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PNE-FM-80-1
UC-78

EXTENDED BURNUP CORE MANAGEMENT FOR ONCE-THROUGH URANIUM FUEL CYCLES IN LWRS

MASTER

FIRST ANNUAL REPORT FOR THE PERIOD 1 JULY 1979 - 30 JUNE 1980

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AUGUST 1980

WORK PERFORMED UNDER CONTRACT
DE-AC02-79ET34021

SCHOOL OF NUCLEAR ENGINEERING
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DOE/ET/34201-1
PNE-FM-80-1
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First Annual Report

For the Period

1 July 1979 - 30 June 1980

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August 1980

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Prepared For The

U. S. Department of Energy
Division of Energy Technology
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ABSTRACT

Detailed core management arrangements are developed requiring four operating cycles for the transition from present three-batch loading to an extended burnup four-batch plan for Zion-1. The ARMP code EPRI-NODE-P was used for core modeling. Although this work is preliminary, uranium and economic savings during the transition cycles appear of the order of 6 percent.

TABLE OF CONTENTS

	SUMMARY	ii
1.0	INTRODUCTION	1
2.0	CORE MODELING METHODS	2
3.0	SAFETY CONSIDERATIONS	4
	Core Peaking Factors	4
	Moderator Temperature Coefficient	7
4.0	THE ZION REACTOR	7
	First Cycle	7
	Subsequent Cycles	11
5.0	INITIAL TRANSITION CYCLE ESTIMATE	15
6.0	THREE-TO-FOUR BATCH TRANSITION CYCLES	19
	Development of Transition Cycle Starting Conditions	19
	The Transition Scheme	21
	First Transition Cycle	24
	Second Transition Cycle	25
	Third Transition Cycle	34
	Fourth Transition Cycle	34
	Moderator Temperature Coefficient (MTC)	39
7.0	URANIUM UTILIZATION AND ECONOMICS	39
	Uranium Resource and Separative Work Utilization	39
	Fuel Cycle Cost Estimation	49
8.0	CONTINUING TASKS	53
	REFERENCES	54

SUMMARY

The objective of the program is to develop detailed core management procedures leading to extended burnup for once-through fuel cycles. Requirements of Commonwealth Edison's Zion-1 are being examined to assure relevance of the PWR work. During the first program year, substantial efforts were required to implement various ARMP computer modules so that the 3-D core simulator EPRI-NODE-P could be used for modeling. Operating data and fine mesh PDQ-7 calculations were used for normalization.

A preliminary four operating cycle transition to a four-batch equilibrium scheme was developed which includes substantial reinsertion of spent first core assemblies. The reload core arrangements met licensing power peaking requirements but a higher than necessary feed enrichment may have been required. This possibility is being studied with improvements to the transition cycles likely.

The preliminary PWR work demonstrated the feasibility of rapid transition from present three-batch operating practice to four-batch extended burnup loading, with likely uranium and economic savings during the transition cycles of the order of 6 percent.

1.0 INTRODUCTION

The primary objective of the program is to develop detailed fuel management procedures for transition to extended burnup strategies for typical LWRs, including the reinsertion of spent fuel from the storage pool. Extended burnup management options are also being examined. The work is intended to serve as background for utility management in evaluating the extended burnup option and planning demonstration programs that could lead to commercialization.

Two features of the program are important in providing the desired applicability to real-life situations. First, reload core designs are being developed for an actual reactor rather than for a hypothetical one. Second, calculational methods used to determine acceptability of loading patterns are similar to those used commercially for this purpose.

The first feature has been satisfied by basing the present PWR study on the Commonwealth Edison Zion-1 Plant. In the case of the second feature, PWR core modeling procedures using the Advanced Recycle Methodology Program (ARMP) are being utilized. These procedures have been developed for the Electric Power Research Institute to provide standard calculational approaches for the utility industry that are acceptable to the Nuclear Regulatory Commission for licensing purposes. In the present work, the three-dimensional core simulator, EPRI-NODE-P, which is part of the ARMP system, serves as a primary tool.

Certain approximations were made, as will be described, in the core modeling to expedite obtaining an initial set of transition cycles. Although these approximations are appropriate in light of the limited resources available and the objectives of the study, modeling is being improved by continuing efforts to improve the confidence level of the results.

Commonwealth Edison Company staff are cooperating in the study by providing helpful guidance. However, the results presented here were developed independently so that they could be made generally available without compromising proprietary restrictions. Also, since the ARMP code modules are proprietary, they are described in only general terms.

2.0 CORE MODELING METHODS

PWR core analysis makes use of multigroup, two-dimensional finite difference depletion codes of the PDQ-type and nodal methods to describe three-dimensional and thermal-hydraulic effects. Confidence in the nodal representation strongly depends upon normalization with PDQ-type results.

The Advanced Recycle Methodology Program[1] (ARMP) is a system of codes which can simulate a light water reactor (LWR) core in the various configurations encountered throughout multi-cycle operation. The simulation is done with the nodal core EPRI-NODE-P for pressurized water reactors (PWRs) which performs global reactor analysis by simultaneously solving for the effective multiplication factor and the three-dimensional core power, temperature, void, xenon, and exposure distributions.

