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Optimum Discharge Burnup for Nuclear Fuel

A Comprehensive Study of Duke Power's Reactors

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Technical Report

Optimum Discharge Burnup For Nuclear Fuel

A Comprehensive Study of Duke Power's Reactors

TR-112571

Final Report, December 1999

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REPORT SUMMARY

Economic analysis of two pressurized water reactors (PWRs) shows that increasing the discharge burnup of light water reactor (LWR) fuel above current values can result in significant cost benefits. Optimum discharge burnup levels, however, may not be achievable without exceeding the current limit on enrichment.

Background
Recent years have seen a trend toward increases in burnup levels at which LWR fuel is discharged. This trend is fueled by expectations of improved economic performance. In a few cases, discharge burnups have approached levels where further increases will require extending currently licensed burnup limits. Extending licensed limits and demonstrating that high-burnup fuel has adequate operating margins may require costly demonstration programs. Therefore, it is necessary to have a clear measure of the benefits that can be achieved by further burnup extensions.

Objectives
- To estimate economic benefits of implementing burnup extensions in a realistic utility environment.
- To determine whether an optimum burnup level exists above which costs no longer decrease.
- To identify potential technical obstacles in achieving desired optimum burnup levels.

Approach
The investigator calculated the economic advantages of transitioning to different levels of discharge burnup for two of Duke Power's PWRs (Oconee and Catawba) using standard core (loading) design and economics codes. He developed different core loading strategies that would extend discharge burnups from their current values of around 45 GWd/MTU to as high as 77 to 78 GWd/MTU by going through a number of transition cycles. He determined whether establishing such high discharge cycles would result in violating constraints on pin power or reactivity. The investigator then calculated the cost impact of the high-burnup cycles assuming eight different economic scenarios.

Results
The analysis showed that increasing discharge burnups above the current values for Duke Power can result in cost reductions from $1 M to $5 M per cycle, depending on the plant and the assumed economic scenario for market conditions. Most of the assumed economic scenarios showed an optimum between 60 and 70 GWd/MTU for the two plants. Principal exceptions were scenarios with high spent fuel storage costs or high fabrication cost. For these scenarios, benefits

continued to improve without reaching an optimum within the examined range. The analysis also identified potential technical obstacles to reaching the desired burnups. A major example is the current limitation in enrichment for LWR fuel to 5%. The highest burnups that can be economically achieved without exceeding this limitation are below or at the low end of the optimum range.

EPRI Perspective

One key objective of the Robust Fuel Program established by the utility industry is to obtain sufficient fuel performance-related data to ensure that LWR fuel has appropriate margins when operated at high burnups. Such data also can provide the basis for extending currently licensed burnup limits. Although performance data above the current limits will be needed for ensuring margins even if limits are not extended, an industry-wide economic benefit analysis is needed to help focus efforts toward the appropriate burnup range. This study, which quantifies benefits for Duke Power, constitutes a first step. To obtain an understanding on an industry-wide basis, EPRI is currently conducting a survey of other utility practices. It is anticipated that these survey results will be used to generalize this study's conclusions and extend them to other utility conditions and reactor types.

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Keywords

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ABSTRACT

EPRI has recently initiated the Robust Fuel Program to address fuel performance and reliability issues associated with U.S. light-water nuclear reactors. This program is ultimately expected to foster the development of nuclear fuel assemblies that can achieve rod burnups of 75 GWD/MTU or more with adequate operating margin. Previous analyses have shown that fuel costs continue to decrease as batch discharge burnup approaches 50 GWD/MTU, indicating that the ability to extend fuel burnup beyond current design and regulatory limits is at least economically justifiable. However, given changes in refueling design strategies, the stirrings of electric power industry deregulation, and lack of progress on the part of the Department of Energy in building and operating a high-level waste repository, the assumptions made in those earlier economic evaluations need to be refined and updated. The purpose of this study is to determine the fuel batch discharge burnups that minimize nuclear fuel costs for Duke Power's reactors, and assess the technical difficulties that must be overcome in order to realize such burnups.

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1
BURNUP OPTIMIZATION – HISTORY AND FOUNDATION FOR CURRENT STUDY

1.1 Background

Duke Power, a Duke Energy company, operates seven Pressurized Water Reactors (PWRs) at three nuclear sites: Oconee units 1, 2, and 3 in Seneca, SC; McGuire units 1 and 2 in Cornelius, NC; and Catawba units 1 and 2 in Clover, SC. The Oconee reactors are Babcock & Wilcox 2568 MWth (846 MWe) PWRs, while the McGuire and Catawba reactors are 4-loop Westinghouse designs rated at 3411 MWth (1129 MWe).

Duke Power has performed all nuclear fuel management engineering functions (except for LOCA analyses) in-house since 1985, and has used the flexibility afforded through vendor independence to pursue lower fuel costs and higher core design thermal limits.

One of the more important components of nuclear design efficiency and fuel cost-effectiveness is discharge burnup (DB) optimization.* Duke Power has investigated this on several occasions in the past. In 1984, a DB analysis was performed for Oconee 15-month equilibrium cycles.[1] In that study, batch DBs from 35 to 50 GWD/MTU were modeled by varying fuel assembly reload quantities. As expected, the "direct" fuel capital costs continued to decrease with higher DB. Factoring in the appropriately discounted "indirect" fuel financing costs brought the overall economic optimum DB to somewhere between 45 and 50 GWD/MTU. Since then, Duke Power has performed several less formal evaluations of DB economics for Oconee and McGuire/Catawba as operating cycles have lengthened and fuel assembly designs have changed. The results of these assessments were reasonably consistent with those from the early study. Most recently, a 1995 limited-scope analysis of McGuire and Catawba fuel batch feed quantities found the lowest fuel costs for the smallest feed case considered, which yielded a batch DB close to 50 GWD/MTU.[2]

Elsewhere in the industry, a 1984 EPRI report prepared by S. M. Stoller Corp. examined equilibrium 12- and 18-month cycles for a McGuire/Catawba-sized PWR.[31] This report showed

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

an economic optimum batch DB between 40 and 50 GWD/MTU for the 12-month cycles, but no minimum cost for the 18-month cycles, which were evaluated with DBs of up to 55 GWD/MTU.

Finally, a 1994 OECD project considered, among other reactor types, a 1300 MWe PWR operating on 12- to 24-month cycles.[4] When a quantity-based spent fuel disposal charge was factored into the calculations, the OECD analysis also found no optimum burnup; overall costs continued to decrease as batch DB approached 60 GWD/MTU.

Because of changes in nuclear fuel market conditions, increased sophistication and accuracy of neutronics modeling codes, and uncertainty about the future for high-level waste storage and disposal, Duke Power had planned to revisit high-burnup economics with another comprehensive evaluation in 1997. At the same time, however, the EPRI Nuclear Power Council was initiating the Robust Fuel Program to address the limitations of existing nuclear fuel products and advance the technology that would allow higher-burnup operation.[5] Since one of the first activities under this program is to determine optimum DBs for light water reactors, it was decided to tailor the new Duke Power study to suit the objectives of the Robust Fuel Program.

1.2 Scope of Current Study

This report includes descriptions and summaries of the cycle models and core loading patterns for Duke Power's Catawba and Oconee reactors, economic evaluations for all cycle designs performed, cladding corrosion predictions for selected fuel DBs, and a discussion of the obstacles to advancing fuel assembly burnup beyond current limits.

It is assumed that a Robust Fuel Assembly, capable of fuel rod burnup to at least 75 GWD/MTU, will become available by the year 2005. This date is therefore chosen as the starting and reference point for the core design calculations. Catawba and Oconee 18-month cycle depletions are carried out, with various assembly reload quantities, to obtain bounding sets of batch DBs between 40 and 80 GWD/MTU. These cycle designs are described and summarized in Section 2. Since a realistic transition to the highest DBs requires that several cycles be modeled, the years 2005 to 2025 encompass the study period for this report. The 20-year scope allows each DB case to reach its equilibrium enrichment and assembly loading pattern. The end of the study period also approximates the expiration dates for Catawba's and sister plant McGuire's operating licenses.

An economic evaluation of the different Catawba and Oconee DB designs constitutes Section 3. A suitable price range is considered for uranium, separative work, fabrication, and fuel assembly dry storage. Rates for price escalation and corporate cost of capital are also varied. For each of the Catawba and Oconee cycles modeled, batch fuel costs are calculated using the Present Value of Revenue Requirements method, the recommended technique for regulated public utilities. Results from the different cost sets are then compared as a function of batch DB to discern an economic optimum.

Though the explicit computations in this study are performed only for 18-month cycles with Duke Power's nuclear plants, Section 3.9 discusses the applicability of those results to longer cycle lengths and to other assembly and core designs.

Achieving the optimum batch DB in most cases will require fuel enrichments well above 5 wt% ^{235}U. The many issues associated with licensing such enrichments are covered in Section 4.2.

Fuel cladding corrosion estimates for the different Catawba and Oconee DB designs indicate that the current regulatory oxidation limit will present a challenge even for advanced cladding designs. This and other potential inhibitors to achieving ultra-high burnup, whether mechanical, operational, or regulatory in nature, are discussed in Section 4.3.

1.3 Computer Codes Used in This Analysis

Neutronics

Modeling of the transition and equilibrium fuel cycles for Catawba and Oconee was accomplished with Studsvik's CASMO (Cell Assembly Module) and SIMULATE computer codes.[6,7] CASMO performs fine-mesh two-dimensional transport calculations on a fuel assembly to determine pertinent nuclear cross-section information. The user models a reactor core with SIMULATE, which applies the CASMO cross-sections to predict steady-state reactor behavior as the core is depleted in a cycle of operation.

Fuel assembly loading patterns for Catawba and Oconee were generated with X-IMAGE and WinScope, two interactive graphical interfaces to the SIMULATE code.[8,9] The Electric Power Research Center's FORMOSA (Fuel Optimization for Reloads – Multiple Objectives by Simulated Annealing) code was also used to help determine optimum assembly placement within the reactor core.[10] FORMOSA uses a Simulated Annealing optimization technique to find candidate fuel and burnable poison loading patterns that satisfy the user's objectives, whether they be minimizing power peaking, maximizing burnup of discharge assemblies, or maximizing end-of-cycle core reactivity.

Economics

To compute the economics data for this report, Duke Power employed SBB (Sub-Batch Burnup), an in-house program that takes neutronics code results (enrichments, cycle lengths, assembly burnups) and calculates batch fuel capital costs and revenue requirements, given sets of user-defined economics variables.[11]

Corrosion Analysis

EPRI's PFCC (PWR Fuel Cladding Corrosion) program[12] was used to obtain corrosion estimates for both standard (Zircaloy-4) and advanced claddings. An "improvement factor," applied to the PFCC standard cladding model, provided the corrosion predictions for advanced cladding.

2
CYCLE DESIGNS

2.1 Introduction

In order to adequately define the optimum batch DBs for Duke Power's reactors, a suitable set of core designs must be modeled to achieve bounding and intermediate target burnups. In addition, the different design streams must start from a common cycle and transition in a realistic manner to the final equilibrium assembly loading patterns. The consistent application of this plan will allow a proper understanding of the economic implications associated with changing batch DBs.

Since Catawba and McGuire are sister plants that operate on 18-month cycles and have essentially the same core design constraints, it is necessary to model only one of these reactors. Catawba unit 1 is chosen for analysis along with Oconee unit 1.

