THE FUEL CYCLE ECONOMICS OF PWR EXTENDED BURNUP

by

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ABSTRACT

Increasing the discharge burnup of pressurized water reactor fuel can reduce fuel cycle and total system energy costs and improve uranium utilization. A reload design methodology was developed for the Zion Nuclear Station to increase the discharge burnup of the fuel in order to accrue these benefits. Licensable, optimized transition and equilibrium loading patterns were developed to reach discharge burnups of 36,000 MWD/MTU, 40,000 MWD/MTU, and 45,000 MWD/MTU. The fuel cycle costs for each of these three cases were then calculated to determine the economically optimum discharge burnup. The discharge burnup of 45,000 MWD/MTU demonstrated a 2.3 percent savings in fuel cycle cost, a 5.5 percent improvement in uranium utilization, and a 16.7 percent decrease in spent fuel production. However, power peaking problems in the reload design loading patterns may preclude its adoption as a near-term goal. A review of the applicable literature has shown that other technical factors will not adversely affect the implementation of an extended burnup program.

Thesis Supervisor: Michael J. Driscoll

Title: Professor of Nuclear Engineering

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To Virginia, whose love and friendship has provided both inspiration for the last five years, and a bright outlook for the future;

and to Jay, who could always make me laugh, even when that inspiration and outlook seemed far away.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Interest in optimizing uranium utilization in the light water reactor once-through fuel cycle was considerably stimulated as a result of the United States government's 1977 decision to indefinitely defer the reprocessing of spent fuel. This policy decision was originally promulgated as a means for mitigating the weapons proliferation problem, but has since been reinforced by economic and spent fuel disposal arguments. The nuclear industry and the U.S. Department of Energy subsequently sought to compensate for the unavailablity of reprocessing by increasing the utilization of uranium in its first and only operating lifetime.

Improving uranium utilization can reduce fuel cycle cost, benefit long range resource management by reducing U_3O_8 requirements, and can lighten the burden on the back end of the fuel cycle by reducing the amount of spent fuel discharged. The single most effective near-term means of increasing uranium utilization is to increase the discharge burnup of the fuel (S-1). This approach can also increase plant capacity factors (by increasing the ratio of burnup cycle to refueling shutdown durations), with considerable attendant economic benefits.

Limitations on discharge burnups have conventionally been set by fuel vendors, based on fuel integrity and other licensing-related considerations. Extensive fuel performance experience, which includes demonstration exposures of high burnup assemblies (M-1), has now shown that LWR fuel burnup can be safely increased to the point where utilities are free to set target burnups based upon a less constrained set of criteria. While the primary focus of work in this area is to determine the economically optimum burnup level, due consideration must be given to the engineering limits placed upon the fuel and to the actual reload design process by which the higher discharge burnups are reached.

1.2 Objectives

The primary goal of the present work is to investigate the fuel cycle economic benefits of extended burnup in pressurized water reactors (PWRs) under practical constraints. Since PWRs represent approximately 66 percent of the large central station power reactors operating or under construction in the United States, and 55 percent in the world (V-1), the results have wide applicability; no appreciable loss of generality (and a considerable gain in realism) is incurred by the selection of Commonwealth Edison Company's (Edison) Zion Nuclear Station's Unit 2 as a representative operating station at near-equilibrium conditions. A brief synopsis of the operating history of this unit is presented in Table 1.1.

There are generally two approaches to increasing the discharge burnup of nuclear fuel: either increasing the cycle length, or increasing the

TABLE 1.1 Zion Unit 2 Operating History

Cycle	Cycle Burnup MWD/MTU	Enrichment w/o U-235	Number of assemblies*	Discharge Burnup MWD/MTU
1	17,630	2.25	65	20,655
		2.79	64	30,225
		3.29	64	36,108
2	10,466	3.06	60	31,174
3	10,788	2.80	64	31,563
4	9264	2.91	60	30,820
		3.31	4	46,122
5	12,618	3.22	72	34,116
6	10,465	3.21	28	35,673
		2.71	32	31,997
7	10,500	3.21	44	34,075
		2.80	12	26,910
8	13,100	3.19	32	36,544
		2.80	36	30,485

*Note: Upon occasion, a small number of previously irradiated assemblies were re-inserted during later cycles, after a cycle or more of residence in the spent fuel pool.

number of batches in the core. It has been noted that the latter has a greater effect on reducing fuel cycle costs than the former (A-1). The former has been studied extensively (B-1, M-2); consequently, many utilities are moving from annual to 18-month or even 24-month operating cycles (S-1). Increasing the cycle length has the effect of decreasing the outage length per year, and therefore increasing the capacity factor. In this case, the fuel system costs as well as the fuel cycle costs must be analyzed because the cycle energy changes.

In the latter case, when the discharge burnup is increased by increasing the number of batches in the core, it is possible to hold the the cycle energy constant. With constant cycle energy, the system as a whole sees the same energy being produced at the plant, the replacement energy costs remain the same, and therefore the system costs are not affected. In this case, it is appropriate to examine the effect of extended burnup on fuel cycle costs only. This was the approach followed in this work: the number of batches was fractionally increased from just under three batches to just over three batches. Cycle length was held constant at 18 months, which was determined by Momsen and Dale (M-2) to be more economic than a 12-month cycle for Zion Station. A more detailed description of this scheme is presented in Appendix A.

As a first step in this investigation, licensable, optimized low leakage loading patterns were developed for 18-month cycles of 13,700 MWD/MTU duration, beginning with cycle 10 as the first transition cycle. The target from that point was to reach equilibrium by cycle 13, and equilibrium discharge burnups of 36,000 MWD/MTU, 40,000 MWD/MTU, and 45,000 MWD/MTU by cycle 14.

Information from the completed loading patterns was then used to calculate the fuel cycle economics for each case using two fuel cycle cost codes. From these economics results, an economically optimum discharge burnup level was then identified.

Finally, in support of the validity of the methodology and results, an examination of the literature on studies of other technical factors (e.g., fuel performance) that may affect the implementation of an extended burnup program is documented.

1.3 Previous Fuel Cycle Cost Studies

Other studies of fuel cycle economics have indicated that fuel cycle costs generally improve at higher burnups. Most studies indicate a broad fuel cycle cost minimum between discharge burnups of 45,000 and 60,000 MWD/MTU. These studies are generally based on point reactor models, and fuel system considerations such as twelve- versus eighteen-month cycle analyses. The S. M. Stoller Corporation's 1984 study for EPRI on fuel cycle costs as a function of burnup (S-2) surveyed a group of U.S. utilities to determine realistic ranges of economic parameters including fuel-cycle component costs, interest rates, and accounting practices. Using their SAROS fuel cycle economics code, they determined the optimum discharge burnup for PWRs to be between 40 and 52 GWD/MTU for annual operating cycles, depending upon the economic conditions, and above the upper limit of the study (55 GWD/MTU) for eighteen-month cycles.

Scherpereel and Frank (S-3) report minimum fuel cycle cost at discharge burnups of 53 GWD/MTU for 12-month operating cycles, and 56 GWD/MTU for 18-month cycles. Their study was based on a fuel system analysis comparing 12-month and 18-month cycles using assumed fuel-cycle component costs. Analysis of annual cycles at Arkansas Power & Light Company (B-2) indicates minimum fuel cycle cost at 50 GWD/MTU. Most studies of extended discharge burnup refer to the possibility of fuel cycle cost savings (D-1, F-1, O-1), but the derivation of their numbers is not always clear.

In view of the number of reactors that are either already at, or committed to, 18-month operating cycles, it is desirable to perform a detailed study of the possibility of decreasing the fuel cycle costs by increasing the discharge burnup, without changing the cycle length. As described earlier, cycle burnup is dependent upon fresh fuel loading (number and enrichment of feed assemblies), and can be held constant for different loadings. Discharge burnup is then increased by decreasing the number of fresh feed assemblies, and increasing their enrichment. The fuel cycle costs for the different loadings can then be calculated and compared.

1.4 Organization of This Work

The remainder of this work is organized as follows:

Chapter Two presents the procedure followed in this investigation. Included in the description is the reload design procedure, from determining fresh fuel requirements to the final loading pattern. Also discussed are the method for calculating fuel cycle economics, and the computer system involved in both of these steps.

Chapter Three presents the results of the reload design procedure and the fuel cycle economic analysis for each of the three discharge burnup cases: 36,000 MWD/MTU, 40,000 MWD/MTU, and 45,000 MWD/MTU.

Chapter Four compares the fuel cycle costs, and the uranium utilization calculated for the three cases. Comparisons are also presented between the results from the two fuel cycle cost codes, between the different neutronic models, between the results of Chapter Three and those of analytical models, and between the results of Chapter Three and results obtained by Edison in their work on previous cycles for Zion Station.

Chapter Five presents a compilation of the results of previous studies of factors affecting the implementation of an extended burnup program. The factors that are addressed include fuel performance experience, the safety and licensing acceptability of an extended burnup program, the environmental effects of such a program, and its impact on fuel cycle services such as fuel fabrication.

Chapter Six presents a summary and conclusions. Recommendations for future work and analysis are also presented.

The two appendices appearing at the end of this work contain the following information: A) The refueling strategy followed in this work is described in detail; and B) Loading pattern and assembly data is given for the reload designs developed in this work.

CHAPTER 2

PROCEDURE

2.1 Introduction

A comparison of fuel cycle economics for different discharge burnups requires input in several categories, which define in a precise way how fuel batches having these discharge burnups differ. These differences arise from the way in which the discharge burnup is reached, namely, from the reload design program. For each target discharge burnup, a program must be designed to increase the burnup of the fuel from its present level to the discharge burnup of interest. This chapter presents the methodology required to accomplish this goal. Once the reload program has been designed, the fuel cycle cost for each case can be calculated and compared. Only then can the optimum discharge burnup be determined.

2.2 Fresh Fuel Loading Determination

The first step in developing a loading pattern is to determine the number and enrichment of the feed assemblies required to reach the desired cycle and discharge burnups. The target cycle burnup is calculated based on system planning and reactor performance considerations. The target cycle burnup used in this study, based on an 18-month cycle and a capacity factor of 68 percent, was 13,700 MWD/MTU. The target fuel discharge burnup is usually determined from fuel warranty limits; however, in this work, current limits were exceeded to examine reload design characteristics at extended burnups. The three discharge burnups used in this work were 36,000 MWD/MTU, 40,000 MWD/MTU, and 45,000 MWD/MTU.

The Nuclear Fuel Services Department of Commonwealth Edison Company first determines the number of feed assemblies from the target cycle and discharge burnups, using the formula:

$$\text{Number of feed assemblies} = \frac{\text{Target Bc}}{\text{Target Bd}} \times 193 \quad , \qquad (2.1)$$

where Bc is the core average cycle burnup, Bd is the batch average discharge burnup, and 193 is the total number of assemblies in the core. The value given by this calculation is then rounded to the nearest multiple of four (in the interest of maintaining a symmetric core loading pattern) to yield the number of feed assemblies. This is a very simple and approximate model, but it has been proven historically to yield satisfactory results.

The required enrichment of the feed assemblies is then estimated from the loading and yields of previous cycles. The yield of a cycle is a measure of the efficiency of that cycle in terms of fissile material required per unit energy produced, and is defined as

$$\text{Yield} = \frac{\text{Xf} \times \text{Number of Feed Assemblies} \times 1000}{\text{Bc}} \ , \ \frac{\text{kg U-235}}{\text{MWDth}} \ , \qquad (2.2)$$

where Xf is the feed assembly enrichment in w/o U-235, Bc is the core average cycle burnup in MWD/MTU, and 1000 is the conversion factor from kilograms to metric ton. By this definition, low yield indicates a high efficiency. This provides a starting point for the feed enrichment; a two-dimensional nodal theory code is later used to determine the enrichment more precisely.

2.3 Loading Pattern Development

Once the fuel loading has been determined, work on the actual loading pattern can begin. Using actual data from previous cycles, and the number of feed assemblies and their enrichment (as calculated in the previous section), a loading pattern can be developed following set criteria and restrictions.

2.3.1 Criteria and Restrictions

There are a number of criteria and restrictions which must be adhered to when designing a loading pattern. These are based on reactor physics and engineering considerations. First, the power peaking factor (assembly average enthalpy rise hot channel factor, $F\Delta H$), as used by Edison in their internal nuclear design procedure, should be less than or equal to 1.435 at all burnups, where $F\Delta H$ is taken to be

$$F\Delta H = \frac{\text{Maximum Hot Channel Enthalpy Rise}}{\text{Assembly Average Enthalpy Rise}} . \tag{2.3}$$

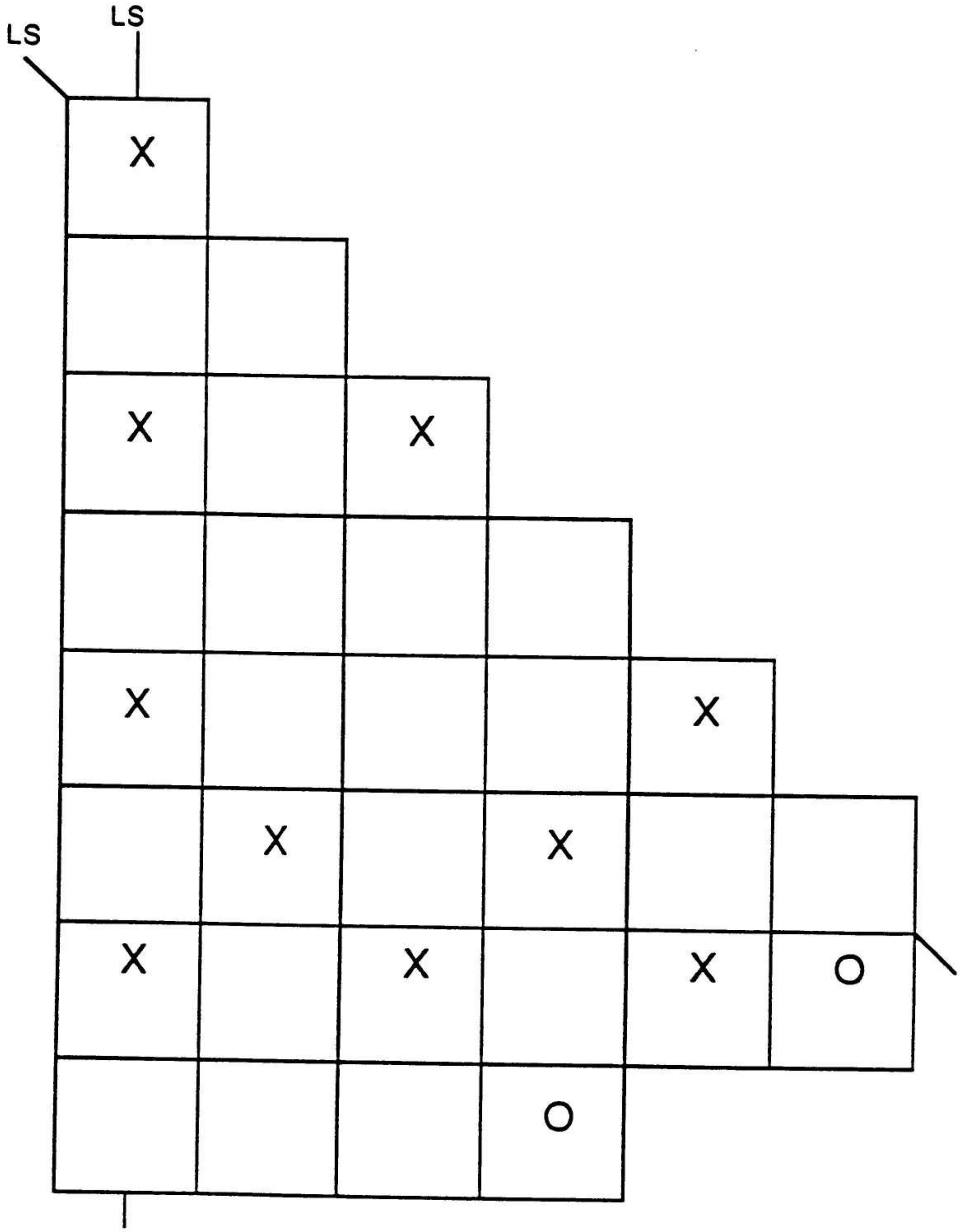
This limit was established to ensure that the fuel does not reach the departure from nucleate boiling condition.

