increasing discharge burnup when the economic model described in Appendix A is used. The results do not identify an optimum discharge burnup. The costs continue to decline as the batch average discharge burnup was increased to the maximum values considered in the study. The economic analysis assumes no change to enrichment, manufacturing, transportation, licensing, or storage/disposal costs when fuel in excess of 5.0 w/o is used.

To achieve the high discharge burnup values, fuel in excess of the current limit of 5.0 w/o U^{235} was considered. There are a variety of barriers that would need to be overcome to use fuel enriched in excess of 5.0 w/o. Significant one-time costs are associated with modifying fuel manufacturing facilities to allow for production of fuel enriched in excess of 5.0 w/o. New fuel shipping containers must also be designed, manufactured, and licensed also at a significant cost. Spent fuel racks and dry storage casks are not currently licensed for fuel with enrichments greater than 5.0 w/o and might require modification or replacement. The increased duty and residence time associated with high burnup fuel may require fuel design modifications and improved structural materials that will increase manufacturing costs. Taken together, the costs associated with new fuel designs and the increased manufacturing costs may significantly erode the benefits of using fuel with enrichments greater than 5.0 w/o.

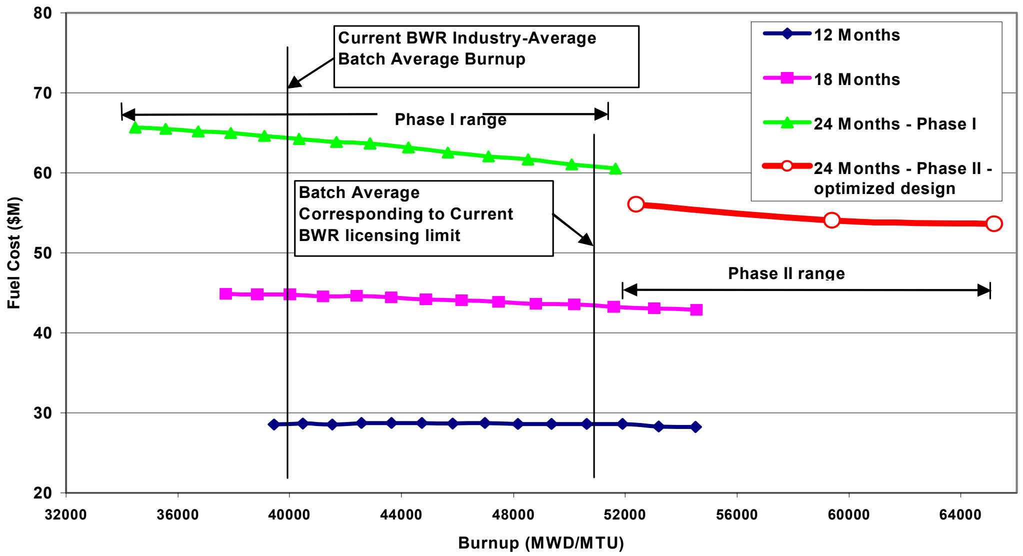
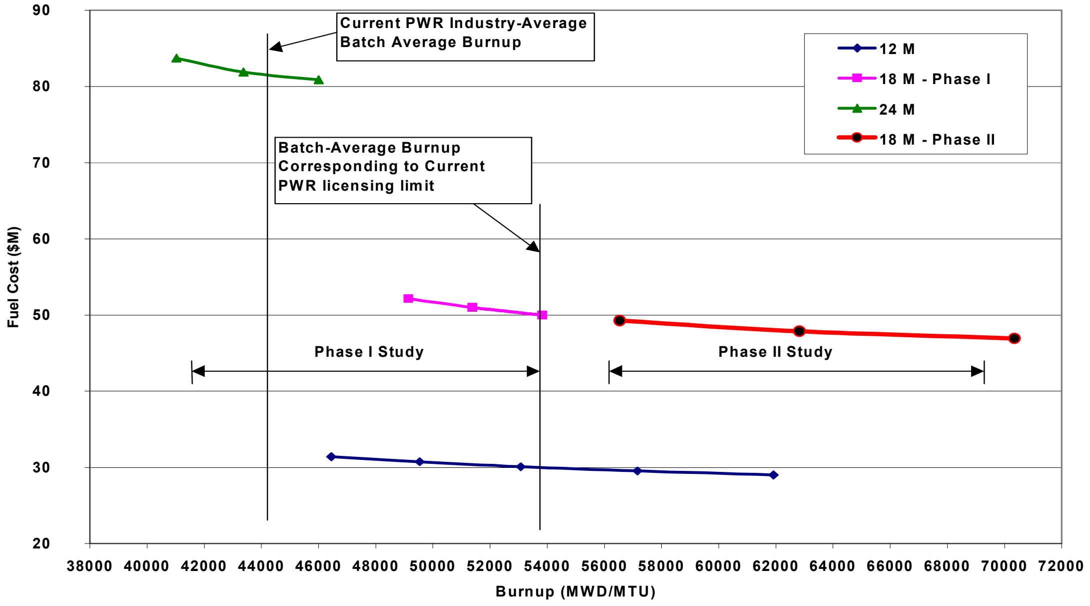


Figure ES-1
Fuel cost as a function of discharge burnup for 24 month cycle BWR



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CYCLE LENGTH AND BURNUP OPTIMIZATION STUDY DESCRIPTION

1.1 Background

The purpose of Phase II of this study is to perform an evaluation of the fuel economics for different cycle lengths and discharge burnups using fuel enriched to greater than 5.0 w/o. Phase I of this study [1] provided results for both Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs) for fuel enriched to no more than the current limit of 5.0 w/o. The choice of cycle length and discharge burnup significantly affects the operating costs of BWRs and PWRs.

The choice of cycle length, or interval between refueling outages, affects total energy production, fuel costs, and outage costs for a nuclear power plant. Most plants were originally designed assuming operation with 12 month intervals between refuelings. In the United States, most BWRs and PWRs have extended their cycle lengths to 18 or 24 months, while many European and Asian plants continue to operate with 12 to 15 month cycles. Increasing cycle length can increase energy production and reduce outage costs by reducing the number of refueling outages during the operating lifetime of a plant. This comes at the expense of increased fuel costs, however.

The choice of fuel discharge burnup also affects the fuel costs for a nuclear power plant. Increasing discharge burnup allows for more regions or batches of fuel to reside in the core at the same time, which tends to utilize fuel more efficiently. Fewer new feed fuel assemblies are also required each cycle resulting in lower fuel fabrication and storage costs. Increased fuel burnup requires the use of higher enrichment fuel, however, which increases enrichment costs. The cost of enrichment is non-linear, so at some point the increased enrichment costs offset the improved efficiency and reduced fuel assembly requirements. Increasing fuel burnup may also require the use of advanced fuel assembly designs and materials to withstand the higher duty and longer operational life of the fuel assemblies.

The organizations involved in this study are the Exelon Nuclear Company, the Westinghouse Electric Company, and Penn State University. The Electric Power Research Institute (EPRI) is organizing the study. The study is jointly sponsored by EPRI and by DOE’s Nuclear Plant Optimization (NEPO) program.

Exelon operates 17 nuclear plants including 5 PWR units and 12 BWR units. The PWRs include Byron 1 and 2, Braidwood 1 and 2 and Three Mile Island Unit 1. The BWR units are Limerick 1 and 2, Peach Bottom 1 and 2, Dresden 2 and 3, Quad Cities 1 and 2, LaSalle 1 and 2, Clinton, and Oyster Creek. Exelon also has performed reload designs and engineering analysis for both BWRs and PWRs.

Westinghouse is a reactor and fuel supplier with a nuclear operations experience base of more than 2200 reactor-years. Westinghouse currently supplies fuel for more than 65 nuclear power plants worldwide including PWRs and BWRs. Westinghouse also has extensive experience in engineering analysis and reload core design.

The Nuclear Engineering Program at Penn State is a separate degree program in the Department of Mechanical and Nuclear Engineering offering degrees at the Bachelor's, Master's and PhD level. Penn State conducts cutting-edge research in neutronics, thermal-hydraulics, materials, reactor control, reactor simulation, radiation transport, transient safety analysis, and in the nuclear sciences. Penn State faculty have developed several successful fuel management optimization programs for BWRs and PWRs. These programs have been supplemented with advanced economics models that allow the results from fuel burnup and cycle length analyses to be used as a basis for economic analyses.

In this study, Westinghouse, Exelon and Penn State University provided the engineering analysis for the BWR fuel management. Westinghouse performed the PWR fuel management analysis with input from Exelon. Exelon and Penn State University performed the economic evaluation of the fuel management results for both BWRs and PWRs. All organizations contributed to the final report.

The results from Phase I of this study showed that both the BWR and PWR fuel costs decline for all cycle lengths from 12 to 24 months as discharge burnup is increased up to the maximum achievable with fuel enrichments less than 5 w/o. For the BWR cases, the increase in fuel cost with increasing cycle length is modest and the additional energy produced combined with fewer outages would appear to favor the 24 month cycle operation. For the PWR cases, the increase in fuel cost with increasing cycle length is more pronounced. The choice of optimum cycle length will depend on outage costs as well as the value of the additional energy produced by the 18 or 24 month cycles.

In Phase I of the study, the fuel management was constrained by the current 5 w/o enrichment limits. This precluded the study of very high burnup cores for 18 or 24 month cycles. The current study extends the previous study to consider enrichments greater than 5 w/o. This enrichment increase allows the discharge burnup[1] for 18 and 24 month cycles to be significantly increased. The BWR study considers 24 month cycles while the PWR study considers 18 month cycles. As expected with the high enrichments and discharge burnups, the lead rod burnups significantly exceed the current licensing limit of 62000 MWD/MTU. Efforts are currently underway to increase the licensed lead rod burnup limit.

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[1] As in Reference 1, one of the variables of interest in this study is *batch discharge burnup*. Burnup, defined as the total amount of thermal energy produced from a quantity of nuclear fuel, is expressed throughout this report in terms of megawatt-days per metric ton of uranium (MWD/MTU). A batch is defined as the entire set of nuclear fuel assemblies that begin reactor irradiation at the same time. These assemblies do not necessarily have to end their productive lives concurrently, or even be of the same initial uranium enrichment or fuel loading. For example, some fuel assemblies in a batch might operate for three cycles, while other assemblies in that batch might produce power for four or more cycles before being permanently discharged from the reactor. A specific batch discharge burnup represents the average of all the assembly discharge burnups in that batch of fuel.

1.2 Scope of Current Study

This report includes descriptions of the BWR and PWR fuel management analysis performed for Phase II of the optimum cycle length and discharge burnup study. The BWR study extends the previous batch discharge burnup range for 24 month cycles up to about 65000 MWD/MTU. The PWR study extends the previous batch average burnup range for 18 month cycles up to 65000 - 70000 MWD/MTU. A range of discharge burnups were examined using fuel enriched to greater than 5.0 w/o. Peak rod burnups in excess of the currently licensed limits are considered.

Single reference plants were chosen for both the BWR and PWR studies. The BWR analysis considers a large 3323 MW_{th}, 764 fuel assembly General Electric BWR plant as the reference BWR. The PWR study uses a 3587 MW_{th}, 193 fuel assembly Westinghouse plant as the reference PWR.

The BWR fuel management is described in Section 2 of this report. The PWR fuel management is described in Section 3. The economic analyses of the BWR and PWR fuel management results are described in Section 4, and the economics model is further summarized in Appendix A. Section 5 discusses considerations for using fuel enriched in excess of 5.0 w/o and Section 6 presents the conclusions of the study.

1.3 Computer Codes Used in This Analysis

1.3.1 BWR Neutronics

The BWR study uses standard Westinghouse BWR nuclear design computer codes, PHOENIX and POLCA [2].

PHOENIX is the standard Westinghouse depletion program for BWR fuel assembly and rod cell calculations. PHOENIX is a two-dimensional, multi-group transport theory code, which is used for the calculation of eigenvalue, spatial flux and reaction rate distributions, as well as depletion of fuel assembly rod cells. The code can simulate BWR cruciform control blades containing cylindrical absorber elements, water gaps, burnable absorber rods, burnable absorbers that are integral with the fuel, water rods, and the presence of objects in the water gaps such as neutron detectors. In addition to rod cell and fuel assembly calculations, quadruple assembly calculations, consisting of four assemblies in a 2x2 array, can be performed. This option is used for the detailed calculation of rod-wise power distributions, reaction rates, reactivities, and detector constants for the case of different types of adjacent fuel assemblies in a mixed core. PHOENIX provides the two-dimensional cross section libraries used by the three-dimensional core simulator POLCA. It also produces the local peaking patterns used as input to the critical power margin, linear heat generation margin, and emergency core cooling system evaluation calculations.

POLCA is a three-dimensional code for simulating the neutronic, thermal, and hydraulic behavior of a reactor core. The code solves the coupled thermal-hydraulic and neutronic equations. The code calculates the three-dimensional power distribution in the reactor taking into account all important phenomena that must be included. In POLCA, the reactor core is divided into computational nodes in which the neutronic characteristics of each node are described by homogenized equivalent two-group macroscopic cross sections. The three-dimensional power distribution calculated by POLCA includes the thermal-hydraulic feedback effects of the coolant flow and void distribution, the influence of control rods, as well as important reactivity feedback effects such as those due to Doppler feedback and xenon absorption.

1.3.2 PWR Neutronics

The PWR study uses standard Westinghouse computer codes used for PWR core design. Two principal computer codes, PHOENIX-P [3] and ANC [3 and 4], have been used for the PWR fuel management studies.

PHOENIX-P is a two-dimensional, multi-group transport theory code, which utilizes a 70 energy group cross section library. The code provides the capability for cell lattice modeling on an assembly level. PHOENIX-P is used in this study to provide homogenized, two-group cross sections for nodal calculations and feedback models. ANC is an advanced nodal code, which provides a depletable 3-D model of the core. ANC is used in this study as a static 3-D neutronic model of the core. ANC is used to determine critical boron concentrations, radial power distributions, reactivity coefficients, and cycle lifetime. ANC also calculates discrete rod powers and rod burnups from the nodal information.

1.3.3 Neutronics Applicability Above 5.0 w/o

The neutronics codes used in the study have been applied to actual core designs containing fuel enriched up to 5.0 w/o. As burnup levels have increased and enrichments have approached 5.0 w/o, no degradation in the accuracy of the neutronic predictions has occurred. The neutronic methods are expected remain accurate for fuel enriched in excess of 5.0 w/o.

1.3.4 Economics

The economic analysis for this study was performed using a computer code developed by Penn State University and reviewed by Exelon. This code takes input from the fuel management studies such as cycle length, number of fuel assemblies, fuel mass, and fuel enrichment and calculates the fuel cost based on a set of economic variables and cost parameters.

2
BWR CYCLE DESIGNS

2.1 Introduction

Phase I of this study investigated the burnup yield for enrichments up to 5 w/o for 12, 18, and 24 month cycles. It was concluded in Phase I that both BWR and PWR fuel costs decline for all cycle lengths from 12 to 24 months as discharge burnup is increased consistent with the current maximum achievable with fuel enrichments of 5 w/o U^{235}. The intent of the Phase II study is to extend the evaluation of fuel cycle costs as discharge burnup is increased by considering U^{235} fuel enrichments in excess of 5 w/o. This Section evaluates the incremental energy gain associated with an increase in maximum U^{235} enrichment from 5 w/o to 6 w/o for the BWR case. Based on the results in this section, the corresponding impact on fuel cycle costs are evaluated in Section 4. The incremental energy gain associated with the maximum enrichment increase is expressed in terms of increased batch discharge burnup, which corresponds to a decrease in the number of feed fuel assemblies.

Extension of the fuel cycle cost evaluation from a maximum U^{235} enrichment of 5 w/o to 6 w/o for the BWR case is addressed by considering the impact on a 24-month equilibrium cycle composed of BWR 10x10 fuel in a large 764-assembly BWR. The fuel design used in this study is the Westinghouse SVEA-96 Optima2 fuel design. The study was performed in a two-step process:

1. The first step is a reference three-dimensional evaluation of a SVEA-96 Optima2 equilibrium core for a maximum U^{235} enrichment of 4.95 w/o. The maximum enrichment of 4.95 w/o was selected as a reasonable upper limit to assure that the current 5 w/o limit is satisfied. This evaluation is referred to below as the Reference Analysis.

   The Phase I study used GE14 assemblies to evaluate the impact of enrichments less than 5 w/o on batch discharge burnups. As discussed in Section 2.3.2, the consistency between the results of the SVEA-96 Optima2 Reference Analysis and the Phase I results demonstrates that the Phase II results can be confidently compared with the Phase I results.

2. The second step is an extension of the Reference Analysis to consider a maximum enrichment of 6 w/o. This extension is accomplished with a series of perturbation studies based on two-dimensional PHOENIX calculations as well as three-dimensional POLCA results to assess the impact of allowing a maximum U^{235} enrichment of 5.95 w/o in the assembly nuclear design. The maximum enrichment of 5.95 w/o is considered to preserve a reasonable manufacturing margin of 0.05 w/o to the maximum target enrichment. This perturbation approach allows a clear identification of the physical processes involved in providing the additional energy by an enrichment increase as well as the limitations required by reactivity constraints and control of thermal limits. This process provides a consistent

sensitivity to enrichment increase beyond the current maximum enrichment of 5 w/o for a single fuel design (SVEA-96 Optima2). Therefore, the process is self-contained, and the results of this study can be compared with those of Phase I in a meaningful way in spite of the fact that different fuel designs in different cores were considered in the Phase I evaluation.

Furthermore, two cases are considered which define a reasonable range in the relative benefit associated with extending the maximum enrichment to 6 w/o. The "Optimized for Extended Enrichment" option represents an optimistic case since it assumes that losses in shutdown margin and thermal margin associated with the 1 w/o U^{235} enrichment increase can be completely accommodated by design improvements to the assembly mechanical design. It is judged that this option is achievable. The "Current Bundle Optimization" option is pessimistic since it assumes that no changes to the assembly mechanical design are made to reoptimize the assembly for the higher enrichments. Therefore, comparison of the fuel cycle costs for both cases with the Reference Analysis results in which the maximum enrichment of 4.95 w/o is less than the current limit of 5 w/o provides a reasonable range for which to assess the expected benefit of an increase in maximum enrichment from 5 w/o to 6 w/o in a large BWR.

2.2 Cycle Design and Reactor Core Features

The BWR plant selected for this evaluation is a 764-assembly BWR with a rated core power of 3323 MW_{th} and a rated core flow of 108 Mlb/hr. The core power level is slightly lower than the 3458 MW_{th} 764-assembly BWR core modeled in Phase I.

The Reference Analysis was based on typical design criteria similar to those used in Phase I. These criteria can be summarized as follows:

- Standard reactivity margins (Shutdown Margin, Hot Excess Reactivity).
- Maintenance of conservative margins to Technical Specification thermal limits.
- Other design constraints typically used in current applications.

Standard reactivity margins

Hot Excess Reactivity: The hot excess reactivity curve is equivalent to the Technical Specification "Reactivity Anomaly Curve," which shows expected control rod inventory in the core versus cycle burnup. A flatter curve reduces the need to move control rods. Flatness of the hot excess curve is determined by subtracting the Beginning-Of-Cycle (BOC) hot excess reactivity from the maximum hot excess reactivity for the cycle. A smaller value indicates a flatter hot excess curve. A relatively flat hot excess reactivity curve is desirable since it provides greater flexibility for cycle operation. There are no specific Technical Specification requirements for hot excess reactivity. However, normal design practice is to impose a minimum hot excess reactivity of about 0.8 % Δk at the beginning of cycle. This margin allows for design methodology uncertainties.

Shutdown Margin: Shutdown margin requirements are set by the Technical Specification. Plant Technical Specifications typically requires that 0.38 % Δk shutdown margin is demonstrated with the strongest rod withdrawn. The typical design criterion is 1.0 % Δk.

Margin to Technical Specification Thermal Limits

Minimum Critical Power Ratio (MCPR): Minimum Critical Power Ratio (MCPR) is defined as the ratio of the assembly critical power to operating power, where critical power is the assembly power required to initiate transition boiling. Current typical practice is to design cores with at least 7% margin (a 0.93 design limit).

Maximum Linear Heat Generation Rate (MLHGR): Maximum Linear Generation Rate is the ratio of the highest heat flux in an individual rod to the limiting value. This limit is associated with cladding strain and fuel pellet centerline melt. Current typical practice is to require a design limit of at least 10 % (a 0.90 design limit)

Maximum Average Planar Heat Generation Rate (MAPLHGR): Average Planar Heat Generation Rate is the average heat flux in the fuel rods in a fuel assembly at an axial location. This limit is associated with Emergency Core Cooling System (ECCS) criteria. Current typical practice is to assure at least 10% margin in the design phase or a design limit of 0.9 .

The design margins to limits used for the Reference Analysis in the Phase II study are shown in Table 2-1.

Table 2-1
BWR Plant Characteristics and Design Constraints

Parameter	Value
Reactor Power	3323 MW_{th}
Cycle length	660 EFPD
Number of Fuel Assemblies in Core	764
Shutdown Margin	> 1.0 % Δk
MCPR design margin	>12%
LHGR margin	>15%
MAPLHGR margin	>15%
Hot Excess Reactivity	> 0.8 % early in the cycle
Peak Rod Average Burnup	62000 MWD/MTU

The thermal limit design margins assumed in the Reference Analysis are somewhat greater than those used in Phase I. Since the Phase II evaluation is performed by perturbations of the Reference Analysis, and the Reference Analysis is for enrichments below 5 w/o, the conclusions of the extended enrichment analysis are not significantly affected by the more limiting design margins to thermal limits used in Phase II, and the relative impact of increasing the maximum enrichment to 6 w/o can be compared with the results in Phase I. The larger design margins to thermal limits are typically used in practice to provide greater flexibility during cycle operation.

The peak rod average burnup in the Reference Analysis leads to a batch average discharge burnup of 52400 MWD/MTU for a feed fuel size of 232 assemblies. Comparisons with Tables 2.3 through 2.6 in the Phase I report show that the batch discharge burnup of 52400 MWD/MTU is consistent with the results of Phase I. In the Phase II evaluation described below, the batch discharge burnup is allowed to increase to accommodate the decrease in the number of feed assemblies associated with the enrichment increase.

Other Design Features

The Reference Analysis was also performed with the following realistic operating constraints intended to simulate an actual plant application:

Use of shallow control rods: The control rod patterns developed in the Reference Analysis made minimal use of shallow control rods. Eliminating the use of shallow control rods improves capacity factor since moving shallow control rods while complying with thermal limits requires relatively large core power reductions. These core power reductions could have a slight negative impact on cycle length.

Control Cell Core: The use of a control cell core allows relatively large cycle burnup intervals between control rod sequence changes. Control rod sequence exchanges were made at cycle burnup intervals of 3000 MWD/MTU.

Spectral Shift: Relatively modest use of flow spectral shift was used to reflect typically conservative high power density plant operation.

Quarter Core Symmetry: Quarter core symmetry was maintained to reflect typical plant practice and provide consistency with older core monitoring systems.