As stated in Section 1.2, the year 2005 is the reference point for the Catawba and Oconee designs. All of the core models in this study begin with the same forecast end-of-cycle data, from just prior to the reference year. By varying assembly feed quantities, subsequent cycles are designed to eventually achieve batch DBs ranging from 40 to 80 GWD/MTU.

2.2 Cycle Design and Reactor Core Features

It is important to maintain consistency from one set of batch DB designs to the next so that valid comparisons can be made. The following general criteria are used for each of the Catawba and Oconee cycles analyzed:

- 18-month refueling frequency
- Same enrichment for each assembly in a fuel batch (no split batches)
- Axial blankets used in all designs
- Very-low-leakage core loading patterns
- Same end-of-cycle reactivity
- Base Load (100% of rated power) operation
- No power coastdown at end-of-cycle
- Reactivity control achieved only with burnable poisons (integral for Catawba, discrete for Oconee) and soluble boron

Most of the above features form the current design and operating philosophies for Duke Power's reactors. Section 3.9 includes a discussion of alternatives to these criteria and their anticipated effects on the observed economic trends.

Table 2.1 lists the specific reactor and fuel features for Catawba and Oconee. Duke Power expects to be using these fuel designs or similar versions in 2005. The 2.0 wt% ^{235}U enrichment in the axial blankets is chosen both for simplicity and because Duke Power has determined this enrichment to be optimum for all of its reactors.[13,14] That optimum, however, is based on current batch DBs of 45 GWD/MTU; it is likely that the most economic blanket enrichment increases with higher DBs.

Table 2.2 lists the main designer-imposed constraints for the Catawba and Oconee cycle models. The maximum radial rod powers are based on expected margins to thermal operating limits in the year 2005. Oconee has higher allowable rod peaks than Catawba because of its lower specific power.

Table 2-1
Reactor and Fuel Descriptions for Catawba and Oconee

	Catawba-1	**Oconee-1**
Reactor Core Rated Power (MWth)	3411	2568
Specific Power (W / gram U)	38.7	31.6
Number of Assemblies in Reactor	193	177
Fuel Assembly Design Type	W Performance +	FCF MkB11
Fuel Assembly Rod Array Size	17 x 17	15 x 15
Fuel Assembly Heavy Metal Weight (kgU)	456.2	459.3
Active Fuel Stack Height (inches)	144	143
Axial Blanket Length (Top or Bottom)	6	6
Axial Blanket Enrichment (wt % ^{235}U)	2.00	2.00
Axial Blanket Fuel Pellet Design	Annular	Solid
Fuel Rod Outer Diameter (inches)	0.374	0.416
Burnable Poison Type Used	Integral – ZrB_2	Discrete – B_4C/Al_2O_3

Table 2-2
Cycle Design Constraints

	Catawba-1	Oconee-1
Cycle Length (Effective Full Power Days)	500	500
Cycle Burnup (GWD/MTU)	19.4	15.8
Target Beginning-of-Cycle Core Reactivity (ppm Boron)	1800	1700
Target End-of-Cycle Core Reactivity (ppm Boron)	10	5
Maximum Radial Pin Power	1.65	1.80
Range of Batch Discharge Burnups (GWD/MTU)	40 to 80	40 to 80

2.3 Transition and Equilibrium Cycle Neutronics Calculations

With the design data and constraints discussed in Section 2.2, several different target burnup cases are modeled for Catawba and Oconee by varying the batch assembly feed quantities and adjusting enrichments to meet end-of-cycle reactivity goals. The batch center-region enrichment requirements for each of these cases are listed in Tables 2.3 and 2.4.

For both Catawba and Oconee the higher DB (lower assembly feed quantity) designs require more transition cycles to achieve equilibrium. This is because the common “starter” cycle for either reactor has a batch DB of about 45 GWD/MTU; to realistically reach a batch DB of 80 GWD/MTU entails reducing batch feed quantities gradually.

Tables 2.3 and 2.4 indicate that there is a transition penalty associated with an increase in batch DB. As batch feed quantity is reduced from one cycle to the next, some assemblies that would have been permanently discharged are faced with another cycle of irradiation, which lowers the core reactivity slightly. To make up for this penalty, the first few batches of a reduced-feed case require relatively higher enrichments than the equilibrium cycle. For example, the 72-feed design for Catawba (eventual batch DB of 51.4 GWD/MTU) requires enrichments of 4.82 wt% ^{235}U in the first cycle. The next two cycles effectively average to the final (and lower) equilibrium enrichment of 4.77 wt% ^{235}U. The economics for both the transition and equilibrium cycle results will be evaluated in Section 3.

Tables 2.5 and 2.6 show the important equilibrium cycle computational results. The highest burnup case for Catawba and Oconee (77 and 78 GWD/MTU batch DBs, respectively) violates the constraints for radial pin power, as defined in Table 2.2. The Catawba design for the highest DB case also exceeds the beginning-of-cycle core reactivity constraint. However, because the highest batch DB design is not generally the economic optimum in this study, as Section 3 illustrates, the violation of cycle design constraints for this case is not particularly important. The loading pattern / burnable poison adjustments necessary to bring these highest DB designs "within spec" would only decrease their economic attractiveness further.

Figures 2.1 through 2.4 illustrate the equilibrium cycle core loading patterns for all the different Catawba and Oconee burnup designs. As batch feed quantities are varied, the very-low-leakage scheme is maintained consistently; that provides the basis for making meaningful economic comparisons among the different core designs.

There are, of course, many other core loading options a designer could devise and implement. These can be considered perturbations to the very-low-leakage class of designs developed in this study. Such alternatives might be necessary if, for example, the reactor has more restrictive power peaking limits, or if it is operated with longer or shorter intervals between refuelings. Section 3.9 discusses the effects on optimum fuel burnup from changes to different core design variables.

Table 2-3
Catawba Feed Batch Enrichment Requirements (wt% ^{235}U)
(all cycles designed to 500 EFPD --
all assemblies have 2.00 wt% ^{235}U annular axial blankets)

Catawba Cycle	Batch Feed Quantities (Number of Assemblies)						
	88 Feed	80 Feed	72 Feed	68 Feed	64 Feed	60 Feed	48 Feed
15	*4.00*	*4.40*	*4.82*	*4.82 (72)**	*4.82 (72)**	*4.82 (72)**	*4.82 (72)**
16	*4.21*	*4.42*	*4.82*	*4.82 (72)**	*4.82 (72)**	*4.82 (72)**	*4.82 (72)**
17	*4.12*	4.41	*4.73*	*5.17*	*5.17 (68)**	*5.17 (68)**	*5.17 (68)**
18	*4.16*	4.41	4.77	*5.01*	*5.25 (64)**	*5.25 (64)**	*5.25 (64)**
19	4.14	4.41	4.77	*4.95*	*5.26*	*5.26 (64)**	*5.26 (64)**
20	4.14	4.41	4.77	*5.03*	5.24	*5.78*	*5.78 (60)**
21	4.14	4.41	4.77	*5.02*	5.24	*5.58*	*6.02 (56)**
22	4.14	4.41	4.77	5.01	5.24	*5.49*	*6.68 (52)**
23	4.14	4.41	4.77	5.01	5.24	5.56	*6.73*
24	4.14	4.41	4.77	5.01	5.24	5.56	*6.86*
25	4.14	4.41	4.77	5.01	5.24	5.56	*7.17*
26	4.14	4.41	4.77	5.01	5.24	5.56	*6.94*
27	4.14	4.41	4.77	5.01	5.24	5.56	6.91
28	4.14	4.41	4.77	5.01	5.24	5.56	6.91

* -- The numbers in parentheses indicate a different batch feed quantity for these transition cycles

Table 2-4
Oconee Feed Batch Enrichment Requirements (wt% ^{235}U)
(all cycles designed to 500 EFPD --
all assemblies have 2.00 wt% ^{235}U solid axial blankets)

Oconee Cycle	Batch Feed Quantities (Number of Assemblies)				
	68 Feed	56 Feed	48 Feed	40 Feed	36 Feed
23	*3.60*	*4.35*	*5.14*	*5.14 (48)**	*5.14 (48)**
24	*3.72*	*4.24*	*4.88*	*5.58 (44)**	*5.58 (44)**
25	3.69	*4.25*	*4.64*	*5.74*	*5.74 (40)**
26	3.69	4.26	*4.97*	*5.60*	*6.43*
27	3.69	4.26	*4.80*	*5.57*	*6.49*
28	3.69	4.26	*4.78*	*5.66*	*6.33*
29	3.69	4.26	*4.82*	*5.69*	*6.26*
30	3.69	4.26	*4.82*	5.66	*6.19*
31	3.69	4.26	4.81	5.66	*6.25*
32	3.69	4.26	4.81	5.66	*6.25*
33	3.69	4.26	4.81	5.66	6.25
34	3.69	4.26	4.81	5.66	6.26
35	3.69	4.26	4.81	5.66	6.26
36	3.69	4.26	4.81	5.66	6.26

* -- The numbers in parentheses indicate a different batch feed quantity for these transition cycles

Table 2-5
Catawba Equilibrium Cycle Neutronics Code Predictions

Number of Feed Fuel Assys	Center Region Enrich (wt % ^{235}U)	Batch Average Discharge Burnup (GWD/MTU)	Core Reactivity at Cycle Start (ppm Boron)**	Core Reactivity at Cycle End (ppm Boron)	Max 2-D radial pin power	Max 3-D total peak power	Maximum Assembly Burnup (GWD/MTU)*	Maximum Fuel Pin Burnup (GWD/MTU)*
88	4.14	42.1	1785	6	1.44	1.87	51.1, 46.0	53.1, 47.5
80	4.41	46.3	1807	10	1.51	1.97	58.7, 49.1	60.2, 51.4
72	4.77	51.4	1807	13	1.53	1.91	64.3, 55.6	65.9, 59.6
68	5.01	54.5	1807	11	1.51	1.92	64.9, 61.0	66.3, 65.3
64	5.24	57.9	1781	7	1.53	1.88	71.4, 64.5	72.9, 67.7
60	5.56	61.7	1797	16	1.57	1.91	72.2, 67.4	73.8, 69.7
48	6.91	77.1	2296	8	1.73	2.24	87.0, 76.3	89.0, 79.7

* The first burnup is in the center fuel assembly. The second burnup shown is the next highest (or overall maximum) calculated.

** Critical boron concentration at 100% rated power, equilibrium xenon conditions.

Table 2.6
Oconee Equilibrium Cycle Neutronics Code Predictions

Number of Feed Fuel Assys	Center Region Enrich (wt % ^{235}U)	Batch Average Discharge Burnup (GWD/MTU)	Core Reactivity at Cycle Start (ppm Boron)**	Core Reactivity at Cycle End (ppm Boron)	Max 2-D radial pin power	Max 3-D total peak power	Maximum Assembly Burnup (GWD/MTU)*	Maximum Fuel Pin Burnup (GWD/MTU)*
68	3.69	41.1	1552	4	1.57	1.99	53.8, 48.0	56.8, 52.1
56	4.26	49.9	1640	4	1.60	2.06	59.2, 58.3	63.3, 62.3
48	4.81	58.2	1605	2	1.63	2.04	68.2, 65.3	70.8, 70.3
40	5.66	69.9	1620	5	1.78	2.21	80.1, 77.2	84.8, 81.0
36	6.26	77.6	1644	5	1.90	2.35	84.0, 83.7	87.8, 88.6

* The first burnup is in the center fuel assembly. The second burnup shown is the next highest (or overall maximum) calculated.