ARMP system support codes are used to generate the necessary constants (commonly referred to as "B" constants) for the nodal code. There are two depletion codes EPRI-CELL and CPM which both use multigroup transport theory. The former is a one-dimensional cell code while the latter is a two-dimensional assembly code. The code combination, PDQ7-II/HARMONY, is used for two-dimensional diffusion theory assembly and core calculations using two groups and has a flexible representation of the depletion dependent cross sections. Also used are file management and processing codes such as NUPUNCHER, EPRI-FIT and SUPERLINK-P. These various code modules are linked together in a complex processing sequence.

In brief, the group constants generated by EPRI-CELL are used as input into PDQ7/HARMONY, which combines the cells into an array describing a quarter assembly. The assembly is depleted and data are gathered on the behavior of the averaged assembly as a function of temperature, soluble boron concentration and exposure e.g., k_∞, $\nu\Sigma_f$, $\Delta\rho_{xenon}$, $\Delta\rho_{B-10}$, etc. These data are then fitted with polynomials and their parameters yield the "B" constants. These contants, obtained for each different assembly type in a reload core, are subsequently used together with several other adjustable parameters in EPRI-NODE-P, which couples the assemblies together to model core behavior in three dimensions.

In the present PWR work, the "B" constants for assemblies without burnable poison (BP) rods were generated using standard procedures. Seven sets were generated covering the enrichment range from 2.25 to 4.1 w/o U-235. However, the PDQ-7/HARMONY depletion steps were somewhat longer (5000 vs 2000 MWD/T) than recommended for design purposes to reduce computing costs. Linear interpolation was used for intermediate enrichments.

For the preliminary study described in this report period, it was assumed that the addition of LBP to an assembly affected only the variation of k_∞ with exposure and the variation of k_∞ and M^2 with temperature. The transport code, CPM, was then used to describe these variations and a table of suitable "B" constants generated for various combinations of enrichments and numbers of BP rods used in an assembly. Although this approach is crude, it was felt to be adequate for preliminary work. Improvements in the LBP modeling are currently underway making use of additional EPRI-CELL and one-quarter core PDQ runs.

Normalization of EPRI-NODE was accomplished by comparison with fine-mesh PDQ-7 results and detailed two-dimensional and axial power maps for the Zion-1 first core hot zero power (HZP) case. Details of the normalization procedure are given in Reference 2.

The one-and-half group 3-D nodal code SIMULATE has also been implemented and is being used for certain special applications. Currently active is a two-dimensional assembly modeling program wherein a four node per assembly SIMULATE representation is being compared with 1/4-core fine-mesh PDQ-7 results.

3.0 SAFETY CONSIDERATIONS

A nuclear fuel reload design must meet the plant technical specifications, particularly in the areas of core peaking factors and kinetic characteristics such as the moderator temperature coefficient (MTC) and control rod worths. Extending the burnup of the fuel also requires considerations in the area of fuel performance.

Core Peaking Factors

A major portion of this study is directed toward the evaluation of the core peaking factors for the reload designs under consideration. With both power generation and cycle length fixed, the objective is to develop a loading pattern which will satisfy the peaking factor constraints prescribed by the Nuclear Regulatory Commission.

Core peaking factors are defined for PWRs as follows:

$$F_Q \equiv \frac{\text{Maximum heat flux in core}}{\text{Average heat flux in core}}$$

$$F_{\Delta H} \equiv \frac{\text{Maximum (hot channel) coolant enthalpy rise}}{\text{Average coolant enthalpy rise}}$$

Assembly location decisions are primarily affected by the enthalpy rise factor, $F_{\Delta H}$, constraint. Thus it is emphasized here.

$F_{\Delta H}$ can be expressed as

$$F_{\Delta H} = F_I \cdot F_{(X,Y)} \cdot F_U \quad ,$$

where

$$F_I \equiv \frac{\int_0^H q'(\text{peak assembly})\,dZ}{H \cdot q'\ (\text{avg assembly})} \quad ,$$

$\int_0^H q'(\text{peak assembly})\, dZ$ ≡ integral of assembly linear power for the assembly containing the rod with the highest integrated power,

H ≡ Core height,

$q'(avg)$ ≡ Average assembly linear power,

$F_{(X,Y)}$ ≡ Local power peaking factor. This is the maximum pin power to average assembly power ratio within each particular assembly,

F_U ≡ Uncertainty factor.

The limits on F_Q and $F_{\Delta H}$ for full rated power operation are 2.235 and 1.55 respectively.[3] The uncertainty factor, F_U, used in this study for both F_Q and $F_{\Delta H}$ is 8 percent. This margin includes a heat flux allowance of 3 percent for manufacturing tolerances such as local variations in enrichment, pellet density and diameter, etc., and a 5 percent heat flux allowance for uncertainty in the monitoring system, the calculational model, or any abnormal effects such as rod bowing. The integral enthalpy term, F_I, can be obtained directly from the three-dimensional code, EPRI-NODE-P.