The hot zero-power moderator temperature coefficient (MTC) should be negative at the beginning of each cycle. This ensures a decrease in core reactivity with an increase in temperature. The MTC becomes more negative as the cycle progresses; hence, positivity is only a concern at the beginning of the cycle.

No feed assemblies can be placed in the corner positions of the core (peripheral positions having two reflected faces: see Fig. 2.1); this is known as a "low leakage" loading pattern. This restriction is based on reducing the fluence to the reactor vessel, particularly to the welds, which are located near the corners of the core.

Edison uses Wet Annular Burnable Absorbers (WABAs) in their PWR feed assemblies for reactivity control (S-4). These are placed within the feed assemblies in the tubes which might otherwise be occupied by control rods. This requires the restriction that no feed assemblies requiring burnable absorbers be located in control rod positions, which are shown in Fig. 2.1.

The feed enrichments to be used in a reload design are limited by the licenses of the spent fuel pool and the fuel fabrication facility, where adequate margins to criticality must be preserved. This restriction does not apply in a theoretical study such as this one, but it will become a



X Control Rod Position
O Corner Position
LS Line of Symmetry

Fig. 2.1 Control Rod and Corner Positions
1/8 Core Symmetry

consideration in the implementation of an extended burnup program.

2.3.2 Reload Design Techniques

Reload design has not yet been fully automated at Edison, so that a large part of the design process is still handled by the designer. The designer uses powerful computer codes to model the response of the core to a particular loading pattern. However, the optimization process is accomplished largely through an iterative sequence, which is strongly influenced by the experience of the designer, who develops a feel for the response of the core to even a subtle change in the loading pattern.

There are certain techniques, however, that aid the designer in reload design. Dividing the feed assemblies into subgroups having two different enrichments helps avoid reaching power peaking limits. The two enrichments should not differ by more than 0.2 w/o U-235; a wider split can cause a large disparity in power density between two subgroups within the same batch, which defeats the purpose of splitting the feed assemblies.

Since the goal in loading pattern design is to minimize the power peaking throughout the core, swapping a higher reactivity assembly into a higher power location is not desirable. Likewise, placing two feed assemblies next to each other may not work, depending upon their location (i.e., peripheral vs. interior) in the core. For best results, the designer should minimize the power peaking without burnable poison in the core. Once this is done, the number of WABAs added can consequently be minimized, and the reactivity losses due to residual poison at end-of-cycle will be decreased.

2.4 Loading Pattern Determination Procedure

This section describes the actual process by which a reload core is designed. It begins with a general description of the computer system and programs employed by Edison. It will then present the system and programs in more detail as they apply to this work. The reload design process is summarized in Fig. 2-2.

2.4.1 Neutronic methods

The primary linkage code at Edison is the Nuclear Analysis Module Execution System (NAMES). NAMES provides both linkage and control functions for Edison's entire PWR neutronics methodology and ensures a unified nuclear design approach (C-1). NAMES eliminates extensive manual data manipulation and computation, and monitors and directs the data flow. Figure 2-3 illustrates the standard design path for the generation of the neutronic models.

The individual neutronics codes used by Edison were obtained from Westinghouse Electric Corporation in 1978. Reference C-1 is a topical report documenting the benchmarking of Edison's PWR reload design methods using those codes.

The reload design calculation process begins with the ADD

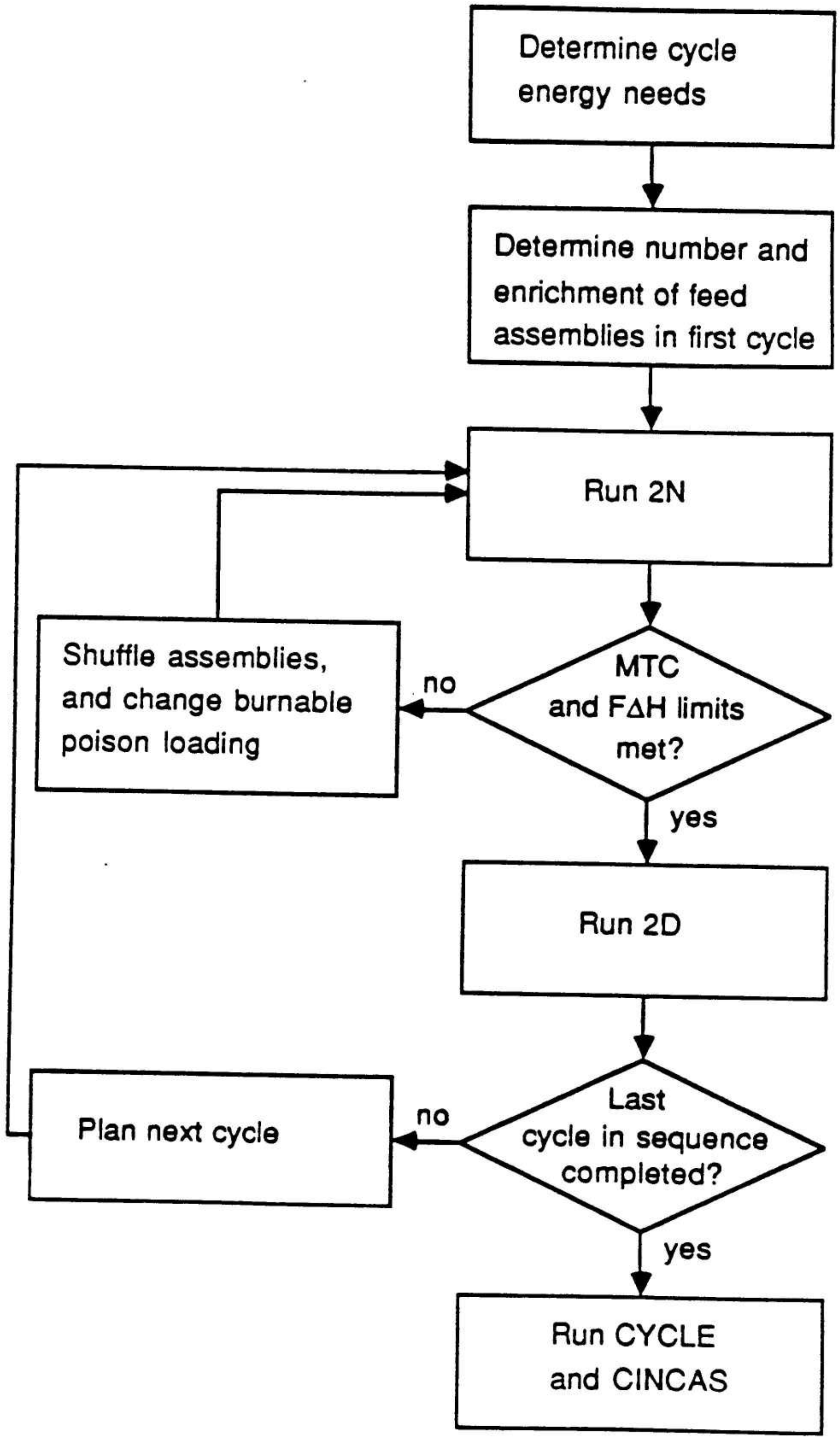


Fig. 2.2 Simplified Reload Design Process

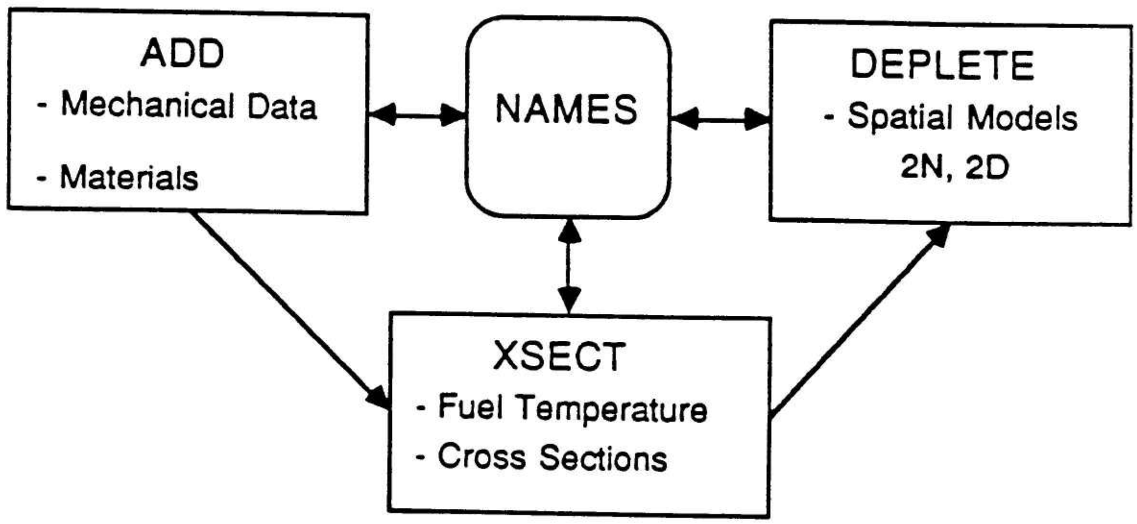


Fig. 2.3 Neutronic Calculation Design Path

(Assembly Data Description) sequencer, which builds a file containing validated mechanical data and material composition information for each unique assembly fuel type. This file is then sent to XSECT, which calculates fuel temperatures using FIGHT-H, plus macroscopic and microscopic few-group cross sections using 0D, and generates a consolidated cross section file. FIGHT-H calculates fuel temperatures based on LASER (P-1) and REPAD (O-2) results. 0D is taken from Westinghouse's LEOPARD (B-3) and CINDER (E-1). Finally, the DEPLETE sequencer accesses the appropriate consolidated cross section files and uses the designer's fuel loading pattern to generate the spatial neutronic models for the neutronic codes. The neutronic codes of interest in this work are 2N, a two-dimensional nodal theory code, and 2D, a two-dimensional spatial few-group diffusion theory code. 2N comes from Westinghouse's PALADON (C-2), and 2D comes from their TURTLE (A-2) code.

There are other computer codes used in the nuclear design process which are not controlled by NAMES. These are CYCLE, a zero-dimensional fuel cycle data code; CINCAS, a fuel cycle economics code (F-2); and SUNKCOST, a simple fuel cost code written by Edison.

2.4.2 Nuclear design in this work

The reload cycles designed in this work are based on the Zion 2 Cycle 9 reload cycle calculations performed by D. Lee in Nuclear Fuel Services (L-2). Cycle 9 employed 76 feed assemblies at an enrichment of 3.2 w/o, and reached a cycle burnup of 12,000 MWD/MTU. The fuel data from the end of that cycle was used as the input for the shuffled assemblies in Cycle 10. The input for the feed assemblies in Cycle 10 was generated separately for each of the three target discharge burnup cases using consolidated cross section files from XSECT, and using the method presented in Section 2.2 for determining the number of feed assemblies.

A "best guess" loading pattern for Cycle 10 was determined using the concepts described in Section 2.3 and the results of the Cycle 9 reload design. The loading pattern, the data from Cycle 9, and the feed assembly data described above were then input to 2N to generate cycle data. This cycle data was subsequently examined to decide what fuel assembly swaps, rotations, or WABA additions were required to meet power peaking limit and MTC criteria. These changes were made, and 2N was rerun. This process was repeated until an "optimized" loading pattern was reached. In the present work, "optimized" is applied loosely, implying only that power peaking limit and MTC criteria were met.

The final loading pattern found in 2N was then input to 2D to verify the calculated cycle data. 2D is regarded by Edison as the code which provides the best representation of actual core performance. Once the Cycle 10 pattern was optimized in 2D, the entire process was repeated using the calculated data from Cycle 10 as a basis for the loading pattern search in Cycle 11. This was repeated again for all cycles through Cycle

14. The results from 2D for each cycle were then used to calculate the batch average discharge burnup for each batch charged subsequent to Cycle 9.

After the reload design was completed for all five cycles, data from 2D was input to CYCLE to generate data for cycles 15 through 20. This step verifies that an equilibrium has been reached in the reload design.

The entire neutronic analysis for Cycles 10 through 20 was repeated for each of the three target discharge burnup cases.

2.5 Fuel Cycle Economics Calculations

Finally, when the entire neutronic analysis was finished, the data from 2D and CYCLE were used in CINCAS and SUNKCOST to calculate fuel cycle economics. SUNKCOST is a simple code which takes the fresh fuel loading and the unit cost for each step in the front end as input and calculates the fuel cost for each cycle in a present worth analysis. CINCAS is a more complex code which also uses the specific burnup history of each assembly, the performance of the reactor, the payment schedule for each step in the front end, and the economic conditions prevalent in the period of concern.

2.6 Chapter Summary

The process, from the specification of Cycle 9 data to the economic analysis is described in this chapter; it is next applied to each of the three cases (discharge burnup goals) of interest. The results of the neutronic analysis and the results of the economic analysis, both presented in Chapter 3, provide a basis for comparison of the three cases. These comparisons are presented in Chapter 4.