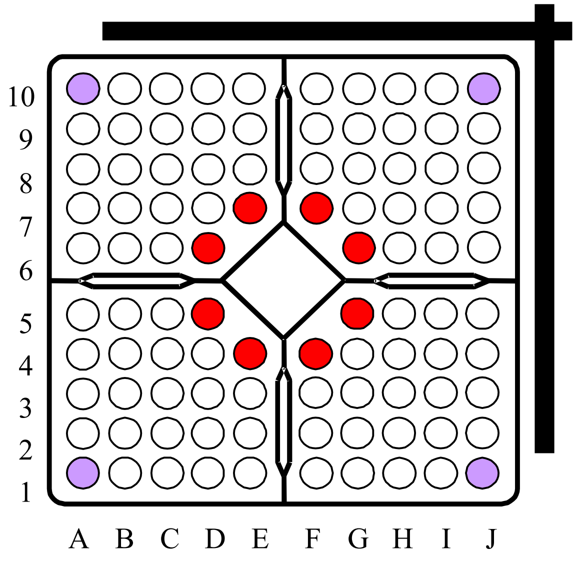
2.3 Equilibrium Cycle Neutronics Calculations

Phase I of this study investigated increasing the burnup level at which the fuel is discharged. The Phase I study maintained the current 5 w/o limit on enrichment. Phase II evaluates the increase in fuel burnup, allowing a corresponding reduction in the number of feed fuel assemblies, for enrichments in excess of 5 w/o. As noted above, the Phase II study is based on the SVEA-96 Optima2 fuel design. Section 2.3.1 contains a description of the SVEA-96 Optima2 fuel design used in the Reference Analysis. Section 2.3.2 is a discussion of the Reference Analysis equilibrium cycle core design. Section 2.3.3 contains the discussion of the extension of maximum U^{235} enrichment from 5 w/o to 6 w/o and its impact on cycle energy.

2.3.1 Fuel Assembly Design

The SVEA-96 Optima2 fuel design is an evolutionary form of the 10x10 SVEA-96/96+ fuel design which was originally introduced into the U.S. in 1989. The SVEA-96 Optima2 design has been specifically formulated to support the high energy cycles resulting from current industry initiatives toward higher core power and longer cycles requiring improved shut down margin and margins to thermal limits.

As shown in Figure 2-1, there are 96 fuel rods in the fuel assembly including 84 full-length rods and 12 part-length rods. Eight of the part-length rods are placed adjacent to the central water channel. These rods extend to about two-thirds of the height of the full-length rods. The remaining four part-length rods are at the four outer corners of the fuel assembly and are approximately one-third of the length of the full-length rods. The use of part-length fuel rods results in a wetter lattice in the upper part of the core. This change shifts the optimum moderation to a higher coolant temperature corresponding to a lower coolant density, which significantly improves the shut down margin. The axial design of the assembly also provides improved hot reactivity characteristics.



🟣 **1/3 part-length rods**
🔴 **2/3 part-length rods**
○ **full-length rods**

Figure 2-1
Lattice Layout for SVEA-96 Optima2

The fuel rod design has been improved relative to the original SVEA-96/96+ design to increase the uranium weight of the assembly. An advanced spacer and the use of eight spacers in the assembly provide the dryout performance required for high-energy cycles with relatively small feed batches. The fuel rod pitch and sub-channel design has been optimized to reduce pressure drop in order to further improve dryout performance.

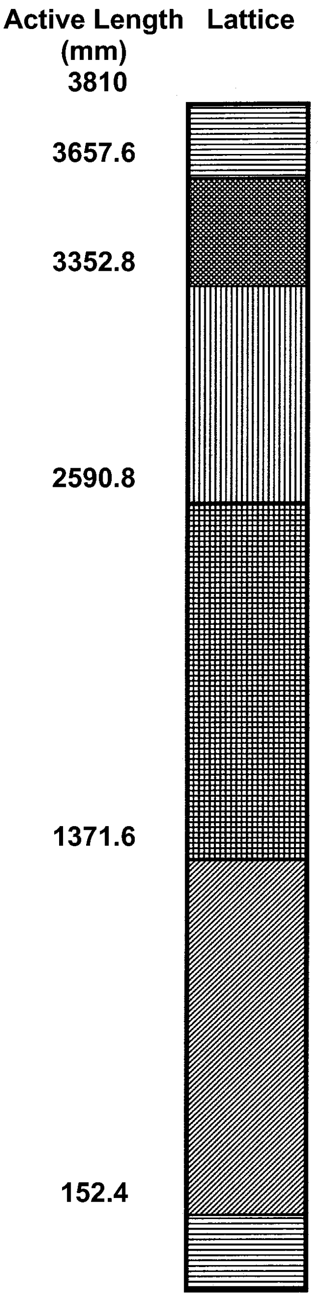
The Reference Analysis describes an equilibrium SVEA-96 Optima2 core with the characteristics given in Table 2-2 and utilizes assemblies with two nuclear designs. These assembly nuclear designs are designated OA07 and OA08 and differ only in the gadolinia loading as shown in Figures 2-2 and 2-3. Figures 2-2 and 2-3 show axial design characteristics of the two designs. The notation to the right of each of the six axial zones show the total number of fuel rods in the zone, the average U^{235} enrichment of the zone, and the number of fuel rods which contain gadolinia with the gadolinia concentration of those rods. For example, the third zone up from the bottom of the OA07 assembly shown in Figure 2-2 has 92 fuel rods with a lattice average enrichment of 4.673 w/o U^{235} with 15 of the fuel rods containing gadolinia with a concentration of 7 w/o. As shown in Figures 2-2 and 2-3, the bottom two axial zones contain all 96 fuel rods, the third zone up from the bottom contains 88 fuel rods, and the top three zones contain 84 fuel rods. The top and bottom zones contain natural uranium. As noted above, the maximum enrichment in the Reference Analysis lattices is 4.95 w/o.

As shown in Table 2-2, the OA07 assembly has a slightly higher uranium mass than the OA08 assembly due to the slightly greater gadolinia loading in the OA08 assembly. The batch average burnup in the Reference Analysis is 52400 MWD/MTU, and both the OA07 and OA08 assemblies have an assembly average enrichment of 4.25 w/o.

Table 2-2
Reference Analysis Assemblies

Item	Value
Total Number of Feed Assemblies per Batch	232
Number of Feed Assembly Types per Batch	176 (OA07) 56 (OA08)
Assembly Average Enrichment (w/o U^{235})	4.25
Assembly Uranium Mass (kgU)	180.5 (OA07) 180.1 (OA08)
Uranium Batch Mass (kgU)	41.85
Batch Discharge Burnup (MWD/MTU)	52400

BUNDLE TYPE 0A07



- ✓ Average Lattice Enrichment = 0.711 % Natural U

- ✓ Number of Fuel Rods = 84 Rods
- ✓ Average Lattice Enrichment = 4.348 % U^{235}
- ✓ 15 Fuel Rods with 5.00 % Gd_2O_3

- ✓ Number of Fuel Rods = 84 Rods
- ✓ Average Lattice Enrichment = 4.348 % U^{235}
- ✓ 15 Fuel Rods with 7.00 % Gd_2O_3

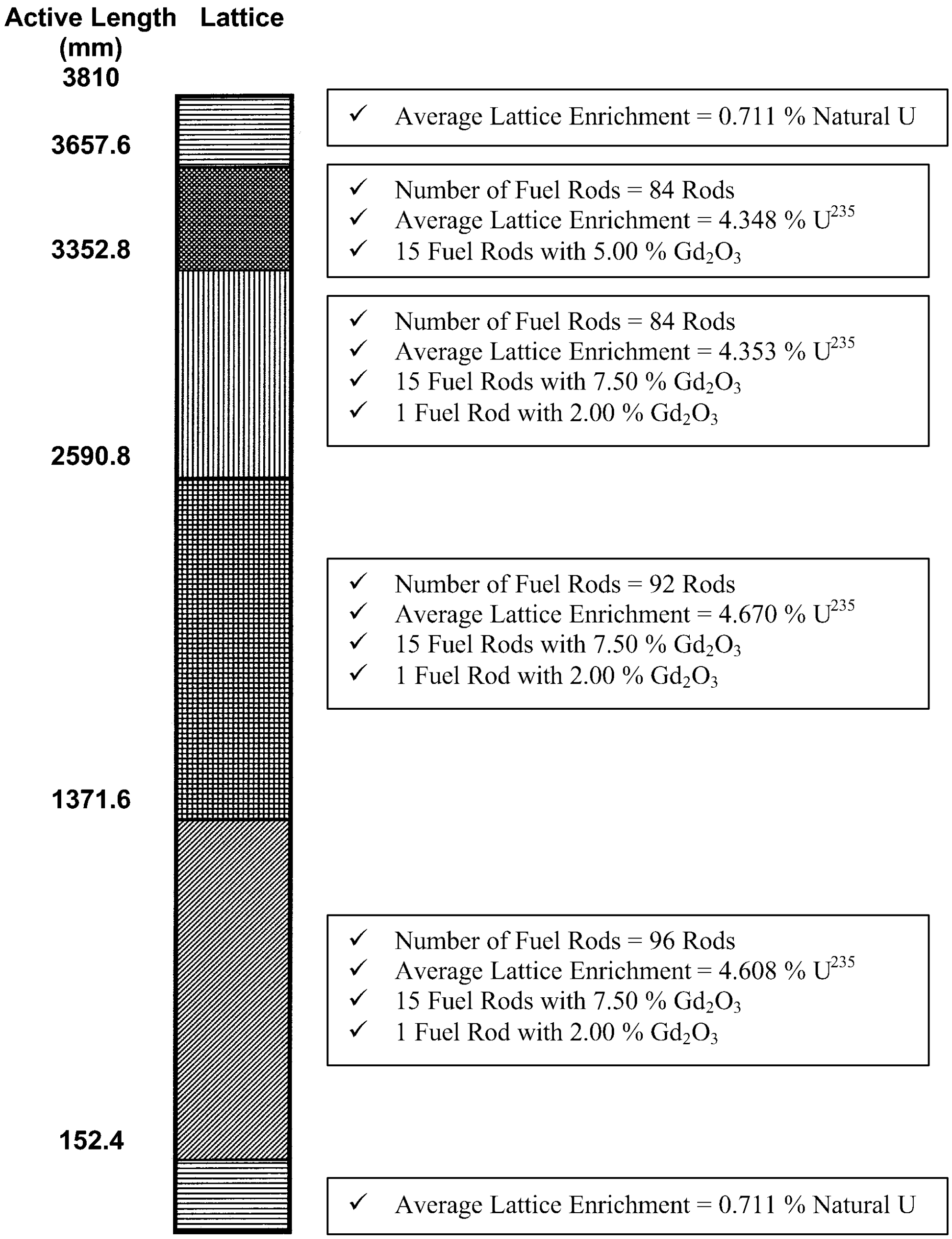
- ✓ Number of Fuel Rods = 92 Rods
- ✓ Average Lattice Enrichment = 4.673 % U^{235}
- ✓ 15 Fuel Rods with 7.00 % Gd_2O_3

- ✓ Number of Fuel Rods = 96 Rods
- ✓ Average Lattice Enrichment = 4.612 % U^{235}
- ✓ 15 Fuel Rods with 7.00 % Gd_2O_3

- ✓ Average Lattice Enrichment = 0.711 % Natural U

Figure 2-2
Assembly AO07 Axial Design

BUNDLE TYPE 0A08



- ✓ Average Lattice Enrichment = 0.711 % Natural U

- ✓ Number of Fuel Rods = 84 Rods
- ✓ Average Lattice Enrichment = 4.348 % U^{235}
- ✓ 15 Fuel Rods with 5.00 % Gd_2O_3

- ✓ Number of Fuel Rods = 84 Rods
- ✓ Average Lattice Enrichment = 4.353 % U^{235}
- ✓ 15 Fuel Rods with 7.50 % Gd_2O_3
- ✓ 1 Fuel Rod with 2.00 % Gd_2O_3

- ✓ Number of Fuel Rods = 92 Rods
- ✓ Average Lattice Enrichment = 4.670 % U^{235}
- ✓ 15 Fuel Rods with 7.50 % Gd_2O_3
- ✓ 1 Fuel Rod with 2.00 % Gd_2O_3

- ✓ Number of Fuel Rods = 96 Rods
- ✓ Average Lattice Enrichment = 4.608 % U^{235}
- ✓ 15 Fuel Rods with 7.50 % Gd_2O_3
- ✓ 1 Fuel Rod with 2.00 % Gd_2O_3

- ✓ Average Lattice Enrichment = 0.711 % Natural U

Figure 2-3
Assembly AO08 Axial Design

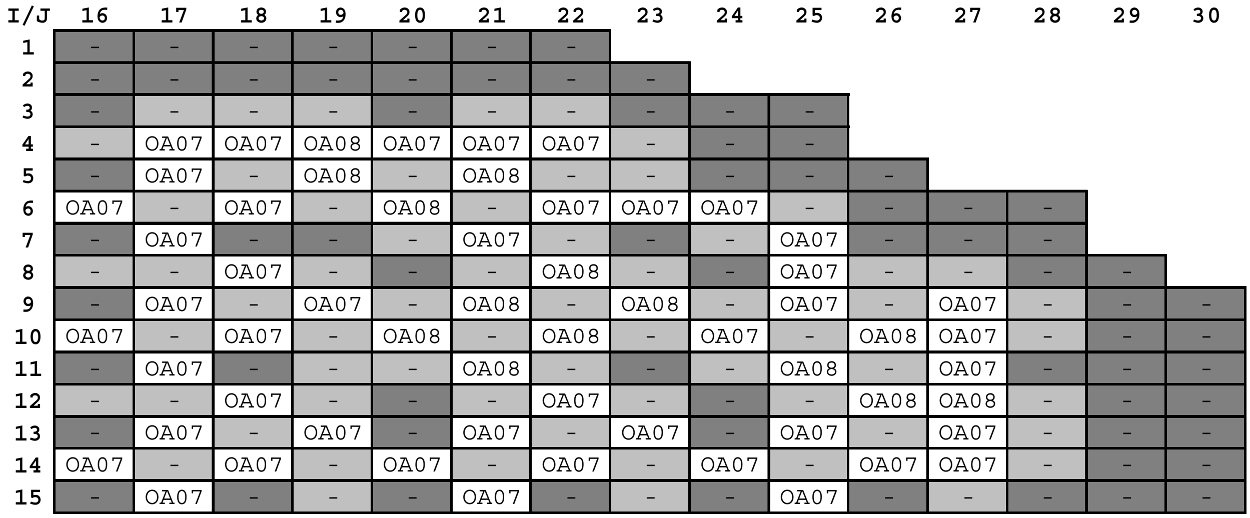
2.3.2 Reference Analysis Core Design

As shown in Table 2-1, 176 OA07 and 56 OA08 feed assemblies are loaded in the Reference Analysis equilibrium cycle resulting in a total batch size of 232 assemblies. The Reference Analysis loading pattern is shown in Figure 2-4. The locations labeled OA07 and OA08 are feed fuel locations. The high burnup assemblies (dark gray) are loaded at the periphery, while the once-burned assemblies (light gray) tend to occupy interior locations with the feed fuel. This pattern minimizes neutron leakage from the core while maintaining shutdown margin and thermal limit design criteria. Some high burnup assemblies are also moved into the central portion of the core provide control cells and increase margin to the thermal limits or reactivity limits.

Control rod patterns for the Reference Analysis equilibrium cycle are shown in Figure 2-5. The numbers in the figure represent the number of notches withdrawn. The notation “---“ indicates that the control rod is fully withdrawn. As shown in Figure 2-5, control rod exchanges are performed every 3000 MWD/MTU.

The loading pattern shown in Figure 2-4 and the control rod sequences in Figure 2-5 provides a cycle depletion which fulfills the cycle energy requirement of 660 Effective Full Power Days (EFPD) and satisfies thermal margin and reactivity design criteria. As shown in Figures 2-6 and 2-7 the design criteria for Hot Excess Reactivity and Shutdown Margin identified in Table 2-1 are satisfied throughout the cycle. Similarly, Figures 2-8 and 2-10 demonstrate that at least 15 % margin to the LHGR and APLHGR limits is achieved throughout the cycle (Figures 2-8 and 2-10). Figure 2-9 shows that at least 12 % margin to the CPR limit is achieved throughout the cycle. Therefore, the design criteria identified in Table 2-1 are satisfied by the Reference Analysis.

The SVEA-96 Optima2 enrichment required to satisfy the energy requirements for the Reference Analysis is consistent with the results in the Phase I study for the GE14 24-month cycle case. The Reference Analysis was performed for a cycle energy of 660 EFPD for a rated thermal power of 3323 MW_{th}. The Phase I GE14 24-month cycle analysis was performed for a 700 EFPD cycle at a rated thermal power of 3458 MW_{th}. If the Phase I GE14 24-month cycle average enrichment is corrected for the cycle energy difference, the Phase I analysis would have required an assembly average enrichment of 4.275 w/o compared with the Phase II Reference Analysis enrichment of 4.25 w/o. This agreement is considered to be very good recognizing that different assembly designs were used. Different analysis methods might also introduce minor differences. This good agreement supports the conclusion that the Phase II results can be confidently compared with the Phase I results.



I/J	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	-	-	-	-	-	-	-								
2	-	-	-	-	-	-	-	-							
3	-	-	-	-	-	-	-	-	-	-					
4	-	OA07	OA07	OA08	OA07	OA07	OA07	-	-	-					
5	-	OA07	-	OA08	-	OA08	-	-	-	-	-				
6	OA07	-	OA07	-	OA08	-	OA07	OA07	OA07	-	-	-	-		
7	-	OA07	-	-	-	OA07	-	-	-	OA07	-	-	-		
8	-	-	OA07	-	-	-	OA08	-	-	OA07	-	-	-	-	
9	-	OA07	-	OA07	-	OA08	-	OA08	-	OA07	-	OA07	-	-	-
10	OA07	-	OA07	-	OA08	-	OA08	-	OA07	-	OA08	OA07	-	-	-
11	-	OA07	-	-	-	OA08	-	-	-	OA08	-	OA07	-	-	-
12	-	-	OA07	-	-	-	OA07	-	-	-	OA08	OA08	-	-	-
13	-	OA07	-	OA07	-	OA07	-	OA07	-	OA07	-	OA07	-	-	-
14	OA07	-	OA07	-	OA07	-	OA07	-	OA07	-	OA07	OA07	-	-	-
15	-	OA07	-	-	-	OA07	-	-	-	OA07	-	-	-	-	-

Figure 2-4
Core Loading Scheme

Position in notches withdrawn

0.0 EFPH (0 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	0	---	42	---	42	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	6	---	42	---	---	---
7	---	---	---	---	---	---	---	---
8	38	---	---	---	0	---	---	---

200.0 EFPH (201 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	6	---	---	---	44	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	10	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	44	---	---	---	6	---	---	---

1000.0 EFPH (1005 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	8	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	14	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	---	---	8	---	---	---

2000.0 EFPH (2009 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	10	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	14	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	---	---	10	---	---	---

3000.0 EFPH (3014 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	12	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	0	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	0	---	---	---	12	---

4000.0 EFPH (4018 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	4	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	0	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	0	---	---	---	4	---

5000.0 EFPH (5023 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	0	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	0	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	0	---	---	---	0	---

6000.0 EFPH (6027 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	8	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	0	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	0	---	---	---	8	---	---	---

Figure 2-5
SVEA-96 Optima2 Equilibrium Cycle Loading Control Rod Sequence

Position in notches withdrawn

7000.0 EFPH (7032 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	8	---	---	---	16	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	0	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	0	---	---	---	8	---	---	---

8000.0 EFPH (8036 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	6	---	38	---	6	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	0	---	38	---	---	---
7	---	---	---	---	---	---	---	---
8	0	---	---	---	6	---	---	---

9000.0 EFPH (9041 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	14	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	0	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	0	---	---	---	0	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	0	---	---	---	14	---

10000.0 EFPH (10045 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	0	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	0	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	0	---	---	---	0	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	0	---	---	---	0	---

11000.0 EFPH (11050 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	0	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	0	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	0	---	---	---	0	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	0	---	---	---	0	---

12000.0 EFPH (12055) MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	0	---	---	---	---			
3	---	---	---	---	---	---		
4	0	---	---	---	0	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	0	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	0	---	---	---	0	---	0	---

13000.0 EFPH (13059 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	0	---	---	---	0	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	0	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	0	---	---	---	0	---	---	---

14000.0 EFPH (14064 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	4	---	---	---	4	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	4	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	0	---	---	---	4	---	---	---

15000.0 EFPH (15068 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	8	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	0	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	0	---	---	---	8	---

15840.0 EFPH (14912 MWD/MTU)

	8	9	10	11	12	13	14	15
1	---	---	---	---				
2	---	---	---	---	---			
3	---	---	---	---	---	---		
4	---	---	---	---	---	---	---	
5	---	---	---	---	---	---	---	---
6	---	---	---	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	---	---	---	---	---	---	---	---

Figure 2-5 (continued)
SVEA-96 Optima2 Equilibrium Cycle Loading Control Rod Sequence