Nodal codes, however, cannot predict the local peak pin to average assembly peaking factor, $F_{(X,Y)}$, due to their coarse representation. Diffusion theory codes such as PDQ-7 are required to model quarter cores on a pin-by-pin basis to give the local peaking factors directly. For purposes of planning assembly placement, a map was prepared of average within assembly peaking factors to be expected at each position using data provided by the Commonwealth Edison Company. These values were then combined with the $F_{\Delta H}$ limit and the uncertainty factor to yield a map of average assembly power peaking criteria that could be compared directly with assembly power values obtained from EPRI-NODE-P. This map is shown in Figure 1. A somewhat similar approach involving axial factors was used to determine if node peaking values were within F_Q constraints but is not described here.

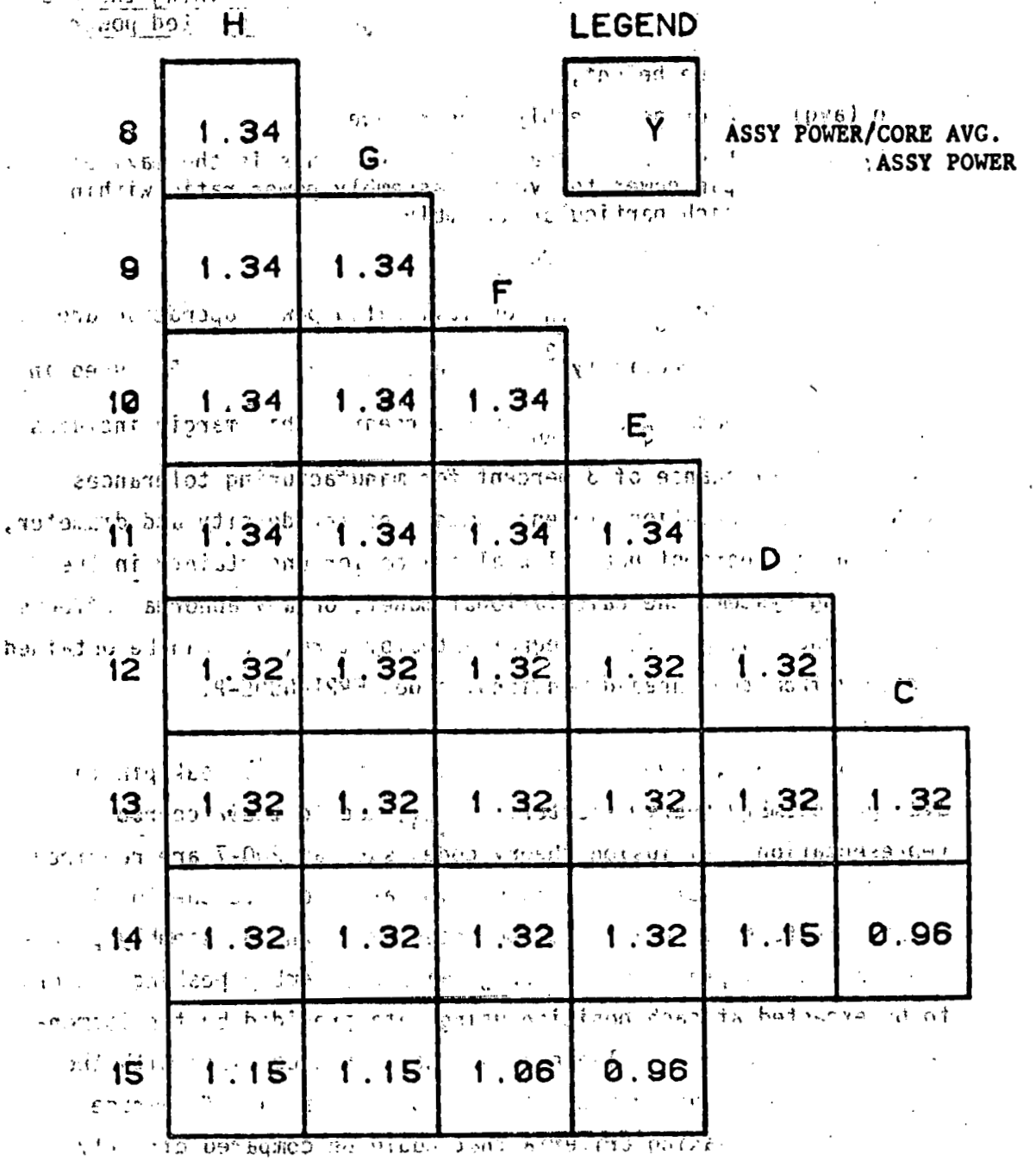


Figure 1 : EPRI-NODE-P, average assembly power peaking criteria.

Moderator Temperature Coefficient

The limiting conditions for operation of the moderator temperature coefficient (MTC) is that it be just negative for the hot zero thermal power condition at beginning of cycle (BOC) and be able to satisfy a 1.6% $\Delta\rho$ shutdown margin for the rated thermal power condition at end of cycle (EOC).[3] This means that the MTC cannot be more negative than 3.9×10^{-4} $\Delta\rho/°F$. The MTC is obtained from EPRI-NODE by varying the moderator temperature and comparing k_{eff} with that at the reference temperature.