CHAPTER 3

RESULTS

3.1 Introduction

The data generated using the nuclear design procedure outlined in the previous chapter are presented in this chapter. Loading patterns for Cycles 10-14 to reach each of the three target discharge burnups were developed. Approximate cycle data for Cycles 15-20 were also calculated. Loading pattern development results and cycle data were then used as input for an economic analysis. The results presented in this chapter are compiled from the output of the reload design process using 2N, 2D, CYCLE, CINCAS, and SUNKCOST, and allow both neutronic and economic comparison of the three target discharge burnup cases: 36,000 MWD/MTU, 40,000 MWD/MTU, and 45,000 MWD/MTU.

3.2 Case One: Discharge Burnup of 36,000 MWD/MTU

A discharge burnup of 36,000 MWD/MTU is very close to the discharge burnup currently being reached by the fuel at Zion Station (see Table 1.1). This case can therefore be regarded as a base case to which the other two cases can be compared. Since this case is the closest to the cycles currently being designed, the loading pattern development in this case was the easiest to perform, in terms of the number of changes that were necessary to the "best guess" pattern to find a pattern that meets the

MTC and power peaking limits. Even with a low-leakage loading pattern, the power peaking limit was met in most of the patterns tested without the addition of burnable poison. However, it was found necessary to add burnable poison to meet the MTC limit, because burnable poison takes the place of soluble poison (boron). If the concentration of boron in the moderator is too high, the core will experience a positive MTC.

This pattern also reached steady-state the most quickly because the new steady-state was not very different from the old steady-state. In fact, the feed assembly loading for Cycle 10 turned out to be the steady-state loading, i.e., the number and enrichment of the assemblies loaded did not change from the loading in Cycle 10.

3.2.1 Neutronic analysis

The neutronic analysis began with the determination of the number of feed assemblies required to reach the target discharge burnup. This was accomplished using Equation 2.1, and gave a result of 73 feed assemblies. Since the number of feed assemblies must be a multiple of four, 72 feed assemblies were used. Working backward through Equation 2.1 with 72 feed assemblies gives a target discharge burnup of 36,724 MWD/MTU. According to this simple model, by using this number of feed assemblies, this target discharge burnup is as near to the goal of 36,000 MWD/MTU as can be expected. Examination of the yields (see section 2.2) of previous cycles showed that the feed enrichment should be approximately 3.4 w/o

U-235.

Using these numbers, and the loading pattern development procedure presented in Section 2.3, a "best guess" loading pattern was determined. This pattern was input to 2N, and adjusted as necessary to reduce the power peaking and MTC. Subsequent iterations using 2N showed that splitting the feed assembly batch into 52 feed assemblies at 3.4 w/o U-235 and 20 feed assemblies at 3.2 w/o U-235 was necessary to reach the cycle burnup of 13,700 MWD/MTU. A total of 672 WABAs (see section 2.3.1) were required to adjust the power peaking and to reduce the MTC to meet its limit. This final loading pattern was then confirmed with a 2D run, which predicted a final cycle energy of 13,711 MWD/MTU, and a yield of 17.56. Figure 3.1 shows assembly data for this loading pattern. This figure is included as an illustrative example of the type of loading pattern assembly data used in this study; loading patterns and assembly data for all cycles in the three cases are presented in Appendix B.

The results of this cycle were then used to determine a "best guess" loading pattern for Cycle 11 using the same feed assembly loading. This process was repeated for all cycles through cycle 14. Using assembly cycle burnup data from 2D, the batch average discharge burnup (calculated using the method described in Appendix A) reached in the fuel loaded in Cycle 11 was 36,729 MWD/MTU, which is very close to the target discharge burnup.

25,968 6,1 0.905 38,120					
14,173 2,2 1,273 29,744	3.4 F 20 1.315 17,444				
12,425 6,6 1.384 28,709	13,079 7,4 1.334 28,719	26,353 3,2 1.012 39,309			
3.2 F 16 1.422 17,662	15,700 5,2 1.267 31,100	3.4 F 16 1.285 17,076	26,637 7,1 0.896 39,158		
15,442 4,1 1.265 30,780	14,875 6,5 1.237 29,991	15,563 5,4 1.241 31,118	3.2 F 12 1.301 17,162	29,845 6,2 0.948 42,609	
3.4 F 12 1.359 17,190	20,132 7,5 1.204 34,457	3.2 F 12 1.352 17,570	15,726 6,3 1.241 31,033	3.4 F 8 1.318 16,469	3.4 F 0 1.361 14,060
26,353 3,2 0.980 37,585	3.4 F 8 1.357 16,046	13,781 7,2 1.246 28,151	3.4 F 4 1.350 14,785	15,445 4,3 1.003 24,759	28,558 7,3 0.719 33,501
29,845 6,2 0.616 35,985	8911 8,3 1.010 18,056	3.4 F 0 1.111 10,655	24,122 8,2 0.728 29,441		

Feed Assemblies

ww F	Enrichment, w/o
xx	No. of WABAs
yy	FΔH
zz	EOC Burnup, MWD/MTU

Shuffled Assemblies

ww	BOC Burnup, MWD/MTU
xx	Location in previous cycle
yy	FΔH
zz	EOC Burnup, MWD/MTU

Fig. 3.1 Cycle 10, Case One Assembly Data

Finally, the equilibrium fuel assembly loading, and the cycle burnup sharings calculated from the results of 2D, were input to CYCLE to generate cycle and discharge burnups for Cycles 15-20. Burnup sharing is used in the place of power sharing, and is calculated for each assembly by normalizing the assembly cycle burnup to the core average cycle burnup. CYCLE output shows a steady-state discharge burnup of 36,717 MWD/MTU, a steady-state cycle burnup of 13,698 MWD/MTU, and a steady-state yield of 17.58. Fuel cycle data from 2N for Cycles 10-14 are shown in Table 3.1; data from 2D and CYCLE for Cycles 10-20 are shown in Table 3.2.

3.2.2 Economic analysis

The results of the neutronic analysis were then used in SUNKCOST and CINCAS to determine the fuel cycle costs for this case. SUNKCOST takes proprietary economic data and the feed assembly loading for each cycle, and calculates the total cost for each cycle and the cumulative costs for the study. The results of this analysis for this case are presented for Cycles 10-20 in Table 3.3.

CINCAS takes as input the number of feed assemblies and their beginning and ending enrichment for each batch, the burnup in each cycle for each batch, the refueling schedule for all cycles, and proprietary economic data. From this, the code calculates cycle and cumulative costs, and levelized cycle and cumulative costs. The results for this case for

TABLE 3.1 2N Results for Case One

Cycle	Loading No. @ w/o	BPs	Cycle Energy MWD/MTU
10	20 @ 3.2 52 @ 3.4	672	13,760
11	20 @ 3.2 52 @ 3.4	592	13,808
12	20 @ 3.2 52 @ 3.4	576	13,880
13	20 @ 3.2 52 @ 3.4	592	13,952
14	20 @ 3.2 52 @ 3.4	576	13,964

TABLE 3.2 2D and CYCLE Results for Case One

Cycle	Loading No. @ w/o	BPs	Cycle Energy MWD/MTU	Yield	Discharge Burnup MWD/MTU
10	20 @ 3.2 52 @ 3.4	672	13,711	17.56	35,911
11	20 @ 3.2 52 @ 3.4	592	13,688	17.59	36,729
12	20 @ 3.2 52 @ 3.4	576	13,653	17.63	36,706
13	20 @ 3.2 52 @ 3.4	592	13,702	17.53	36,714
14	20 @ 3.2 52 @ 3.4	576	13,701	17.58	36,716
15	20 @ 3.2 52 @ 3.4		13,698	17.58	36,717
16	20 @ 3.2 52 @ 3.4		13,697	17.58	36,717
17	20 @ 3.2 52 @ 3.4		13,698	17.58	36,717
18	20 @ 3.2 52 @ 3.4		13,698	17.58	36,717
19	20 @ 3.2 52 @ 3.4		13,698	17.58	36,717
20	20 @ 3.2 52 @ 3.4		13,698	17.58	36,717

TABLE 3.3 SUNKCOST Results for Case One

Cycle	Cycle Cost*	Cumulative Cost*
10	40.046	40.046
11	36.772	76.818
12	33.765	110.583
13	31.004	141.587
14	28.469	170.056
15	26.141	196.197
16	24.004	220.201
17	22.041	242.242
18	20.239	262.481
19	18.584	281.065
20	17.064	298.129

* costs in millions of dollars, cycle costs present-valued to BOC 10, cumulative cost is arithmetic sum of cycle costs

TABLE 3.4 CINCAS Results for Case One

Cycle	Cycle Cost,* million $	Cumulative Cost,# million $	Levelized Cycle Cost,* mills/kwhe	Levelized Cumulative Cost,# mills/kwhe
10	33.442	33.442	3.691	3.691
11	62.129	86.285	6.863	5.148
12	75.740	141.075	8.367	6.052
13	85.454	193.653	9.441	6.706
14	93.902	242.794	10.373	7.223
15	103.147	288.704	11.394	7.669
16	113.313	331.600	12.517	8.074
17	124.483	371.682	13.751	8.450
18	136.756	409.133	15.107	8.805
19	150.242	444.128	16.597	9.143

* costs present-valued to cycle startup
# costs present-valued to June 1, 1987 (BOC 10)

Cycles 10-19 are presented in Table 3.4.

3.3 Case Two: Discharge Burnup of 40,000 MWD/MTU

This case represents more of a divergence from the cycles currently being designed than does the first case. In order to reach this discharge burnup, the number of feed assemblies had to be decreased, and the feed enrichment had to be increased. This made power peaking problems more likely; the loading pattern search was more difficult than in the first case, and required a greater number of assembly shuffles and burnable poison adjustments. In all the loading patterns for this case, sufficient burnable poison added to meet the power peaking limit also reduced the MTC to within its limit.

3.3.1 Neutronic analysis

Equation 2.1 showed that 66 feed assemblies were needed in this case; however, 66 is halfway between multiples of four, so the actual number of feed assemblies used must be based on other considerations. Examination of the yields of previous cycles showed that using 68 feed assemblies would allow the enrichment to remain below 3.7 w/o U-235, the Technical Specification licensing limit on the spent fuel pool. Using 68 feed assemblies in Equation 2.1 showed that the appropriate target discharge burnup for this case was 38,884 MWD/MTU. This number of feed assemblies required a feed enrichment of approximately 3.6 w/o U-235, based on previous cycles.

The final 2N run for Cycle 10 for this case showed this estimate of feed enrichment to be very close. A feed assembly batch split of 56 assemblies at 3.6 w/o U-235 and 12 assemblies at 3.4 w/o U-235 was required to reach the target cycle burnup. Again, 672 WABAs were needed to reduce the power peaking and MTC to their limits. The 2D run for this pattern confirmed the feed assembly loading, and showed a cycle burnup of 13,711 MWD/MTU, and a yield of 17.68. Again, the reload design determination was repeated through Cycle 14 using 2N and 2D, and for Cycles 15-20 using CYCLE. 2N results are presented in Table 3.5, and 2D and CYCLE results appear in Table 3.6. The feed assembly loading for the steady-state cycles was calculated to be 28 assemblies at 3.6 w/o U-235 and 40 assemblies at 3.4 w/o U-235. This loading gave an average steady-state cycle burnup of 13,751 MWD/MTU, an average yield of 17.22, and an average discharge burnup of 39,019 MWD/MTU.

3.3.2 Economic analysis

The results of the neutronic analysis were again used as input to SUNKCOST and CINCAS for the economic analysis. The results of the SUNKCOST analysis of Cycles 10-20 are shown in Table 3.7, and the results of the CINCAS analysis of Cycles 10-19 are shown in Table 3.8.

3.4 Case Three: Discharge Burnup of 45,000 MWD/MTU

The final case represents quite a departure from the cycles currently

TABLE 3.5 2N Results for Case Two

Cycle	Loading No. @ w/o	BPs	Cycle Energy MWD/MTU
10	12 @ 3.4 56 @ 3.6	672	13,712
11	28 @ 3.4 40 @ 3.6	656	13,772
12	56 @ 3.4 12 @ 3.6	592	13,904
13	40 @ 3.4 28 @ 3.6	560	13,904
14	36 @ 3.4 32 @ 3.6	528	13,952

TABLE 3.6 2D and CYCLE Results for Case Two

Cycle	Loading No. @ w/o	BPs	Cycle Energy MWD/MTU	Yield	Discharge Burnup MWD/MTU
10	12 @ 3.4 56 @ 3.6	672	13,711	17.68	39,299
11	28 @ 3.4 40 @ 3.6	656	13,748	17.40	39,024
12	56 @ 3.4 12 @ 3.6	592	13,728	17.05	38,639
13	40 @ 3.4 28 @ 3.6	560	13,694	17.28	39,033
14	36 @ 3.4 32 @ 3.6	528	13,726	17.31	39,097
15	40 @ 3.4 28 @ 3.6		13,792	17.17	39,083
16	40 @ 3.4 28 @ 3.6		13,702	17.28	38,933
17	40 @ 3.4 28 @ 3.6		13,771	17.20	39,045
18	40 @ 3.4 28 @ 3.6		13,755	17.22	39,015
19	40 @ 3.4 28 @ 3.6		13,733	17.24	
20	40 @ 3.4 28 @ 3.6		13,751	17.22	

TABLE 3.7 SUNKCOST Results for Case Two

Cycle	Cycle Cost*	Cumulative Cost*
10	40.582	40.582
11	36.720	77.302
12	32.843	110.145
13	30.616	140.761
14	28.218	168.979
15	25.814	194.793
16	23.703	218.496
17	21.765	240.261
18	19.986	260.247
19	18.351	278.598
20	16.851	295.449

* costs in millions of dollars, cycle costs present-valued to BOC 10, cumulative cost is arithmetic sum of cycle costs

TABLE 3.8 CINCAS Results for Case Two

Cycle	Cycle Cost,* million $	Cumulative Cost,# million $	Levelized Cycle Cost,* mills/kwhe	Levelized Cumulative Cost,# mills/kwhe
10	32.809	32.809	3.622	3.622
11	59.699	83.585	6.595	4.988
12	77.514	139.659	8.563	5.992
13	84.850	191.865	9.373	6.644
14	93.584	240.839	10.328	7.164
15	103.273	286.805	11.324	7.612
16	112.599	329.431	12.429	8.014
17	124.113	369.393	13.631	8.388
18	136.200	406.692	14.976	8.741
19	149.435	441.499	16.457	9.076

* costs present-valued to cycle startup

costs present-valued to June 1, 1987 (BOC 10)

being designed and operated at Zion. In order to reach this discharge burnup, the number of feed assemblies had to be further decreased, and the feed enrichment had to be increased to enrichment levels which have never been used at Zion. These changes made the reload design difficult due to power peaking problems, especially in the first two transition cycles. In the transition cycles, fresh assemblies at 3.6 and 4.0 w/o U-235 were mixed with burned assemblies that were originally 3.2 w/o U-235; consequently, there were large discrepancies in power levels between fresh and burned fuel assemblies.