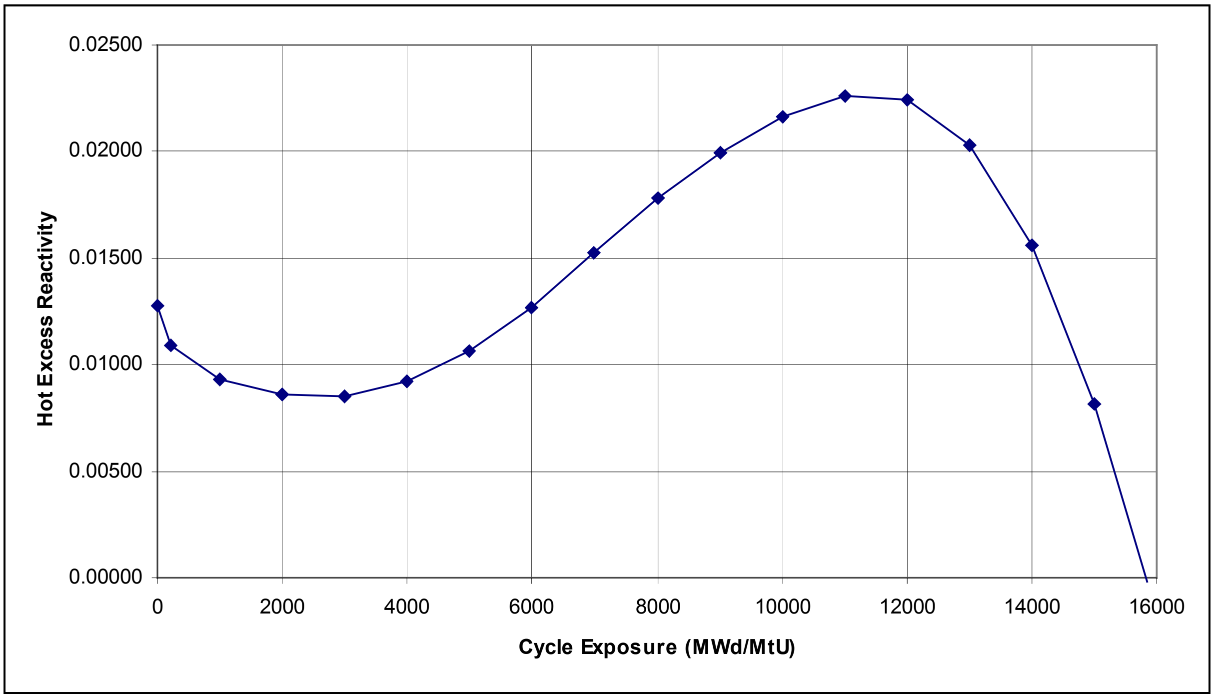


Figure 2-6
Hot Excess Reactivity versus Cycle Burnup

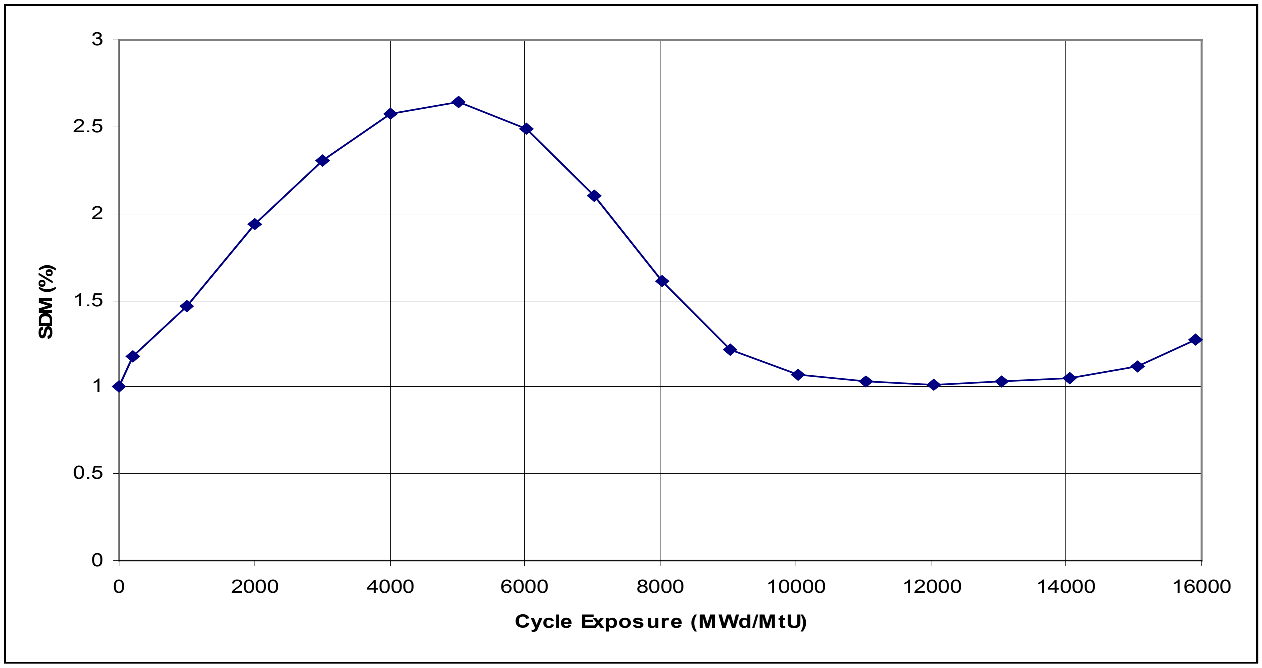


Figure 2-7
Shutdown Margin (SDM) Versus Cycle Burnup

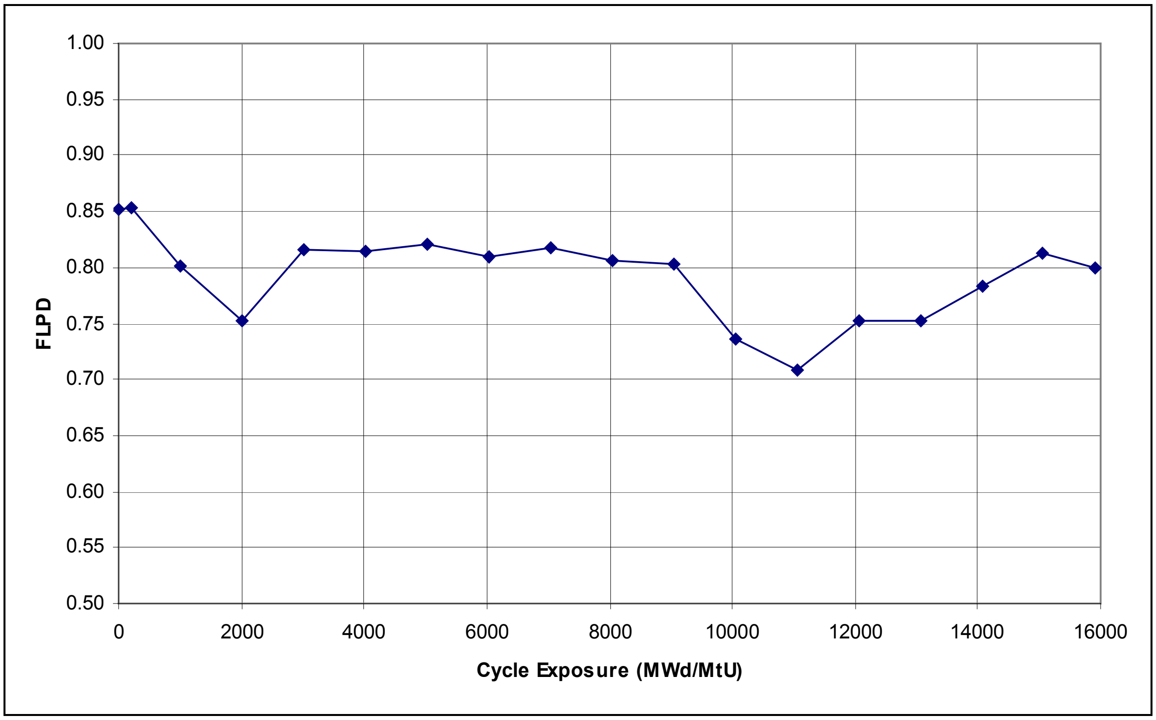


Figure 2-8
Limiting Ratio of LHGR limit to LHGR (FLPD) as a Function of Cycle Burnup

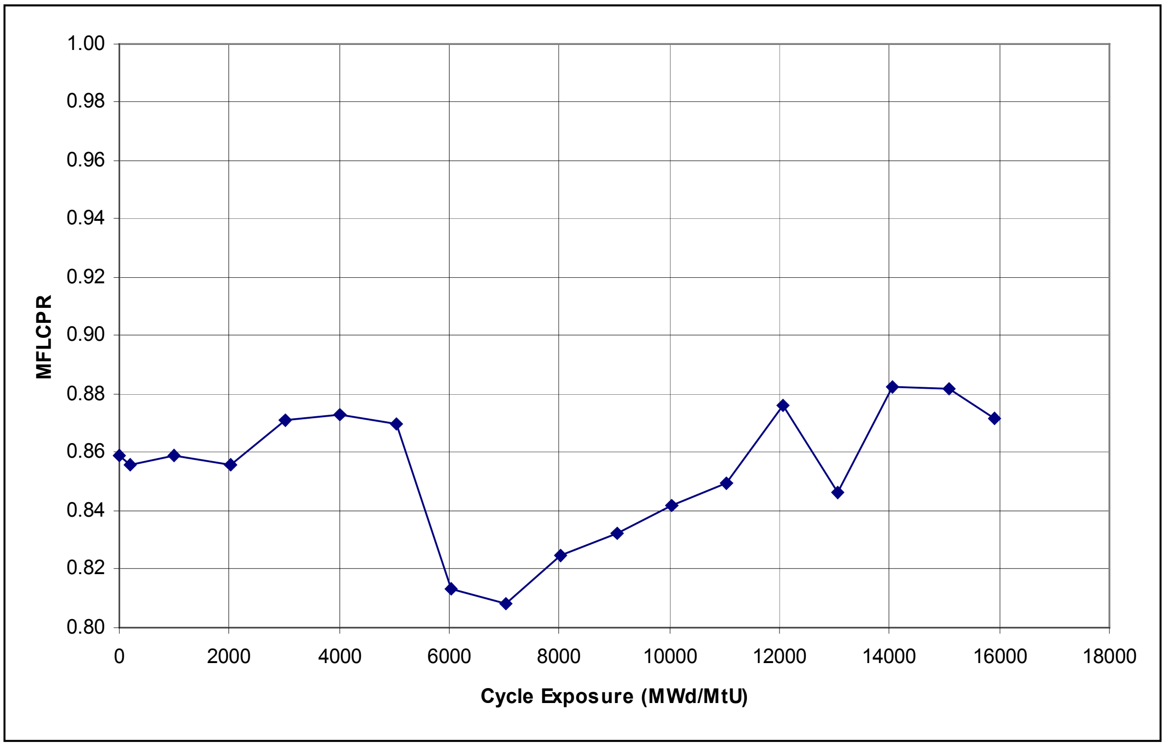


Figure 2-9
Limiting Fraction of CPR to CPR Limit (MFLCPR) Versus Cycle Burnup

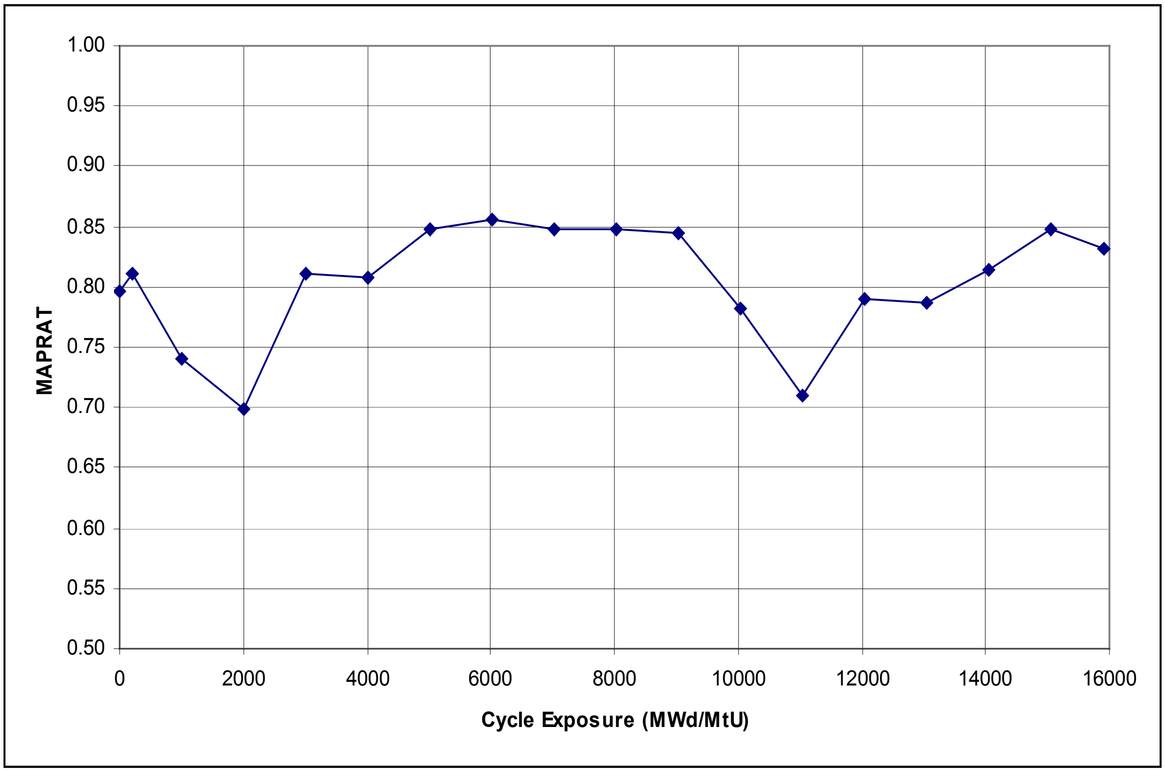


Figure 2-10
Maximum Fraction of Average Planar Linear Heat Generation Rate to the Limit (MAPRAT) versus Cycle Burnup

2.3.3 Extension of Reference Analysis to a Maximum Enrichment of 6 w/o

The second step in the process described in Section 2.1 is an extension of the Reference Analysis to a maximum enrichment of 6 w/o. This extension is accomplished with a series of perturbation studies based on two-dimensional PHOENIX calculations as well as three-dimensional POLCA results to assess the impact of extending the maximum U^{235} enrichment to 5.95 w/o in the assembly nuclear design. The maximum enrichment of 5.95 w/o assumes a reasonable manufacturing margin to the assumed maximum enrichment of 6 w/o of 0.05 w/o.

The first step in extending the Reference Analysis to a maximum nominal enrichment of 6 w/o is to perform a series of two-dimensional lattice calculations to establish the energy gain associated with the enrichment increase and the impact on thermal margins of relative fuel rod power distribution changes on thermal margins. The second step in the extension process is to evaluate the impact of the enrichment increase on core-wide reactivity limits (e.g. shutdown margin) and assembly peaking, which are not captured by the two-dimensional evaluation in the initial step.

2.3.3.1 Energy Gain Associated with Peak Enrichment Increase to 5.95 w/o U^{235}

The total energy gain associated with increasing the enrichment of the Reference Analysis fuel assemblies described in Section 2.3.1 to a maximum pin enrichment of 5.95 w/o was established by performing a series of lattice depletion calculations with PHOENIX. Specifically, the fuel pin enrichments in enriched lattices in different AO07 and AO08 zones were scaled to maximum lattice enrichments of 5.45 and 5.95 w/o. The intermediate set of calculations with a maximum enrichment of 5.45 w/o was performed as a check of the linearity of the energy increase as a function of enrichment in the in the 5 to 6 w/o range. The energy increase associated with a particular lattice is reflected by the burnup at which a particular reference k_∞ is reached. The overall energy increase associated this scaling process was established from a synthesis of the individual lattice results to be 15100 MWD/MTU per w/o assembly average enrichment which represents an increase in energy of about 29 %. For the equilibrium cycle described in Section 2.3.2, this energy increase corresponds to a 15100 MWD/MTU increase in batch discharge burnup, which would support a decrease in batch size from 232 assemblies to 180 feed assemblies for a constant cycle energy.

These lattice calculations also demonstrate that the increase in peak enrichment from 4.95 to 5.95 w/o has a very minimal effect on relative pin power. This conclusion is illustrated in Figures 2-11 through 2-14 for the OA08 assembly described in Figure 2-3. Figures 2-11 through 2-14 show that the increase in pin enrichment from 4.95 to 5.95 w/o has very little impact on the maximum relative pin power at all lattice burnups. This behavior is also reflected in the corresponding maps of relative pin power at various burnups. For an actual design, even the minor impact on relative pin power shown in Figures 2-11 through 2-14 could be corrected by minor adjustment in the burnable absorber (gadolinia) and enrichment design. Therefore, it is concluded that increasing the maximum enrichment to a nominal 6 w/o value would not significantly impact dryout or Linear Heat Generation Rate (LHGR) thermal margins due to increased relative fuel rod powers for a fixed assembly power.

Without additional design changes, however, this increase in assembly energy and corresponding decrease in batch size, would not support the same shutdown margin or thermal margin performance of the unperturbed Reference Analysis core described in Section 2.3.2. The reduction in batch size would reduce the number of feed fuel gadolinia rods, thereby reducing the shutdown margin. The associated increase in batch discharge burnup would also increase the spread in assembly reactivity in the core further reducing the shutdown margin. Furthermore, the reduction in feed fuel batch size for a given cycle energy will increase the maximum assembly peaking factors which will reduce thermal margins. Measures to improve shutdown margin and margins to thermal limits for the increased enrichment case are discussed in Section 2.3.3.2.