4.0 THE ZION REACTOR

Zion Unit 1 is one of two, four-loop, 1050 MW(e), Westinghouse reactors operated by the Commonwealth Edison Company. The core consists of 193 fuel assemblies, each containing 204 fuel rods, 20 thimbles used for control rods or burnable poison but otherwise filled with water, and one instrumentation tube, arranged in a 15 x 15 array as shown in Figure 2. Zion has four full-length control banks, one part-length control bank, and four shutdown banks (see Figure 3). The core operates at an average temperature of 559°F and a pressure of 2250 psia.

First Cycle

The life of Zion Unit 1 began with an all fresh core divided into three equal batches each with a different enrichment (see Figure 4). The loading was sixty-five assemblies of 2.25 w/o U-235 enrichment as region 1; sixty-four assemblies of 2.80 w/o U-235 enrichment as region 2 assemblies; and sixty-four assemblies of 3.30 w/o U-235 enrichment as region 3. Region 1 assemblies contained no burnable poison or source rods. However, many region 2 and 3 assemblies contained various combinations of each. In all, there were a total of twelve assembly types or "colors", i.e., different combinations of enrichment, burnable poison and source rod loadings,

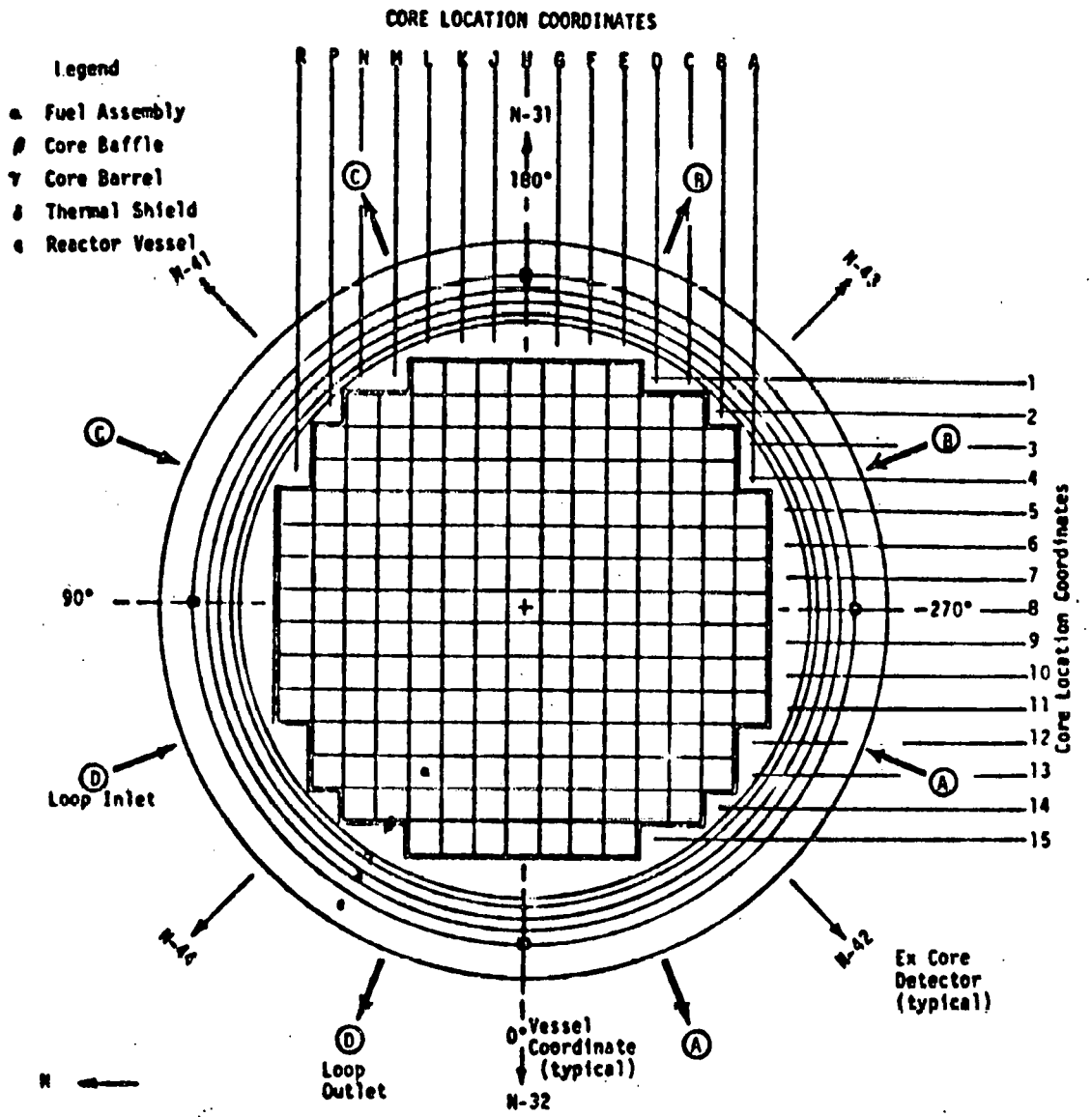
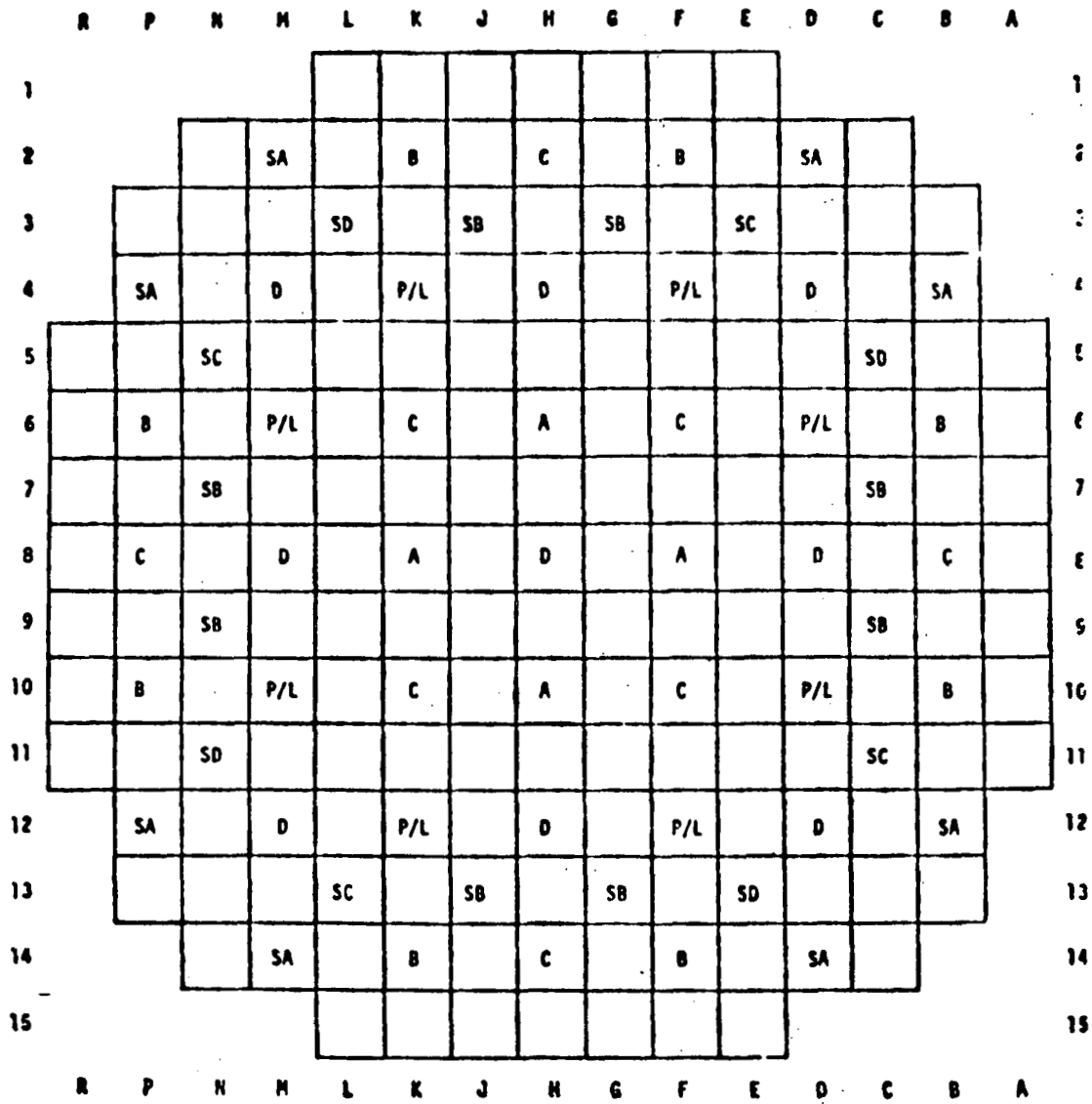


Figure 2: Reactor plan view showing the core location coordinates of the Zion reactor