Unlike the first two cases, where the steady-state number of feed assemblies was loaded in Cycle 10, successful loading pattern development for Cycles 10 and 11 in this case was impossible using the steady-state number of feed assemblies. As a result, this case had to have two intermediate cycles interposed to make the transition from the Cycle 9 loading to the steady-state loading. The loading pattern search was the most difficult of the three cases, and as many as 250 assembly shuffles and burnable poison adjustments per pattern were required, compared to approximately 30 per pattern in the first case, and approximately 90 per pattern in the second. Again, in all the loading patterns for this case, burnable poison added to meet the power peaking limit also reduced the MTC to its limit.

3.4.1 Neutronic analysis

Equation 2.1 suggested that 59 feed assemblies were needed in this case; therefore, 60 feed assemblies were used. Using 60 feed assemblies in Equation 2.1 showed that the appropriate target discharge burnup for this case was 44,068 MWD/MTU. Examination of previous cycles showed that a feed enrichment of approximately 3.9 w/o U-235 was required to reach the target cycle burnup.

As mentioned above, the loading pattern search in Cycles 10 and 11 using 60 feed assemblies failed to yield a successful result. Power peaking and MTC limits could not both be met using the loading pattern strategy and type of burnable poison assumed in this work. It became necessary to design two transition cycles, each using 64 feed assemblies, to be able to reach steady-state conditions without compromising the power peaking and MTC limits. Even with the use of transition cycles, the reload cycles never quite reached a conventional steady-state; the fresh fuel loading and the loading patterns were very similar after Cycle 12, but they never reached a constant state. Because a steady-state was reached in the other two cases, the cause of the absence of a steady-state in this case may be worth investigating. According to Lewins (L-1), if the number n, which is found by dividing the number of assemblies in the core by the number of assemblies in the reload batch, is an integer, then the feed assembly enrichment will not converge to a single value for a fixed cycle length, but will exhibit a cyclic behavior. In the present instance, n is not an integer, but it is very close to being an integer in Cycles 10 and 11. This may have caused a perturbation which carried through to later cycles.

The reload design determination was repeated through Cycle 14 using 2N and 2D, and for Cycles 15-20 using CYCLE. 2N results are presented in Table 3.9, and 2D and CYCLE results appear in Table 3.10. The feed assembly loading for the "steady-state" cycles was calculated to vary around 60 feeds at 3.8 w/o U-235. This loading gave an average steady-state cycle burnup of 13,710 MWD/MTU, an average yield of 16.61, and an average discharge burnup of 44,286 MWD/MTU.

3.4.2 Economic analysis

The results of the neutronic analysis were used as input to SUNKCOST and CINCAS for the economic analysis. The results of the SUNKCOST analysis of Cycles 10-20 are shown in Table 3.11, and the results of the CINCAS analysis of Cycles 10-19 are shown in Table 3.12.

3.5 Chapter Summary

This chapter presented the results of the reload loading pattern design process. Using the procedure described in Chapter 2, loading patterns were designed to reach each of three target discharge burnups: 36,000 MWD/MTU, 40,000 MWD/MTU, and 45,000 MWD/MTU. Results of both neutronic and economic analyses of these cases have been presented. The

TABLE 3.9 2N Results for Case Three

Cycle	Loading No. @ w/o	BPs	Cycle Energy MWD/MTU
10	36 @ 3.6	688	13,580
	28 @ 4.0		
11	40 @ 3.6	608	13,724
	24 @ 3.8		
12	12 @ 3.6	544	13,868
	48 @ 3.8		
13	40 @ 3.8	544	13,916
	20 @ 4.0		
14	16 @ 3.6	496	13,844
	44 @ 3.8		

TABLE 3.10 2D and CYCLE Results for Case Three

Cycle	Loading No. @ w/o	BPs	Cycle Energy MWD/MTU	Yield	Discharge Burnup MWD/MTU
10	36 @ 3.6 28 @ 4.0	688	13,645	17.71	43,661
11	40 @ 3.6 24 @ 3.8	608	13,716	17.10	43,796
12	12 @ 3.6 48 @ 3.8	544	13,682	16.49	43,775
13	40 @ 3.8 20 @ 4.0	544	13,695	16.94	45,429
14	16 @ 3.6 44 @ 3.8	496	13,657	16.46	44,114
15	60 @ 3.8		13,721	16.58	44,969
16	48 @ 3.8 12 @ 4.0		13,706	16.83	44,132
17	60 @ 3.8		13,682	16.67	43,927
18	12 @ 3.6 48 @ 3.8		13,681	16.48	
19	12 @ 3.6 48 @ 3.8		13,781	16.36	
20	60 @ 3.8		13,691	16.72	

TABLE 3.11 SUNKCOST Results for Case Three

Cycle	Cycle Cost*	Cumulative Cost*
10	40.692	40.692
11	36.273	76.965
12	33.152	110.117
13	30.324	140.441
14	26.894	167.335
15	25.082	192.417
16	23.299	215.716
17	21.148	236.864
18	19.194	256.058
19	17.625	273.683
20	16.373	290.056

* costs in millions of dollars, cycle costs present-valued to BOC 10, cumulative cost is arithmetic sum of cycle costs

TABLE 3.12 CINCAS Results for Case Three

Cycle	Cycle Cost,* million $	Cumulative Cost,# million $	Levelized Cycle Cost,* mills/kwhe	Levelized Cumulative Cost,# mills/kwhe
10	30.732	30.732	3.392	3.392
11	57.616	79.736	6.365	4.757
12	75.971	134.694	8.393	5.779
13	84.506	186.689	9.336	6.465
14	92.385	235.035	10.224	6.994
15	101.107	280.037	11.144	7.439
16	112.029	322.447	12.362	7.850
17	123.575	362.236	13.660	8.235
18	135.277	399.283	14.955	8.593
19	148.826	433.948	16.333	8.931

* costs present-valued to cycle startup
# costs present-valued to June 1, 1987 (BOC 10)

loading pattern design process became more difficult as the reload designs became less like the cycles currently being designed and operated.

CHAPTER 4

COMPARISONS OF RESULTS

4.1 Introduction

This chapter presents comparisons between the results described in Chapter 3. Results are compared both between the three cases, and between the different methods of calculation. The former category includes comparisons of fuel cycle costs and uranium utilization, while the latter is comprised of comparisons of the two cost codes, the two neutronic models, and of analytic and neutronic results. A comparison of the neutronic results and the results from previously designed and operated cycles is also made.

4.2 Fuel Cycle Costs

CINCAS and SUNKCOST were used to calculate the fuel cycle costs for each of the three cases. The results from these codes can be compared to examine the economics of the cycles leading to the three different burnup levels. The levelized fuel cycle costs present-valued to the startup of each cycle as calculated in CINCAS are shown in Table 4.1 for each case. Table 4.2 shows the levelized cumulative costs present-valued to June 1, 1987, the startup date for Cycle 10. Levelized unit costs, which are calculated by dividing the present worth cost by the present worth energy, are compared because they give the most useful representation of the relative cost for a cycle. Levelizing also helps to account for the effects of small differences in

TABLE 4.1 CINCAS Levelized Cycle Costs
mills/kwhe

Cycle	Case One	Case Two	Case Three
10	3.691	3.622	3.392
11	6.863	6.595	6.365
12	8.367	8.563	8.393
13	9.441	9.373	9.336
14	10.373	10.328	10.224
15	11.394	11.324	11.144
16	12.517	12.429	12.362
17	13.751	13.631	13.660
18	15.107	14.976	14.955
19	16.597	16.457	16.333

TABLE 4.2 CINCAS Levelized Cumulative Costs
mills/kwhe

Cycle	Case One	Case Two	Case Three
10	3.691	3.622	3.392
11	5.148	4.988	4.757
12	6.052	5.992	5.779
13	6.706	6.644	6.465
14	7.223	7.164	6.994
15	7.669	7.612	7.439
16	8.074	8.014	7.850
17	8.450	8.388	8.235
18	8.805	8.741	8.593
19	9.143	9.076	8.931

energy production in the three cases.

Examination of the CINCAS results indicates that, although the costs are close, case three was generally lower in cost than case two, and case two was generally lower in cost than case one. In terms of cycle cost, when compared to case one, case two showed decreases of 0.7 percent for steady-state, and 0.85 percent overall for Cycles 10-19. Case three demonstrated decreases of 1.1 percent for steady-state, and 2.3 percent overall. Likewise, for cumulative costs, case two showed a 0.7 decrease over Cycles 10-19 as compared to case one, and case three showed a decrease of 2.3 percent. This percentage difference translates into a cost savings over cycles 10-19 of approximately 2.63 million dollars for case two, and 10.18 million dollars for case three (see Tables 3.4, 3.8, and 3.12).

A general idea of the effect of higher discharge burnups on fuel cycle cost may be gained by plotting fuel cycle cost versus discharge burnup (Fig. 4.1). This is the way results are usually presented in the literature (B-1, F-1, S-2, S-3). Examination of Fig. 4.1 shows that the fuel cycle costs never reached a minimum for the discharge burnups studied here, although one would anticipate a broad minimum at even higher burnups.

The results of the SUNKCOST analysis of cycle and cumulative costs are presented in Tables 4.3 and 4.4, respectively. Again, the values are very similar for the three cases. Case two demonstrated a decrease in cumulative cost of 0.9 percent as compared to case one, and case three

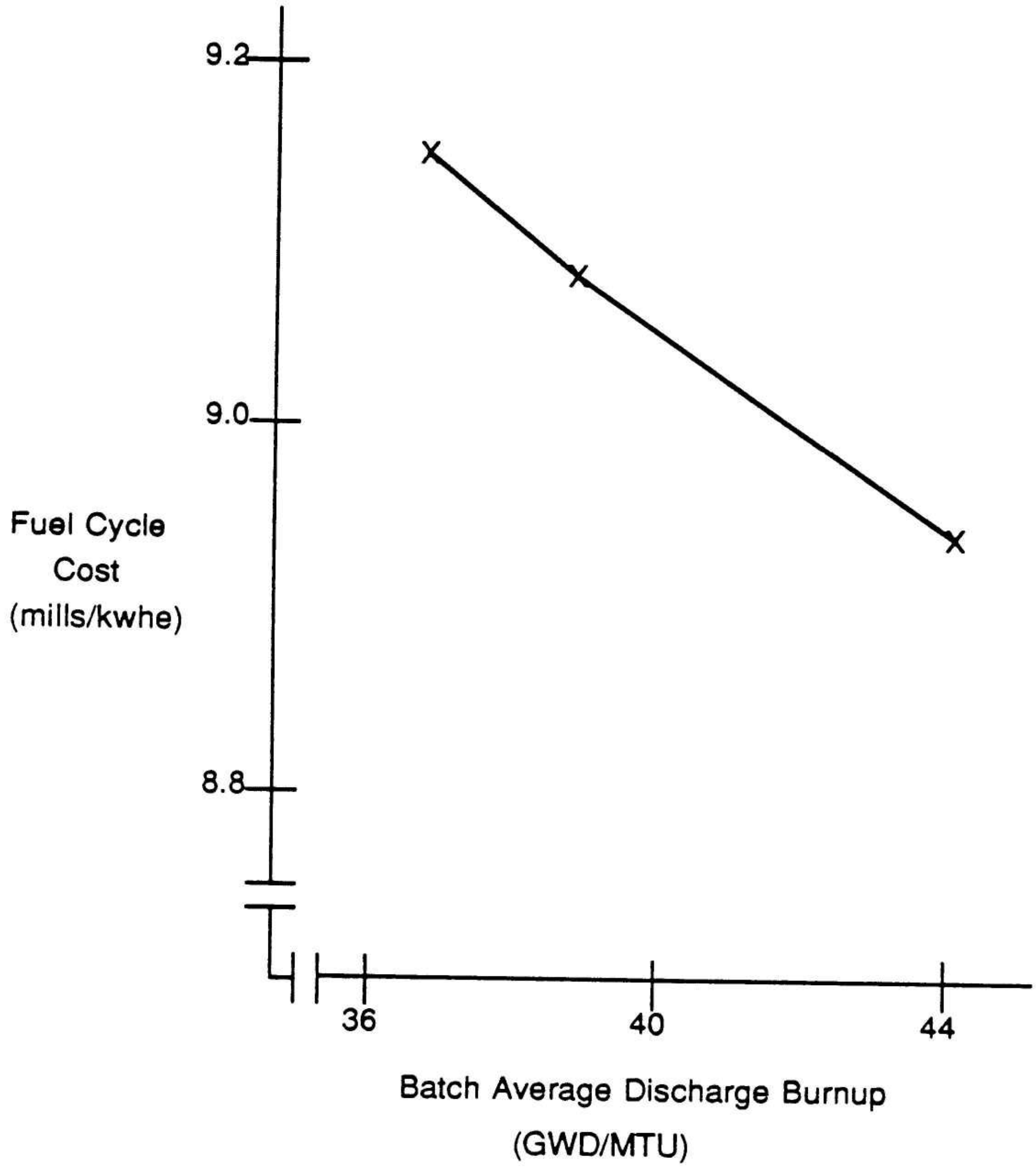


Fig. 4.1 Fuel Cycle Cost as a Function of Discharge Burnup, for Constant Cycle Length

TABLE 4.3 SUNKCOST Cycle Costs, in millions of dollars

Cycle	Case One	Case Two	Case Three
10	40.046	40.582	40.692
11	36.772	36.720	36.273
12	33.765	32.843	33.152
13	31.004	30.616	30.324
14	28.469	28.218	26.894
15	26.141	25.814	25.082
16	24.004	23.703	23.299
17	22.041	21.765	21.148
18	20.239	19.986	19.194
19	18.584	18.351	17.625
20	17.064	16.851	16.373

TABLE 4.4 SUNKCOST Cumulative Costs, in millions of dollars

Cycle	Case One	Case Two	Case Three
10	40.046	40.582	40.692
11	76.818	77.302	76.965
12	110.583	110.145	110.117
13	141.587	140.761	140.441
14	170.056	168.979	167.335
15	196.197	194.793	192.417
16	220.201	218.496	215.716
17	242.242	240.261	236.864
18	262.481	260.247	256.058
19	281.065	278.598	273.683
20	298.129	295.449	290.056

demonstrated a decrease of 2.7 percent.

Although the calculation in SUNKCOST is very simple, and the results are not equivalent to those produced by the much more sophisticated calculation in CINCAS (differences of 20 to 32 percent in absolute value are common), SUNKCOST does accurately model the relative cost trends exhibited by CINCAS, and is useful for doing a rough comparison among different cases. The percentage differences in the three cases are very similar in CINCAS and SUNKCOST. While SUNKCOST may not deliver an accurate picture of absolute cycle cost, it does accurately predict the effects of changes in the fuel cycle.