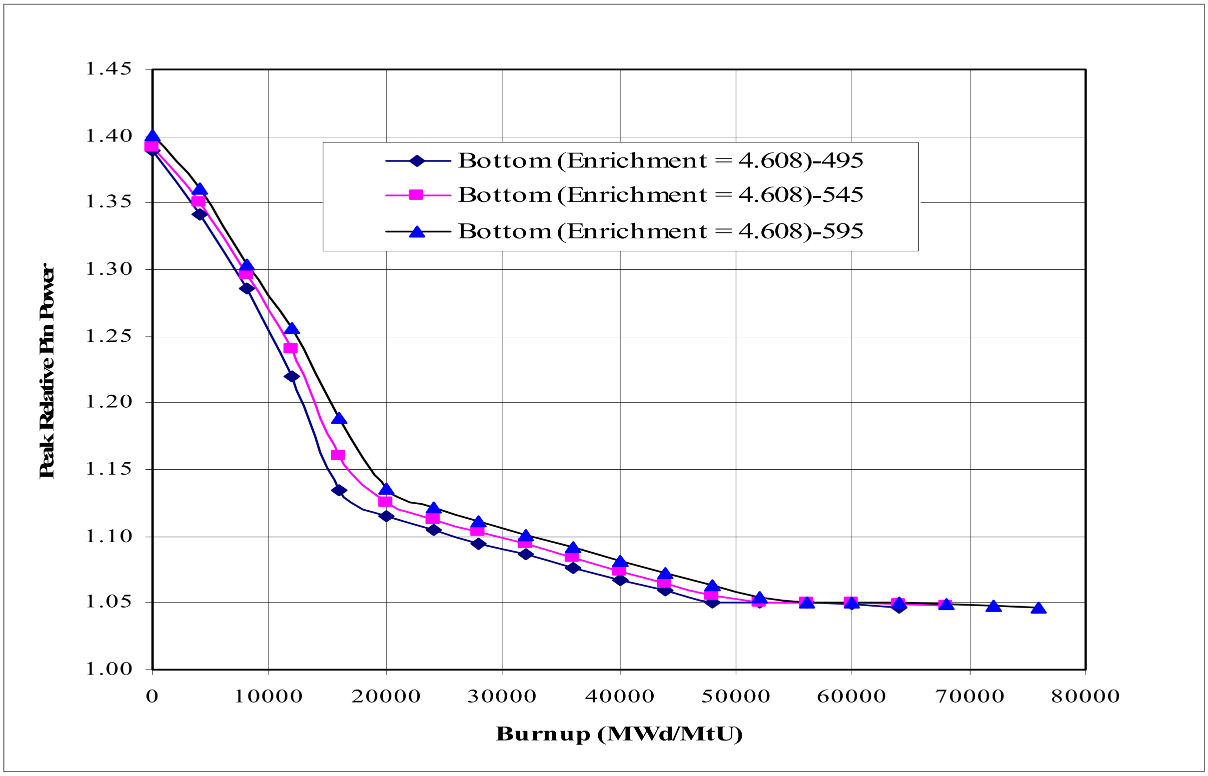


Figure 2-11
Maximum Relative Pin Power for AO08 Assembly Bottom Enriched Zone

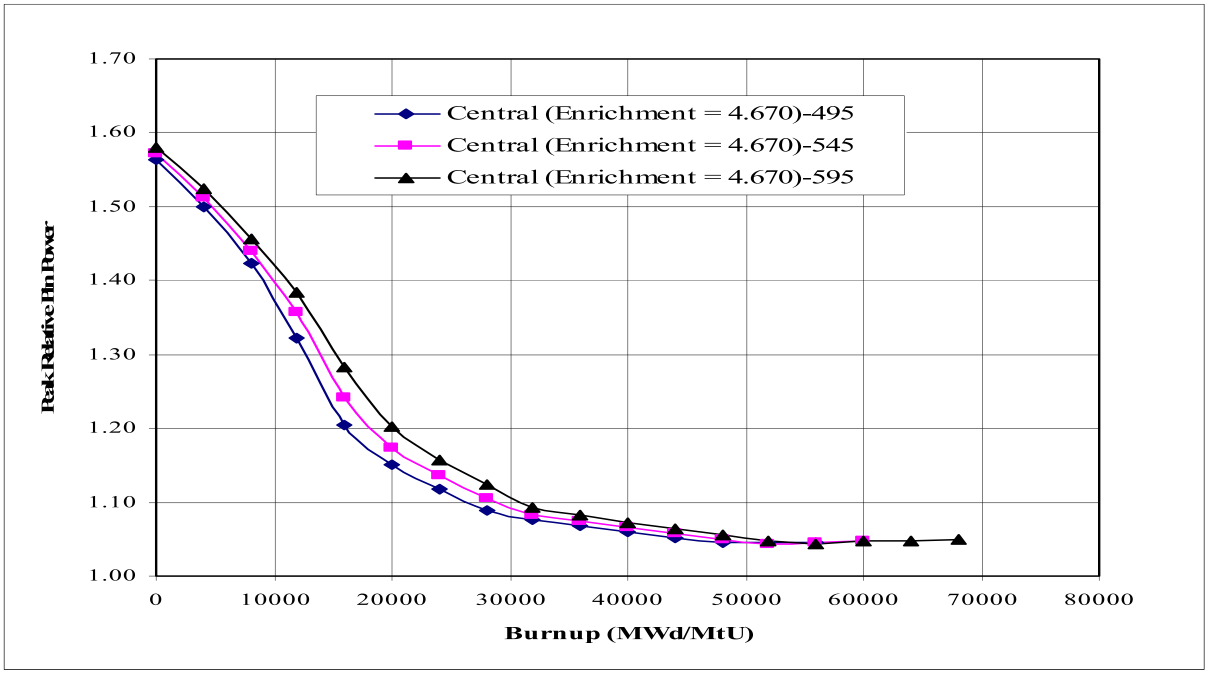


Figure 2-12
Maximum Relative Pin Power for AO08 Assembly Central Enriched Zone

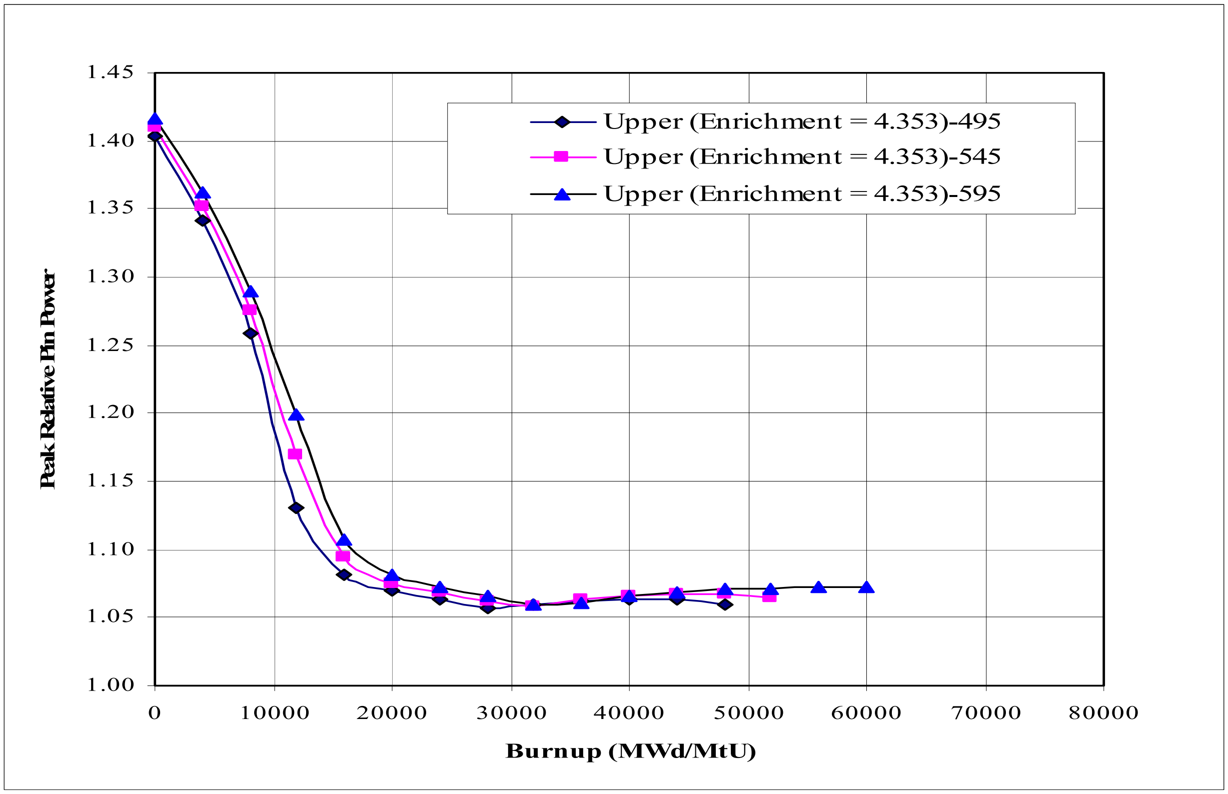


Figure 2-13
Maximum Relative Pin Power for AO08 Assembly Bottom Enriched Zone

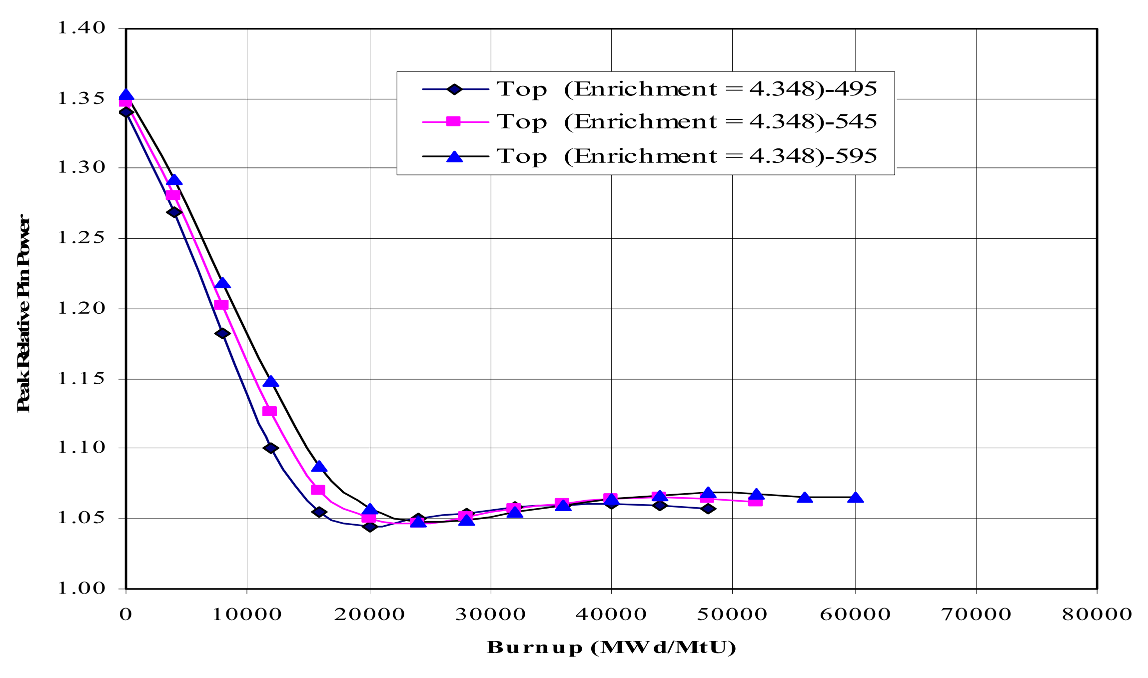


Figure 2-14
Maximum Relative Pin Power for AO08 Assembly Central Enriched Zone

2.3.3.2 Measures to Improve Shutdown Margin and Thermal Margins

Two approaches for recovering the Reference Analysis shutdown margin and margins to thermal limits for the increased enrichment case have been evaluated which are considered to provide a range of batch discharge burnups which could be achieved in practice. The first approach is referred to below as the “Optimized for Extended Enrichment” option and involves mechanical design changes to the assembly to preserve the batch discharge burnup gain of 15100 MWD/MTU for a 1 w/o assembly average enrichment increase. The second approach is referred to as the “Current Bundle Optimization” option and maintains the current assembly mechanical design. This option recovers shutdown margin and thermal limit margins by changes in the nuclear design of the assembly and core loading at some expense to the batch discharge burnup gain associated with the enrichment increase.

The “Optimized for Extended Enrichment” option recognizes that assemblies currently being utilized in reload applications such as the SVEA-96 Optima2 assembly have been optimized for maximum enrichments below 5 w/o for maximum discharge peak burnups near 53000 MWD/MTU. Consequently, this option would reoptimize the assembly mechanical design for enrichments in excess of 5 w/o. It is anticipated that design modifications to improve reactivity performance at the higher burnup could involve changes such as fuel rod diameter and pitch, placement of part length rods, and internal water channel dimensions. These changes could, for example, be introduced to compensate for the spectrum hardening associated with higher U^{235} enrichments. In addition, the use of natural uranium blankets was determined to be optimum for average enrichments near 3 w/o. Modification of the size and/or enrichment of the axial blankets in BWR assemblies for higher enrichments would be expected to improve performance. Margins to thermal limits could be improved by changes in spacer design and assembly axial design to flatten axial power shapes. It should be noted that the Reference Analysis was performed for the relatively large design thermal margins given in Table 2-1. Some relaxation of these design margins could be justified. Therefore, it is judged that mechanical design changes could be introduced to recover the reductions in shutdown margin and margins to thermal limits associated with the increase in maximum enrichment to 6 w/o U^{235}. However, for the purposes of assuring that the evaluation of the relative benefit of a 1 w/o enrichment gain is realistic, the value of 15100 MWD/MTU per w/o enrichment increase is assumed to be an upper limit of the potential benefit in this study.

The Current Bundle Optimization option represents the other extreme in which the reactivity and thermal margin performance is recovered by assembly and core nuclear design changes without any further optimization of the assembly mechanical design. In this case shutdown margin is recovered by increasing the number of burnable absorber (uranium oxide-gadolinia) rods in each of the feed assemblies to compensate for the reduction in feed assemblies. Loading of the same number of burnable absorber rods in the 5.95 w/o maximum enrichment case as the 4.95 w/o maximum enrichment Reference Analysis case would require an increase in the average number of burnable absorber rods per assembly of about 4.4 rods. Reduction of the feed batch sizes for a given cycle energy also increases the spread in assembly reactivity. This increase in the range of assembly reactivities tends to decrease the magnitude of the difference between hot full power reactivity and cold controlled reactivity, which leads to a loss in shutdown margin. Furthermore, the increase in U^{235} enrichment causes the neutron spectrum to become somewhat harder (i.e. less thermal), which reduces the reactivity worth of the BWR control rods and causes further erosion in shutdown margin. Accommodation of these effects increases the number of additional burnable absorber rods required per assembly to about 5. Addition of 5 burnable absorber rods to the assembly will increase the residual poisoning effect of the burnable absorber rods. Nuclear design experience with the SVEA 10x10 fuel leads to the conclusion that the residual burnable absorber poisoning effect in this case would lead to an energy loss of about 1400 MWD/MTU in batch discharge burnup.

The Current Bundle Optimization option also requires that the increase in relative assembly power associated with the feed batch size decrease provided by the enrichment increase be accommodated in the nuclear design. The reduction in batch size and optimized loading pattern for the reduced batch size associated with the 15100 MWD/MTU discharge burnup increase will lead to an increase in assembly peaking of about 20 %. Compensation for this increase in assembly peaking with the Reference Analysis assembly designs would require some addition of feed fuel assemblies and some fuel assembly shuffling which would also increase core leakage. This is a typical design consideration, and extensive design experience is available to quantify the effect. Application of this experience leads to the conclusion that compensation for the 20 % increase in assembly peaking would lead to a further reduction in batch discharge burnup of 1000 MWD/MTU.

Therefore, the batch discharge burnup gain for the Current Bundle Optimization option requires a decrease in batch discharge burnup relative to the Optimized for Extended Enrichment option of 15100 - 1400 –1000 = 12700 MWD/MTU. The Optimized for Extended Enrichment assumes that losses in shutdown margin and thermal margin associated with the 1 w/o U^{235} enrichment increase can be completely accommodated by design improvements to the assembly mechanical design. The Current Bundle Optimization option assumes no mechanical design changes to reoptimize the assembly for the higher enrichments. Therefore, comparison of the fuel cycle costs for both of the increased enrichment cases with the Reference Analysis results for which the maximum enrichment is 4.95 w/o provides a reasonable range for which to assess the expected benefit of an increase in maximum enrichment from 5 w/o to 6 w/o in a large BWR.

The batch discharge burnups associated with the increases in nominal maximum enrichment to 5.5 and 6.0 w/o are shown in Table 2-3, and the batch discharge burnup is plotted as a function of assembly average enrichment in Figure 2-15. The data in Table 2-3 were used in the BWR economic evaluations in Section 4.

Table 2-3
Enrichment Requirements

Maximum Nominal Enrichment (w/o U^{235})	Maximum Actual Enrichment (w/o U^{235})	Assembly average enrichment (including blankets) (w/o U^{235})	Enrichment Average over Non-blanket Enriched Zone (w/o U^{235})	Batch Average Discharge Burnup (MWD/MTU)	
				Optimized for Extended Enrichment	Current Bundle Optimization
5.0	4.95	4.25	4.56	52400	52400
5.5	5.45	4.67	5.02	59400	58400
6.0	5.95	5.10	5.48	65200	63200

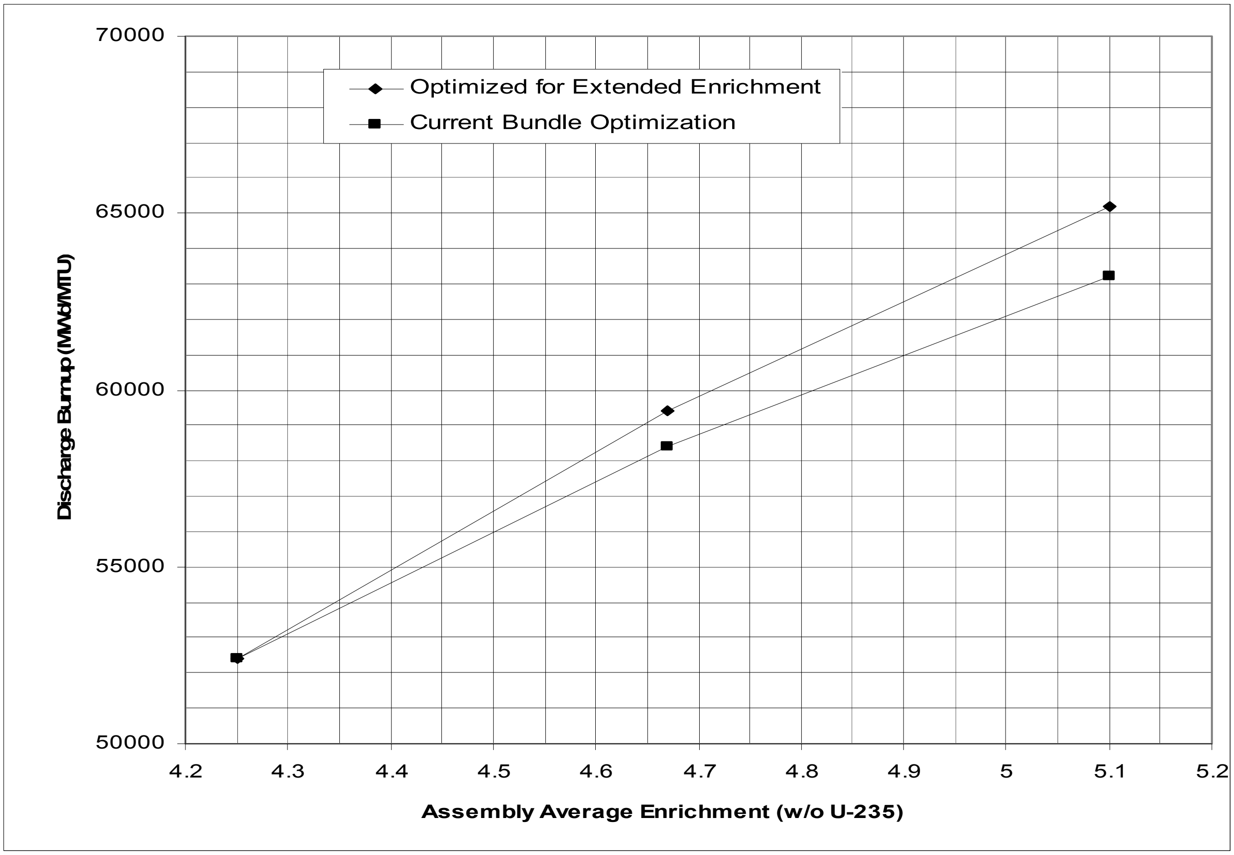


Figure 2-15
Energy Gain as a Function of Assembly Average Enrichment

2.4 Further BWR Design Considerations for High Enrichments, Long Cycles, and High Burnup

Nuclear design considerations associated with maintaining shutdown margin and margins to thermal limits for increased enrichments are discussed in Section 2.3. This section addresses additional considerations associated with plant design, high burnup, and alternative options to increasing enrichment or to be considered in conjunction with increasing enrichment.

2.4.1 Burnup Limits

The peak rod average burnup currently accepted for U.S. commercial power reactors is 62000 MWD/MTU. The peak rod-average burnups associated with the batch discharge burnups of 63200 and 65200 MWD/MTU associated with the Current Bundle Optimization and the Optimized for Extended Enrichment options in Table 2-3 will be on the order of 75000 and 77000 MWD/MTU, respectively. Rod internal pressure can be a limiting constraint in BWR fuel rods, and design measures might be required to avoid the approach to rod internal pressure limits for these increases in rod average burnups. Possible design alternatives to reduce rod internal gas pressures could include increased plenum lengths or advanced fuel pellet designs, which reduce the release of fission gases from the fuel pellet. Furthermore, continued focus on optimizing fuel cladding materials and heat treatments as well as coolant water chemistries to minimizing cladding corrosion and hydriding would be an important factor in supporting higher discharge burnups associated with an enrichment increase beyond the current upper limit.

2.4.2 Axial Blanket Design

Natural or low-enrichment axial blankets involve a trade-off between reduced axial neutron leakage and increased axial power peaking in the central part of the fuel rod. As noted in Section 2.3, the use of six-inch natural uranium blankets was determined to be optimum for assembly average enrichments near 3 w/o. The use of six-inch natural uranium blankets is not optimum for current allowed maximum enrichments corresponding to an assembly average enrichment of about 4.25 w/o and would be even less desirable for enrichments in excess of 5 w/o. Loss of U^{235} associated with natural uranium blankets could be easily accommodated by increasing enrichments in the central part of the fuel rod for the relatively low assembly average enrichments in the past. In effect, this option is no longer available when the maximum enrichment is set to the maximum allowed enrichment.

The use of enriched blankets should be specifically evaluated on a case basis and may vary depending on the specific situation. However, it estimated that for peak enrichments at the current 5 w/o limit, enriching the six-inch blankets to 2-2.5 w/o or reducing the height of the natural uranium axial blankets to 3 inches would reduce axial peaking substantially and could lead to an increase in batch discharge burnup of 2 to 3 MWD/MTU. Therefore, while blanket design optimization would not provide the magnitude of energy gain associated with a maximum enrichment increase to 6 w/o, it could provide some (perhaps 20 %) of the benefit associated with an enrichment increase of 1 w/o. It could also be used in conjunction with an enrichment increase to further increase assembly energy. Of course, the enrichment of the axial blankets would have to be balanced against increased fluence to core structural components. This consideration would be particularly important at the top of a BWR core.

2.4.3 Increase Assembly Uranium Weight

Another alternative for increasing assembly energy is the addition of uranium mass to the assembly. In principle, potential options to achieve this end are increases in pellet density and radius as well as increases in pellet stack length. Possible changes in pellet radius are very limited since increases in pellet radius are constrained by the need to maintain acceptable fuel rod spacing, clad outer diameter, cladding thickness, and pellet-cladding gaps. Increases in pellet stack length are considered possible depending on the assembly design. The potential for increases in the stack length, which reduce the fuel rod plenum volume, may be limited due to the need to support potentially higher internal pressures as the batch discharge burnup is increased. Increasing pellet density is considered to be a fruitful area for further development in the effort to increase uranium mass.

3

PWR CYCLE DESIGNS

3.1 Introduction

PWR studies have been completed for 18 month cycles using fuel enriched in excess of 5.0 w/o. The reference plant chosen for the PWR study was a typical 4-loop, 193 assembly Westinghouse NSSS operating at uprated power conditions. Key core characteristics are shown in Table 3-1. These characteristics are identical to the core used for the Phase I study.

Table 3-1
PWR Reactor Description

	Reference Westinghouse 4 Loop PWR
Reactor Core Rated Power (MW_{th})	3587
Inlet Temperature (°F)	547.0
Effective Core Flow Excluding Bypass (gpm)	374400
Core Average Temperature (°F)	581.0
Number of Fuel Assemblies	193
Core Initial Heavy Metal Weight (kgU)	
Performance+ Fuel	79.84
RFA Fuel	87.29
Specific Power (W/g)	44.94

Consistent with recent trends, the cores were assumed to operate with high capacity factors and very short refueling outages. To extend the Phase I 18 month cycle results to higher burnup ranges, the number of feed assemblies was reduced and the enrichments were increased in excess of 5.0 w/o. Cases having a range of discharge burnup up to 65000 - 70000 MWD/MTU were established.

As in the previous study, the PWR cases employed very low leakage loading patterns with burned fuel in all locations on the core periphery. All cycles were depleted at 100% power conditions with no coastdown at end of cycle. The economic results are discussed in Sections 4 of this report.

3.2 Cycle Design and Reactor Core Features

The reference fuel design chosen for the PWR study was the Westinghouse 17X17 Performance+ fuel design. This fuel design uses the 0.360" OD fuel rod. The fuel cladding, grids, guide thimbles, and instrument thimbles use ZIRLO™ material for enhanced corrosion resistance. Intermediate flow mixing grids are used to provide additional thermal margin and support the peaking factors assumed as constraints for the analysis. ZrB_2 integral fuel burnable absorbers (IFBA) are used for reactivity control. Each fuel rod contains partially enriched 8 inch annular axial blankets. The annulus provides additional space in the fuel rod to accommodate fission gas release as well as helium generation from the IFBA depletion. The blanket enrichment is normally 3.20 w/o.

An alternate fuel design considered in the study is the Westinghouse 17X17 Robust Fuel Assembly (RFA) design. This design is similar to the Performance+ design except for using the larger 0.374" fuel rod OD. Use of a larger fuel rod allows for a fewer number of feed assemblies to be loaded for a given enrichment. This might be of some benefit for the higher burnup 18 month cases. Modified ZIRLO™ grids are also used to accommodate the larger fuel rods, and the guide thimbles are thicker to provide enhanced structural stability. Key fuel parameter assumptions are summarized in Table 3-2 for the Performance+ and RFA fuel designs.

Core power distributions are constrained by core peaking factor limits. Limits are typically applied to the maximum fuel rod average power relative to core average rod power, and the maximum local power relative to core average power. For Westinghouse fuel, the maximum relative fuel rod average power is called $F_{\Delta H}$ and the maximum local relative power is called $F_Q(z)$. The peaking factor limits and other constraints assumed in the study are typical of high duty 4-loop PWRs and are summarized in Table 3-3.

The cycle length assumed in the study reflects a very short refueling outage duration and high capacity factor during operation. A 15 day refueling outage is assumed along with a 98% operating capacity factor. Based on these assumptions, the cycle length is summarized for the 18 month cycles in Table 3-4.

Table 3-2
PWR Fuel Description

	Westinghouse 17X17 Performance+	Westinghouse 17X17 Robust Fuel Assembly (RFA)
Fuel Assembly Rod Array	17X17	17X17
Cold Active Fuel Stack Height (in)	144.0	144.0
Clad Outer Diameter (in)	0.360	0.374
Pellet Outer Diameter (in)	0.3088	0.3225
Axial Blanket Length (Top or Bottom)	8.0	8.0
Axial Blanket Enrichment (wt % U^{235})	3.20	3.20
Axial Blanket Fuel Pellet Design	Annular	Annular
Assembly Initial Heavy Metal Loading (kgU)	413.67	452.28
Clad, Grid, and Thimble Material	ZIRLO™	ZIRLO™
Number of Guide Thimbles	24	24
Number of Instrumentation Thimbles	1	1
Burnable Poison Type Used	Integral – ZrB_2	Integral – ZrB_2

Table 3-3
PWR Cycle Design Constraints

	Westinghouse PWR
Enrichment (w/o U^{235})	No Constraint
Maximum Rod Relative Power, $F_{\Delta H}$	1.70
Maximum Local Relative Power, $F_Q(z)$	2.60
Shutdown Margin (% $\Delta\rho$)	> 1.30
Maximum Allowed MTC (pcm/°F)	5.0
Target MTC (pcm/°F)	< 3.0
Target BOC Maximum Boron Concentration (ppm)	1750

Table 3-4
PWR Cycle Lengths

	18 Month
Cycle Duration (days)	547.5
Refueling Outage (days)	15
Operating Capacity Factor (%)	98.0
Cycle Length (EFPD)	521.6
Performance+ Fuel Cycle Burnup (MWD/MTU)	23430
Robust Fuel Assembly Cycle Burnup (MWD/MTU)	21432

3.3 Equilibrium Cycle Neutronics Calculations

Equilibrium cycle neutronics calculations are performed for each case to accurately determine the enrichment requirements necessary to meet the specified cycle energy requirements. The equilibrium cycle approach can accurately determine the fuel requirements for a given case while also maintaining consistency from case to case. All core reactivity effects influencing fuel economics such as core leakage, batch powers and burnups, and burnable absorber residual penalties are consistently accounted for in an equilibrium cycle.

For each equilibrium cycle, a fuel loading pattern is determined that meets all required constraints. The core model is repeatedly depleted using the same fresh fuel locations and burned fuel shuffles until an equilibrium cycle is established where the core power distribution, peaking factors, and boron concentrations are identical from one cycle to the next. Boron concentration differences at any burnup step are 1 ppm or less from one cycle to the next allowing for very accurate determinations of enrichment requirements. The fuel enrichments were adjusted to obtain an end of cycle boron concentration of 0 ppm at the desired cycle burnup. Fuel enrichments were determined to the nearest 0.001 w/o for accurate economic comparisons of the different discharge burnups and cycle lengths.

For Phase I of the study, enrichment constraints limited the minimum number of feed assemblies to 84 for the Performance+ design and 80 for the RFA design. This resulted in region average discharge burnups of about 54000 MWD/MTU for Performance+ and 52000 MWD/MTU for RFA. In Phase II, the minimum number of feed assemblies is reduced to 64 for both fuel types. This increases region average discharge burnups to near 70000 MWD/MTU for Performance+ fuel and to near 65000 MWD/MTU for RFA fuel.

3.3.1 18 Month Cycle Neutronics

In the Phase II study, the 18 month cycle was chosen for additional fuel management analysis reducing the number of feed assemblies to attain higher discharge burnups. For Performance+ fuel, additional cases using 80, 72, and 64 feed assemblies were completed. 72 and 64 feed assembly cases were also generated for RFA fuel.

Similar philosophies were used in the various loading patterns to maintain a consistent fuel management approach. A mix of second and third cycle assemblies were placed on the core periphery, with all available third cycle assemblies placed in the locations with two faces adjacent to the baffle. As the number of feeds was reduced and more third cycle assemblies were available, they were placed in the positions with two faces adjacent to the baffle until all these locations were filled to further reduce neutron leakage.

The fuel requirements for the 18 month cycles using the Performance+ fuel design are summarized in Table 3-5. Core characteristics and key parameters such as boron concentrations, MTCs, peaking factors, and burnups are also summarized in Table 3-5. Similar data is provided for RFA fuel in Table 3-6.