** Critical boron concentration at 100% rated power, equilibrium xenon conditions.

88 feed -- 4.14 wt% U-235

7040 IFBA Rods @ 1.5X Loading in New Fuel

	H	G	F	E	D	C	B	A
8	2/A09 35.3 51.1	1/H10 24.4 43.4	New 0 24.4	1/F10 24.3 45.4	New 0 25.4	1/G09 23.5 45.3	New 0 23.5	1/H12 25.4 36.2
9	1/H10 24.4 43.4	New 0 23.5	1/C09 25.7 46	New 0 24.9	1/G11 24.9 46	New 0 25.7	New 0 23.5	1/D10 24.6 35.3
10	New 0 24.4	1/G13 25.8 46.1	New 0 24.3	1/C11 23.8 44.2	New 0 24.6	1/F14 22.3 43.5	New 0 22.3	1/C12 22.2 32.4
11	1/F10 24.3 45.4	New 0 24.9	1/E13 23.9 44.2	1/C13 17.8 37.8	1/G14 23.5 43	New 0 23.8	New 0 19.6	2/F15 32.4 39.1
12	New 0 25.4	1/E09 24.9 46	New 0 24.6	1/B09 23.5 43	1/H14 23.5 42.5	New 0 22.2	1/B11 19.6 32	
13	1/G09 23.5 45.3	New 0 25.8	1/B10 22.3 43.5	New 0 23.9	New 0 22.3	New 0 17.8	2/D14 32.1 38.6	
14	New 0 23.5	New 0 23.5	New 0 22.3	New 0 19.6	1/E14 19.6 32.1	2/B12 32 38.6		
15	1/H12 25.4 36.2	1/F12 24.6 35.3	1/D13 22.3 32.4	2/A10 32.4 39.1	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup			

80 feed -- 4.41 wt% U-235

7680 IFBA Rods @ 1.5X Loading in New Fuel

	H	G	F	E	D	C	B	A
8	2/G12 43.2 58.7	1/H10 25.7 45.5	New 0 25.7	1/G09 24.5 46.3	1/E14 20.5 41.7	1/E11 26 45.1	2/F15 34.9 49	2/A10 34.9 42.1
9	1/H10 25.7 45.5	New 0 24.5	1/F14 22.4 44.3	New 0 26	1/G14 21.1 43.2	New 0 24.6	New 0 21.2	2/B12 38 45.9
10	New 0 25.7	1/B10 22.4 44.4	1/C13 18.5 40.5	1/G13 24.6 46.3	New 0 25.9	1/E09 26 47.3	New 0 22.4	1/E13 25.5 34.9
11	1/G09 24.5 46.3	New 0 26	1/C09 24.6 46.3	New 0 26	1/C12 23.5 45.5	New 0 25.5	New 0 20.7	2/F10 40.5 46.9
12	1/E14 20.5 41.7	1/B09 21.2 43.2	New 0 25.9	1/D13 23.5 45.5	1/B11 20.7 42.5	New 0 23.5	1/F12 25.9 38	
13	1/E11 26 45.1	New 0 24.6	1/G11 26 47.2	New 0 25.5	New 0 23.5	New 0 18.5	2/D12 42.5 48.6	
14	2/F15 34.9 49	New 0 21.1	New 0 22.4	New 0 20.5	1/D10 25.9 38	3/H15 42.1 48.1		
15	2/A10 34.9 42.1	2/D14 38 45.8	1/C11 25.5 34.9	2/H12 41.7 47.9	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup			

72 feed -- 4.77 wt% U-235

8160 IFBA Rods @ 1.5X Loading in New Fuel

	H	G	F	E	D	C	B	A
8	2/H09 48.2 64.4	1/H10 27.1 48.2	New 0 27.1	1/E11 26.3 48.9	1/G14 21.8 44.3	1/B09 21.9 43.5	2/F10 41.5 55.5	2/D12 47.5 53.8
9	1/H10 27.1 48.2	New 0 26.1	1/F12 26.8 49.2	New 0 26.7	1/E09 26.7 49.1	New 0 26.4	New 0 21.9	2/H12 44.3 51.9
10	New 0 27.1	1/D10 26.8 49.2	1/C13 18.7 41.5	2/F15 32.8 53.5	New 0 26.8	1/E13 25.1 47.5	New 0 22.3	1/D13 23.2 32.8
11	1/E11 26.3 48.9	New 0 26.7	2/A10 32.8 53.5	New 0 26.3	1/G13 26.4 48.4	New 0 25.1	1/F14 22.3 37.9	2/C10 47.5 52.8
12	1/G14 21.8 44.3	1/G11 26.7 49.1	New 0 26.8	1/C09 26.4 48.5	1/G09 26.1 47.5	New 0 23.2	2/B11 37.9 47.7	
13	1/B09 21.9 43.5	New 0 26.4	1/C11 25.1 47.5	New 0 25.1	New 0 23.2	New 0 18.7	3/D14 47.7 53.2	
14	2/F10 41.5 55.5	New 0 21.8	New 0 22.3	1/B10 22.3 38	2/E14 38 47.7	3/B12 47.7 53.2		
15	2/D12 47.5 53.8	2/H13 43.5 51.1	1/C12 23.2 32.8	2/F13 47.5 52.8	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup			

68 feed -- 5.01 wt% U-235

8000 IFBA Rods @ 1.5X Loading in New Fuel

	H	G	F	E	D	C	B	A
8	2/E11 47.9 64.8	1/G09 26 47.7	New 0 26.3	2/H12 42.2 61.1	1/C13 20.4 42.2	2/F10 44 60.8	2/D12 45.8 59.3	2/H09 47.7 54.9
9	1/G09 26 47.7	New 0 26	2/A09 35.6 55.6	New 0 26.1	1/E09 26.1 48.4	New 0 25.5	New 0 22.4	1/G13 25.5 35.6
10	New 0 26.3	2/G15 35.6 55.7	1/G14 22.4 44	1/F12 27 48.9	New 0 27	2/E14 39.1 58.7	New 0 22.6	2/D14 38.5 47.1
11	2/H12 42.2 61.1	New 0 26.2	1/D10 27 48.9	1/H10 26.3 47.9	1/D13 25.1 47.9	New 0 25.8	1/F14 22.6 39.1	2/E12 47.9 53.5
12	1/C13 20.4 42.2	1/G11 26.2 48.4	New 0 27	1/C12 25.2 47.9	1/B09 22.4 45.8	New 0 25.2	1/E13 25.8 38.5	
13	2/F10 44 60.8	New 0 25.5	2/B11 39.1 58.7	New 0 25.8	New 0 25.1	New 0 20.4	3/A10 47.1 53.7	
14	2/D12 45.8 59.3	New 0 22.4	New 0 22.6	1/B10 22.6 39.1	1/C11 25.8 38.5	3/F15 47.1 53.6		
15	2/H09 47.7 54.9	1/C09 25.5 35.6	2/B12 38.5 47.1	2/D11 47.9 53.5	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup			

Figure 2-1
Catawba Equilibrium Core Designs

64 feed -- 5.24 wt% U-235

8304 IFBA Rods @ 1.5X Loading in New Fuel

	H	G	F	E	D	C	B	A
8	3/E15 55.1 71.3	1/G09 26.2 48.3	New 0 26.6	2/H12 46.1 64.6	1/D13 24.4 46.1	2/C13 38.8 57.6	2/E11 46.1 60.7	2/H09 48.3 56.1
9	1/G09 26.2 48.3	New 0 26.2	2/E14 40.6 59.7	New 0 26	1/F12 27.3 49.9	New 0 26.6	New 0 23.5	1/E13 26.6 37.1
10	New 0 26.6	2/B11 40.6 59.8	1/H10 26.6 46.8	2/A09 37.1 56.7	New 0 27.3	2/B12 38.4 59.2	New 0 23.6	2/D12 46.7 55
11	2/H12 46.1 64.6	New 0 25.9	2/G15 37.1 56.7	1/C12 24.4 46.1	1/G13 26.6 49.5	New 0 26.6	1/B10 23.6 40.6	2/E12 49.5 55.2
12	1/D13 24.4 46.1	1/D10 27.3 49.9	New 0 27.3	1/C09 26.6 49.5	1/G14 23.5 46.7	New 0 24.4	1/G11 25.9 38.4	
13	2/C13 38.8 57.6	New 0 26.6	2/D14 38.5 59.2	New 0 26.6	New 0 24.4	1/B09 23.5 38.8	2/D09 49.9 55.7	
14	2/E11 46.1 60.7	New 0 23.5	New 0 23.5	1/F14 23.5 40.6	1/E09 26 38.5	2/G12 49.9 55.6		
15	2/H09 48.3 56.1	1/C11 26.6 37.1	2/F10 46.8 55	2/D11 49.5 55.1	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup			

60 feed -- 5.56 wt% U-235

8512 IFBA Rods @ 1.5X Loading in New Fuel

	H	G	F	E	D	C	B	A
8	3/E09 57.4 72.7	1/H14 22.5 44.7	New 0 27.8	2/B09 46.7 64.7	1/C13 19.9 42.5	2/E11 49.1 67.4	New 0 22.5	3/G11 57.4 65.6
9	1/H14 22.5 44.7	2/G14 46.7 65.4	New 0 26.6	2/A09 38.2 57.4	1/F12 27.6 50.1	New 0 27	1/E13 26.8 46.7	1/G13 26.9 38.2
10	New 0 27.8	New 0 26.5	2/H12 42.5 60.6	2/F15 37.7 56.8	New 0 27.7	2/E14 41 61.8	New 0 23.6	1/G10 26.5 37.7
11	2/B09 46.7 64.7	2/G15 38.2 57.4	2/A10 37.7 56.7	1/H10 27.8 49.1	1/D13 24.2 47.8	New 0 26.9	1/F14 23.6 41	2/D09 50.1 56.3
12	1/C13 19.9 42.5	1/D10 27.7 50	New 0 27.6	1/C12 24.3 47.8	2/H09 44.7 63.9	New 0 24.3	2/D11 47.8 57.9	
13	2/E11 49.1 67.4	New 0 26.9	2/B11 41 61.8	New 0 26.8	New 0 24.2	New 0 19.9	3/A11 56.3 62.1	
14	New 0 22.5	1/C11 26.9 46.7	New 0 23.6	1/B10 23.6 41	2/E12 47.8 57.9	3/E15 56.2 62		
15	3/G11 57.4 65.6	1/C09 27 38.2	1/F09 26.6 37.7	2/G12 50 56.2	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup			

48 feed -- 6.91 wt% U-235

7488 IFBA Rods @ 1.5X Loading in New Fuel

	H	G	F	E	D	C	B	A
8	3/H09 73.4 86.8	2/H13 54.6 73.4	New 0 30.3	2/E11 54.5 75.2	2/H14 49.4 69.8	1/G11 30.2 54.6	1/H10 30.3 49.4	3/H12 69.8 75.9
9	2/H13 54.6 73.4	New 0 28.1	2/B09 50.2 71	New 0 30.2	2/C12 47.8 69.8	New 0 29.4	1/D10 30.7 50.2	3/G12 69.7 76
10	New 0 30.3	2/G14 50.2 71	2/D12 51.2 70.4	2/B11 41.9 64.3	New 0 30.7	3/D11 64.5 82.6	New 0 23.1	3/E10 64.3 71.1
11	2/E11 54.5 75.2	New 0 30.2	2/E14 41.9 64.3	1/E09 30.2 54.5	2/B12 41.9 64.5	New 0 28.2	1/B10 23.1 41.9	4/A10 71.1 76.1
12	2/H14 49.4 69.8	2/D13 47.8 69.7	New 0 30.7	2/D14 41.9 64.5	1/G09 28.1 51.2	1/C11 28.2 47.8	1/C09 29.4 41.9	
13	1/G11 30.2 54.6	New 0 29.4	3/E12 64.5 82.6	New 0 28.2	1/E13 28.2 47.8	3/F10 70.4 78.6	3/G10 71 74.9	
14	1/H10 30.3 49.4	1/F12 30.7 50.2	New 0 23.1	1/F14 23.1 41.9	1/G13 29.4 41.9	3/F09 71 75		
15	3/H12 69.8 75.9	3/D09 69.8 76.1	3/F11 64.3 71	4/F15 71.1 76.1	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup			