4.3 Uranium Utilization

Although the fuel cycle costs were the primary focus of the comparisons in this work, it was also desirable to compare the uranium utilization in the three cases, because that is the primary source of fuel cycle savings. Uranium utilization is generally considered to be the energy generated in megawatt days thermal per short ton of yellowcake purchased, though the precise definition is inconsistent. Since the reactor system design and the reload strategy is constant for the three cases, this analysis will use the definition derived by Driscoll, et al. (D-2), in which uranium utilization is given by:

$$U = \frac{Bd\ (F - W)}{1.3\ (P - W)}\ ,\ MWD/STU_3O_8 \quad , \qquad (4.1)$$

where F, P, and W are the enrichment in w/o U-235 of the feed, product, and tails, respectively, at the enrichment facility, and Bd is the discharge burnup of the fuel in MWD/MT.

The uranium utilization for each cycle in each case is shown in Table 4.5 based on natural uranium feed (0.711 w/o U-235) and tails of 0.2 w/o U-235. As expected, the uranium utilization improves as the discharge burnup increases. For the average uranium utilization in the steady-state cycles, the utilization was 1.8 percent better for case two and 5.5 percent better for case three when both were compared to case one.

4.4 Neutronic Codes

If significant changes are made in nuclear reload designs, it may become necessary to re-evaluate the accuracy of the neutronics codes used to calculate cycle data, particularly in the case of the nodal code, 2N. For this reason, a comparison of cycle burnups has been made between the results produced by 2N and 2D. Table 4.6 presents this comparison for the three cases. It can be seen that there is good general agreement between the two neutronics codes, but the discrepancies do increase somewhat as the cycles become less similar to Cycle 9.

TABLE 4.5 Uranium Utilization in the Three Cases Studied, in MWD/STU_3O_8

Cycle	Case One	Case Two	Case Three
10	4489.1	4591.0	4800.6
11	4591.4	4623.6	4954.0
12	4588.5	4661.7	4833.4
13	4589.5	4674.4	4870.1
14	4589.8	4665.3	4889.2
15	4589.9	4680.4	4910.1
16	4589.9	4662.4	4765.7
17	4589.9	4675.8	4796.3
18	4589.9	4672.2	**

** Discharge burnups were not calculated for Cycle 18 in Case Three

TABLE 4.6 A Comparison of 2D and 2N Cycle Burnups, in MWD/MTU

	Case One			Case Two			Case Three		
Cycle	2N	2D	% diff.	2N	2D	% diff.	2N	2D	% diff.
10	13,760	13,711	0.4	13,712	13,711	0	13,580	13,645	0.5
11	13,808	13,688	0.9	13,772	13,748	0.2	13,724	13,716	0.1
12	13,880	13,653	1.7	13,904	13,728	1.3	13,868	13,682	1.4
13	13,952	13,702	1.8	13,904	13,694	1.5	13,916	13,695	1.6
14	13,964	13,701	1.9	13,952	13,726	1.6	13,844	13,657	1.4

from Cycle 9. There appears to be no increase in the observed discrepancies as higher burnups are achieved. Average percentage differences between the two neutronics codes were found to be 1.3 percent for the first case, and 0.9 for the second and third cases.

4.5 Analytic and Neutronic Models

It is also desirable to evaluate the accuracy of the simple analytical tools and estimation methods used to initially determine the number of feed assemblies and the feed enrichment required to reach a certain discharge burnup. Specifically, the results of Equation 2.1, and the method of using the yields of previous cycles to estimate the feed loading are compared to the results obtained using 2D and CYCLE. This comparison is presented in Tables 4.7 and 4.8 for discharge burnup and enrichment. It can be seen that the analytical models are quite good at predicting the performance of the steady-state batches. The predictions are not quite as accurate for the transition cycles, but are still quite useful for rough scoping purposes. The discharge burnups are predicted to within an average of 0.3 percent in the steady-state, and within an average of 1.5 percent for the transition cycles. The enrichments are predicted to within an average of 2.6 percent for the steady-state, and to within an average of 2.7 percent for the transition cycles.

TABLE 4.7 Analytical versus Neutronic Code Results for Discharge Burnup in MWD/MTU

	Case One	Case Two	Case Three
Analytical Results *	36,724	38,884	44,068
2D Results			
Cycle			
10	35,911	39,299	43,661
11	36,729	39,024	43,796
12	36,706	38,639	43,775
13	36,714	39,033	45,429
14	36,716	39,097	44,114
steady-state	36,717	39,019	44,343

* Eq. 2.1

TABLE 4.8 Analytical versus Neutronic Code Results for Enrichment in w/o U-235

	Case One	Case Two	Case Three
Analytical Results *	3.40	3.60	3.90
2D Results			
Cycle			
10	3.34	3.56	3.78
11	3.34	3.52	3.68
12	3.34	3.44	3.76
13	3.34	3.48	3.87
14	3.34	3.49	3.75
steady-state	3.34	3.48	3.79

* Eq. 2.2

4.6 Historical Results

Finally, to gain some perspective on the general designs developed in this work, it was advantageous to compare the results obtained here to the results obtained in previous cycles designed and operated by Edison. The best way to do this was to compare the yields of the reload designs; the yield is a measure of efficiency defined by Edison as (roughly) the amount of fissile material required per unit energy produced, as defined by Eq. 2.2:

$$\text{Yield} = \frac{\text{Xf} \times \text{Number of Feed Assemblies} \times 1000}{\text{Bc}}\ , \qquad (2.2)$$

where Xf is the enrichment of the feed assemblies, and Bc is the core average cycle burnup. The designer tries to design a cycle with a yield equivalent to or less than those of past cycles; if the reactor system design and the reload design strategy are constant, a lower yield indicates a more neutronically efficient cycle.

Figure 4.2 presents the yields of past cycles, and the average yields obtained for the cycles designed in this work. It can be seen that the cycles designed in this work are at least equivalent in neutronic efficiency to those of the past. It should also be noted that the yields of the cycles designed here improve with higher discharge burnup. This is consistent with the increased uranium utilization at higher discharge burnups.

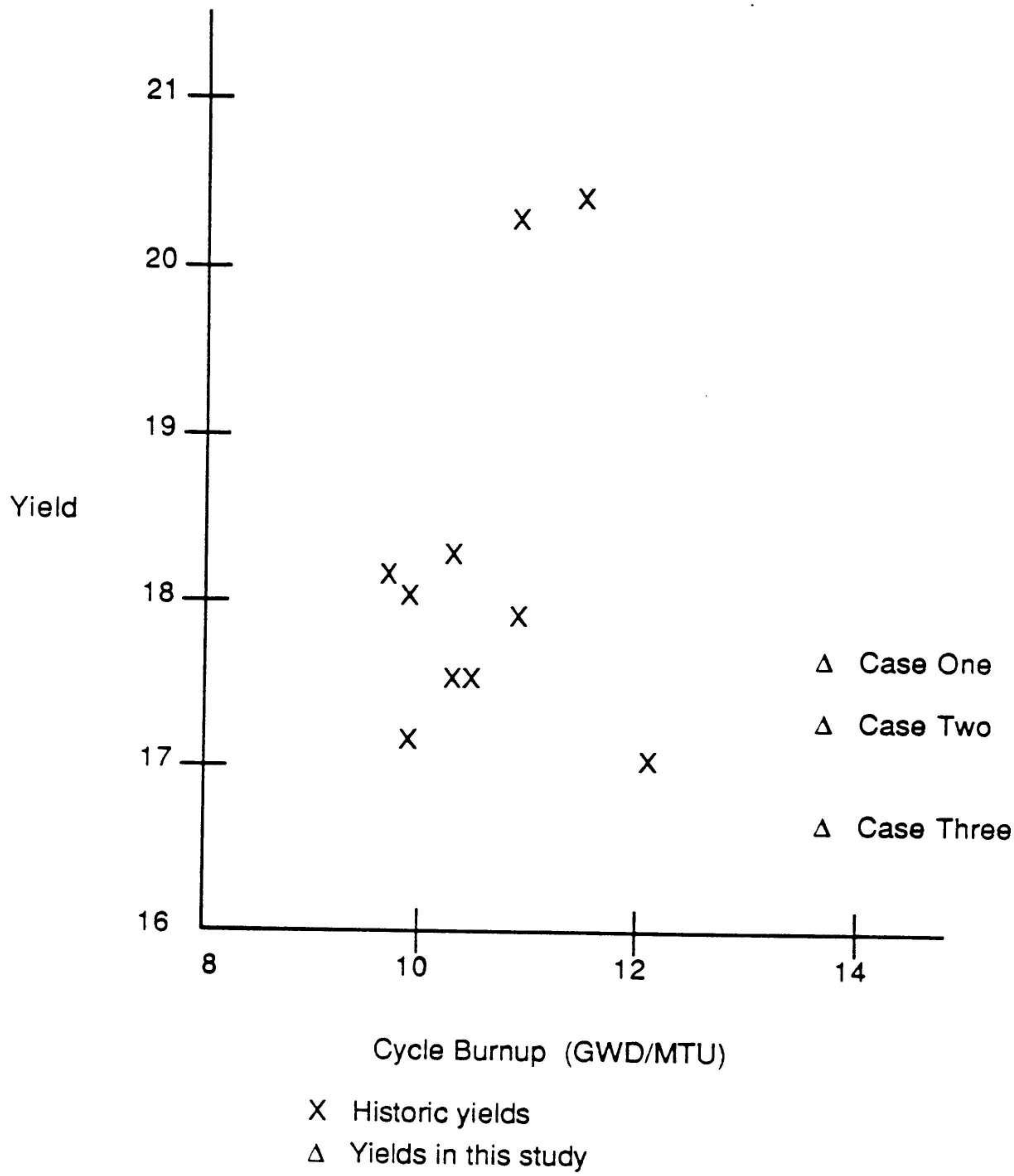


Fig. 4.2 Historic and Present Yields versus Burnup

4.7 Chapter Summary

In this chapter, a number of comparisons have been made for the three cases examined, between the different neutronic and economic analysis models, and between the results obtained here and those of previously designed and operated cycles. The reload designs leading to a discharge burnup of 45,000 MWD/MTU demonstrated the lowest fuel cycle costs, the highest uranium utilization, and the best yield of the three cases. When compared to the first case, fuel cycle costs were decreased in the third case by 2.3 percent, uranium utilization was increased by 5.5 percent, and the yield was improved by 5.5 percent.

The two neutronics codes, 2N and 2D, compared favorably over the range of this study. There was agreement in cycle burnup to within 1.3, 0.9, and 0.9 percent for cases one, two, and three, respectively. The simple analytical tools and estimation methods embodied in Eqs. 2.1 and 2.2 also performed quite well when compared to the neutronics codes. They predicted the discharge burnup within an average of 0.9 percent, and the feed enrichment within an average of 2.6 percent.

Finally, the cycles designed in this work compares favorably on the basis of cycle yield, or cycle efficiency, to cycles previously designed and operated by Edison.

CHAPTER 5

A STUDY OF OTHER TECHNICAL FACTORS

5.1 Introduction

Determination of the economically optimum burnup level is not enough in itself to justify making the transition to extended discharge burnup. Consideration must be given to other technical factors which might affect the implementation of an extended burnup program. These factors include fuel performance, safety and licensing acceptability, environmental effects, and the impact on fuel cycle services of fuel at higher burnups. Analytical or experimental determination of the effects of these factors is beyond the scope of this study; however, studies of these factors have been conducted; their results appear in the literature. These results will be compiled here as they apply to an extended burnup program.

5.2 Fuel Performance

By far, the most work on these factors has been done in the area of fuel performance, as this is likely the most limiting factor in extended burnup fuel. PWR fuel vendors Westinghouse (W), Combustion Engineering (CE), and Babcock & Wilcox (B&W) have conducted extensive high burnup fuel demonstration projects (A-1, K-1, M-1, M-3) to study the effects of high burnup on fuel performance. The primary topics of concern in the fuel performance experiments have been waterside corrosion of the fuel, fission gas release, fuel rod and fuel assembly dimensional changes, and pellet-clad interaction.

5.2.1 Waterside corrosion

Cladding corrosion and consequent hydrogen uptake in the cladding can lead to clad failure. The primary controlling factor in the corrosion process is the temperature of the clad-coolant interface. As the corrosion builds up, the thermal resistance increases, and the temperature of the interface increases, which accelerates the rate of corrosion. Crud build-up on the surface also increases the thermal resistance. W experiments (K-1) have shown that corrosion can be limited by controlling the coolant lithium-to-boron ratio to minimize crud build-up. With this control, waterside corrosion is not expected to be life limiting at high burnups. CE (A-1) and B&W (M-3) also report that, with proper attention, waterside corrosion will not be a limiting condition at high burnups. Ongoing experiments (D-3) should determine more precisely the effects of waterside corrosion on fuel performance.

5.2.2 Fission gas release

Fission gas production in the fuel is mainly dependent on fuel temperature and burnup (W-1). As the fuel accumulates high burnup toward the end of life, it is expected that the fission product inventory in the fuel will increase. However, at higher burnups, the fuel generally operates at lower powers, and therefore at lower temperatures. This will have the effect of limiting the fission product build-up; consequently, fission gas production at high burnups should not have intolerable consequences during both steady-state and accident conditions. Since the primary concern of fission gas production is the decay heat exhibited in the storage of spent fuel, higher burnup fuel with higher fission gas inventories will require a longer cooling time upon discharge from the core before any further handling (M-1). Further demonstration projects are currently being conducted to better understand the effects of fission gas build-up (D-3).

5.2.3 Fuel dimensional changes

Dimensional changes in the fuel rods and fuel assemblies include fuel assembly growth, fuel assembly bow, grid spring relaxation and rod fretting, fuel rod bow, fuel rod growth, fuel column growth and fuel swelling, and cladding creep. W experiments showed that assembly bow, grid spring relaxation, and rod bow tended to occur and saturate early in burnup. The other factors increased continuously with burnup, but remained within acceptable limits. The fuel rods also showed no indication of significant fretting wear. Overall, the mechanical condition of the assemblies was very good.

Results from CE studies (M-1) indicate that growth of fuel rods and assemblies is greater at higher burnups, but is easily accomodated by limited design changes in the fuel. Their evidence also showed that rod bowing and assembly bowing both occur rapidly in the first cycle of operation, and tend to saturate by the third cycle of operation.

Matheson et al., reported (M-3) that for B&W fuel, the fuel rod growth rate increased in the fifth cycle of operation, though current fuel designs have a gap allowance which will permit burnups exceeding 50 GWD/MTU without affecting operating limits. They also found that fuel rod creep ceases in the range of 40 GWD/MTU. With respect to overall fuel performance, they stated that fuel failure was found not to increase linearly with burnup. High burnups have not shown a higher rate of fuel failure. This confirms the results of the CE studies.