Table 3-5
18 Month Cycle PWR Fuel Requirements and Core Characteristics With Performance+ Fuel

	80 Feed	72 Feed	64 Feed
Fuel Type	Performance+	Performance+	Performance+
Cycle Length (EFPD)	521.6	521.6	521.4
Number of Feeds Enr1	48	24	64
Enrichment 1 (w/o)	4.940	5.177	6.145
Number of Feeds Enr2	32	48	-
Enrichment 2 (w/o)	5.340	5.717	-
8" Annular Blanket Enrichment (w/o)	3.200	3.200	3.200
Feed Region Average Enrichment, Including Blankets (w/o)	4.936	5.336	5.891
Number of IFBA	7744	7104	7248
Maximum HFP Boron Concentration (ppm)	1587	1718	1704
Maximum HZP Boron Concentration (ppm)	2157	2316	2336
Maximum HZP MTC (pcm/°F)	+3.7	+3.6	+2.2
Maximum $F_{\Delta H}$	1.57	1.54	1.57
Maximum $F_Q(z)$	2.08	2.05	2.04
Center Assembly Lead Rod Burnup (MWD/MTU)	76395	73455	83837
Other Assembly Lead Rod Burnup (MWD/MTU)	65758	78756	82267
Batch Average Discharge Burnup (MWD/MTU)	56544	62827	70349

Table 3-6
18 Month Cycle PWR Fuel Requirements and Core Characteristics With RFA Fuel

	80 Feed	**72 Feed**	**64 Feed**
Fuel Type	RFA	RFA	RFA
Cycle Length (EFPD)	521.6	521.6	521.7
Number of Feeds Enr1	48	24	64
Enrichment 1 (w/o)	4.580	4.800	5.665
Number of Feeds Enr2	32	48	-
Enrichment 2 (w/o)	4.950	5.315	-
8" Annular Blanket Enrichment (w/o)	3.200	3.200	3.200
Feed Region Average Enrichment, Including Blankets (w/o)	4.593	4.972	5.447
Number of IFBA	7744	7104	5504
Maximum HFP Boron Concentration (ppm)	1543	1696	1900
Maximum HZP Boron Concentration (ppm)	2207	2396	2629
Maximum HZP MTC (pcm/°F)	-0.1	-0.1	+0.9
Maximum $F_{\Delta H}$	1.53	1.55	1.57
Maximum $F_Q(z)$	1.99	2.02	2.09
Center Assembly Lead Rod Burnup (MWD/MTU)	68689	68339	76896
Other Assembly Lead Rod Burnup (MWD/MTU)	60994	73078	75285
Batch Average Discharge Burnup (MWD/MTU)	51709	57456	64643

3.3.2 Results for 12 and 24 Month Cycles

Explicit neutronic calculations for 12 and 24 month cycles were beyond the scope of this study. However, the 18 month cycle results provide guidance on extrapolating the previous 12 and 24 month cycle results from the Phase I study to higher burnups. Expected 12 month cycle behavior is provided in Table 3-7. The 48 feed Phase I case is repeated while 44 and 40 feed cases are added. The 24 month cycle behavior is summarized in Table 3-8. The 132 feed Phase I case is repeated while 112 and 96 feed cases are added.

Table 3-7
Expected 12 Month Cycle PWR Fuel Requirements With Performance+ Fuel

	48 Feed	**44 Feed**	**40 Feed**
Fuel Type	Performance+	Performance+	Performance+
Cycle Length (EFPD)	342.7	342.7	342.7
Number of Feeds Enr1	48	44	40
Feed Region Average Enrichment, Including Blankets (w/o)	4.834	5.201	5.630
Batch Average Discharge Burnup (MWD/MTU)	61917	67546	74300

Table 3-8
Expected 24 Month Cycle PWR Fuel Requirements With Performance+ Fuel

	132 Feed	**112 Feed**	**96 Feed**
Fuel Type	Performance+	Performance+	Performance+
Cycle Length (EFPD)	700.2	700.2	700.2
Number of Feeds Enr1	132	112	96
Feed Region Average Enrichment, Including Blankets (w/o)	4.925	5.440	6.000
Batch Average Discharge Burnup (MWD/MTU)	46001	54215	63251

3.4 PWR Fuel Design Considerations

While increasing enrichments above 5.0 w/o appear attractive for the PWR designs, other barriers such as modification and licensing of fabrication facilities, transportation, and storage of high burnup, high enrichment assemblies may make implementation difficult. Design modifications to current fuel may allow for increased uranium loadings. This may provide benefits similar to increased burnup by reducing the number of fresh assemblies required. Increased fuel density and the use of solid rather than annular blankets for non-IFBA rods allow for increased uranium loading in an assembly.

The UO_2 density assumed in the Phase I and 2 studies was 95.5% of the theoretical UO_2 density. An additional 1% increase in uranium loading could be accomplished by increasing the density to 96.5%. Fuel rods containing increased density pellets are currently being irradiated to demonstrate acceptable fuel performance. Further increases in density may be possible although concerns over fuel pellet swelling with burnup may limit the increase.

Additional increases in uranium loading are possible by replacing the annular blanket pellets in non-IFBA rods with solid blanket pellets. The annular pellets are used to provide additional internal volume for fission gases and helium generated by depletion of the B^{10} in the IFBA rods. Annular pellets are required for the IFBA rods to obtain acceptable fuel rod internal pressure. The annular pellets may not be needed in the non-IFBA rods, however. Replacement of the annular blankets with solid blankets would increase the assembly uranium loading by about 1.7% for the RFA cases in this study and about 1.8% for the Performance+ cases.

Combining increased fuel pellet density with the replacement of annular blankets by solid blanket pellets can result in increased assembly uranium loading by 2.7-2.8%. While this is not quite sufficient to reduce the feed region by 4 assemblies, it can provide some of the benefits of associated with increased burnup while reducing the need to consider enrichments above 5.0 w/o.

Alternatively the fuel rod diameter could be increased above the 0.374" OD considered for RFA fuel. Previous studies indicate that fuel costs begin to increase for fuel rod diameters above 0.374" however because of the reduced H/U ratio. Without enough moderator in the lattice, fuel efficiency is decreased. Larger diameter rods may reduce the need to increase enrichments above 5.0 w/o, however the reduced fuel efficiency from the dry lattice will offset any benefits from the increased assembly uranium loading.

3.5 Considerations for High Enrichments and High Burnup

The current licensing limit for maximum fuel rod burnup for U. S. commercial reactors is 62000 MWD/MTU. Increasing burnups beyond this range may require further fuel assembly design modifications to accommodate the increased fuel rod duty associated with higher duty and increased residence times. Fuel rod internal pressure and cladding corrosion will increase with higher burnups. Possible design alternatives to reduce rod internal gas pressures could include increased plenum lengths or advanced fuel pellet designs, which reduce the release of fission gases from the fuel pellet. Advanced cladding materials are expected to be required to achieve rod burnups in the 65000 to 75000 MWD/MTU range.

The plant safety analysis basis would also have to be reviewed for continued applicability considering high enrichments greater than 5.0 w/o and high burnups in excess of 62000 MWD/MTU rod burnups. While the PWR fuel management analysis has demonstrated that key parameters such as boron concentrations, peaking factors, and reactivity coefficients can meet current limits, other assumptions used in the safety analysis tied to enrichment or burnup limits may require further consideration.

4
ECONOMICS EVALUATIONS

4.1 Introduction

In this section batch fuel costs are computed for the different BWR and PWR cases described in Sections 2 and 3. These cost calculations cover a broad range of the economic variables involved in the manufacture, irradiation, and disposal of nuclear fuel. The trends as a function of burnup are shown as well as the sensitivity to various economic variables.

4.2 Economics Model

The fuel cycle economic evaluation is performed by comparing the sum of the net present value of all the fuel cost components and calculating levelized fuel cost per unit energy production for each equilibrium loading case. The cost components are present valued to the start of irradiation time. Energy production time is assumed to occur at the midpoint of the cycle for calculation of levelized fuel cost. The discounted costs are presented in terms of 2001 dollars, while the levelized cost is defined as the fuel cost per unit of electricity sent out by reactor. Levelized fuel cost depends on both the energy production term by the reactor and the fuel cycle cost discounted to the midpoint time of the cycle. See Appendix A for a description of the economics model used for this evaluation. This method is consistent with utility practices for comparing alternative loading options. It considers various component costs including uranium, conversion, enrichment, fabrication and spent fuel storage, and discounting, and escalation methods. For each fuel loading case examined (as a function of cycle length, discharge burnup, and fuel type) discounted and levelized fuel costs are assessed and presented for a range of component prices (low, mid, high market price projections). Fuel cycle data that remains constant for all cases is listed in Table 4-1.

Table 4-1
Fuel Cycle Data

Monetary base time year	2001
Lead time of uranium purchase	10 weeks
Lead time for conversion	8 weeks
Lead time for enrichment	4 weeks
Lead time for fabrication	2 weeks
Lag time for spent fuel storage	0 days
Loss factor for conversion	0.5 %
Loss factor for fabrication	0.0 %
Tail Assays ratio	0.3 w/o

4.3 Economics Variables for Nuclear Fuel Cost Calculations

The overall cost to a company for any capital expenditure is a combination of many price and rate components. For nuclear fuel, these include the following:

Basic Nuclear Fuel Cost Components
Natural Uranium Feed Material
Uranium Conversion Services
Uranium Enrichment Services
Fuel Assembly Fabrication Services
Fuel Disposal / Storage Fees
Working Capital Costs (carrying charges)

Each of these components is subject to escalation with time. Since this study compares equilibrium fuel cycles all starting at the same time, pre-irradiation fuel cost components also occur at the same time. Therefore, escalation of these components is not meaningful for this evaluation. However, a sensitivity analysis is performed on these components. As the fuel discharge date varies for the different cycle lengths, escalation is assumed for the spent fuel disposal/storage fees. The DOE charge for spent fuel disposal is not included in this evaluation, as it is fixed per kw-hr and thus is not affected by the fuel loading option used.

In addition to the above costs, the following regulatory allowances, accounting techniques, taxes, and financing arrangements can affect nuclear fuel cost:

Other Possible Contributors to Nuclear Fuel Costs
Allowance for Funds Used During Construction (AFUDC)
Accelerated Depreciation
Investment Tax Credits
Property Taxes
Leasing Fuel versus Ownership
Insurance Costs

To avoid unnecessary computational complexity in this study, it is reasonable to focus only on the Basic Nuclear Fuel Cost Components listed above. The remaining “Other” fuel costs can be treated effectively by adjusting the working capital rate or “discount rate”, as it will be done for one of the cases considered in Sections 4.5 and 4.6.

4.4 Scope of Economics Evaluations

The economic evaluations include the following:

- Discounted and levelized batch nuclear fuel costs are calculated for each of the equilibrium cases described in Sections 2 and 3.
- Fuel cost calculations are carried out for a range of component prices as shown in Table 4-2 and a range of escalation for spent fuel storage and discount rates as shown in Table 4-3.
- Fifteen different economic cases were studied to understand the sensitivity of each parameter on fuel cycle cost. The cases include the following :

  1. Nominal Case (Reference case)
  2. High Uranium price
  3. Low Uranium price
  4. High Conversion Cost
  5. Low Conversion Cost
  6. High Enrichment Cost
  7. Low Enrichment Cost
  8. High Fabrication Cost
  9. Low Fabrication Cost
  10. High Storage Cost
  11. Low Storage Cost
  12. High Escalation Rate
  13. Low Escalation Rate
  14. High Discount Rate
  15. Low Discount Rate

Table 4-2
Unit Prices for Each Component

Component	Low	Nominal	High
Uranium ($/kg U)	18.30	31.35	47.00
Conversion ($/kg U)	3.50	5.00	7.00
Enrichment ($/SWU)	80	105	130
Fabrication ($/kg U) BWR	255	275	350
Fabrication ($/kg U) PWR	185	210	275
Spent fuel storage ($/Assembly) BWR	0	20,000	40,000
Spent fuel storage ($/Assembly) PWR	0	50,000	100,000

Table 4-3
Economic Parameters

Parameter	Low	Nominal	High
Escalation rate for spent fuel storage (% per year)	2	3	5
Discount Rate (% per year)	7	9.5	12

4.5 Optimum Discharge Burnup BWRs – Equilibrium Cycle Economics

Discounted costs are presented in terms of 2001 dollars, while the levelized costs are defined as the fuel cost per unit of electricity sent out by the reactor. Discounted and levelized batch costs as a function of burnup for a 24 month cycle in a large BWR are considered. The BWR case is addressed in Section 2 by considering the impact on a 24 month equilibrium cycle composed of BWR 10x10 fuel in a large 764 assembly BWR. The fuel used in this study is the Westinghouse 10x10 SVEA-96 Optima2 design.

Two cases are considered in Section 2 which define a range in the relative benefit associated with extending the maximum enrichment to 6 w/o. The “Optimized for Extended Enrichment” option assumes that losses in shutdown margin and thermal margin associated with the 1 w/o U-235 enrichment increase can be completely accommodated by design improvements to the assembly mechanical design and is considered the most likely scenario. The “Current Bundle Optimization” option is pessimistic since it assumes that no changes to the assembly mechanical design are made to re-optimize the assembly for the higher enrichments. This case represents a minimum benefit associated with an increase in enrichment above 5 w/o. The batch average discharge burnups as a function of enrichment given in Table 2-3 represent the neutronic results input to the fuel cycle cost calculations.

Discounted and levelized batch costs as a function of burnup based on the data in Table 2-3 are shown in Figures 4-1, 4-2, 4-3 and 4-4 for nominal fuel cost assumptions. Some conclusions that can be drawn from these figures are:

For the Optimized for Extended Enrichment case (Figures 4-1 and 4-2):

- Fresh fuel savings are more than the increase in uranium, conversion, and enrichment cost components due to a lower required feed material amount. Therefore, fuel cost declines with increased burnup.
- Levelized fuel cost also declines with increased burnup.
- Mechanical design changes for this bundle provide greater batch size savings than the current bundle optimization case. This means that smaller fresh fuel batches are used to reach the cycle energy requirement resulting in lower fuel cost for the case optimized for extended enrichment .
- The 24 month cycle shows about $2.418 million, or 4.31 %, reduction in fuel cost per cycle as the batch average discharge burnup increases from 52400 to 65200 MWD/MTU. The levelized fuel cost shows a decline in cost of 0.2 mills/kWh or 4.73 % over the same burnup range.
- For each 1000 MWD/MTU increase in batch average discharge burnup, the fuel cost declines by $ 0.188 million or 0.36 % for discounted cost, and 0.34 % for the levelized fuel cost.

For the Current Bundle Optimization case (Figures 4-3 and 4-4):

- The 24 month cycle shows about $0.907 million, or 1.62 % reduction in fuel cost per cycle as the batch average discharge burnup increases from 52400 to 58400 MWD/MTU. The levelized fuel cost shows a decline in cost of 0.09 mills/kWh or 2.13 % over the same burnup range.
- For each 1000 MWD/MTU increase in batch average discharge burnup smaller than 58400 MWD/MTU, the fuel cost declines by $ 0.151 million or 0.27 % for discounted cost, and 0.35 % for the levelized fuel cost.
- The fuel cost shows about $ 0.208 million, or 0.38 %, increase per cycle as the batch average discharge burnup increases from 58400 to 63200 MWD/MTU in this case. In this case, the increase in uranium, conversion and enrichment cost components at the high enrichment level outweighs the corresponding energy increase benefit. The Current Bundle Optimization case requires more fresh fuel bundles to satisfy cycle energy requirements than the Optimized for Extended Enrichment case. In this case, the fresh fuel savings is less than the uranium, conversion, enrichment cost components increase due to required feed material and increased SWU for batch average discharge burnups greater than 58400 MWD/MTU. The levelized fuel cost shows a corresponding increase in cost of 0.02 mills/kWh or 0.1 % over the same burnup range.

- It should be noted that the predicted cost increase in this case for the batch discharge burnup of 58400 MWD/MTU also is a consequence of the assumed fuel cycle cost parameters for the nominal case. For example, higher back-end costs with the remaining parameters kept at their nominal case values would result in a continuing decrease in fuel cycle cost for batch burnups in excess of 58400 MWD/MTU.
- For each 1000 MWD/MTU increase in batch average discharge burnups in excess of 58400 MWD/MTU, the fuel cost increase by $ 0.043 million or 0.08 % for discounted cost, and 0.10 % for the levelized fuel cost.

The results of the sensitivity analysis on the cost components are given in Figures 4-5, 4-6, 4-7 and 4-8. Some conclusions from these figures for the large BWR are:

For the Optimized for Extended Enrichment case:

- Savings with burnup extension are shown for all sensitivity cases and range from $3.209 million per cycle for the high storage cost case to $1.628 million per cycle for the low storage cost case.
- The levelized fuel cost shows a decrease in cost of 0.25 mills/kWh over the same burnup range per cycle for the high storage cost case and 0.14 mills/kWh per cycle for the low storage cost case.

For the Current Bundle Optimization Case:

- Savings with batch average discharge burnups increasing from 52400 to 63200 MWD/MTU range from $1.383 million per cycle for the high storage cost case to $0.013 million per cycle for the low storage cost case.
- Savings with batch average discharge burnups increasing from 52400 to 58400 MWD/MTU range from $1.311 million per cycle for the high storage cost case to $0.503 million per cycle for the low storage cost case.
- Fuel cost changes with batch average discharge burnups increasing from 58400 to 63200 MWD/MTU range from $0.073 million savings per cycle for the high storage cost case to $0.489 million increase per cycle for the low storage cost case.
- The fuel cost shows about $ 1.118 million savings per cycle as the batch average discharge burnup increases from 52400 to 63200 MWD/MTU for the low enrichment cost case.
- Fuel cost shows about $ 0.928 million savings per cycle as the batch average discharge burnup increases from 52400 to 58400 MWD/MTU for the high uranium cost case. Due to increases in uranium, conversion and enrichment cost components at the high enrichment level, fuel costs show about $ 0.300 million increase per cycle as the batch average discharge burnup increases from 58400 to 63200 MWD/MTU
- Levelized fuel cost shows about 0.09 mills/kWh savings per cycle as the batch average discharge burnup increases from 52400 to 58400 MWD/MTU for the high uranium cost case. Due to increases in uranium, conversion and enrichment cost components at the high enrichment level, fuel cost shows about 0.03 mills/kWh increase per cycle as the batch average discharge burnup increases from 58400 to 63200 MWD/MTU

- Because, levelized fuel cost summarized in Appendix A, depends on both the energy production term by the reactor and the discounted fuel cycle cost to midpoint time of the cycle, it is more sensitive to the changes in discount rate. Front-end fuel cycle costs increase with increasing discount rate while back-end fuel cycle costs decrease with increasing discount rate. This is because front-end payments are made before electricity production, while back-end payments are made after electricity production. From Figures 4-6 and 4-8, it can be seen that high uranium cost, high enrichment cost, and high discount rate case have larger levelized fuel costs than the other cases for the 24 month cycle.

The current NRC-approved maximum peak rod burnup is 62000 MWD/MTU and the industry-planned extension for BWRs is 70000 MWD/MTU.

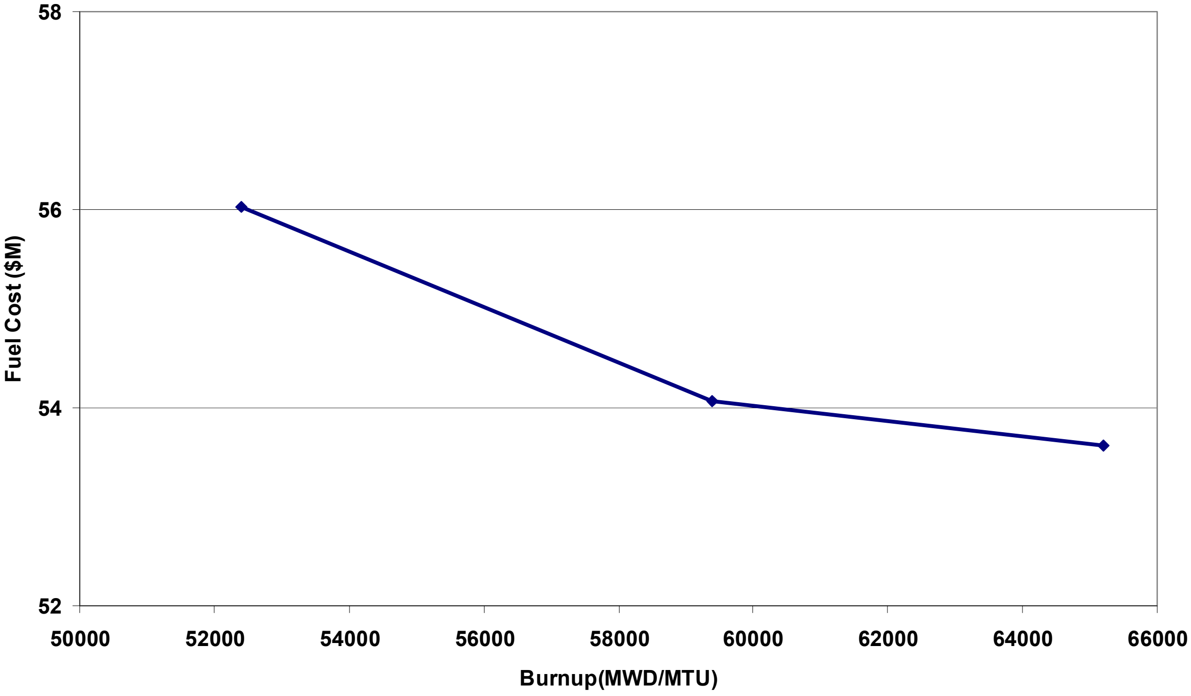


Figure 4-1
Fuel cost for 24 month cycle with Westinghouse SVEA-96 Optima2 optimized for extended enrichment fuel design

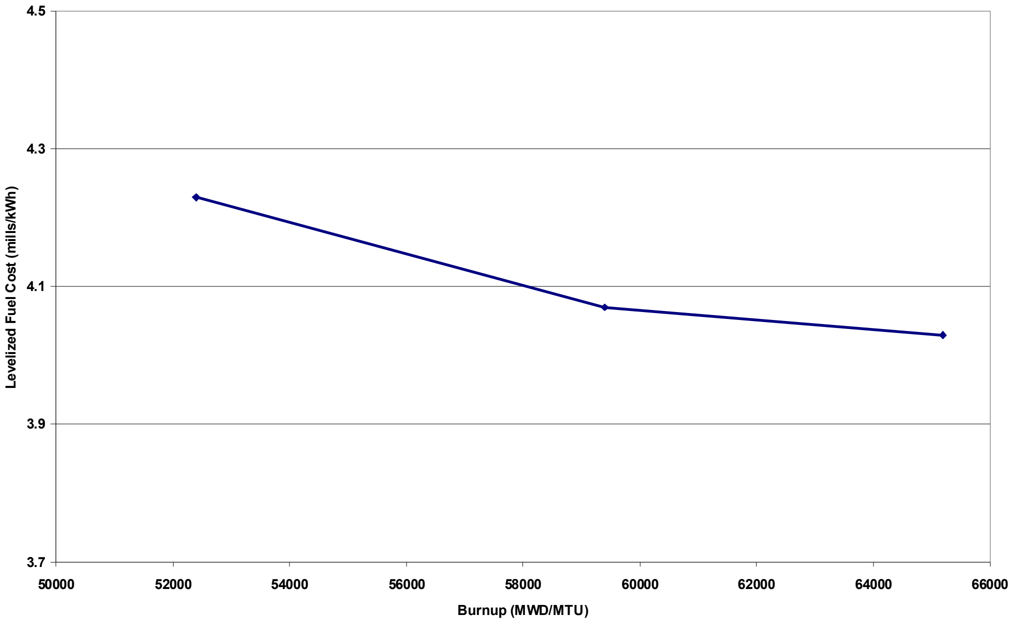


Figure 4-2
Levelized fuel cost for 24 month cycle with Westinghouse SVEA-96 Optima2 optimized for extended enrichment fuel design