Figure 2-2
Catawba Equilibrium Core Designs (Continued)

68 feed -- 3.69 wt% U-235

52 Burnable Poison Assemblies in New Fuel

	8	9	10	11	12	13	14	15
H	2/K13 38.3 54	New 0 22	2/P11 30.6 47.9	New 0 22.6	1/H09 22 41.3	New 0 21.4	1/H11 22.6 36.8	2/H14 36.8 42.6
K	New 0 22	1/H13 21.4 40.6	New 0 22.3	1/M12 21 40.5	New 0 22.3	1/L13 19.9 38.3	New 0 17.6	1/K12 22.3 29.3
L	2/P11 30.6 47.9	New 0 22.3	2/M14 30.5 47.8	New 0 22	2/K15 29.3 45.7	New 0 19.9	1/P09 17.6 30.2	2/L14 30.2 34.8
M	New 0 22.6	1/N11 21 40.5	New 0 22	1/K10 22.3 40.9	New 0 21	1/N13 14.9 31	1/M10 22 30.5	
N	1/H09 22 41.3	New 0 22.3	2/R09 29.2 45.6	New 0 21	1/L09 22.3 38.2	New 0 14.9	2/M13 31 35.8	
O	New 0 21.4	1/O10 19.9 38.3	New 0 19.9	1/O12 14.9 31	New 0 14.9	2/N12 38.2 43.7		
P	1/H11 22.6 36.8	New 0 17.6	1/K14 17.6 30.2	1/L11 22 30.6	2/O11 31 35.8			
R	2/H14 36.8 42.6	1/N09 22.3 29.2	2/P10 30.2 34.8	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup				

56 feed -- 4.26 wt% U-235

40 Burnable Poison Assemblies in New Fuel

	8	9	10	11	12	13	14	15
H	3/L15 44.1 59.2	New 0 22.3	1/H09 22.3 42	New 0 23.3	3/K15 41.7 57	1/K12 22.6 39.8	1/N09 22.7 37.2	2/H10 42 47.8
K	New 0 22.3	2/L14 34.2 50.6	1/N13 17.1 36.6	1/L11 22.9 42.9	New 0 22.6	1/N11 22.6 41	New 0 18.4	2/M13 35.5 41.7
L	1/H09 22.3 42	1/O12 17 36.6	2/H14 37.2 53.5	New 0 22.9	2/M09 42.9 58.2	New 0 21.2	1/O10 21.1 34.2	2/H13 39.8 44.1
M	New 0 23.3	1/M10 22.8 42.9	New 0 22.8	2/P10 34.2 51.7	New 0 22.7	1/P09 18.4 35.5	2/K10 36.6 44.3	
N	3/K15 41.7 57	New 0 22.7	2/K11 42.9 58.2	New 0 22.6	1/H11 23.3 41.5	New 0 17.1	2/O09 41 45.9	
O	1/K12 22.6 39.8	1/M12 22.7 41	New 0 21.1	1/K14 18.4 35.5	New 0 17	3/R09 41.6 48		
P	1/N09 22.7 37.2	New 0 18.4	1/L13 21.2 34.2	2/L09 36.6 44.3	2/K13 41 45.8			
R	2/H10 42 47.8	2/O11 35.5 41.6	2/N12 41.5 45.7	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup				

48 feed -- 4.81 wt% U-235

48 Burnable Poison Assemblies in New Fuel

	8	9	10	11	12	13	14	15
H	4/L15 53.4 68.2	New 0 23.3	1/H09 23.3 43.9	New 0 23.7	3/H15 50.3 65.3	1/H11 23.7 42.1	1/L11 23.7 39.7	2/H10 43.9 50.3
K	New 0 23.3	2/H13 42.1 58.3	1/M12 23.6 42.7	2/L14 36.8 54.7	New 0 23.4	2/O12 32.1 50	New 0 19.4	2/K10 42.7 49.1
L	1/H09 23.3 43.9	1/M10 23.6 42.7	2/N12 41.5 57.8	New 0 23.7	3/P11 48.2 63.8	New 0 22.6	1/O10 22.6 36.8	3/R09 49.1 53.4
M	New 0 23.7	2/P10 36.8 54.7	New 0 23.6	2/H14 39.7 57.7	New 0 23.6	1/N09 23.3 40.3	2/M13 40.3 48.2	
N	3/H15 50.3 65.3	New 0 23.3	3/M14 48.2 63.7	New 0 23.5	1/N11 23.5 41.5	1/P09 19.4 32.1	3/K13 50 53.9	
O	1/H11 23.7 42.1	2/N13 32.1 50	New 0 22.6	1/K12 23.4 40.3	1/K14 19.4 32.1	4/R10 53.4 57.8		
P	1/L11 23.7 39.7	New 0 19.4	1/L13 22.6 36.8	2/O11 40.3 48.2	3/O09 50 53.9			
R	2/H10 43.9 50.3	2/L09 42.7 49.1	3/K15 49.1 53.4	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup				

40 feed -- 5.66 wt% U-235

40 Burnable Poison Assemblies in New Fuel

	8	9	10	11	12	13	14	15
H	4/N14 64.8 80	New 0 24.7	2/K10 45 61.9	1/H09 24.7 44.8	3/H10 61.9 77.2	New 0 25.3	1/H13 25.3 42.4	2/L09 45 51.5
K	New 0 24.7	2/H11 44.8 62.2	1/N11 25.2 45	2/M13 43.2 61.1	New 0 25.2	2/O12 36.4 55.9	1/L11 25.1 40.9	3/P10 52.1 57.5
L	2/K10 45 61.9	1/M12 25.1 45	3/N12 58.3 73.5	New 0 25.1	4/K15 57.5 73.5	New 0 23.4	2/P09 40.9 52.1	4/P11 62.5 65.7
M	1/H09 24.7 44.8	2/O11 43.2 61.2	New 0 25.1	3/H15 51.5 69.2	New 0 25.1	1/N09 25.2 43.2	3/K13 55.9 62.6	
N	3/H10 61.9 77.2	New 0 25.2	4/R09 57.5 73.5	New 0 25.2	2/H14 42.4 58.3	1/O10 23.5 36.3	3/K11 61.1 64.8	
O	New 0 25.3	2/N13 36.3 55.8	New 0 23.5	1/K12 25.2 43.2	1/L13 23.4 36.4	3/K09 62.2 66.7		
P	1/H13 25.3 42.4	1/M10 25.1 40.9	2/K14 40.9 52.1	3/O09 55.8 62.5	3/M09 61.2 64.9			
R	2/L09 45 51.5	3/L14 52.1 57.5	4/M14 62.6 65.8	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup				

Figure 2-3
Catawba Equilibrium Core Designs (Continued)

36 feed -- 6.26 wt% U-235

36 Burnable Poison Assemblies in New Fuel

	8	9	10	11	12	13	14	15
H	4/N12 68.1 84	New 0 25.7	3/H14 53 69.8	1/H09 25.7 46.8	4/H10 69.8 83.7	2/P09 40 56.5	2/K14 40.1 53	2/H11 46.8 52.8
K	New 0 25.7	3/H13 56.5 73	1/L11 26.2 47	2/L09 47 65.6	New 0 25.6	2/O12 39.3 57.7	1/L13 24.9 40.1	3/L14 57.2 62.3
L	3/H14 53 69.8	1/M10 26.2 47	4/M14 65.2 80.4	New 0 26.2	4/R09 62.3 78.8	New 0 24.9	2/O11 45.6 57.2	4/N14 69.7 72.9
M	1/H09 25.7 46.8	2/K10 47 65.6	New 0 26.2	4/P11 65.2 81.7	New 0 26.2	1/N11 26.1 45.6	3/K13 57.7 65.2	
N	4/H10 69.8 83.7	New 0 25.6	4/K15 62.3 78.8	New 0 26.1	3/H15 52.8 68.1	1/N09 25.6 39.3	3/M09 65.6 69.7	
O	2/P09 40 56.5	2/N13 39.3 57.8	New 0 24.9	1/M12 26.2 45.6	1/K12 25.6 39.3	4/K09 73 77.4		
P	2/K14 40.1 53	1/O10 24.9 40	2/M13 45.6 57.2	3/O09 57.8 65.2	3/K11 65.6 69.6			
R	2/H11 46.8 52.8	3/P10 57.2 62.3	4/P12 69.6 72.8	cycles burned / prev loc beginning-of-cycle burnup end-of-cycle burnup				

Figure 2-4
Catawba Equilibrium Core Designs (Continued)

3
ECONOMICS EVALUATIONS

3.1 Introduction

In this section batch fuel costs are computed for the different Oconee and Catawba DB designs described in Section 2. These cost calculations canvas a broad range of the economics variables involved in the construction, irradiation, and disposal of nuclear fuel. Once economic optimum burnup regions are determined for the Oconee and Catawba cores, the dynamics behind observed trends will be discussed.

3.2 Economics Variables for Nuclear Fuel Cost Calculations

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

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

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

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

To avoid unnecessary computational complexity in this study, it is reasonable to focus only on the Basic Nuclear Fuel Cost Components listed above. As for the “Other” components, AFUDC charges are, in practice, highly variable from one cycle to the next (depending on contract delivery lead times and uranium inventories), and will likely be one of the first allowances to disappear as the nuclear industry undergoes deregulation. The remaining "Other" fuel costs can be treated effectively by adjusting the working capital rate, as will be done for one of the cases considered in Section 3.5.

3.3 Scope of Economics Evaluations

The Oconee and Catawba DB economic analyses include the following:

- Batch nuclear fuel costs are calculated for each of the 14-cycle transition-to-equilibrium streams designed in Section 2, for the following assembly reload quantities: Oconee 68, 56, 48, 40, and 36 feed; Catawba 88, 80, 72, 68, 64, 60, and 48 feed.
- Fuel cost calculations are carried out with eight different cost sets. Table 3.1 lists the prices and rates constituting each cost set, and Section 3.5 provides more detail about the scenarios these sets are modeling.
- Economics computations are performed using the Present Value of Revenue Requirements (PVRR) method traditionally employed by regulated utilities. With this method, customer revenue requirements are determined that recover the capital and financing costs of an expenditure.[15] The best economic alternative is that which minimizes the total discounted value of revenue receipts. The PVRR technique is compatible in the long-term with the Net Present Value (NPV) method typically used in unregulated industries.[16] An analyst using the NPV method examines all the cash flows (revenues, disbursements, taxes, depreciation, insurance, etc.) associated with a capital expenditure, and seeks to maximize shareholder value.