5.2.4 Pellet-clad interaction

It has been postulated that pellet-clad interaction (PCI) may be a major concern at high burnups due to the increased fission product inventory and clad creep (W-1). However, analysis of W and other data (W-1) has shown that PCI tends to saturate after approximately 15,000 MWD/MTU of burnup. The lower power levels experienced by the highly burned fuel limit the PCI effects. It is the belief of Matheson et al. (M-3), that the risk of cladding breach at higher burnup is no more significant than at normal burnups.

CE fuel rod performance has been discussed in terms of the number of rods that have been found to leak. Andrews and Matzie reported (A-1) that CE experience has shown that most fuel defects occur in the first cycle of operation. Of a total of 799,500 rods with one cycle of exposure as of November 1, 1984, 0.0175 percent were found to leak. This percentage decreased to 0.008 percent for rods with two cycles of exposure, and 0.006 for rods with three cycles of exposure. Of 109,000 rods with more than three cycles of exposure, none were found to leak. The conclusion they drew from this is that the extended residence time has not resulted in any life limiting conditions within the bounds of plant operation thus far.

5.3 Safety and Licensing Acceptability

In addition to the analysis of reload designs under normal operating conditions, it is important to examine the effects of extended burnup on safety and licensing acceptability in the case of an accident. W used point reactor reload designs to study the consequences of four major accidents: rod ejection, steamline break, loss of coolant (LOCA), and rod/bank out of position. They also evaluated the kinetics parameters, and compared them with limits previously established for the Surry units. They found that the conclusions of the Surry FSAR accident analyses were valid for the reload designs in their study. From this, they concluded that no extraordinary licensing problems exist from a safety analysis point of view, and that standard licensing procedures apply.

5.4 Environmental Effects

The current generic assessment of the environmental impact of the nuclear fuel cycle contained in 10CFR51 and other U.S. Nuclear Regulatory Commission (NRC) reports did not consider burnups beyond 33,000 MWD/MT, according to Mauro, Eng, and Coleman (M-3). Their study sought to extend the applicability of current generic analyses to extended burnups by duplicating the methods originally used by the NRC, and investigating the impacts at higher burnups. Their results showed that the impacts of extended burnup are comparable to or less than those currently listed by the NRC. They concluded that the current NRC impact values and generic analyses are applicable to fuel burnups up to 60,000 MWD/MTU. The environmental impacts of an extended burnup program are no greater than those of current burnup levels, and they will not limit the implementation of such a program.

5.5 Impact on Fuel Cycle Services

Because higher burnups require higher enrichments, the impact of extended burnup on such fuel cycle services as shipping and fabrication should be assessed. W performed a detailed study (K-2) of the impacts of enrichments as high as 4.5 w/o U-235, and found that no research and development projects would be required to produce fuel with that enrichment. Any facility license modifications could be made using current engineering practices. Evaluation of specific shipping and storage methods may be required to relicense these aspects for higher enrichments; however, major design changes should not be needed.

5.6 Chapter Summary

An evaluation of the effects of a number of factors on the implementation of an extended burnup program was presented in this chapter. Fuel performance studies have demonstrated that, with the possible exception of the effects of waterside corrosion of the cladding, fuel performance will not be compromised at high burnups. Success in current studies of methods for reducing the waterside corrosion rate through advanced cladding or coolant chemistry control would eliminate the remaining concern for extending discharge burnup beyond 50 GWD/MTU (M-3).

No major impact on safety and licensing acceptability is expected with an extended burnup program. The environmental impact of such a program is equivalent to or less than the impact of current operating cycles. Although further study of specific licensing effects on fuel shipping and storage is required, the impact of an extended burnup program on fuel cycle services is expected to be minimal.

Examination of the literature has shown that, although additional study is required in some areas, such as waterside corrosion of fuel rods, the factors presented here will not adversely impact an extended burnup program. According to Kapil and Ankney (K-2), no technical specification changes will be necessary to accomodate extended burnup. Andrews and Matzie (A-1) reported that no insurmountable technical problems are expected as a result of irradiating PWR fuel to extended burnups, and that no discontinuous effects or abrupt limitations have been observed thus far to burnups in excess of 50 GWD/MTU.

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary and Conclusions

Extending the discharge burnup of light water reactor fuel can result in increased uranium utilization and reduced fuel cycle costs. The magnitude of these changes depends upon the reload design program by which the extended burnup is reached. Reload design programs were developed to reach each of three discharge burnups: 36,000 MWD/MTU, 40,000 MWD/MTU, and 45,000 MWD/MTU. The results from these reload designs were then input to a fuel cycle economics code to determine which was the most economical discharge burnup. Finally, studies of other factors that might affect the implementation of an extended burnup program were compiled from the literature.

The process by which a reload design program is produced was presented in Chapter 2. The process begins with data from the previous cycle, a target cycle energy, and a target discharge burnup. Using the methodology outlined in Chapter 2, loading patterns are developed and used to generate the neutronic data required as part of the input for an economic analysis. Based on this data, and the economic conditions of the period of interest, an economically improved discharge burnup level can be calculated.

The results of this reload design process for the three cases were presented in Chapter 3. It was found that the cycles in the first case, which were the closest to those currently being designed and operated by Edison, were the easiest to develop and reached steady-state in the fewest number of cycles. In contrast, the cycles in the third case were difficult to develop. Whereas in the first two cases, the steady-state number and enrichment of feed assemblies were loaded in each cycle starting from Cycle 10, the design process in the third case was unsuccessful in Cycles 10 and 11 with the steady-state loading. The third case therefore required two interim cycles with nonsteady-state loading to start the transition to steady-state cycles.

Power peaking and MTC limits were easily met in the first and second cases. In the third case, power peaking was a problem; the most limiting $F\Delta H$ was very close to its limit in every cycle. The total number of burnable poison rods added to each cycle decreased from the first to the third cases; however, the average number of burnable poison rods per feed assembly increased from 8 in the first and second cases to 8.7 in the third case. This is indicative of the observation that power peaking was more of a problem in the third case.

The fourth chapter presented comparisons of the three cases, and of the different calculational methods employed in the analysis of those cases. Fuel cycle cost was found to decrease by 0.85 percent from the first to the second case, and by 2.3 percent from the first to the third case. This fuel cycle cost savings translates over the 10 cycles in the analysis to approximately 2.63 million dollars for the second case, and 10.18 million dollars for the third. Figure 6.1 presents the fuel cycle cost as a function of burnup to demonstrate the general downward trend in fuel cycle cost with burnup. A minimum fuel cycle cost was not reached in this study, though one is expected to occur at higher burnups.

Uranium utilization improved by 1.8 percent from the first to the second cases, and by 5.5 percent from the first to the third cases. Since the number of feed assemblies required per cycle decreased with increasing burnup, the spent fuel generated per cycle also decreased with increasing burnup. For the steady-state cycles, spent fuel production decreased by 5.6 percent from the first to the second cases, and by 16.7 percent from the first to the third cases. Though not studied in this work, the decrease in spent fuel production may become an additional driving force for extending burnup in the future as spent fuel pools begin to reach their capacity limits.

Good agreement was found between the two neutronics codes, 2N and 2D. They generally corresponded to within 1.3 percent on cycle burnup. These differences did not change significantly with higher burnups, indicating that no changes to 2N will be required to accomodate higher cycle and discharge burnups, and the enrichments that are required to reach those burnups. The simple analytical tools and estimation methods presented in Section 2.2 effectively predict the feed assembly number and

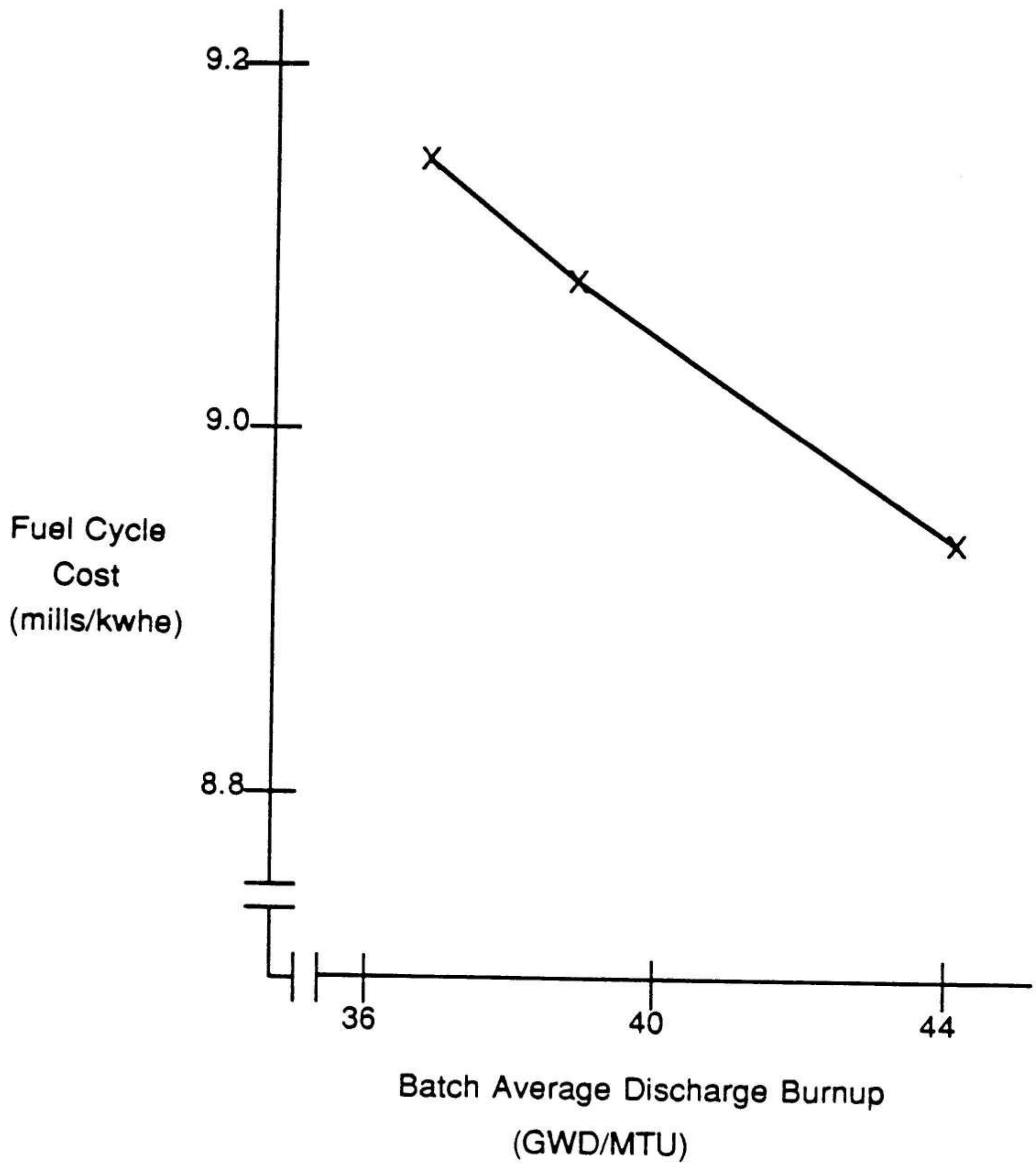


Fig. 6.1 Fuel Cycle Cost as a Function of Discharge Burnup, for Constant Cycle Length

enrichment that will be required to reach predetermined cycle and discharge burnups. The simple cost code, SUNKCOST, however, did not present accurate results when compared to the more detailed CINCAS. SUNKCOST modeled the general cost trends, but exhibited large errors in its predictions of actual costs. In a comparison of the cycles designed in this work with earlier cycles designed and operated at Edison, the cycles designed here are at least equivalent, and in some cases better, in terms of yield or neutronic efficiency. The neutronic efficiency of the cycles designed here also improves with higher discharge burnup.

Studies of other factors that might affect the implementation of an extended burnup program were compiled from the literature. Although further assurance is required on some of the factors, such as waterside corrosion of the cladding, studies to date indicate that there should not be any technical factors which would preclude extending the discharge burnup of LWR fuel. Fuel performance in demonstration projects has been very good. Studies of the safety and licensing effects of extended burnup show that no changes are required in the safety analysis of extended burnup reload designs. The environmental impact of extended burnup is in most cases less than that of current cycles. Finally, further study is required on the specific effects of extended burnup on such fuel cycle services as fuel fabrication, but no major modifications are expected to be needed.

6.2 Recommendations for Future Action and Analysis

The highest burnup (third) case demonstrates the lowest fuel cycle cost, the highest uranium utilization, and the lowest spent fuel generation. However, difficulties in meeting engineering constraints were the greatest in the third case. Power peaking limits were barely met in each cycle, and a large number of iterations were required to produce a successful loading pattern for each cycle. The reload designs were shown to be achievable, but not without an amount of effort that might prove to be too time-consuming for routine reload design. Before a discharge burnup of 45,000 MWD/MTU can be adopted as a goal, changes may be needed in the means and procedures by which it is reached. The type of burnable poison used may need to be changed, and the transition to higher discharge burnups may need to be made over a greater number of cycles.

In addition, the effects of the higher feed assembly enrichment required to reach 45,000 MWD/MTU must be studied, particularly its effects on the fuel fabrication facility and spent fuel pool licenses. Ongoing studies of extended burnup effects on fuel performance should be monitored. The capacity of the spent fuel pools, and the amount of fuel currently projected to be discharged, should be considered. As stated above, a discharge burnup of 45,000 MWD/MTU will reduce the spent fuel generation by 16.7 percent (compared to a discharge burnup of 36,000 MWD/MTU).

No changes should be required to the neutronics codes, 2N and 2D, as a result of an extended burnup program. The simple analytical tools and estimation methods can also be effectively used at higher burnups. However, improvements should be made in SUNKCOST to better model the fuel cycle costs. SUNKCOST does model the cost trends, but greater accuracy in the actual costs it produces will increase its usefulness. Abbaspour's SIMMOD (A-3) is an example of a simple fuel cost code which yields good results (to within 2.52 percent when compared to results from MITCOST-II). Cycles can be designed for higher discharge burnups which are more neutronically efficient than those currently being operated.

It may be desirable to investigate burnups higher than 45,000 MWD/MTU, as a minimum fuel cycle cost was not reached below that burnup. However, some changes, as mentioned above, need to be made in the reload design methodology to reach higher burnups. Once these changes are made, it may also be a good idea to examine the effects of extending the cycle length to 24 months.