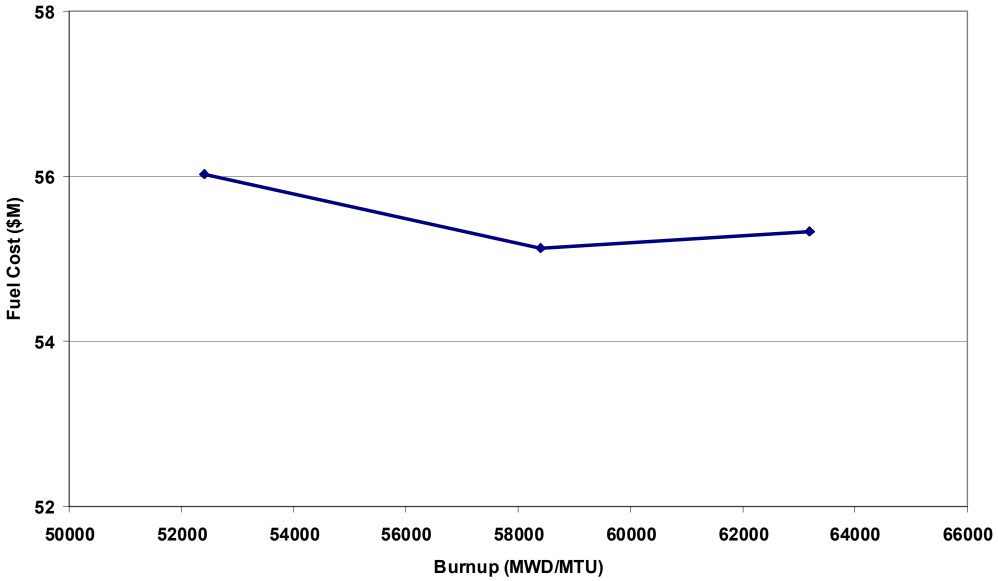


Figure 4-3
Fuel cost for 24 month cycle with Westinghouse SVEA-96 Optima2 current bundle design

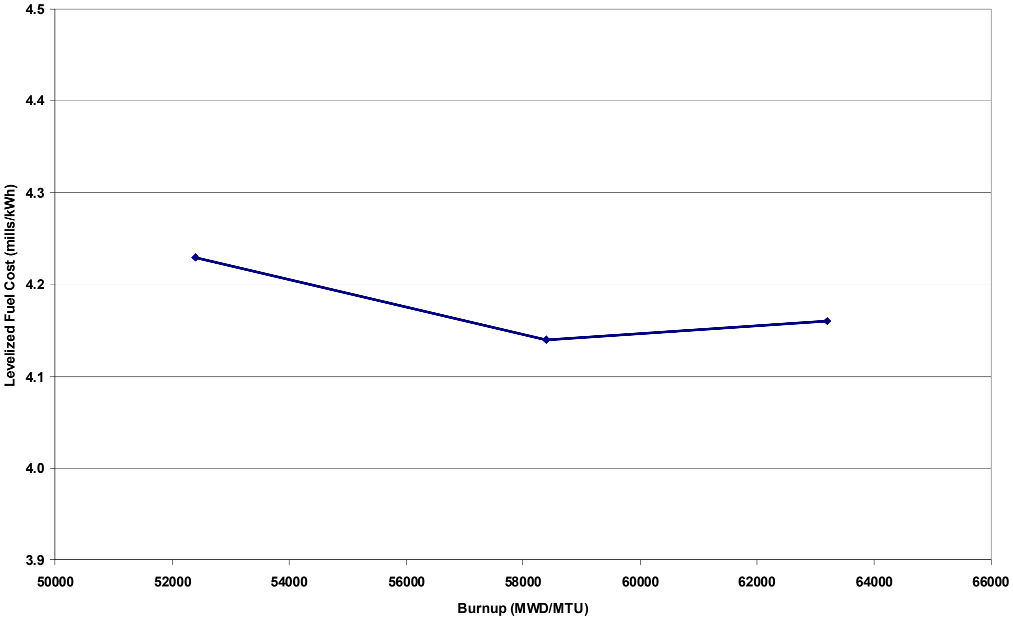


Figure 4-4
Levelized fuel cost for 24 month cycle with Westinghouse SVEA-96 Optima2 current bundle design

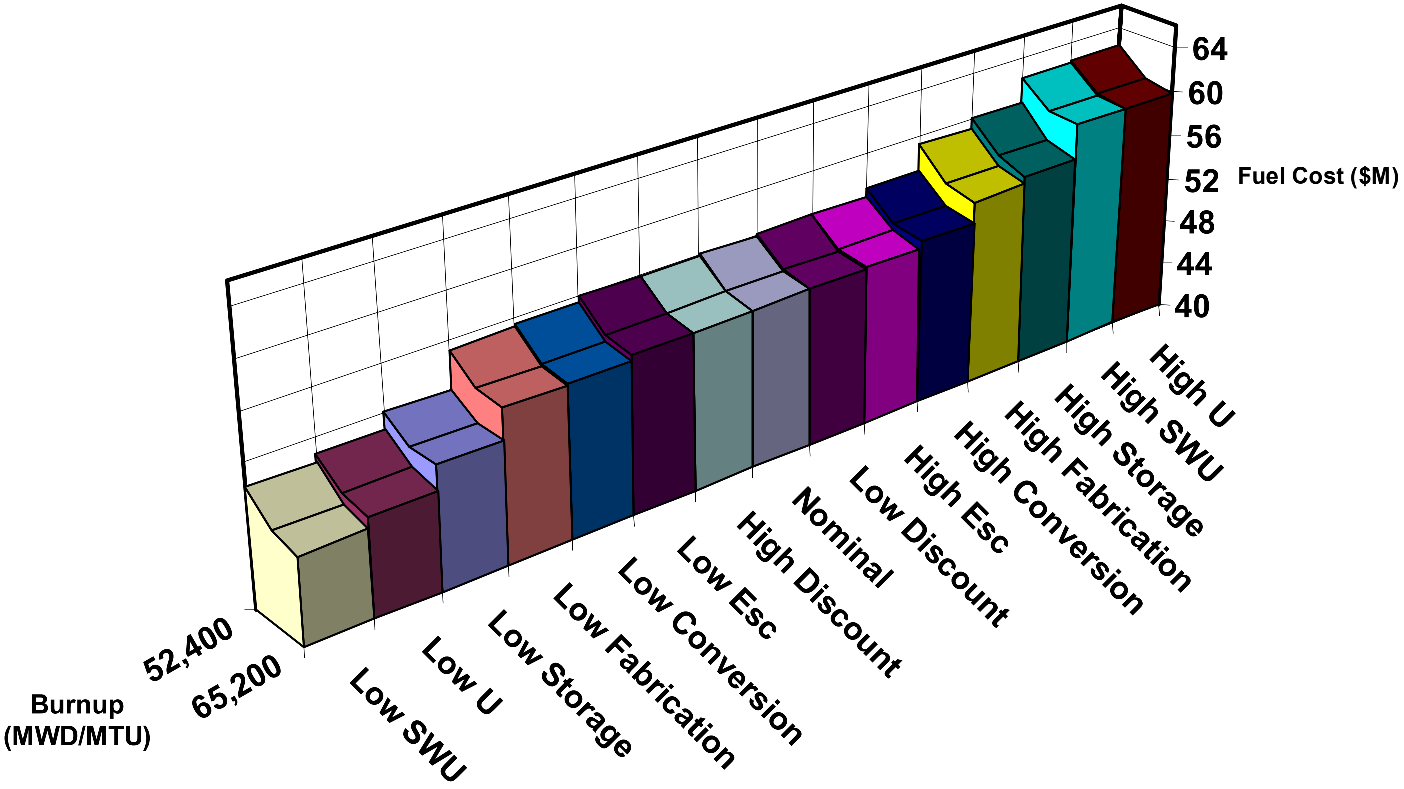


Figure 4-5
Comparison of each fuel cycle parameter effect on fuel cycle cost for BWR Westinghouse SVEA-96 Optima2 optimized for extended enrichment fuel design

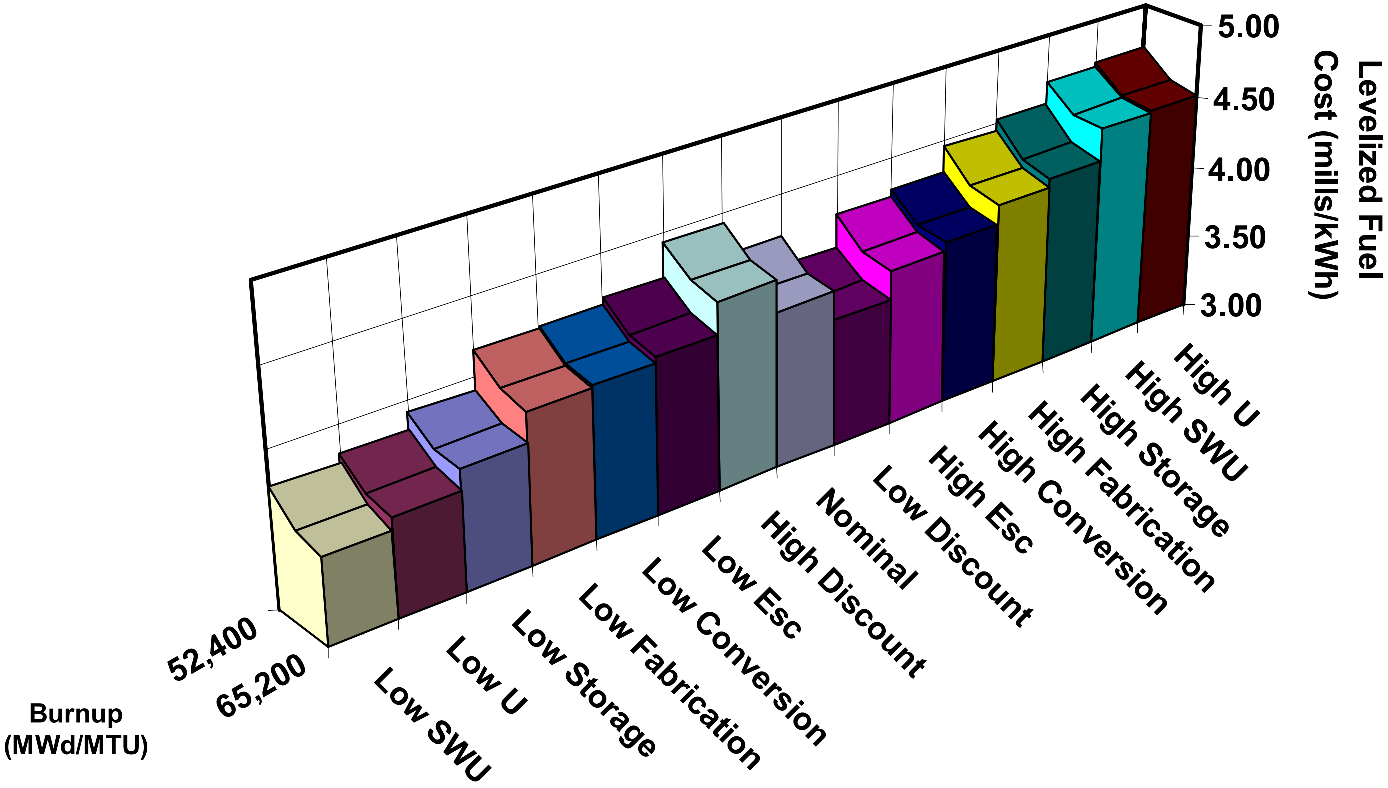


Figure 4-6
Comparison of each fuel cycle parameter effect on levelized fuel cycle cost for BWR Westinghouse SVEA-96 Optima2 optimized fuel for extended enrichment

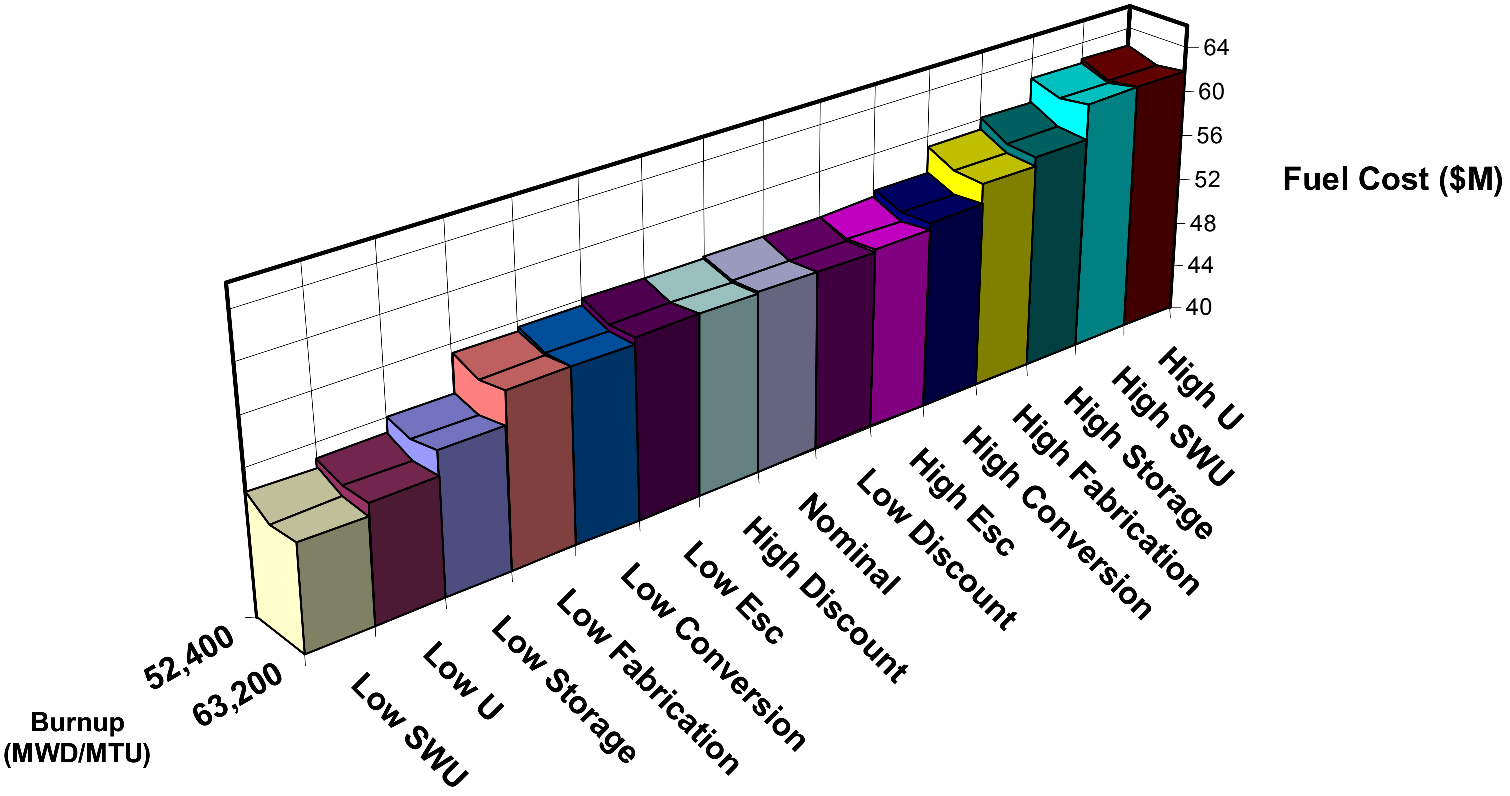


Figure 4-7
Comparison of each fuel cycle parameter effect on fuel cycle cost for BWR Westinghouse SVEA-96 Optima2 current bundle optimization design

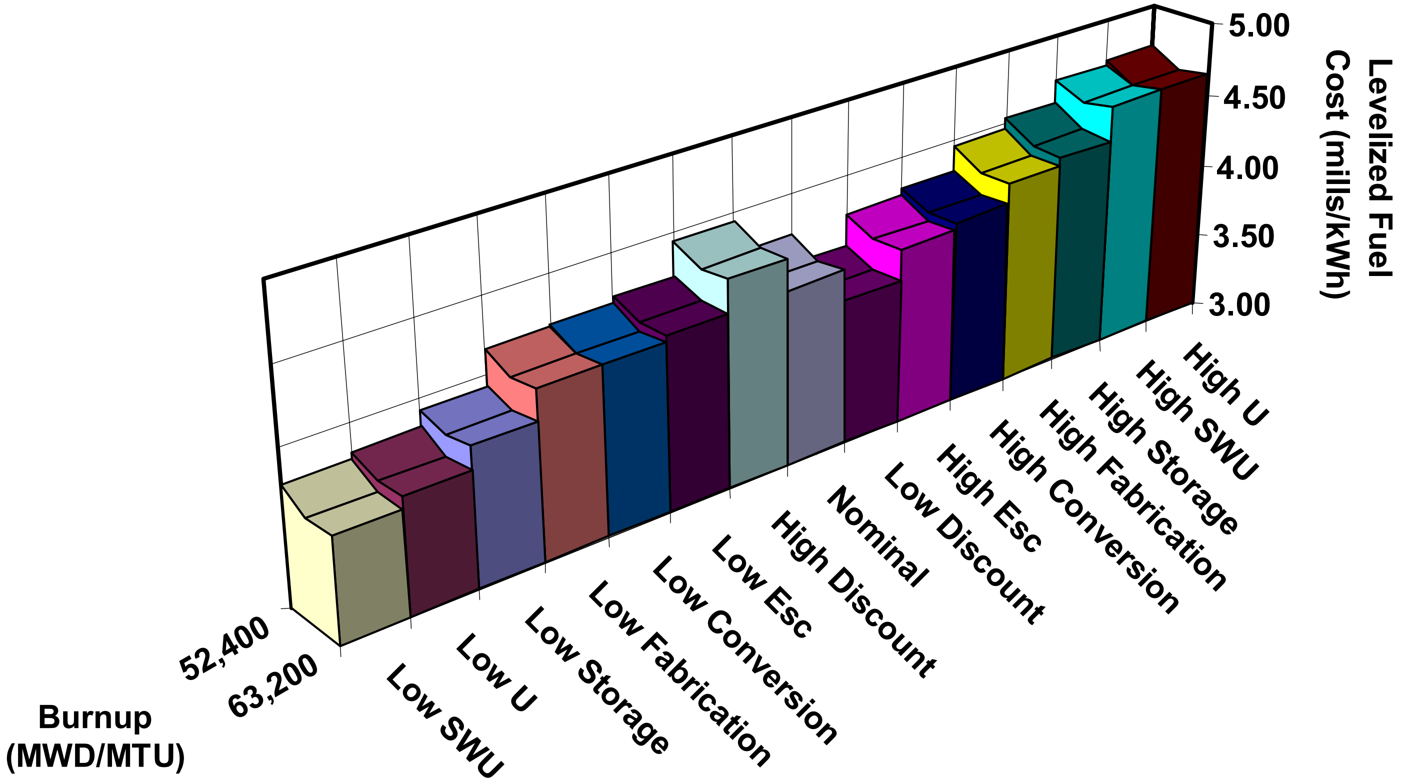


Figure 4-8
Comparison of each fuel cycle parameter effect on levelized fuel cycle cost for BWR Westinghouse SVEA-96 Optima2 current bundle optimization design

4.6 Optimum Discharge Burnup PWRs – Equilibrium Cycle Economics

Discounted and levelized batch costs as a function of burnup for 18 month cycle, with Performance+ and RFA fuel, are shown in Figures 4-9 to 4-12 for nominal fuel cost assumptions.

Some conclusions that can be drawn from these figures are similar to the BWR fuel cases:

- Fuel cost declines with increased burnup for all cases.
- Levelized fuel cost also declines with increased burnup
- Fuel cost savings with increased burnup are very similar between Performance+ and RFA fuel.

The analysis shows for the reference PWRs with the Performance+ fuel for 18 month cycle:

- The fuel cost can be decreased by $ 2.313 million, or 4.69 % when the batch average discharge burnup is increased from 56544 to 70349 MWD/MTU, which is the maximum achievable burnup consistent with the 64 feed case.
- 1000 MWD/MTU increase in batch average discharge burnup would result in a $0.167 million decline in cost (0.34 %) for the 18 months cycle.
- Levelized fuel cost shows a 4.12 % decline in mills/kWh for this burnup range and 0.30 % decline per 1000 MWD/MTU batch average burnup increase in Figure 4-10.

  For the reference PWR with the Robust Fuel;

- The fuel cost can be decreased by $ 2.902 million, or 5.79 % when the batch average discharge burnup is increased from 51710 to 64643 MWD/MTU, which is the maximum achievable burnup consistent with the 64 feed case for this fuel.
- 1000 MWD/MTU increase in batch average discharge burnup would result in a $0.224 million decline in cost (0.45 %) for the 18 months cycle
- Levelized fuel cost shows a 5.82 % decline in mills/kWh for this burnup range and 0.45 % decline per 1000 MWD/MTU batch average burnup increase in Figure 4-12.

The current NRC- approved maximum peak rod burnup is 62000 MWD/MTU and the industry-planned extension for PWRs is 75000 MWD/MTU.

The results of the sensitivity analysis on the cost components are given in Figures 4-13 through 4-16. The are very similar to the BWR results:

- For the reference PWRs with the Performance+ fuel, savings with burnup extension are shown for all sensitivity cases and range from $ 1.487 million per cycle for the low storage cost case to $ 3.040 million per cycle for the high storage cost case.
- For the reference PWRs with the Robust Fuel, savings with burnup extension are shown for all sensitivity cases and range from $ 2.175 million per cycle for the low storage cost case to $ 3.628 million per cycle for the high storage cost case.

- From Figure 4-14 and 4-16, it can be seen that high uranium cost, high enrichment cost, and high discount rate case have larger levelized fuel costs than the other cases, which is similar to BWR results.