3.4 Cost of Capital and Timing of Revenue Receipts

For the market scenarios described in Section 3.5, the start of irradiation is the reference point for each fuel batch's capital expenditures (uranium, conversion, enrichment, fabrication) and discharge storage costs. The SBB code determines, in approximately monthly intervals, the revenue requirements sufficient to cover amortization and working capital charges for the fuel batch being considered. The working capital charges are calculated using a corporate pre-tax cost of capital. All revenue streams are then discounted back to the point of initial capital expenditure. For the purpose of this study, the pre-tax cost of capital is derived from the discount rate by the following formula:

$$\text{pre-tax cost} = \text{discount rate} / (1 - T)$$

where T is the effective corporate taxation rate (40% is used for most of the cases in this analysis).[17,18]

The argument has been made that in a deregulated nuclear industry working capital charges become even more important, because of the added risk to the investor. It is true that higher carrying costs make fuel with higher batch DBs less economically attractive, as long as that fuel is amortized on a units of production accounting basis. The reason for this is that increasing fuel batch DB raises the unamortized value of the in-core fuel inventory.[22] However, in order to transition from a core design with a low batch DB to one with a higher DB, the overall expensing of in-core fuel must temporarily be slowed down. In effect, under current accounting rules, by pushing fuel to higher burnups one is choosing to hold on to the investors' money longer before paying it back.

It is plausible, then, to propose alternative fuel amortization schemes whereby the value of the in-core fuel inventory does not exceed a certain threshold. Such an amortization policy may be allowable and preferable in a deregulated nuclear power market. After all, for core design alternatives at a particular cycle length (e.g., 18 months), the timing of the fuel capital expenditures and the receipt of electric sale revenues is the same, regardless of how long fuel assemblies actually operate in the reactor. It is apparent, then, that working capital charges do not *necessarily* have to enter into the picture. The reader is advised to keep this in mind when comparing the results for the scenarios described in Section 3.5.

3.5 Optimum Discharge Burnup – Transition Cycle Economics

To bound the foreseeable market circumstances in the years 2005 to 2025, eight scenarios are contemplated. Refer to Table 3.1 for specific prices and rates. All prices in are expressed in projected year 2005 dollars. The eight scenarios include:

1. **Mid-range market price projections** for uranium, conversion, enrichment, fabrication, and spent fuel storage. Nominal projections are used for fuel escalation and cost of capital rates.

2. **Low-range projections** for the prices and rates described in case #1.

3. **High-range projections** for the prices and rates described in case #1.

4. **High fuel financing cost**. Same as case #1, but with higher working capital and discount rates. This represents a deregulated environment, in which bondholders and stockholders demand a higher return for the added investment risk. In this scenario a higher effective corporate tax rate (see Section 3.4) is also used, to simulate unfavorable changes in the "Other" nuclear fuel cost components described in Section 3.2. This case also assumes that the units of production accounting method is still used to amortize nuclear fuel costs.

5. **Flat uranium market**. In this case excess production capacity and less-than-anticipated demand conspire to keep uranium prices and escalation low, while all other nuclear fuel costs follow the nominal projections in scenario #1.

6. **Zero spent fuel storage cost**. Same as case #1, but with no storage costs. Here the Department of Energy (DOE) is accepting spent fuel in the year 2005 and thereafter, and so Duke Power no longer incurs costs for additional on-site dry storage. This case assumes that Nuclear Waste Fund fees continue to be assessed on a mills/kWhr basis rather than a waste volume basis.

7. **High spent fuel storage cost**. Here Duke Power either has to continue storing spent fuel on-site during the study period, at a very high cost per assembly (perhaps due to lack of vendor

competition or added regulatory burdens on storage containers), or legislation changes the DOE Nuclear Waste Fund fee to one based on waste volume generated as opposed to energy production.

This case can alternatively be viewed as a high fabrication price scenario, in which further consolidation of fabrication services vendors or necessary product enhancements leads to increased fabrication costs.

8. **Fuel Capital Costs Only.** Same as case #1, but without any consideration of fuel financing costs. By disregarding the working capital charges, one is effectively employing a different technique for fuel amortization than the units of production method. This may be feasible in a deregulated nuclear industry -- see Section 3.4.

With these eight market cases, batch fuel costs are computed for all 14 transition cycles designed to each DB. Total 14-cycle (20-year) batch costs are then calculated in year 2005 dollars, by using the discount rates shown in Table 3.1. Finally, within each particular market scenario, the total cost differences between the various DB designs are figured, relative to the lowest-cost burnup in that scenario. Figures 3.1 and 3.3 show these relative costs for Catawba and Oconee, respectively. For nearly every scenario, minimum Catawba costs occur between batch DBs of 58 and 62 GWD/MTU. Oconee minima appear most often between 58 and 70 GWD/MTU. For the base market scenario (#1), each Catawba and Oconee reactor saves from \$10M to \$20M (in year 2005 dollars) over 20 years, in transitioning from current batch DBs (45 to 50 GWD/MTU) to the optimum range. Since the transition period consists of 14 cycles, this is a \$0.7M to \$1.4M (2% to 4%) reduction in cost per batch.

It is important to consider also the shorter-term savings associated with a transition to higher DBs, especially since, as Section 2.3 explained, there is a noticeable economic penalty in the first few cycles of a transition to higher burnups. The current Oconee operating licenses will expire around 2013, eight years (or five 18-month cycles) after the starting point of this study, so these reactors serve as the logical choice for recomputing short-term transition costs. The results for the eight-year period are shown in Figure 3.5. There is a slight shift to a lower economic optimum DB (~ 60 GWD/MTU), but the per-batch savings in the initial eight transition years is still \$0.5 to \$1.2M with the best-estimate market conditions (scenario #1). Figure 3.5 demonstrates that the economic benefits are realized rather quickly in transitioning to a 60 GWD/MTU batch DB from the current 45 to 50 GWD/MTU.

Figures 3.6 and 3.7 are perhaps more illustrative of the short-term transitional effects associated with changing batch DB. For the Catawba reactor, it takes roughly eight years for the optimum DB case (58 GWD/MTU, corresponding to a batch feed of 64 fuel assemblies) to overcome its transition penalty relative to one of the lower burnup patterns. The eventual economic optimum for Oconee (70 GWD/MTU; 40 feed assemblies) takes nearly twice as long.

3.6 Optimum Discharge Burnup – Equilibrium Cycle Economics

To quantify the long-term benefits of increasing batch DBs, fuel costs for each of the eight market scenarios described in Section 3.5 are recalculated for equilibrium cycles. The results are shown in Figures 3.2 and 3.4 for Catawba and Oconee, respectively. The optimum batch DB on an equilibrium cycle is still around 60 GWD/MTU for Catawba, but closer to 70 GWD/MTU for Oconee.

As Figures 3.2 and 3.4 illustrate for the equilibrium 18-month cycle, current fuel designs to DBs of 45-50 GWD/MTU cost $1.5M to $2.5M more per batch than optimum DB designs, using the nominal market projections for the year 2005. It is notable that the transition and equilibrium cycles both point to an optimum batch DB between 60 and 70 GWD/MTU for all of Duke Power's reactors on 18-month cycles.

Both the transition and equilibrium economic results for Catawba show a "hump" at the batch DB of 55 GWD/MTU (68 feed assemblies), marring what would otherwise be smooth sets of curves in Figures 3.1 and 3.2. It is reasonable to suspect that the design has not been optimized as well as the others; a check of Figure 2.1 verifies this. Normally, as the designer reduces the fuel batch feed quantity, he is able to load more high burnup assemblies at the core periphery, thereby reducing radial leakage. However, Figure 2.1 shows that as feed quantity is reduced from 72 to 68 fuel assemblies, the average core periphery burnup is actually lower, and there is more radial leakage from the 68 feed design versus the 72 feed design. It is easy to find further evidence that the 68 feed Catawba pattern has relatively higher radial leakage than the others, by examining the trend in burnable poison requirements for the designs in Figures 2.1 and 2.2. As assembly feed quantities are reduced, the numbers of IFBA rods required to hold down initial core reactivity increase steadily, with the exception of the 68 feed pattern.

It is likely the 68 feed pattern could be improved enough that the equilibrium enrichment requirement would drop from 5.01 to 4.99 wt% ^{235}U. If this were done, the Catawba curves in Figures 3.1 and 3.2 would display the same smoothness as the Oconee data (Figures 3.3 and 3.4).

3.7 Fuel Assembly Storage and Disposal – Cost Effects

An examination of the assembly storage cases (#6 and #7) in Figures 3.1 through 3.5 shows that the variation in this cost component yields the largest observed total fuel cost differences among the eight market scenarios analyzed. This reflects the great degree of uncertainty in the future for assembly storage and disposal. The assumption for scenario #7 is that eventual dry storage / disposal costs will be directly proportional to the number of assemblies in a new fuel batch.

However, this could turn out to be a somewhat simplistic assumption. Several of the Catawba and Oconee cores designed to high discharge burnups, particularly those with batch DBs above 50 GWD/MTU, require enrichments of 4.5 wt% ^{235}U and higher. As compared with the licensed limitations of the current generation of spent fuel storage casks, such high enrichments and burnups will require enhanced criticality control, radiation shielding, and heat dissipation capability.[21]

It is also quite uncertain what will become of the DOE NWPA fee. A change to a fee based more on waste volume than energy production would provide a huge incentive for nuclear operators to conserve fuel assemblies.

Other considerations that could affect the costs of fuel storage and disposal include fuel pool re-racking and re-licensing for higher enrichments, the opening of an interim spent fuel repository, or the introduction of high-level waste reduction technologies.[23]

The economics cases #6 and #7 were designed to bound these possible future scenarios.

3.8 Uranium Utilization

Why do Figures 3.1 through 3.5 show economic minima? After all, previous studies that evaluated batch DBs to 50 GWD/MTU or more have demonstrated continually decreasing fuel costs. It is helpful to plot the uranium feed and SWU efficiencies as a function of DB; this is done in Figure 3.8 for the Catawba and Oconee equilibrium cycles. Notice that the uranium utilization continues to improve as DB increases, but that SWU utilization decreases above 45-50 GWD/MTU, due to high enriching requirements. At some point, the decrease in SWU efficiency overtakes the increase in uranium utilization, and overall fuel prices start to rise. In this study, that point occurs at batch DBs between 60 and 70 GWD/MTU for most of the market scenarios evaluated.

Figure 3.9 shows optimum batch DB (considering only uranium, conversion, and enrichment costs) for various uranium to enrichment price ratios. The second chart in this figure includes the effects of working capital charges. Uranium to enrichment price ratios have historically varied between 0.3 and 1.5. Any additional expenses for nuclear fuel (fabrication, dry storage, etc.) serve only to increase the optimum batch DB from that shown in Figure 3.9, because these costs should generally be proportional to the number of assemblies in a fuel batch.

3.9 Applicability of Economics Results to Other Cycle Lengths and Designs

Out of the 103 currently operating reactors in the U.S., about 2/3 are on 18-month cycles; the remainder are on 24-month cycles.[19] Those operating at 24 months are mostly BWRs or low power-density PWRs, which can handle the higher excess reactivity requirements – as compared with 18-month cycles – more readily. At least one other report has observed that 24-month cycles favor higher DBs than even 18-month cycles.[3]

Other design variables not explicitly examined in this study include:

- Multiple enrichments in the fuel batch
- Increased assembly uranium loading
- Higher conversion ratio (less-moderated lattice)
- Concurrent partial mixed-oxide (MOX) reloads

- Axial leakage optimization (varying blanket enrichment)
- Load-follow or reduced power mode of operation
- Shorter (12-month) cycle lengths

Without modeling cases for the above variables, it is hard to quantify exactly how they affect the optimum batch DB location. However, these variables probably have minor effects on the optimum DBs determined in this study, since their differences are on the order of those between the Oconee and Catawba reactors (viz., different specific powers, burnable poisons, and fuel assembly designs).