SHUTDOWN BANKS

Symbol	Designation	No. of RCCA's
SA	Shutdown A	8
SB	Shutdown B	8
SC	Shutdown C	4
SD	Shutdown D	4

CONTROL BANKS

Symbol	Designation	No. of RCCA's
A	Control A	4
B	Control B	8
C	Control C	8
D	Control D	9
P/L	Part Lengths	8

Figure 3: Locations of rod cluster control assemblies by bank designation, Zion reactor

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A	
1					3	3	3	3	3	3	3					1
2			3	3	3	1	3	1	3	1	3	3	3			2
3		3	3	2	1	2	1	2	1	2	1	2	3	3		3
4		3	2	2	2	1	2	1	2	1	2	2	2	3		4
5	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3	5
6	3	1	2	1	2	1	2	1	2	1	2	1	2	1	3	6
7	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3	7
8	3	1	2	1	2	1	2	1	2	1	2	1	2	1	3	8
9	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3	9
10	3	1	2	1	2	1	2	1	2	1	2	1	2	1	3	10
11	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3	11
12		3	2	2	2	1	2	1	2	1	2	2	2	3		12
13		3	3	2	1	2	1	2	1	2	1	2	3	3		13
14			3	3	3	1	3	1	3	1	3	3	3			14
15					3	3	3	3	3	3	3					15
	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A	

Symbol	Region	Enrichment (w/o)	No. of Assemblies
1	1	2.248	65
2	2	2.789	64
3	3	3.292	64

Figure 4: Locations of fuel assemblies by enrichment type, Zion Unit 1, cycle 1

which make up the first core. Table 1 describes the content of the various assembly types while Figure 5 shows their location.