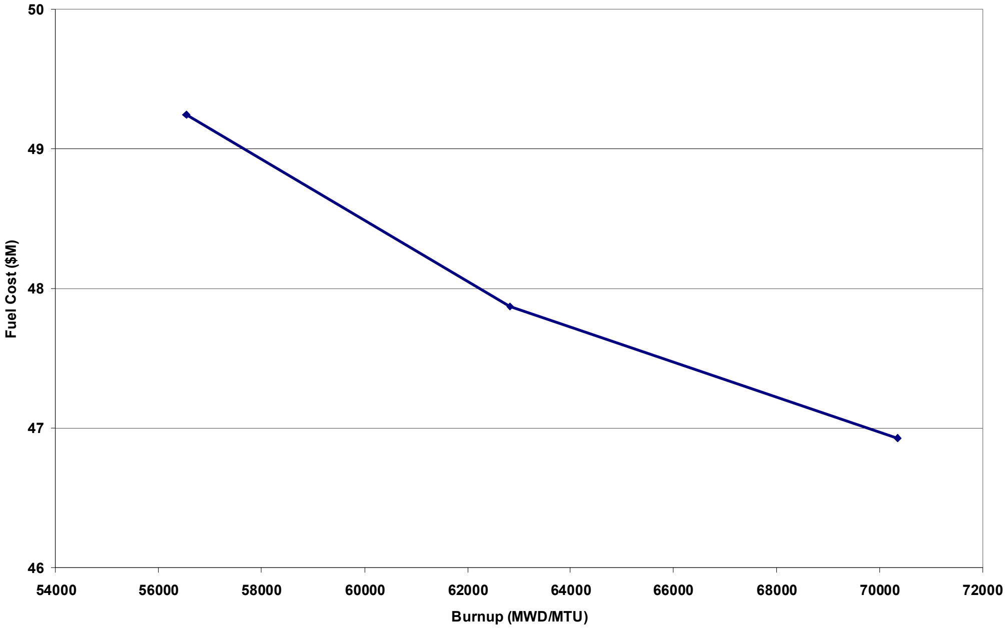


Figure 4-9
Fuel cost for 18 month cycle with Performance+ fuel

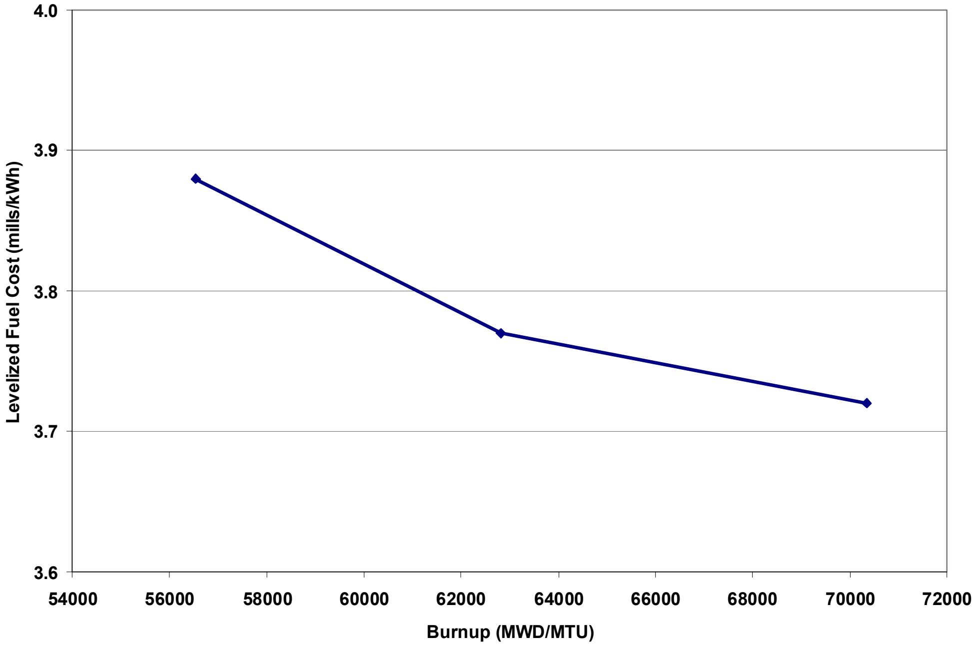


Figure 4-10
Levelized fuel cost for 18 month cycle with Performance+ fuel

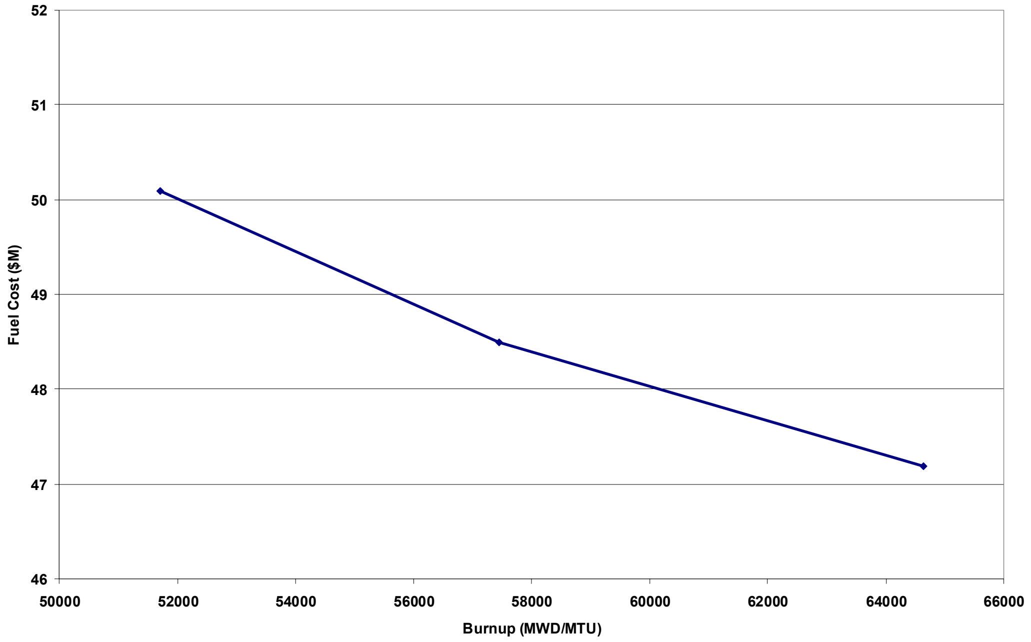


Figure 4-11
Fuel cost for 18 month cycle with RFA fuel

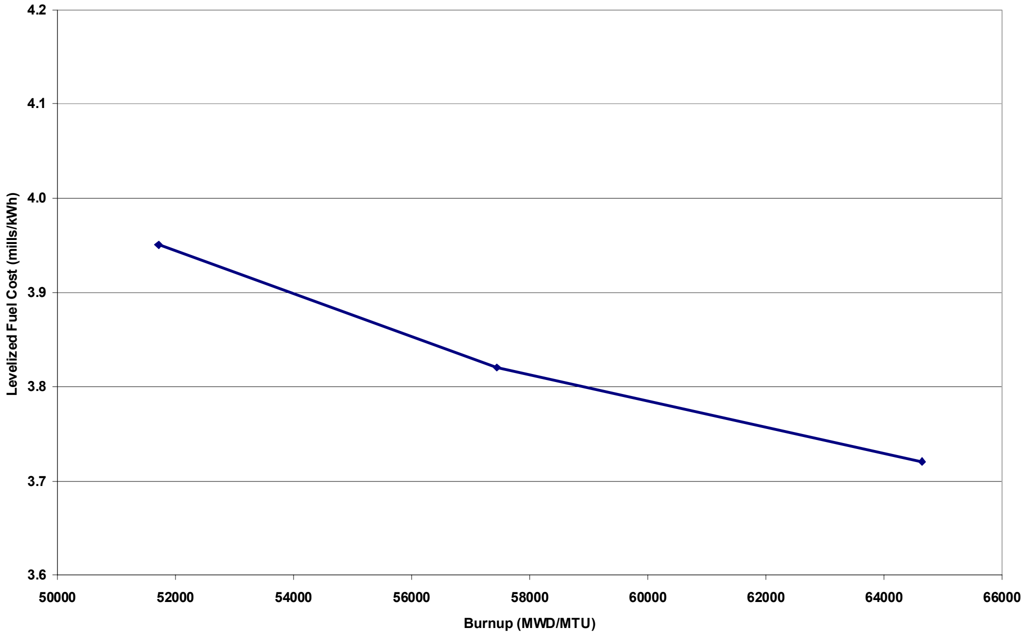


Figure 4-12
Levelized fuel cost for 18 month cycle with RFA fuel

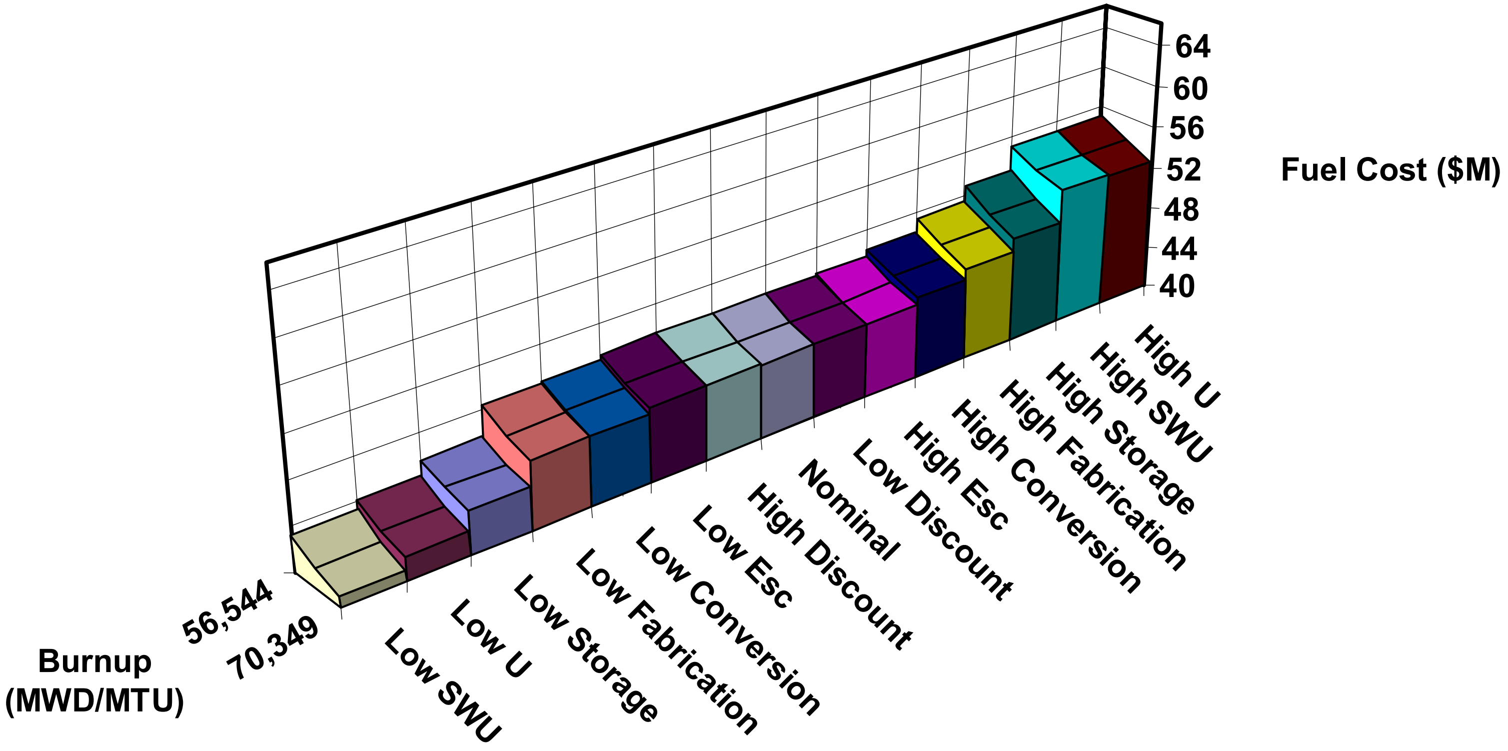


Figure 4-13
Comparison of each fuel cycle parameter effect on fuel cycle cost for PWR Performance+ fuel with 18 month cycle

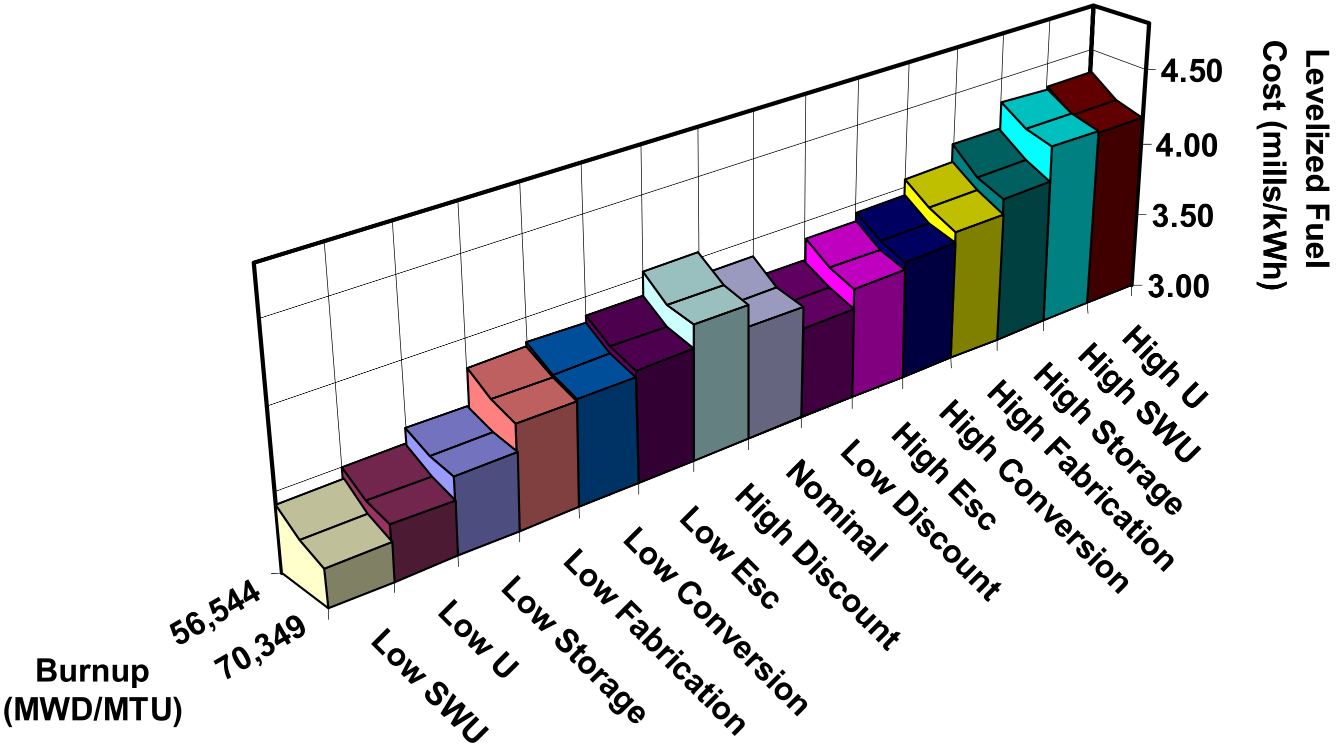


Figure 4-14
Comparison of each fuel cycle parameter effect on levelized fuel cycle cost for PWR Performance+ fuel with 18 month cycle

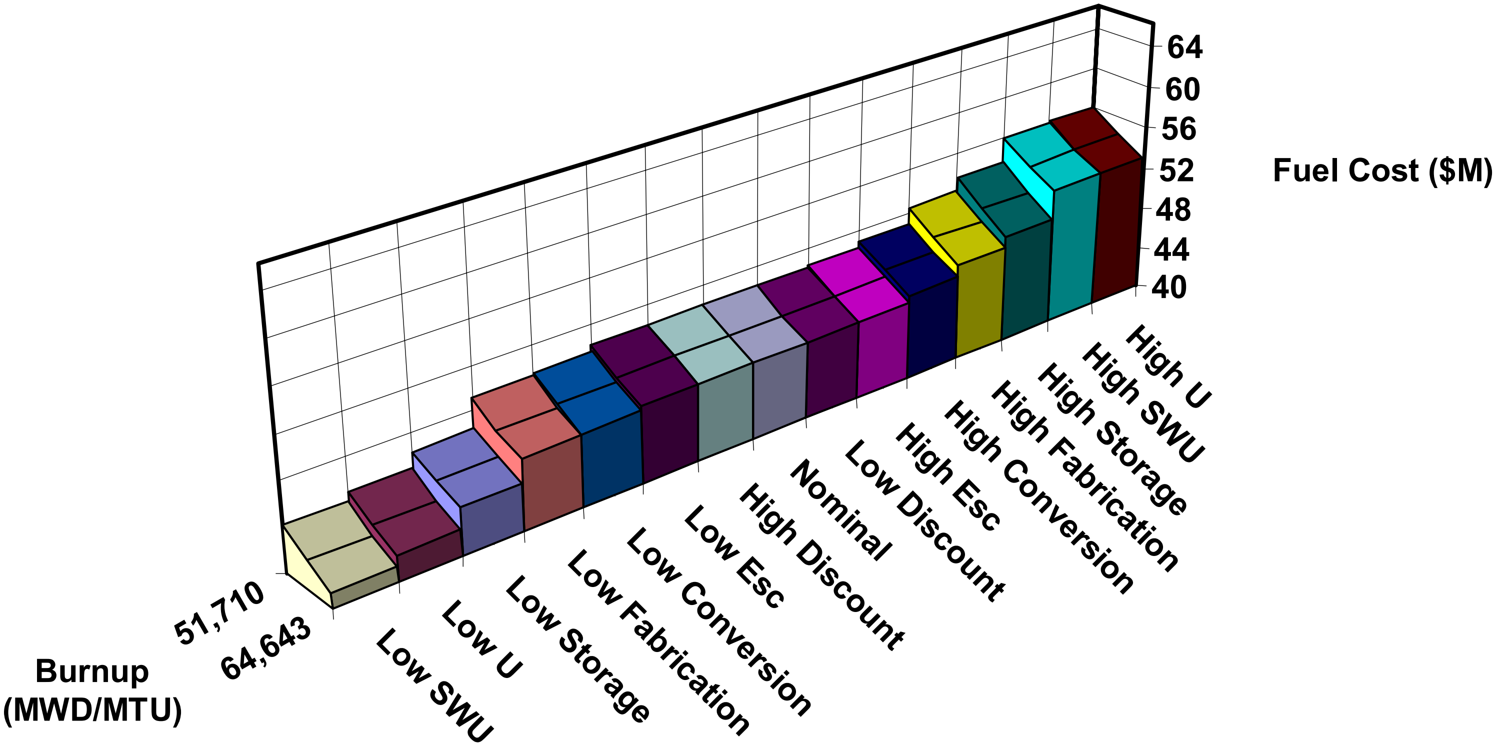


Figure 4-15
Comparison of each fuel cycle parameter effect on fuel cycle cost for PWR RFA fuel with 18 month cycle

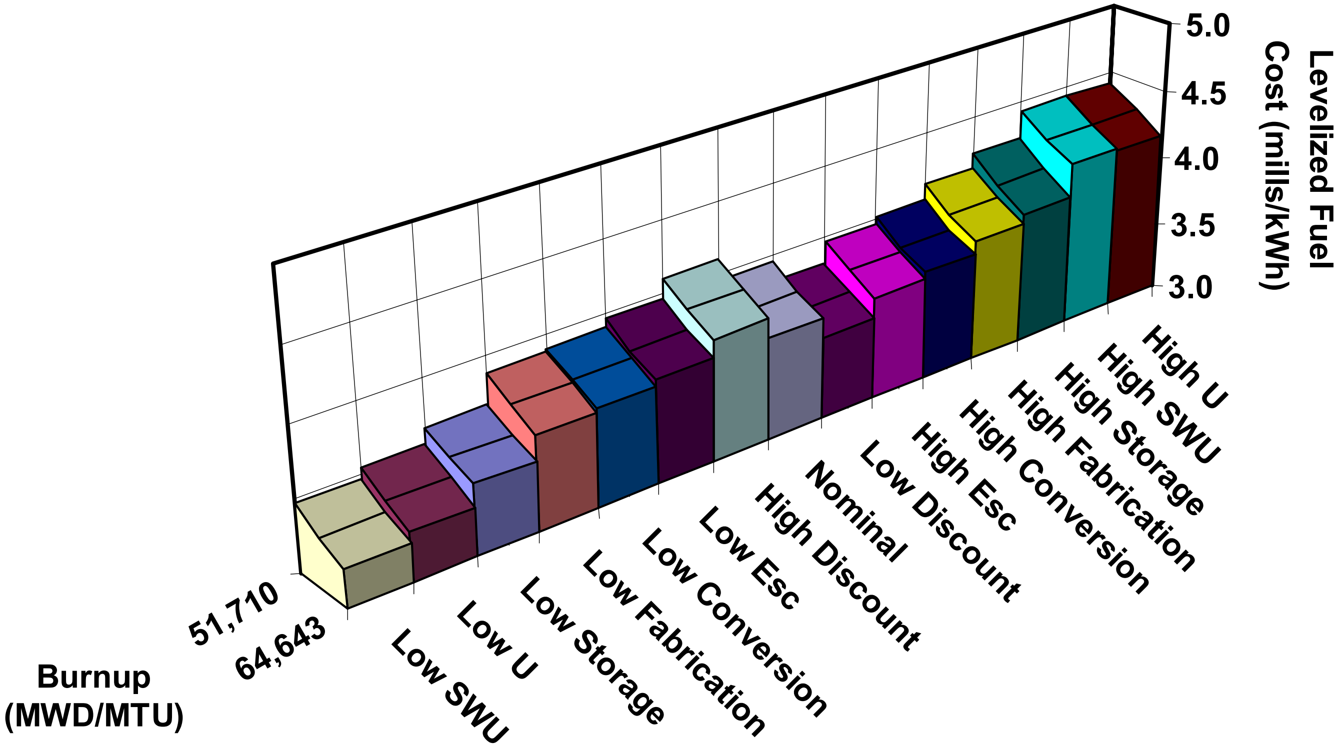


Figure 4-16
Comparison of each fuel cycle parameter effect on levelized fuel cycle cost for PWR RFA fuel with 18 month cycle

4.7 Non-Equilibrium Batch Loading – New Fuel Designs

Much of the benefit of increasing the fuel burnup limit is not captured by an equilibrium fuel cycle evaluation as has been performed for this study. Equilibrium fuel cycles are a strategy that the industry strives for but rarely achieves. Most utilities have found that setting the refueling outage date and keeping achievable power at full rated capacity has been more economical than keeping fuel cost low through the attainment of equilibrium fuel cycles. As a result, non-equilibrium fuel cycles have been the norm. As happens with non-equilibrium fuel cycles, the spread between the maximum rod burnup and the batch average burnup is greater than that obtained from equilibrium fuel cycles. A few examples might illustrate the economic benefit of increased burnup limits not captured by this equilibrium evaluation:

A planned cycle with end of cycle burnups near the current limit achieves a higher than planned cycle capacity factor or the shutdown date is moved out to accommodate some scheduling conflict. A power coastdown results with the potential to exceed the current burnup limit.

A fuel failure occurs near the end of a fuel cycle. While it is identified during the refueling outage, it must be discharged along with its 3 symmetrical fuel assemblies. Additional new fuel assemblies are not available and previously discharged assemblies are available but would exceed current fuel burnup limits in the projected follow-on cycle.

This evaluation was performed for commercially available fuel designs. As fuel vendors are always looking for improved fuel designs, it is expected, with higher fuel burnup limits that improved fuel designs may be developed that take advantage of these higher limits.

5

MECHANICAL, OPERATIONAL, AND REGULATORY CHALLENGES TO INCREASING ENRICHMENT AND BURNUP

5.1 Introduction

The economic analysis presented in Section 4 of this report shows BWR and PWR fuel costs continuing to decline as the batch discharge burnup increases. The designs presented results in rod burnups well in excess of the current regulatory limit of 62000 MWD/MTU. Operating fuel to this high burnup presents challenges to the mechanical integrity of the fuel. Problems associated with operating fuel to high burnups can also affect the operability of the plant. In addition, achieving high burnup can present a variety of regulatory challenges. These challenges include:

- Cladding corrosion associated with high duty and long residence times
- Ensuring mechanical stability of the assembly at high burnup to avoid excessive bowing and incomplete control rod insertion
- Crud deposition and crud related enhanced corrosion or fuel rod failures
- Crud induced axial power shift (Axial Offset Anomaly)
- Maintaining margins to safety analysis limits
- Licensing fuel to burnups in excess of 62000 MWD/MTU
- Modifying and licensing fuel fabrication facilities to produce fuel in enriched in excess of 5.0 w/o
- Transportation and storage of high enrichment, high burnup fuel

EPRI's Robust Fuel Programs, as well as various industry programs, are actively addressing these challenges. These programs are progressing with the goal of achieving the licensing of fuel rod burnups up to 75000 MWD/MTU in the next several years.