Increasing the assembly uranium loading can help mitigate required enrichments and reduce overall batch DB for the same number of feed assemblies, if limits would otherwise be exceeded. Section 4.2 discusses this in more detail.

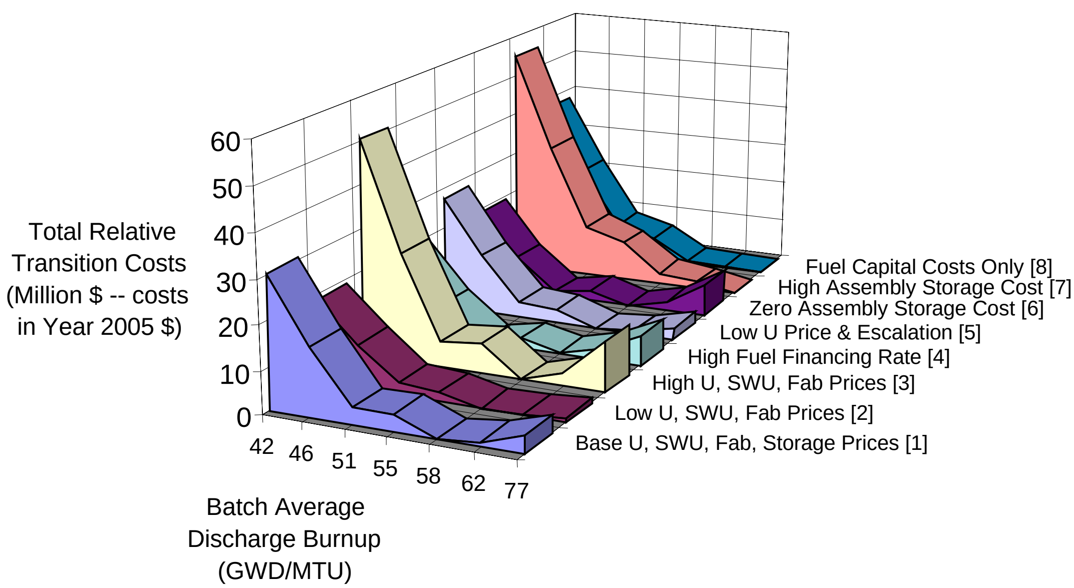


Figure 3-1
Catawba-1 Total 20-year Transition Costs

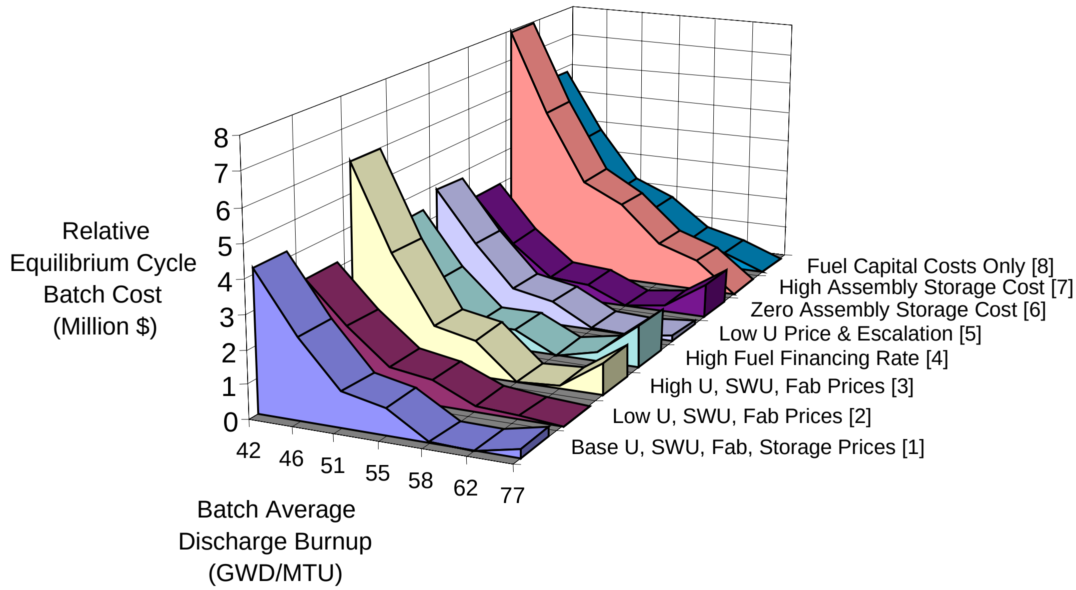


Figure 3-2
Catawba-1 Equilibrium Cycle Cost Comparison

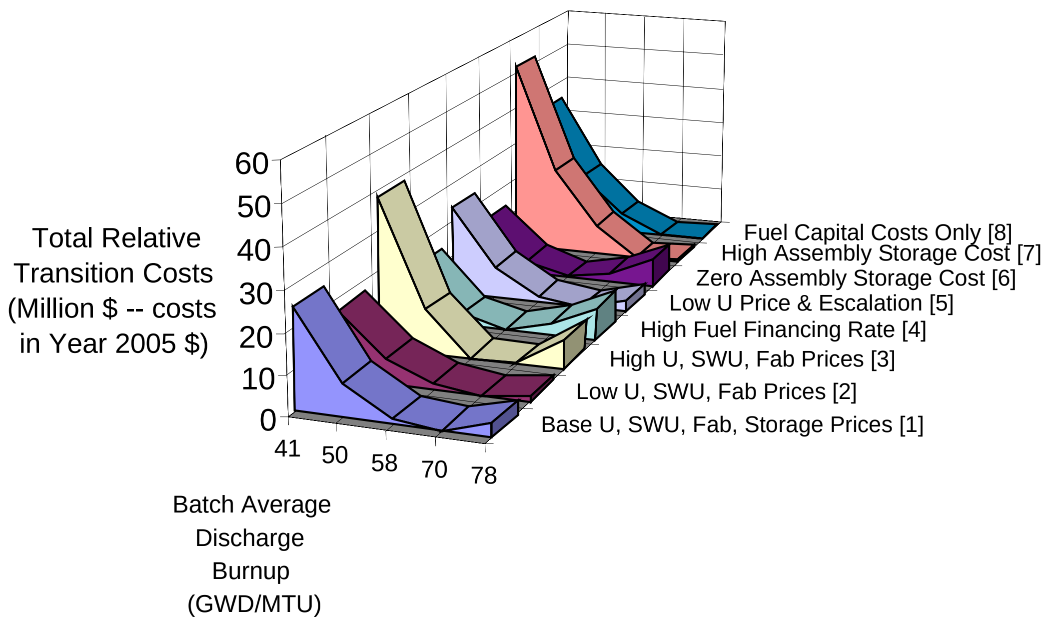


Figure 3-3
Oconee-1 Total 20-year Transition Costs

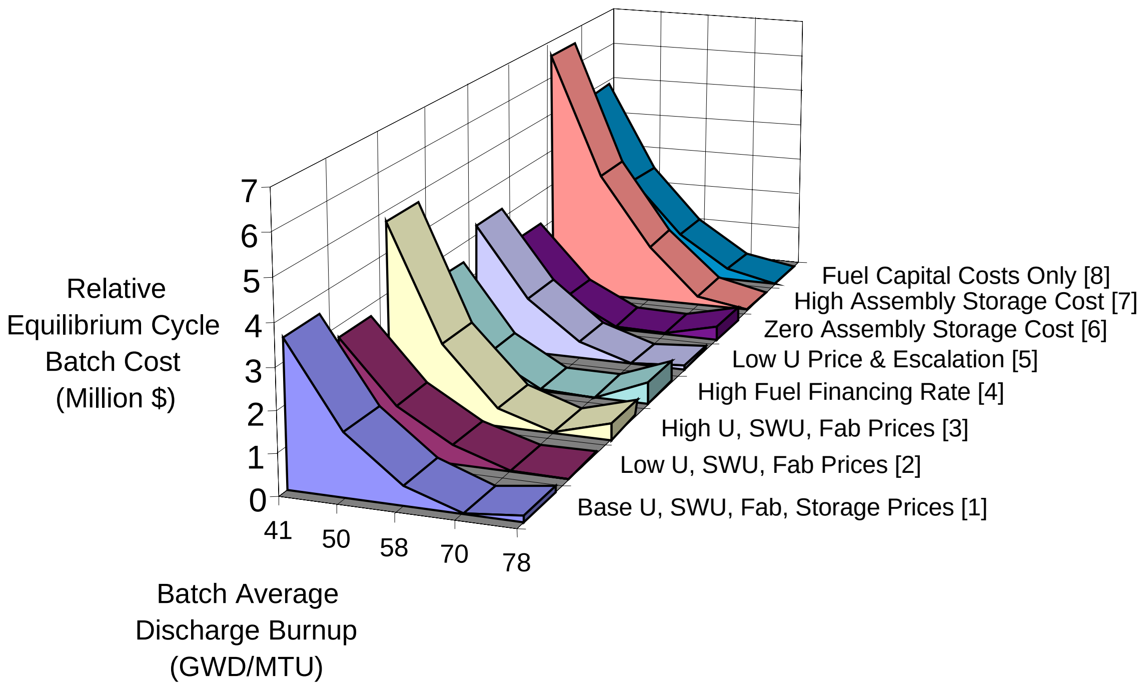


Figure 3-4
Oconee-1 Equilibrium Cycle Cost Comparison

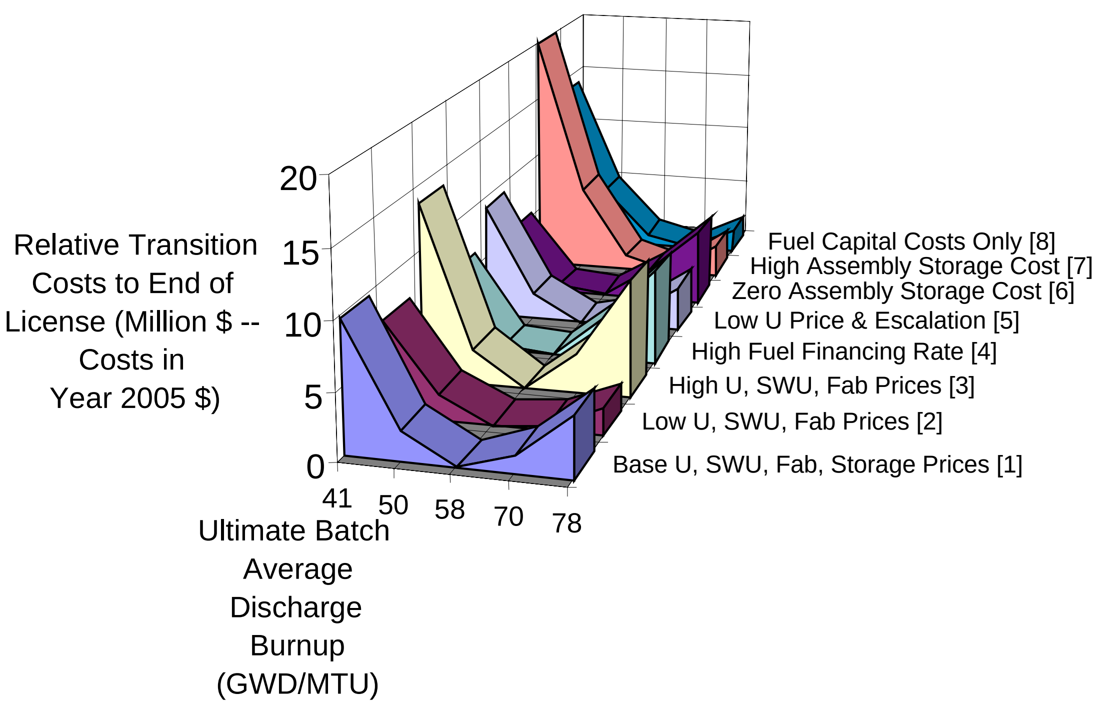


Figure 3-5
Oconee-1 Transition Costs for First 8 Years

Table 3-1
Prices and Rates Used in Economic Calculations
(All prices in year 2005 dollars)