All burnable poison rods in the first core had a boron loading of 0.0603 g-B_2O_3/cm which corresponds to roughly 18 w/o B_2O_3 embedded in a Tempax-like borosilicate glass.

Most of the region-1 fuel assemblies were removed after the first cycle, which lasted 18 months, with an average burnup of 18,700 MWD/T. The region-2 assemblies remained in the reactor for the second cycle and were then discharged after achieving an average cumulative burnup of about 30,000 MWD/T. It is these assemblies which will be reinserted to help ease the proposed transition from a three to four-batch fuel management scheme.

Subsequent Cycles

The basic fuel management strategy for Zion has essentially been the afore mentioned three-batch, out-in cycle plan with the usual insertion of 64 assemblies of 3.2 w/o enrichment every 12 months. Cycle average burnup was normally about 10,000 MWD/T but with some variation depending upon utility needs and refueling schedules.

Zion-1 is currently operating in cycle 5, with cycle 6 start-up planned for November 1980. As can be seen from the cycle 5 loading pattern in Figure 6, burnable poison rods are required to meet the power peaking safety constraints. However, BP rods with boron loadings of about 12.5 w/o B_2O_3 have been used instead of the first core type 18 w/o rods. It has been found that 18 w/o rods retain too great a residual absorption value near end of cycle and hence reduce the neutron economy unnecessarily. Therefore, except for normalization procedures, all core models in this study use burnable poison data derived from the 12.5 w/o B_2O_3 design.

TABLE 1

Assembly Types Found in First Cycle

Type	Enrichment	No. BPR	No. Source Rods	Core Inventory
1	2.25	0	0	65
2	2.80	0	0	4
3	2.80	12	0	10
4	2.80	12	1	2
5	2.80	16	0	24
6	2.80	20	0	24
7	3.30	0	0	28
8	3.30	8*	0	8
9	3.30	9*	0	12
10	3.30	12	0	8
11	3.30	19	1	2
12	3.30	20	0	6
				193

*Asymmetrically loaded

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A	
1						9P		9P		9P						1
2			8P		12P		20P		20S		12P		8P			2
3		8P		20P		12P		SPS		12P		20P		8P		3
4			20P		20P		16P		16P		20P		20P			4
5		12P		20P		16P		16P		16P		20P		12P		5
6	9P		12P		16P		20P		20P		16P		12P		9P	6
7		20P		16P		20P		16P		20P		16P		20P		7
8	9P		12P		16P		16P		16P		16P		12P		9P	8
9		20P		16P		20P		16P		20P		16P		20P		9
10	9P		12P		16P		20P		20P		16P		12P		9P	10
11		12P		20P		16P		16P		16P		20P		12P		11
12			20P		20P		16P		16P		20P		20P			12
13		8P		20P		12P		SPS		12P		20P		8P		13
14			8P		12P		20P		20S		12P		8P			14
15						9P		9P		9P						15

STANDARD ASSEMBLIES

Symbol	# B/P Rods per Insert	# Inserts
20P	20	30
16P	16	24
12P	12	18
9P	9	12
8P	8	8

SPECIAL SOURCE BEARING ASSEMBLIES

Symbol	# B/P Rods per Insert	# Inserts
20S	19	2
SPS	12	2

Figure 5: Location of burnable poison assembly inserts by number of burnable poison rods, Zion Unit 1, cycle 1

	H	G	F	E	D	C
8	1 0					
9	6 0	5 0				
10	6 0	6 0	5 0			
11	6 0	6 0	6 0	5 0		
12	5 0	6 0	5 0	6 0	5 0	
13	5 0	5 0	7 4	5 0	6 0	5 0
14	5 0	7 12	5 0	7 8	7 0	7 0
15	7 0	7 12	7 0	7 0		

LEGEND

XX	REGION NUMBER
YY	NUMBER OF BP RODS

Figure 6 : Zion Unit 1, cycle 5 core reload pattern

Table 2 gives a detailed reload history of Zion Unit-1 up through and including cycle 6 (the transition to four cycles is scheduled to begin in cycle 7 in this study). Cycle 6 is an estimate made by Commonwealth Edison since at the time of this study, no definite loading pattern had been developed. Data through cycle 5 were extracted from reload safety evaluations prepared by Commonwealth Edison. Table 2 provided the information necessary to prepare Table 3 which lists the spent fuel pool inventory as projected at the end of cycle 6. The average cumulative burnups shown in Table 3 were derived from individual assembly burnup estimates supplied by Commonwealth Edison. These average burnups provide the basis for estimating the burnups of the reinserted fuel used in the transition cycles to be described.