Assuming that current studies do not reveal any detrimental effects of extended burnup on fuel performance, it appears that the implemention of an extended burnup program would be advantageous for a utility in terms of fuel cycle cost, uranium utilization, and spent fuel generation. While reload design is reactor specific, it appears that any design difficulties associated with higher burnup fuel can be overcome.

APPENDIX A

REFUELING STRATEGY

A.1 Introduction

In this appendix, the refueling strategy followed in this work will be discussed in greater detail. The objectives of the reload design program have been presented in Chapter 1, and the reload methodology has been described in Chapter 2, but some of the rationale for the underlying decisions may not be self-evident. Thus an explanation of the refueling strategy chosen, together with elementary analytic models illustrative of all key points are presented here.

A.2 Refueling Strategy

Since nuclear units are usually run as base load units, availability of the units is important, expecially during the peak periods of summer and winter. For this reason, reactors are usually run on twelve-, eighteen-, or twenty-four month cycles, with refueling in the spring or fall. It is therefore desirable to keep the cycle length constant. The cycle length for each individual unit is chosen based primarily on economic factors. A large number of reactors are already either at, or committed to, eighteen-month cycles, so it is of interest to examine the fuel cycle cost effects of extended discharge burnup based on a constant cycle length.

With a constant cycle burnup, the only way to increase the discharge burnup is to decrease the number of feed assemblies. This effect is demonstrated in Eq. 2.1:

$$\text{Number of feed assemblies} = \frac{\text{Target Bc}}{\text{Target Bd}} \times 193, \quad (2.1)$$

where Bc is the cycle burnup, Bd is the discharge burnup, and 193 is the total number of assemblies in the core. It can be seen that with a constant cycle burnup, and a constant total number of assemblies in the core, the discharge burnup is inversely proportional to the number of feed assemblies. Moreover, if the number of feed assemblies is decreased to extend the discharge burnup, then the enrichment of those feed assemblies must be increased to keep the cycle burnup constant.

From a simplistic picture of core neutronics, this approach can be described as keeping the total U-235 mass constant in each batch, so that when homogenized over the entire core, this amount of U-235 will drive the core to the same total cycle burnup, independent of the number of feed assemblies used to load the required amount of U-235. The number of feed assemblies, multiplied by their enrichment, is directly proportional to the amount of U-235 in the feed batch; hence, keeping this product (the total U-235 loading) constant should keep a constant cycle burnup. This isn't true in a strict sense; uranium and U-235 utilization improve with higher discharge burnup; thus the core requires less U-235 to reach a given cycle burnup. However, it is a good first approximation.

The discharge burnup is increased when fewer feed assemblies are charged, because the total cycle burnup (which again is constant) is distributed over fewer feed assemblies. With fewer feed assemblies, their enrichment is higher, therefore their reactivity is higher, their power is higher, and their discharge burnup is higher. Moreover, charging more than 1/n th of the core will result in premature discharge (one cycle early) of some of the fuel.

In this work, the reload design is based on three-batch management, but the number of feed assemblies in the steady-state is never equal to exactly one-third of the core. This means that all the feed assemblies in a single batch will not be discharged together; some assemblies will be removed from the core a cycle early. Figure A.1 demonstrates the way in which a batch is split upon discharge. With 193 assemblies in the core, and 72 assemblies in the feed batch, some of the assemblies in the feed batch will remain in the core for two cycles of exposure, while the remainder will stay in the core for three cycles. There will be 23 assemblies discharged after two cycles, and the remaining 49 assemblies will be discharged after three cycles. The batch average discharge burnup is then calculated by averaging the discharge burnups of all 72 assemblies. This batch average discharge burnup is the discharge burnup referred to throughout this work.

One might expect to have a large difference (e.g., one cycle burnup's worth) between the burnups of the assemblies discharged after two cycles,

Cycle	No. of Assemblies	
1	72	Fresh reload fuel batch
2	72	Same batch, burned one cycle
	→	23 Discharged after 2 cycles
3	49	
	→	49 Discharged after 3 cycles
Total assemblies in the core:	193	72 Total discharged

Batch average discharge burnup calculated as the number-weighted average of the discharge burnups of these 72 assemblies

Fig. A.1 Fractional Batch Scheme for Steady-State Cycles in Case One and the burnups of the assemblies discharged after three cycles. However, the assemblies that are discharged after two cycles are the least reactive, and therefore the most highly burned, of the assemblies in the original feed batch. This selection process has the effect of limiting the differences in burnup between the two groups.

A.3 Analytic Models

The effect of a change of burnup on feed assembly enrichment, assuming equal power sharing, and that n is an integer (where n is determined by dividing the total number of assemblies in the core by the number of feed assemblies), can be estimated using the following equation which was fit to Zion data (D-4):

$$Bd = (2n/n+1)\ 9000\ (Xp - 1.0) = Bc/n\ ,\ \text{MWD/MTU}\ , \qquad (A.1)$$

where Bd is the discharge burnup, Xp is the feed assembly enrichment, and Bc is the core average cycle burnup. This relation, however, does not accurately model the strategy followed in this work, because n is not an integer (the number of feed assemblies, N, is greater or less than 193/3).

Another relation is needed for the case in which the enrichment is fixed, and N is varied. An analysis of oversize batch reloads in the steady-state with equal power sharing (D-4), yields the following relations:

$$Bc = \frac{B1}{n\,[\,1 - 0.5(n-1)\,(N/Nt)]}\ ,\ \text{MWD/MTU, and} \qquad (A.2)$$

$$Bd = \frac{B1\,[2n/(n+1)]}{(nN/Nt)\,\{1-[(n-1)/(n+1)]\,[(nN/Nt)-1]\}}\ , \quad MWD/MTU, \qquad (A.3)$$

where Nt is the total number of assemblies in the core, and B1 is the discharge burnup attainable in a one-batch core (which can be estimated using Equation A.1, for example). This equation shows that the cycle burnup increases as the number of feed assemblies is increased. Increasing the number of feed assemblies will, in effect, replace twice- or thrice-burned fuel in the core with fresh fuel. This will add reactivity, which will increase the burnup of the cycle. Again, Equation A.2 does not accurately model the strategy followed in this work, because the feed assembly enrichment was not held constant through this study.

Analysis of the behavior of the case with a fixed cycle length is not as obvious as the analysis in either of the two preceeding cases, because both the number and the enrichment of the feed assemblies can be varied. Analysis of this case involves the concurrent use of Equation A.1 to compute the effect variable enrichment, and Equation A.2 to describe the effect of variable batch size.

The idea behind this analysis is to examine the change in cycle burnup due to a change in the feed assembly enrichment, with n as an integer, and then to find the change in feed assembly number, at fixed enrichment, which will be required to return the cycle burnup to its original value. The cycle burnup will have then remained effectively unchanged, while both the number and the enrichment of the feed assemblies will be changed. The resulting relation for the feed enrichment savings due to an increase in the number of feed assemblies is:

$$(Xp - Xp^*) = (Xp - Xo)\,[(n - 1)/(n + 1)]\,f \;, \quad \text{w/o U-235}, \qquad (A.4)$$

where Xp is the feed enrichment for a reference case, Xp* is the new feed enrichment, Xo is a constant found from curve fitting Bd(n,Xp) computations (and equal to approximately 1.0 for Zion), n is the number (integer) of batches in the core (three in this case), and f is the fractional change in the feed region size (e.g., f is 0.125 for an increase in the feed assembly number from 64 to 72).

The percentage change in discharge burnup, ΔBd/Bd, according to Ref. D-4, is approximately equal to (Xp - Xp*)/(Xp - Xo). As an example of the use of this analytic model, the change from the first to the third cases in this work can be examined. The number of feed assemblies changed from 72 to 64, so f will be 8/64, or 0.125. The feed enrichment for 64 feed assemblies was approximately 3.73 in case three. Using Eq. A.4, the enrichment savings can be calculated to be 0.17 w/0 U-235. The subsequent decrease in discharge burnup is 6.2 percent. This compares to the actual enrichment savings of 0.39 w/o U-235, and a decrease in discharge burnup of 16 percent.

The results of this analytic model and those predicted by the neutronic codes are shown in Fig. A.2 for enrichment versus feed assembly number,

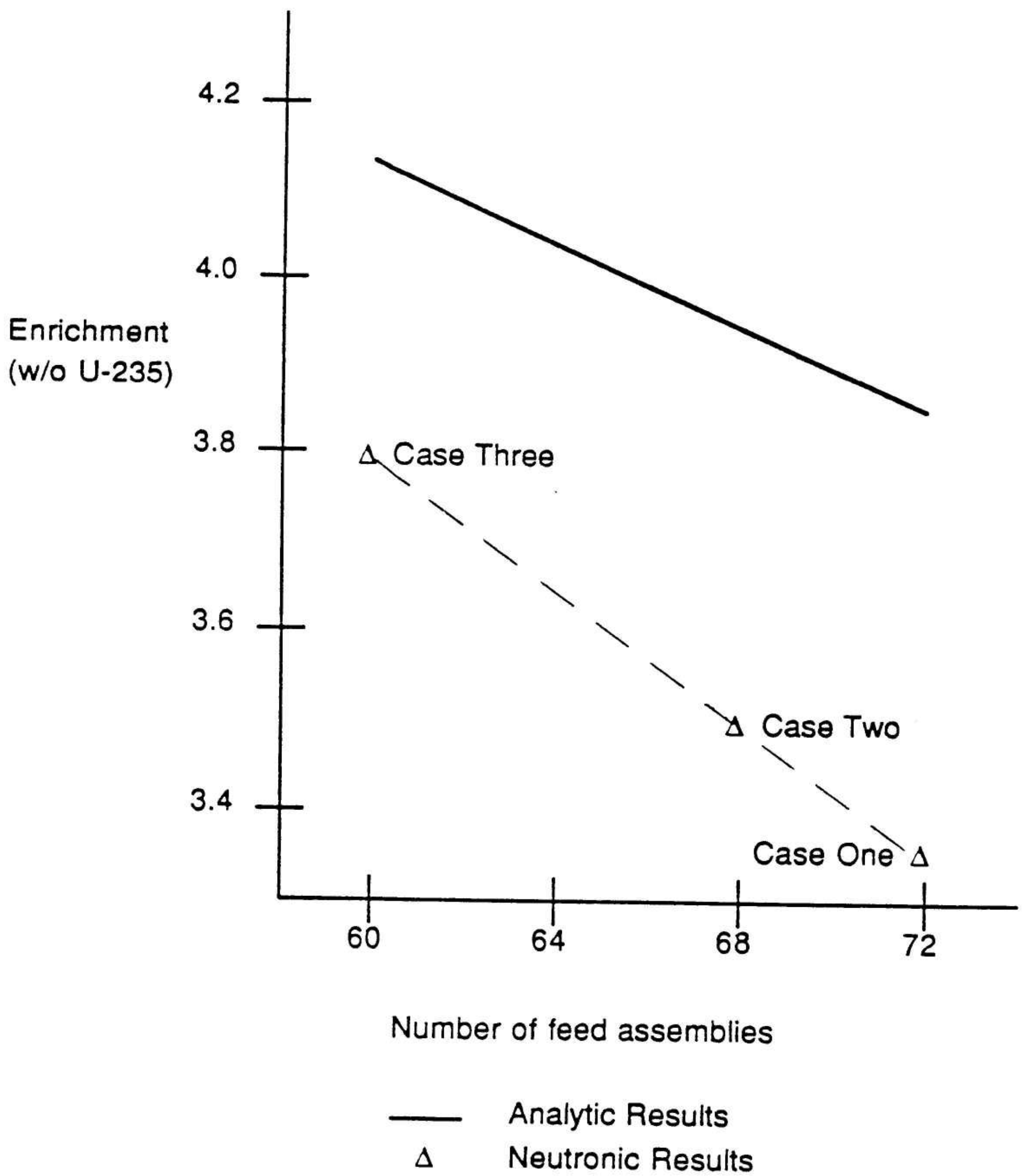


Fig. A.2 Enrichment versus Number of Feed Assemblies; Analytic and Neutronic Results

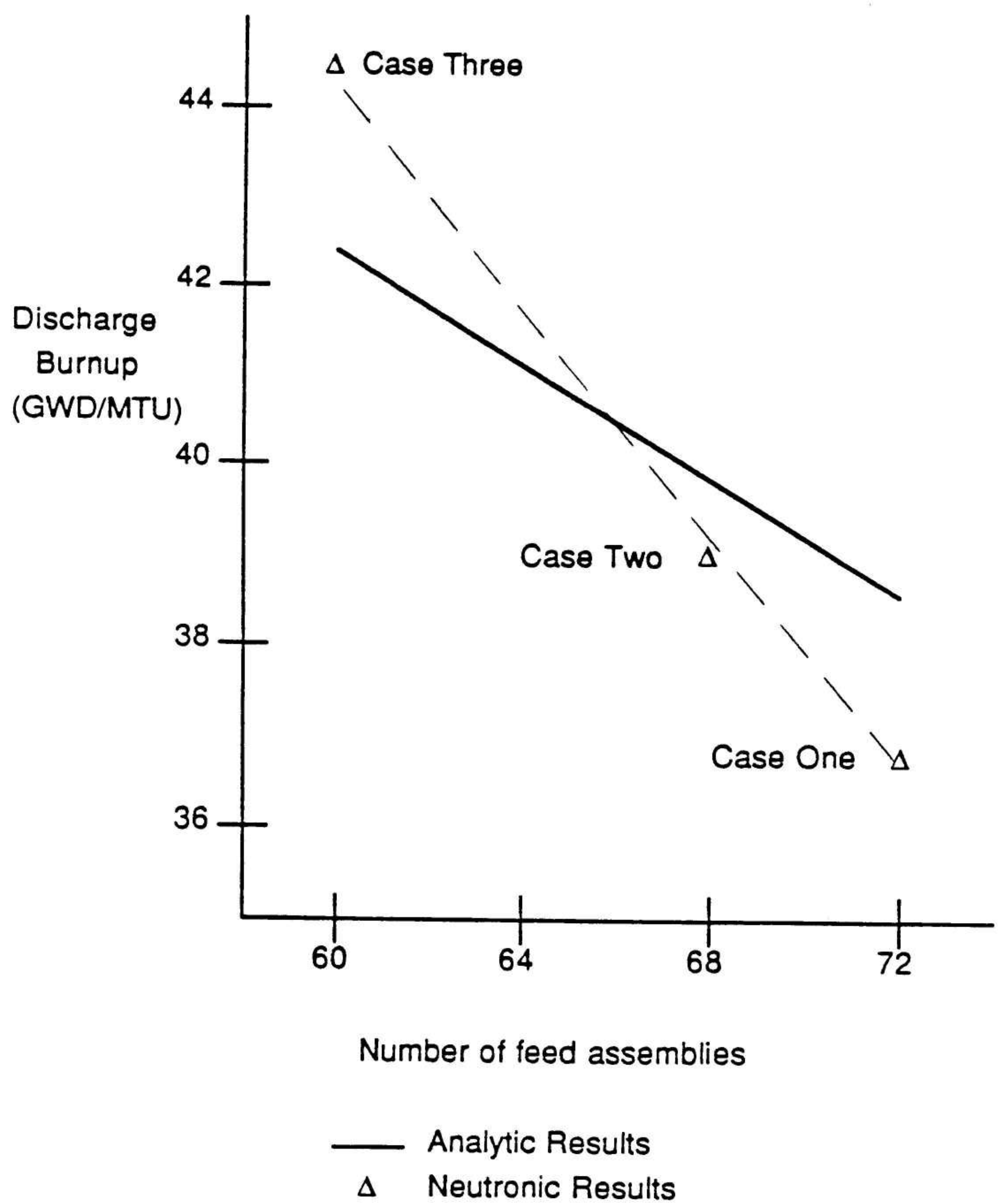


Fig. A.3 Discharge Burnup versus Number of Feed Assemblies; Analytic and Neutronic Results and in Fig. A.3 for discharge burnup versus feed assembly number. Recall that the analytic results are based on a fixed cycle burnup and equal power sharing. It can be seen that both the average feed assembly enrichment, and the average discharge burnup, decrease with an increase in the number of feed assemblies. At a qualitative level, the analytic model confirms the refueling strategy presented above; quantitative agreement is poor, however, because assemblies do not all run at the same power, and because in the actual refueling process, the least reactive twice-burned fuel is selected for discharge.