Case	Uranium + Conversion Price ($/kgU)	Enrichment Price ($/SWU)	Fabrication Price ($/kgU)	Assembly Storage Costs ($/Assy)	Escalation Rates for U, Enr, Fab, Storage (% / yr)	Tails Assay (wt% 235U)	Pre-tax Cost of Capital Rate (% / yr)	Discount Rate (% / yr)	Innage Capacity Factor	Outage Length (Days)
1	45	120	240	50000	3.0, 3.0, 3.0, 5.0	0.3	15	9	0.965	40
2	25	75	150	50000	1.0, 1.0, 1.0, 3.0	0.3	15	9	0.965	40
3	90	180	350	50000	5.0, 5.0, 5.0, 7.0	0.3	15	9	0.965	40
4	45	120	240	50000	3.0, 3.0, 3.0, 5.0	0.3	25	12	0.965	40
5	25	120	240	50000	1.0, 3.0, 3.0, 5.0	0.3	15	9	0.965	40
6	45	120	240	0	3.0, 3.0, 3.0, 5.0	0.3	15	9	0.965	40
7	45	120	240	150000	3.0, 3.0, 3.0, 5.0	0.3	15	9	0.965	40
8	45	120	240	50000	3.0, 3.0, 3.0, 5.0	0.3	Not Used	9	0.965	40

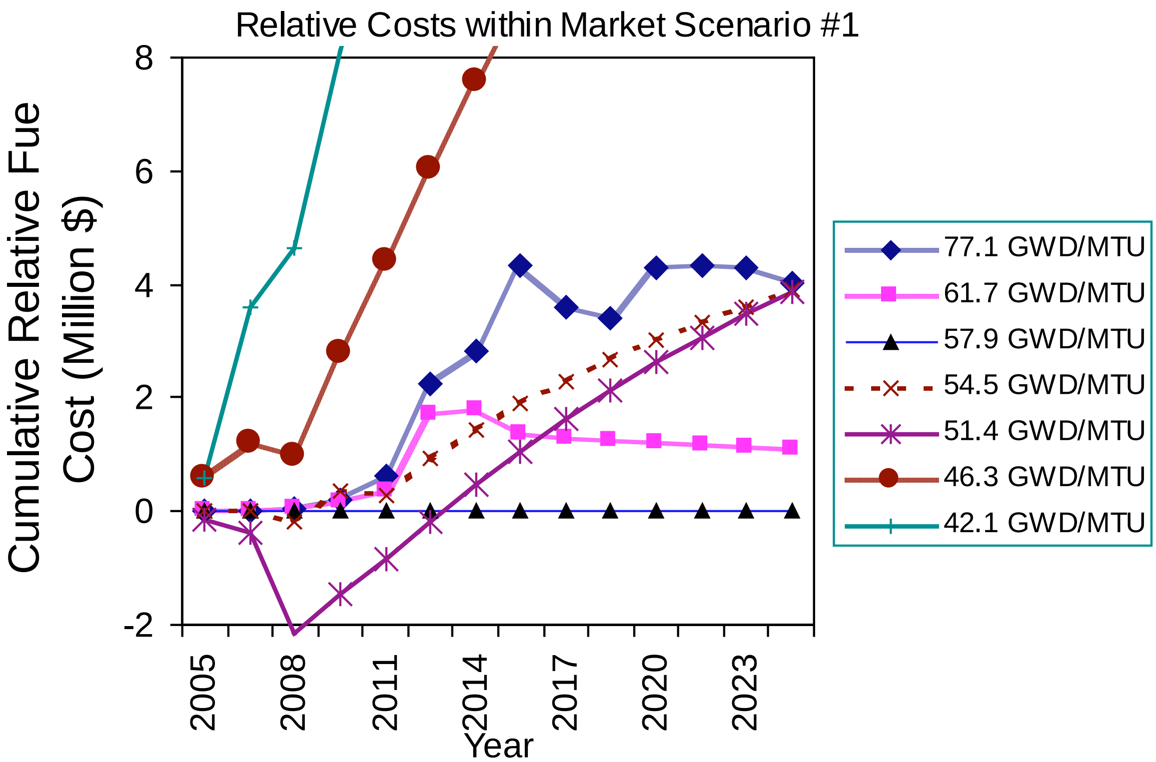


Figure 3-6
Catawba Cumulative Transition Costs

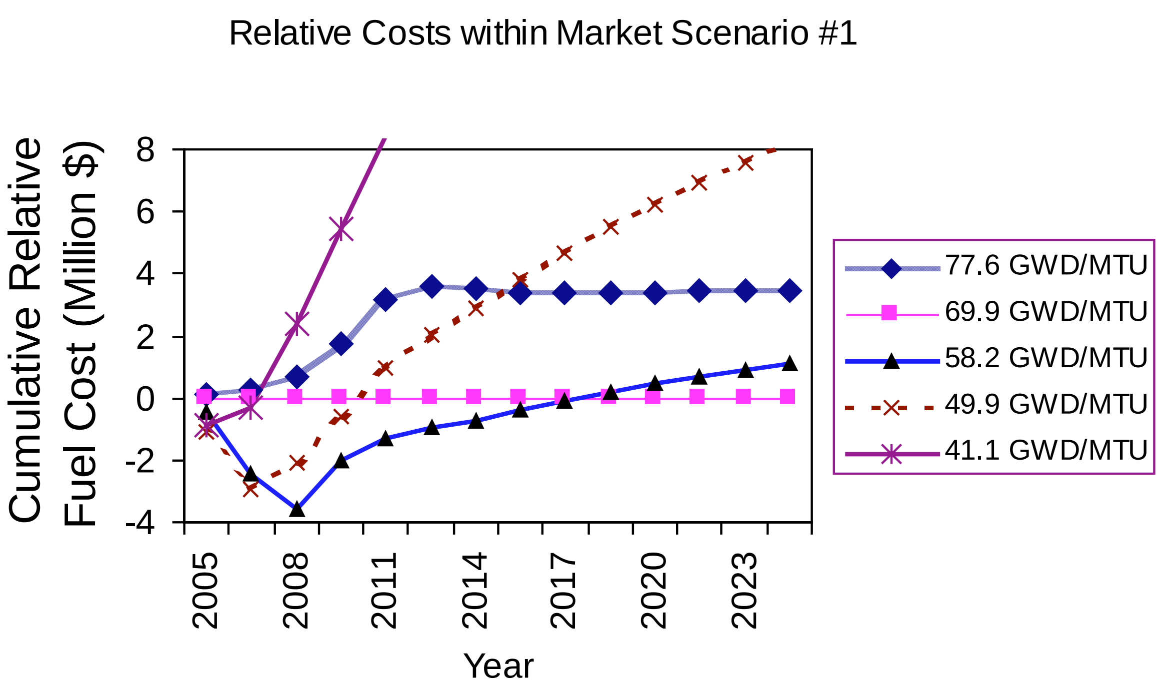


Figure 3-7
Oconee Cumulative Transition Costs

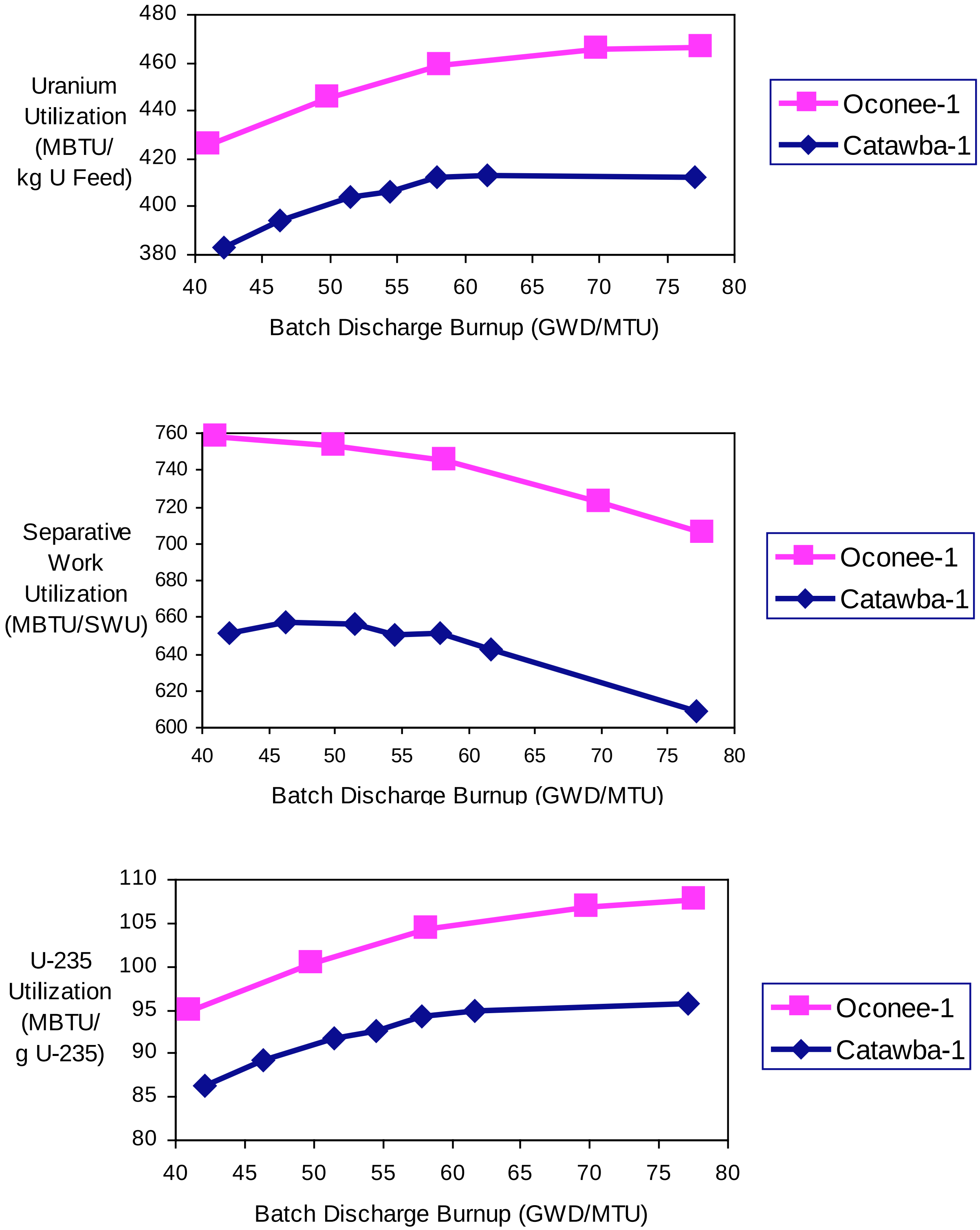
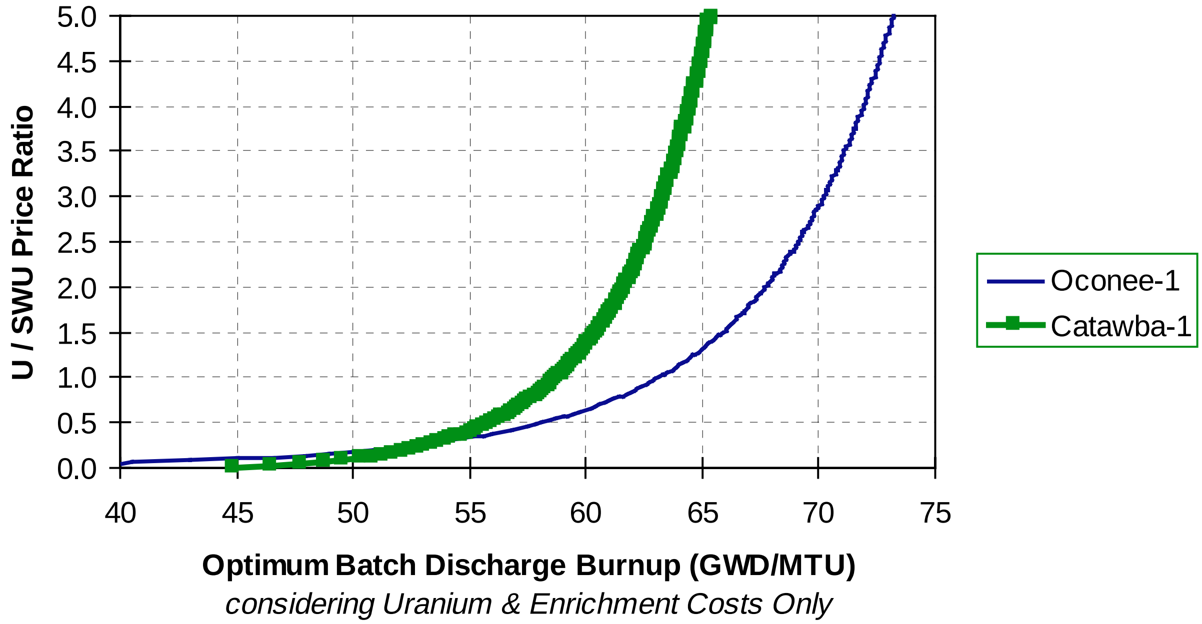