5.0 INITIAL TRANSITION CYCLE ESTIMATE

Once the energy requirements for a given cycle are determined, a first guess as to the fuel inventory must be made. This is usually accomplished by using lumped parameter model (sometimes called the point reactor model) which determines t core average k_∞ by weighting each batch average k_∞ with its respective batch size and estimating the cycle power fraction. Batch size and fresh fuel enrichment (initial k_∞) are treated as variables and the batch power fraction is estimated from past cycle experience. The end of cycle is determined when the core average k_{eff} equals 1.00 (or k_∞ of 1.05) with zero soluble boron. The k_∞ for the different enrichments found in a reload core are usually taken to decrease linearly with exposure. Thus, by properly averaging the batch properties at the end of their projected exposure lengths, a combination of batch sizes and fresh fuel enrichment can be found by trial and error to provide initial estimate of the reload core requirements. This approach was used to develop initial trials for the transition cycles described in the next section.

TABLE 2

Reload History for Zion Unit 1

1st Cycle

Region No.	No. Assys in Core	Enrichment when Fresh, w/o
3	64	3.30
2	64	2.80
1	65	2.25

2nd Cycle

Region No.	No. Assys in Core	Enrichment when Fresh, w/o
4	60	3.2
3	64	3.30
2	64	2.80
1	5	2.25

3rd Cycle

Region No.	No. Assys in Core	Enrichment when Fresh, w/o
5	64	3.2
4	60	3.2
3	64	3.30
2	5	2.80

4th Cycle

Region No.	No. Assys in Core	Enrichment when Fresh, w/o
6	60	2.8
5	64	3.2
4	60	3.2
1	9	2.25

Table 2 continued

5th Cycle

Region No.	No. Assys in Core	Enrichment when Fresh, w/o
7	68	3.2
6	60	2.80
5	63	3.2
1	2	2.25

6th Cycle

Region No.	No. Assys in Core	Enrichment when Fresh, w/o
8	60	3.2
7	68	3.2
6	60	2.80
1	5	2.25

TABLE 3

Projected Unit 1 Spent Fuel Pool Inventory
at the End of Cycle 6* (1981)

Region No.	No. Cycle Exposures	Avg. Cum. Burnup in MWD/T	No. of Assys
† 1	1	18,700	44
1	2	27,300	21
† 2	2	30,500	59
2	3	36,000	5
3	3	35,000	60
3**	4	40,000	4
4	3	32,800	60
5	2	19,700	1
5	3	30,400	63
6	3	30,800	60

*Cycle 6 has been estimated

**Four region 3 assemblies re-inserted into Unit 2 as part of Commonwealth Edison Cooperation in a DOE extended burnup study.

†Fuel Available for re-insertion

6.0 THREE-TO-FOUR BATCH TRANSITION CYCLES

During this period, emphasis was given to developing a preliminary, but credible fuel management plan for the transition of Zion-1 from a three to a four batch approach. This is an iterative process which requires further refinement. With the lumped parameter results as a tentative plan, it is next necessary to establish a starting point for the selection of candidate transition cycles. Only non-proprietary information was utilized so that the results could be made generally available.

Development of Transition Cycle Starting Conditions

Cycle 7 was chosen as the starting point of our transition scheme since it is far enough into the future to allow reasonable analysis (around November 1982) and yet soon enough to permit a realistic estimate of the exposure distributions of the once and twice-depleted assemblies that must make up part of its loading pattern (regions 8 and 7). As mentioned before, Zion 1 is currently operating in cycle 5 and the detailed loading history is accurately known to this point (see Table 2). However, the loading information for cycle 6 and the associated EOC exposure for regions 7 and 8 are not known and must be estimated.* These estimates were made by utilizing projected feed requirements and average EOC batch exposures from Commonwealth Edison for cycle 6. The feed requirement projection was made by consideration of utility energy needs through the year 1981; the EOC batch-average exposure information was estimated from previous Zion loadings with similar feed and cycle length requirements, see Table 4. These data represent Edison's guess in March 1980 of likely batch inventories at the end of cycle 6 around November 1981.

With the batch average exposures fixed, the next step was to

---

*The correct method to estimate the region 7 and 8 EOC exposures for cycles 5 and 6 would be to use EPRI-NODE-P to follow the core from the first cycle through the sixth cycle. However, due to time constraints, a much more approximate method is used which will be described.

TABLE 4

Estimated Cycle 6, EOC Batchwise
Average Exposures from Commonwealth Edison

Region	Enrichment	No. Assys. Loaded	Estimated Average Batch Exposure (GWD/T)
8	3.2	60	9.814
7	3.2	68	22.457
6	2.8	60	30.761

Based on the following cycle lengths:

Cycle	Core Average Exposure (GWD/T)
1	17.8
2	12.0
3	9.5
4	10.0
5	10.7
6	10.6 (estimated)

translate them into individual assembly average exposures. These average assembly exposures were then converted into a twelve node axial exposure distribution as required for use in EPRI-NODE-P.