The economic effects of these changes in feed assembly number and enrichment can also be demonstrated analytically. The levelized fuel cycle cost can be estimated as the front end cost of a batch, divided by the burnup of the batch. For representative current economic conditions, the cost of fresh fuel is approximately equal to 400(Xp) - 100 dollars/kgHM (D-4), and burnup is approximately equal to 13,500(Xp - Xo) MWD/MTU (see Equation A.1) for three-batch fuel management. The levelized fuel cycle cost is therefore roughly proportional to [(Xp - 0.25)/(Xp - 1)], and hence decreases with increasing enrichment (decreasing number of reload assemblies per batch).

A.4 Appendix Summary

The strategy followed in this work was discussed in more detail in this appendix. In simple terms, this strategy was to hold the core average cycle burnup constant, and increase the batch average discharge burnup by increasing the number of feed assemblies, and decreasing their enrichment. The discharge burnup was calculated as the average of the discharge burnups of the assemblies in a particular batch.

Analytic models were presented to justify the refueling strategy. These demonstrate the trends that were to be expected in the actual reload design process.

APPENDIX B

LOADING PATTERN AND ASSEMBLY DATA

In this appendix, additional assembly and core data generated in the neutronics code 2D for Cycles 10-14, for each of the three cases, are presented to illustrate the loading patterns that were developed. Table B.1 shows the limiting $F_{\Delta H}$ factor for each of the reload cores designed. Figures B.1 through B.5 show the loading patterns developed for case one, Fig. B.6 through B.10 show the loading patterns developed for case two, and Fig. B.11 through B.15 show the loading patterns developed for case three.

TABLE B.1 Limiting $F_{\Delta H}$ Factors in the Three Cases Studied

Cycle	Case One	Case Two	Case Three
10	1.426	1.422	1.429
11	1.415	1.416	1.435
12	1.403	1.417	1.435
13	1.412	1.411	1.434
14	1.398	1.425	1.429

6,1 25,968					
2,2 14,173	F 3.4 20				
6,6 12,425	7,4 13,079	3,2 26,353			
F 3.2 16	5,2 15,700	F 3.4 16	7,1 26,637		
4,1 15,442	6,5 14,875	5,4 15,563	F 3.2 12	6,2 29,845	
F 3.4 12	7,5 20,132	F 3.2 12	6,3 15,726	F 3.4 8	F 3.4 0
3,2 26,353	F 3.4 8	7,2 13,781	F 3.4 4	4,3 15,445	7,3 28,558
6,2 29,845	8,3 8911	F 3.4 0	8,2 24,122		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.1 Case One, Cycle 10 Assembly Data

5,1 30,780					
4,1 17,662	3.2 F 12				
6,6 14,060	7,4 14,785	7,3 28,151			
3.4 F 20	4,3 17,076	3.4 F 12	2,1 29,744		
6,1 17,190	7,2 16,046	5,4 17,162	3.2 F 12	7,3 28,151	
3.4 F 12	7,5 24,759	3.2 F 12	6,3 17,570	3.4 F 8	3.4 F 0
2,2 17,444	3.4 F 8	6,5 16,469	3.4 F 0	8,2 18,056	3,2 28,719
3,1 28,709	8,3 10,655	3.4 F 0	5,2 29,991		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.2 Case One, Cycle 11 Assembly Data

4,2 32,970					
4,1 17,830	3.2 F 16				
6,6 13,677	7,4 14,829	2,2 17,105			
3.4 F 12	7,5 26,717	3.4 F 12	5,2 31,536		
6,1 17,502	6,5 16,111	4,3 17,563	3.2 F 8	7,1 31,339	
3.4 F 12	5,4 16,965	3.2 F 12	8,2 20,284	3.4 F 8	3.4 F 0
3,1 30,341	3.4 F 8	7,2 16,308	3.4 F 4	6,3 17,124	7,3 30,735
5,2 31,536	8,3 10,617	3.4 F 0	3,2 30,680		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.3 Case One, Cycle 12 Assembly Data

5,1 32,910					
6,1 17,425	F 3.2 16				
6,6 13,884	7,4 14,430	2,2 17,172			
F 3.4 16	7,5 26,081	F 3.4 12	2,1 33,039		
4,1 17,370	7,2 16,007	8,2 19,889	F 3.2 8	5,2 31,463	
F 3.4 12	5,4 17,580	F 3.2 12	4,3 17,597	F 3.4 8	F 3.4 0
3,1 29,799	F 3.4 8	6,5 16,256	F 3.4 4	6,3 17,535	7,3 30,643
5,2 31,463	8,3 10,553	F 3.4 0	3,2 30,560		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.4 Case One, Cycle 13 Assembly Data

2,1 32,700					
6,1 17,303	F 3.2 16				
6,6 13,912	7,4 14,592	2,2 17,314			
F 3.4 12	7,5 26,509	F 3.4 12	5,1 32,637		
4,1 16,907	7,2 15,980	6,3 17,592	F 3.2 8	5,2 31,225	
F 3.4 12	5,4 17,559	F 3.2 12	4,3 17,448	F 3.4 8	F 3.4 0
3,1 29,898	F 3.4 8	6,5 16,383	F 3.4 4	8,2 19,816	7,3 30,673
5,2 31,225	8,3 10,534	F 3.4 0	3,2 30,294		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.5 Case One, Cycle 14 Assembly Data

2,1 27,834					
4,1 15,442	3.6 F 20				
2,2 14,173	6,5 14,875	7,5 20,132			
3.4 F 16	7,2 13,781	3.6 F 12	6,1 25,968		
7,1 26,637	7,4 13,078	6,2 29,845	3.6 F 12	3,2 26,354	
3.6 F 12	5,4 15,563	3.4 F 12	5,2 15,700	3.6 F 8	6,6 12,425
7,5 20,132	3.6 F 12	6,3 15,726	3.6 F 4	4,3 15,445	8,2 24,121
3,2 26,354	8,3 8911	3.6 F 0	7,3 28,558		

Feed Assemblies

F	
xx	Enrichment, w/o
yy	No. of WABAs

Shuffled Assemblies

xx	Location in previous cycle
yy	BOC Burnup, MWD/MTU

Fig. B.6 Case Two, Cycle 10 Assembly Data

3,2 30,278					
7,5 24,517	3.4 F 12				
2,2 17,660	7,2 16,831	3,1 29,985			
3.4 F 20	7,4 15,270	3.6 F 12	2,1 30,445		
6,6 23,053	6,5 16,336	7,3 30,059	3.4 F 12	4,1 17,488	
3.4 F 12	5,4 17,796	3.4 F 12	8,2 18,637	3.6 F 8	6,1 17,843
7,5 24,517	3.6 F 12	6,3 17,807	3.6 F 4	4,3 17,911	5,2 27,986
3,2 30,278	8,3 11,251	3.6 F 0	4,2 29,296		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.7 Case Two, Cycle 11 Assembly Data

7,3 32,185					
7,5 27,287	3.6 F 16				
6,1 17,788	6,5 16,649	4,1 17,582			
3.4 F 16	5,4 17,672	3.4 F 12	6,2 33,941		
6,6 28,626	7,4 15,060	3,2 32,373	3.6 F 12	3,1 33,252	
3.4 F 12	6,3 17,777	3.4 F 12	8,2 21,026	3.4 F 4	2,2 16,502
7,5 27,287	3.4 F 8	4,3 17,534	3.4 F 4	7,2 16,576	4,2 31,624
6,2 33,941	8,3 11,083	3.4 F 0	5,2 32,172		

Feed Assemblies		Shuffled Assemblies	
F xx yy	Enrichment, w/o No. of WABAs	xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.8 Case Two, Cycle 12 Assembly Data

4,2 33,287					
7,5 25,851	F 3.6 16				
6,1 17,490	6,5 15,606	4,1 17,511			
F 3.4 16	5,4 17,580	F 3.4 12	3,3 33,670		
6,6 26,550	7,4 14,589	3,2 32,755	F 3.4 8	3,1 32,962	
F 3.4 12	6,3 17,794	F 3.4 12	8,2 20,948	F 3.6 4	2,2 17,076
7,5 25,851	F 3.4 8	7,2 16,518	F 3.6 4	4,3 17,763	5,2 30,877
4,2 33,287	8,3 10,805	F 3.6 0	7,3 32,373		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.9 Case Two, Cycle 13 Assembly Data

3,3 33,505					
6,6 27,623	F 3.6 16				
6,1 17,556	6,5 16,146	4,1 17,583			
F 3.4 16	5,4 17,358	F 3.4 12	7,3 31,095		
7,5 26,759	7,4 15,003	3,2 31,509	F 3.6 8	3,1 32,846	
F 3.6 12	4,3 17,611	F 3.4 12	8,2 20,358	F 3.6 4	2,2 17,216
7,5 26,759	F 3.6 8	7,2 16,497	F 3.4 0	6,3 17,723	5,2 29,996
7,3 31,095	8,3 11,130	F 3.4 0	4,2 33,639		

Feed Assemblies		Shuffled Assemblies	
F xx yy	Enrichment, w/o No. of WABAs	xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.10 Case Two, Cycle 14 Assembly Data

7,6 30,909					
4,1 15,442	F 3.6 16				
6,6 12,425	6,3 15,726	2,1 27,834			
F 3.6 20	5,2 15,700	F 3.6 12	6,1 25,968		
2,2 14,173	7,2 13,781	7,5 20,132	F 3.6 12	6,2 29,845	
F 3.6 16	6,5 14,875	7,4 13,078	4,3 15,445	F 3.6 8	F 4.0 8
6,2 29,845	F 4.0 12	8,3 8911	F 4.0 12	5,4 15,563	8,2 24,121
7,1 26,637	3,2 26,354	F 4.0 0	7,3 28,558		

Feed Assemblies

F	
xx	Enrichment, w/o
yy	No. of WABAs

Shuffled Assemblies

xx	Location in previous cycle
yy	BOC Burnup, MWD/MTU

Fig. B.11 Case Three, Cycle 10 Assembly Data

3,2 30,709					
2,2 17,833	3.8 F 16				
6,6 14,923	7,3 23,974	6,1 17,698			
3.6 F 16	7,5 25,166	3.6 F 8	3,1 28,417		
4,1 18,255	7,4 15,453	6,3 28,471	3.6 F 12	5,1 30,248	
3.6 F 16	5,4 17,918	7,2 16,213	6,5 17,347	3.6 F 8	3.8 F 4
3,2 30,709	3.6 F 12	8,3 11,371	3.8 F 12	4,3 17,680	6,2 30,142
2,1 30,566	5,2 29,403	3.8 F 0	6,4 30,649		

Feed Assemblies

F	
xx	Enrichment, w/o
yy	No. of WABAs

Shuffled Assemblies

xx	Location in previous cycle
yy	BOC Burnup, MWD/MTU

Fig. B.12 Case Three, Cycle 10 Assembly Data

7,6 35,112					
6,1 17,541	F 3.8 12				
3,1 31,682	6,5 17,615	3,3 32,926			
F 3.6 16	7,3 27,729	F 3.8 8	2,1 33,518		
2,2 17,841	7,4 15,299	6,2 33,594	F 3.6 12	5,1 34,410	
6,6 14,959	5,4 18,038	7,2 15,296	4,3 17,824	F 3.8 8	F 3.8 4
4,1 17,702	F 3.8 16	8,3 10,935	F 3.8 8	5,2 32,055	6,3 32,935
8,1 35,483	7,5 27,716	F 3.8 0	6,4 33,433		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.13 Case Three, Cycle 12 Assembly Data

8,2 35,105					
4,1 17,348	3.8 F 12				
5,1 34,199	5,4 17,687	7,6 38,271			
3.8 F 16	6,5 17,460	3.8 F 12	7,6 38,271		
6,1 31,293	7,4 15,212	6,2 33,618	3.8 F 8	2,1 32,692	
6,6 14,709	4,3 17,966	7,2 16,125	7,3 27,011	3.8 F 8	4.0 F 4
2,2 17,933	4.0 F 16	8,3 11,226	4.0 F 8	5,2 31,469	3,2 32,461
7,1 31,102	6,3 31,113	3.8 F 0	6,4 33,443		

Feed Assemblies

F	
xx	Enrichment, w/o
yy	No. of WABAs

Shuffled Assemblies

xx	Location in previous cycle
yy	BOC Burnup, MWD/MTU

Fig. B.14 Case Three, Cycle 13 Assembly Data

7,5 39,586					
4,1 17,933	F 3.6 12				
7,6 37,501	4,3 17,878	2,1 32,790			
F 3.6 12	6,5 16,972	F 3.6 12	8,1 37,460		
7,6 37,501	7,4 15,168	3,2 32,918	F 3.8 8	7,1 31,914	
6,6 14,717	5,4 18,109	7,2 16,739	7,3 27,261	F 3.8 8	F 3.8 4
2,2 18,225	F 3.8 16	8,3 11,187	F 3.8 4	5,2 31,214	4,2 33,569
6,1 30,890	6,3 32,054	F 3.8 0	6,2 33,889		

Feed Assemblies

F xx yy	Enrichment, w/o No. of WABAs

Shuffled Assemblies

xx yy	Location in previous cycle BOC Burnup, MWD/MTU

Fig. B.15 Case Three, Cycle 14 Assembly Data

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