Figure 3-8
Fuel Utilization Comparisons



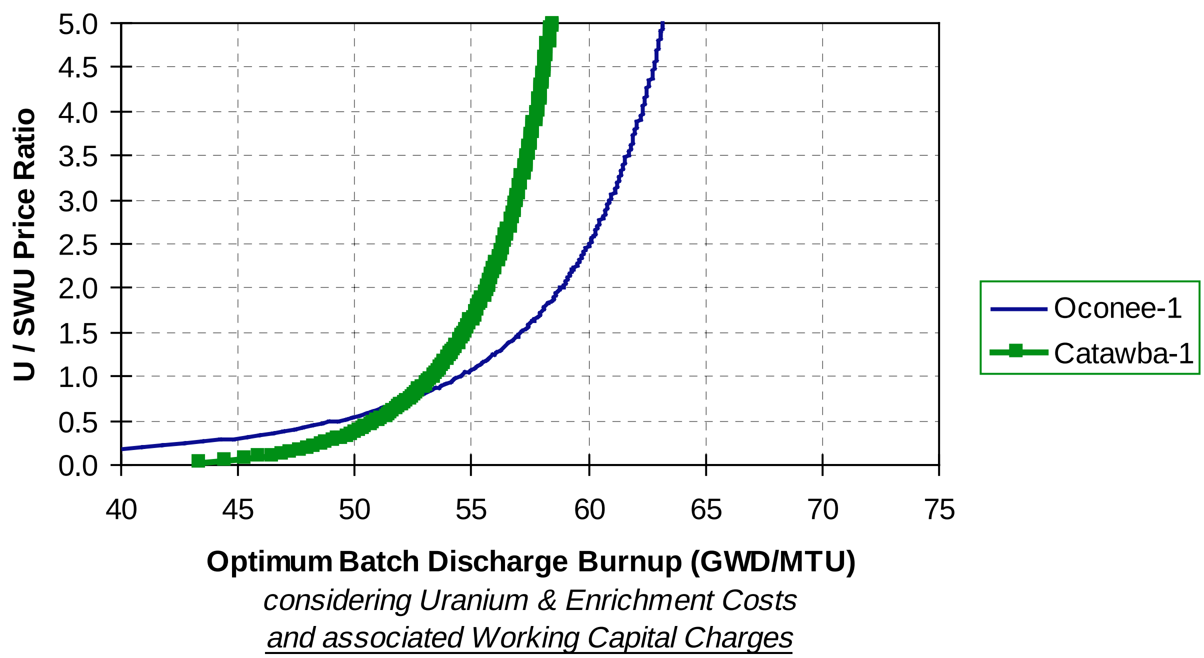


Figure 3-9
Minimum Cost Discharge Burnup at Various U/SWU price ratios

4
MECHANICAL, OPERATIONAL, AND REGULATORY BARRIERS TO INCREASING BURNUP

4.1 Introduction

The economic analysis in Section 3 shows that the optimum batch DB is between 60 and 70 GWD/MTU for both Catawba and Oconee. As Tables 2.5 and 2.6 indicate, such batch DBs are accompanied by maximum fuel rod burnups on the order of 80 GWD/MTU, well beyond the current regulatory limit of 62 GWD/MTU. In addition, the reactor core designs that can achieve these ultra-high burnups directly challenge many operational and regulatory issues facing the industry, including:

- Uranium enrichments above 5 wt% ^{235}U
- Cladding corrosion limits
- Crud deposition and crud-related fuel rod failures
- Cladding integrity at high burnups
- Axial Offset Anomaly (AOA)
- Incomplete Control Rod Insertion (IRI) events
- Reactivity Insertion Accident (RIA) transient responses
- Other general concerns related to operating high energy or high radial power peaking cores, as expressed in INPO SOER 96-2.[20]

EPRI's Robust Fuel Program has been structured to address all of these high burnup barriers over a 5-year period ending in 2002. Following the successful resolution of these issues and satisfactory in-reactor performance of Robust Fuel lead test assemblies, it is hoped that a commercial product, capable of achieving fuel rod burnups of at least 75 GWD/MTU, will be available by 2005.

The next section discusses the problems and possible resolutions or workarounds to using enrichments higher than current licensed limits. Section 4.3 discusses the other obstacles to increased burnup.

4.2 Uranium Enrichments Above 5 wt% ^{235}U

For most of the market scenarios depicted in Figures 3.1 to 3.5, the low end of the optimum DB range in is close to 60 GWD/MTU for both Catawba and Oconee. This burnup corresponds to equilibrium cycle central-region enrichment requirements just under 5 wt% ^{235}U for Oconee, but well above this enrichment limit for Catawba. In addition, the transition to get to these equilibria requires even higher enrichments along the way (see Tables 2.3 and 2.4). Considers, also, that 24-month fuel cycles, being inherently less neutronically efficient than 18-month cycles, require greater enrichments to achieve the same batch DB. It is evident, then, that to reach the optimum batch DBs found in this study, fuel enrichments above 5 wt% ^{235}U will be necessary. What does this entail? The fuel enricher and fabricator will have to increase their licensed limits by performing extensive criticality and radiological hazard reviews, and possibly making plant modifications. At the nuclear station, new fuel vaults and spent fuel pools will need to have their enrichment limits raised as well.[24]

To make all of the changes to support enrichments above 5 wt% ^{235}U could be cost-prohibitive, especially in light of the incremental benefit in fuel cost savings. What other alternatives are there? One possibility is to take the current fuel designs and increase the total uranium loading as much as possible without adversely affecting operating margins. This would reduce both the enrichment requirements and the batch DB for the same batch feed size, as well as improve uranium utilization.[25] In addition, for high central fuel region enrichments (5 wt% ^{235}U and up) the optimum axial blanket enrichment is likely higher than the 2.0 wt% ^{235}U used for the calculations in this study. Raising axial blanket enrichments would help reduce the central region enrichment requirements slightly.

What batch DBs could the Catawba and Oconee cores on 18-month cycles achieve without exceeding 5 wt% ^{235}U? Assuming axial blanket optimization, a glance at Tables 2.5 and 2.6 shows that Catawba could realize 55 GWD/MTU, and Oconee could probably reach 60 GWD/MTU. As Figures 3.1 and 3.2 show, this is somewhat less than the optimum for Catawba, but right at the lower end of the optimum DB range for Oconee. So even if fuel enrichments were to remain restricted to 5 wt% ^{235}U, there is economic incentive to push batch DBs as high as possible.

4.3 Other Barriers

The most concrete of the other barriers listed in Section 4.1 is cladding corrosion. The current regulatory limit of 100 microns oxide thickness is often difficult to meet even with current core designs. To estimate the corrosion for the various Catawba and Oconee DB designs, EPRI's PFCC code was employed, using the most corrosion-resistant cladding available today.

The results of this cursory evaluation indicate that, even with current state-of-the-art claddings, corrosion could significantly inhibit the push to higher fuel burnups. Without advances in cladding corrosion resistance (through better products, enhanced coolant chemistry control, and adherence to assembly power history guidelines), or a relaxation of the regulatory limit for PWRs, reactor cores are essentially limited to batch DBs of 50 GWD/MTU.

For the remaining issues listed in Section 4.1, EPRI's Robust Fuel Program is designed to address each in great detail over the next several years. Compared with just a few years ago, encouraging advances have taken place in understanding and controlling many of these phenomena. In addition, most utilities have implemented the recommendations of INPO SOER 96-2 in the form of procedures and processes from engineering to management to operations. It is apparent that the "infrastructure" is readily taking shape to support the future use of higher fuel burnups.

5 CONCLUSIONS

Economic evaluations within a broad range of market scenarios indicate that for Duke Power's reactors the optimum batch discharge burnup (DB) lies between 60 and 70 GWD/MTU, consistent with earlier Duke Power and industry studies on this subject. The economic parameter with the most uncertainty – dry storage / waste disposal cost – has the largest effect on the magnitude of total fuel cost differences among the various DBs considered.

The calculations performed for this report are predicated on an 18-month fuel cycle. However, other studies have demonstrated that optimum DB increases as cycle length increases, and logic supports that conclusion. One can surmise, then, that for anticipated operation of PWRs in the future, there is an economic incentive to develop an advanced fuel assembly capable of reliably achieving batch DBs of 60 to 70 GWD/MTU, with pin burnups of 75 GWD/MTU or more.

For an equilibrium cycle with a batch DB around 60 GWD/MTU, Oconee fuel batch costs can be reduced by $1M to $4M (2% to 7%) relative to current design practices, while Catawba and sister plant McGuire fuel batch costs drop by $1.5M to $5M (3% to 7%), depending on market conditions.

In order to realize the maximum fuel cost savings with increased batch DBs, enrichments up to 6 wt% ^{235}U need to be authorized and approved from the enricher to the fabricator to the fuel pool. In addition, if current regulatory corrosion limits remain in place, a Robust Fuel Assembly must feature improved resistance to cladding oxidation as compared with present day state-of-the-art products. Finally, operational issues regarding fuel failure mechanisms, power transients, and axial power predictions must be understood and resolved sufficiently to support the increased fuel duties inherent in irradiating fuel to ultra-high burnups.

6
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