5.2 Uranium Enrichments Above 5 w/o U^{235}

Several barriers exist to implementing LWR fuel enriched to greater than 5.0 w/o to achieve high burnup. Increasing enrichments beyond 5.0 w/o may require changes to manufacturing, transportation, licensing, and fuel storage. The costs associated with these upgrades will reduce the benefit of increasing burnups.

5.2.1 Fuel Manufacturing

A major consideration is the need to modify existing manufacturing facilities or build new facilities to produce high enrichment fuel. When current fuel manufacturing plants were built, most plants operated on annual cycles with discharge burnups in the low to mid 30000 MWD/MTU range. First core and reload fuel enrichments were in the 3.0 to 3.5 w/o range. Most of these facilities have been upgraded to allow for manufacturing fuel up to 5.0 w/o by taking advantage of margins available in the criticality area and imposing additional controls to prevent criticality. Little or no margin remains to accommodate further increases in enrichment. This implies that significant physical changes in the manufacturing plants will be required to meet criticality safeguard requirements for fuel enriched in excess of 5.0 w/o.

As part of a NERI program examining advanced LWR fuels, detailed studies were undertaken to determine the need for facility modifications as well as the associated costs to provide production capability for UO_2 fuel enriched in excess of 5.0 w/o [5]. The results of those studies indicated that extensive changes to current facilities would be required in the wet conversion and scrap recovery areas. Those changes would include reducing the diameter of the piping used in these areas. More modest changes would be required in the powder and pelleting areas. The main changes required in those areas would be to reduce the size of the bulk powder containers. The modifications required to allow a current manufacturing facility to produce fuel enriched in excess of 5.0 w/o are roughly estimated to cost about $55-$75 million.

5.2.2 Fuel Transportation

Current new fuel shipping containers are licensed to accept fuel enriched up to 5.0 w/o. Container design modification and re-licensing would be required to ship fuel in excess of 5.0 w/o. Replacement of all current shipping containers at a manufacturing facility with designs modified to accommodate enrichments in excess of 5.0 w/o is estimated to cost up to $20-$30 million.

5.2.3 Safety Analysis and Licensing

Use of high burnup fuel enriched in excess of 5.0 w/o are not expected to have significant consequences for safety analysis. As indicated in Sections 2 and 3, both BWR and PWR fuel management using fuel enriched to greater than 5.0 w/o are still able to meet the key parameter limits and peaking factor constraints. Consideration must be given to the applicability of items such as decay heat correlations and other parameters that may be sensitive to enrichment or high burnup, but no fundamental problems meeting safety requirements are expected.

5.2.4 Spent fuel storage and disposal

Current spent fuel racks are typically designed and licensed to accept fuel up to 5.0 w/o. In many cases, burnup credit is used to allow for storage of this fuel. Fuel enriched to 5.0 w/o can be stored in the racks currently as long as the fuel burnup exceeds a minimum value that is dependent on the particular rack design. For fuel enriched to greater than 5.0 w/o, the burnup credit concept will still remain applicable. High enriched fuel would be designed to achieve high burnup, and when ultimately discharged should have sufficient burnup to be no more reactive than lower enriched, lower burnup fuel. For this scenario, no changes to the spent fuel rack design would be required. Additional criticality analysis and licensing would be required to extend the range of allowed enrichment/burnup combinations to accommodate fuel in excess of 5.0 w/o.

Some portion of the racks must still allow for the storage of fresh or low burnup fuel during refueling outages or in case an unplanned core offload is required. Fuel of increased initial enrichment typically requires larger center-to-center spacings in the rack to meet criticality requirements, or additional neutron absorber loading in the absorber panels. This may require replacing some portion of the spent fuel storage racks to accommodate a core's worth of fuel. Costs for the replacement are estimated to be several million dollars per plant.

Alternatively, the current racks may remain in use with some reduction in the amount of fuel that can be stored by blocking off various cells. Storage of fuel in 3-of-4 or 2-of 4 cell geometry may be adequate to meet criticality requirements.

The heat loads that must be accommodated in the spent fuel storage pool or dry storage casks may also increase because of the increased burnup. This may require modifications to the spent fuel cooling system or changes to dry storage cask designs.

5.3 Conclusions

While the use of fuel enriched in excess of 5.0 w/o U^{235} to achieve high burnups may be beneficial in reducing fuel costs, various other factors may offset the benefits. The increased duty and residence time associated with high burnup fuel may require fuel design modifications and improved structural materials that will increase manufacturing costs. Significant one-time costs are also associated with modifying fuel manufacturing facilities to allow for production of fuel enriched in excess of 5.0 w/o. New fuel shipping containers must also be designed, manufactured, and licensed also at a significant cost. Taken together, the costs associated with new fuel designs and the increased manufacturing costs may significantly erode the benefits of using fuel with enrichments greater than 5.0 w/o.

6
CONCLUSIONS

The Phase II study extends the range of BWR and PWR batch average discharge burnups considered in the Phase I study by using fuel enriched in excess of 5.0 w/o U^{235}. The BWR fuel management considered 24 month cycles while the PWR fuel management considered 18 month cycles. The BWR studies were performed for a large, 764 assembly core and used Westinghouse SVEA-96 Optima2 fuel. The PWR studies were performed with a 4 loop, 193 assembly Westinghouse NSSS and considered both Performance+ and RFA fuel. The BWR study extended the batch average discharge burnup range to 65000 MWD/MTU by considering maximum enrichments up to 6.0 w/o. The PWR study extended the batch average discharge burnup range to 70000 MWD/MTU for Performance+ fuel with enrichments near 5.9 w/o and to near 65000 MWD/MTU for RFA fuel with enrichments near 5.5 w/o.

For both the BWR and PWR, the fuel costs continued to decline with increasing batch average discharge burnup. For the BWR 24 month cycle, the fuel costs decline by $2.4 million, or 4.3% reduction in fuel cost per cycle as the batch average discharge burnup increases from about 52400 MWD/MTU to about 65200 MWD/MTU. For the PWR 18 month cycle with Performance+ fuel, the fuel costs decline by $2.3 million, or 4.7% reduction in fuel cost per cycle as the batch average discharge burnup increases from about 56500 MWD/MTU to about 70300 MWD/MTU. For the PWR 18 month cycle with RFA fuel, the fuel costs decline by $2.9 million, or 5.8% reduction in fuel cost per cycle as the batch average discharge burnup increases from about 51700 MWD/MTU to about 64600 MWD/MTU.

The Phase II study continues to show fuel costs declining with increasing discharge burnup when the economic model described in Appendix A is used. The results do not identify an optimum discharge burnup. The costs continue to decline as the batch average discharge burnup was increased to the maximum values considered in the study. The economic analysis assumes no change to enrichment, manufacturing, transportation, licensing, or storage/disposal costs when fuel in excess of 5.0 w/o is used.

To achieve the high discharge burnup values, fuel in excess of the current limit of 5.0 w/o U^{235} was considered. There are a variety of barriers that would need to be overcome to use fuel enriched in excess of 5.0 w/o. Significant one-time costs are also associated with modifying fuel manufacturing facilities to allow for production of fuel enriched in excess of 5.0 w/o. New fuel shipping containers must also be designed, manufactured, and licensed at a significant cost. Spent fuel pools and dry storage casks are not currently licensed for fuel with enrichments greater than 5.0 w/o and might require modification or replacement. The increased duty and residence time associated with high burnup fuel may require fuel design modifications and improved structural materials that will increase manufacturing costs. Taken together, the costs associated with new fuel designs and the increased manufacturing costs may significantly erode the benefits of using fuel with enrichments greater than 5.0 w/o.

Fuel costs are summarized in the Figures 6-1 through 6-3 for BWRs and PWRs including the results of Phase I and Phase II of the study.

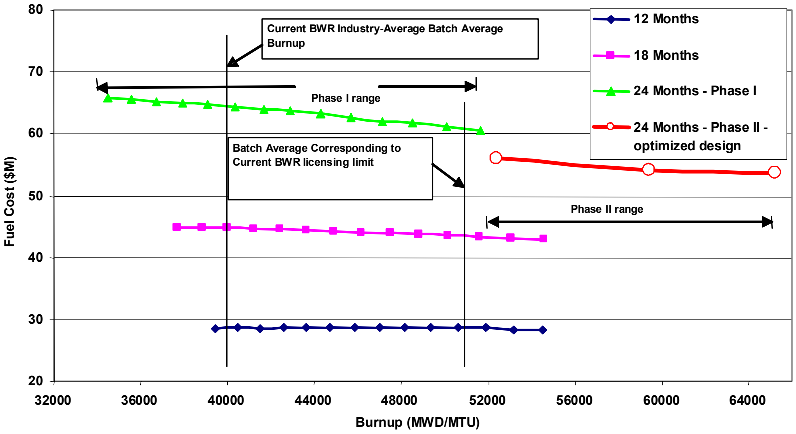


Figure 6-1
Fuel cost as a function of discharge burnup for 24 month cycle BWR

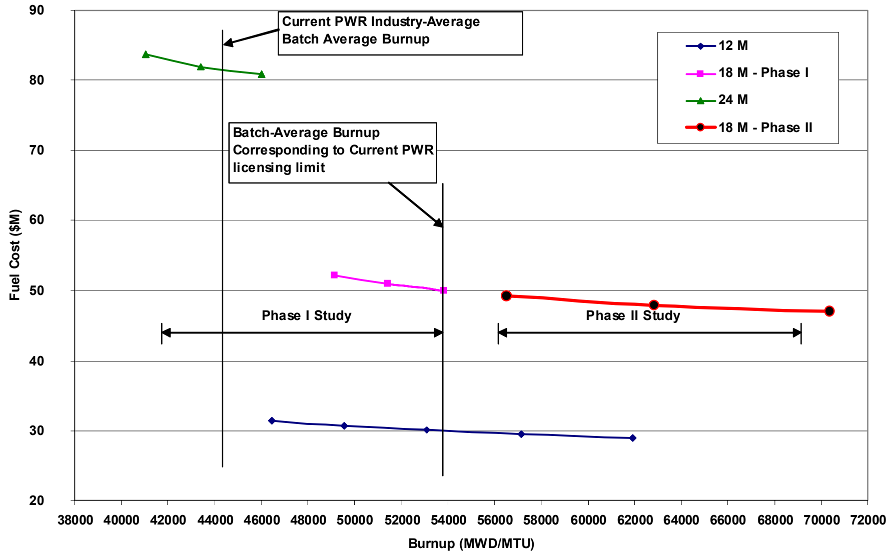


Figure 6-2
Fuel cost as a function of discharge burnup for an 18 month cycle PWR with Performance+ fuel

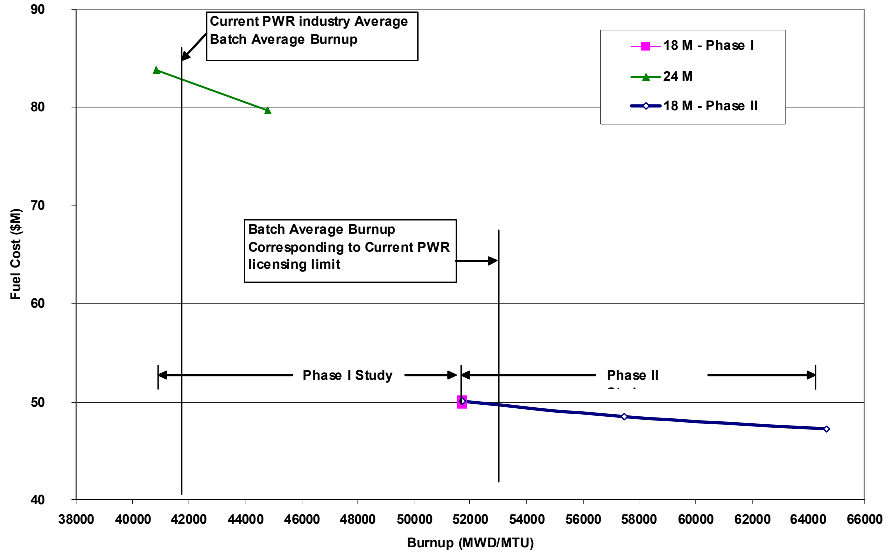


Figure 6-3
Fuel cost as a function of discharge burnup for an 18 month cycle PWR with RFA fuel

7
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A

FUEL CYCLE COST CALCULATION METHODOLOGY

In order to calculate overall fuel cycle cost, the magnitude of each component cost and the appropriate point in time that it occurs must be identified. The quantities of fuel are obtained from reactor neutronic calculations. These quantities of material are adjusted to allow for process losses in the various stages of the nuclear fuel cycle and then multiplied by the unit costs to obtain component costs. A simplified schematic diagram of a BWR reactor fuel cycle is shown in the figure below.

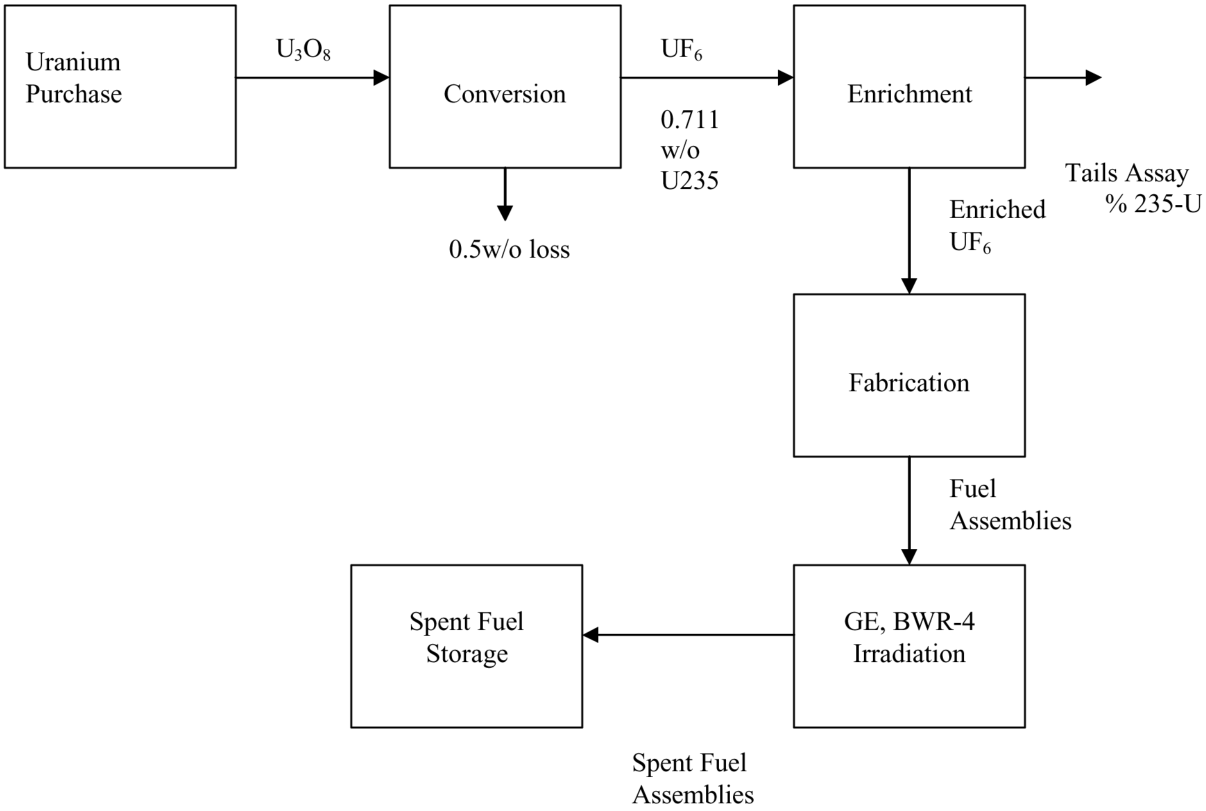

Figure A-1
Simplified fuel cycle diagram of BWR type reactor without final disposal option

Table A-1
Parameter notation for fuel cycle cost calculations

Parameter	Symbol
Discount rate	r
Time	t
Base date of monetary unit	t_b (01/01/2001)
Date of fuel loading	t_c
Fuel residence time	T_r
Mass of uranium feed (kg)	M_f
Mass of uranium charged in reactor (kg)	M_p
Mass of uranium in the tails (kg)	M_t
Fraction of U^{235} in the uranium feed	X_f (0.711 %)
Fraction of U^{235} charged in reactor	X_p
Fraction of U^{235} in the tails	X_t
Fraction of U^{235} discharged	x_d
Conversion factor from kg U to lb U_3O_8 (a lb U_3O_8 per kg U)	a (2.6)
Total component cost	F_i
Unit cost	P_i
Escalation ratio	s_i
Material losses	l_i
Total loss factor	f_i
Lead or lag time	t_i

Where i denotes fuel cycle process as follows :

i=1 symbolizes uranium purchase, i=2 symbolizes conversion process , i=3 symbolizes enrichment process, i=4 symbolizes fabrication process, i=5 symbolizes spent fuel storage process

And monetary units for each fuel cycle process are given as:

P_1 = monetary units per lb U_3O_8, P_2=monetary units per kg U, P_3=monetary units per SWU, P_4=monetary units per kg U fabricated, P_5=monetary units per assembly ($/Assembly)

1) Calculation of each process costs

For each component, process costs for a given equilibrium fuel cycle can be written as:

(a) Cost of Uranium

$$F_1 = M_f \times a \times f_1 \times P_1 \times (1+s_1)^{t-t_b}$$

where

$f_1 = (1+l_2)(1+l_3)(1+l_4)$, $M_f=[(x_p-x_t)/(x_f-x_t)]\ M_p$,

Date of front-end components: $t=t_c-t_i$

(b) Cost of Conversion

$$F_2 = M_f \times f_2 \times P_2 \times (1+s_2)^{t-t_b}$$

where

$f_2 = (1+l_2)(1+l_3)(1+l_4)$

(c) Cost of Enrichment

$$F_3 = S \times f_3 \times P_3 \times (1+s_3)^{t-t_b}$$

where

S=Separative Work Units = $M_pV_p + M_tV_t - M_fV_f$ [4].

$M_t=M_f-M_p$, $V_a= (2x_a-1) \ln[x_a/(1-x_a)]$ and a is subscript for f, p or t.

$f_3 = (1+l_3)(1+l_4)$

Enrichment cost is calculated by considering 0.3 w/o tails assay ratio.

(d) Cost of Fabrication

$$F_4 = M_p \times f_4 \times P_4 \times (1+s_4)^{t-t_b}$$

where

$$f_4 = (1 + l_4) = 1.$$

(e) Cost of Spent Fuel Storage

$$F_5 = Batchsize \times P_5 \times (1 + s_5)^{t-t_b}$$

Date of back-end components, t= t_c+T_r+t_5 ,

where: t_5=0 is assumed for spent fuel storage

Assuming zero loss factor for reactor fuel during irradiation period.

2) Discounting and Levelizing of Fuel Cycle Costs

All the component costs are discounted back to a selected base date and added together in order to arrive at a total fuel cost in present value terms.

The total discounted cost of the nuclear fuel cycle can be written as:

$$\sum_i \sum_{t=t_o-T_1}^{t=t_o+T_r+T_2} Fi(t)/(1+r)^{(t-to)} \qquad \text{(A.1)}$$

where Fi(t)= cost for the i th component at time t , t_o= reference date, T_r = fuel residence time, T_1= maximum value of lead time (in front-end), T_2= maximum value of lag time (in back-end) i= cost component number

If C is the constant levelized fuel cost per unit of electricity sent out by a reactor, the total cost of fuel cycle can also be written as

$$\sum_{t=t_o}^{t_o+T_R} C \times E(t)/(1+r)^{t-t_o} \qquad \text{(A.2)}$$

where ; E(t) = net electrical output at time t.

From the balance of (A.1) and (A.2), levelized fuel cycle cost can be calculated by the following equation (OECD/NEA definition of levelized fuel cycle cost) ;

$$\mathbf{C} = \sum_i \sum_{t=t_c-T_1}^{t=t_c+T_R+T_2} Fi(t)/(1+r)^{(t-t_{mid})} \Big/ \sum_{t=t_c}^{t_c+T_R} E(t)/(1+r)^{t-t_{mid}} \qquad \text{(A.3)}$$

For an equilibrium cycle the energy production is assumed to be at midpoint of the cycle. We define t_{mid} as midpoint time of the cycle, and t_c as date of fuel loading.

$$C = \frac{F_1 \times (1+r)^{-(t_1 - t_{mid})} + F_2 \times (1+r)^{-(t_2 - t_{mid})} + F_3 \times (1+r)^{-(t_3 - t_{mid})} + F_4 \times (1+r)^{-(t_4 - t_{mid})} + F_5 \times (1+r)^{-(t_5 - t_{mid})}}{E \times (1+r)^{(t_o - t_{mid})}}$$

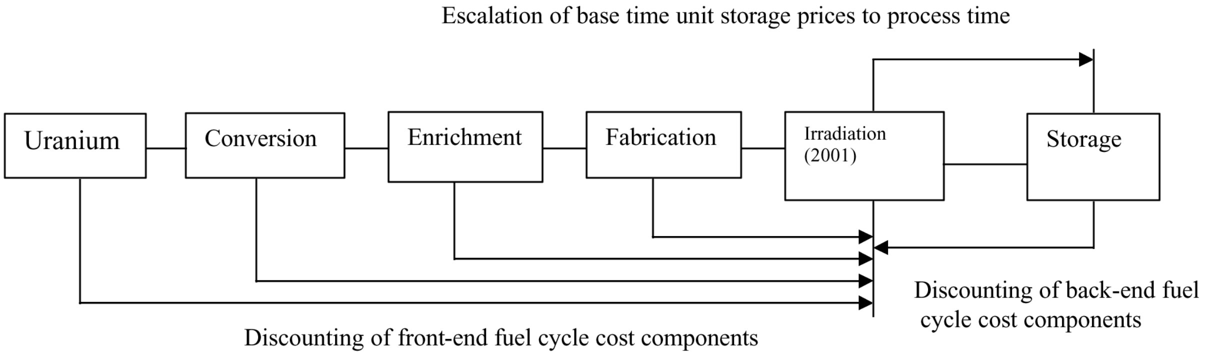

Figure A-2
Escalation and discounting method

3) Summary of the Economic Model

Below the calculation procedure, implemented in the computer code for economic evalulation, is outlined:

1. Find out total U loading for each region
2. Average Enrichment Calculation for each region
3. Commodity Calculations
   - Product mass calculation for each process and every batch region
4. Pre-operational carrying cost for each region
   - Conversion, Fabrication, Ore, SWU components
5. Fuel Operational Carrying Charges for each region
6. Energy Output Present Worth Calculation for each region during the operation
7. For electricity generation term, midpoint of the cycle assumed as reference time to produce cycle energy
8. Present Value of Fuel Carrying Cost for each region

9. Present Value of Energy Output for each region

10. Calculation of levelized fuel cost for each region

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