An estimate of the assembly average exposure distribution was obtained from a 3.2 w/o equilibrium cycle study of the Zion reactor by Rieck[4], who used the nodal code SIMULATE to obtain two and three-dimensional power peaking and exposure ranges of the Zion core. From these data, a normalized assembly-to-batch exposure distribution was obtained for a typical Zion equilibrium loading pattern and applied to cycle 6. The results for the cycle 6 average assembly EOC burnup distribution are given in Table 5. Burnup distributions for regions 1 and 2 fuel, which is slated for reinsertion, were estimated from axial power measurements and calculations for twice-burned assemblies.

The Transition Scheme

The four-cycle transition scheme obtained as a result of detailed three-dimensional analysis with EPRI-NODE-P is summarized in Table 6. Included are the region number of the batches, the original feed enrichment of the batches, the number of assemblies per region and the cycle length of each pattern.

As can be seen, a transition to four batches, in which all power peaking constraints have been met, can be accomplished in four cycles. However, although the first two transition cycles are near the target cycle length of about 10 GWD/T ± 0.2 GWD/T or 312 ± 9 Effective Full Power Days (EFPD), cycles 9 and 10 (both 10A and 10B) are too short and too long respectively. The low cycle length of cycle 9 is due entirely to the use of reinserted region 2 assemblies. The large number and low reactivity of these twice-burned assemblies compared with the once-burned region 1 assemblies tend to drive the reactivity of the core down to unacceptable levels. This shortens the burnup of the other assemblies thereby forcing the introduction of additional

TABLE 5

Estimated Regions 7 and 8
Assembly Exposures

Region 7

# in Core	Exposure (GWD/T)
4	19.942
4	20.391
8	20.391
8	21.738
4	22.188
8	22.188
4	22.412
8	22.861
4	23.984
8	24.658
4	24.882
64	

Region 7 average = 22.457 GWD/T

Region 8

# in Core	Exposure (GWD/T)
8	7.380
8	7.380
8	9.637
8	10.040
4	10.256
8	10.432
8	11.806
8	11.806
60	

Region 8 Average = 9814 GWD/T

TABLE 6

Transition Scenario from Three to Four Batches
as a Result of EPRI-NODE-P Analysis

Cycle	Cycle Length (GWD/T)	Fresh Batch	Irradiated 1 Cycle	Irradiated 2 Cycles	Irradiated 3 Cycles	Reinserted Assemblies Region 1	Reinserted Assemblies Region 2
6	10.6	8-60/ 3.2	7-68/ 3.2	6-60/ 3.2		1-5/ 2.25	
			10.2	20.6		18.7	
7	10.0	9-52/4.0	8-60/ 3.2	7-68/ 3.2		1-13/ 2.25	
			9.8	22.5		18.7	
8	10.3	10-48/ 3.7	9-52/ 4.0	8-60/ 3.2		1-29/ 2.25	2-4 / 2.8
			9.3	20.4		18.7	29.8
9	9.5	11-48/ 3.7	10-48/ 3.7	9-52/ 4.0		1-1/ 2.25	2-44/ 2.8
			8.4	22.4		18.7	29.8
10A	11.3	12-48/ 3.7	11-48/ 3.7	10-48/ 3.7	9-48/ 4.0*	1-1/ 2.25	
			7.9	20.9	32.4	18.7	
10B	10.6	12-48/ 3.7	11-48/ 3.7	10-48/ 3.7	9-48/ 4.0*	1-1/ 2.25	
			7.9	20.9	32.4	18.7	

Key: Region number -- Batch size/Initial enrichment

BOC Exposure (GWD/T)

*Assemblies removed from this batch would be reinserted in later cycles.

reactivity into cycle 10 where no reinserted assemblies are present (observe that even at 33,000 MWD/T the region 9 assemblies have higher reactivity than the once-burned region 1 assemblies). These effects drive the cycle length of the last transition cycle (presumably near equilibrium cycle) to an unacceptably high level. This could be abated somewhat by insertion of residual burnable poison rods into the once burned fuel in the interior of the core, however, as shown in cycle 10B, the cycle length is still excessive. This suggests possible divergence or oscillation of the transition scheme. However, with better management of the regions 1 and 2 assemblies and the possible addition of an extra transition cycle the scheme is likely to converge. Such refinements are currently being studied.

Following is a more detailed description of each transition cycle and a discussion of the problems incured in their development.

First Transition Cycle

The first loading pattern attempted was based on the first cycle of the point reactor model i.e., 56 fresh assemblies having an enrichment of 4.0 w/o U-235, accompanied by 9 reinserted assemblies. After some shuffling adjustments and the insertion of a moderate amount of burnable poison into the highest peaking fresh assemblies, all peaking constraints could be met, but the cycle length was too long at 10.5 GWD/T. Lowering the feed enrichment, by about 0.3 percent, reduced the core reactivity to the desired level but also lowered the power fraction on the periphery causing peaking problems in the interior. This necessitated removal of many BP rods which again raised the core reactivity and the cycle length. Rather than carry out a comprehensive exploration of the interplays of feed enrichment, number of loaded assemblies, assembly location, and burnable poison loading to yield an acceptable combination with lower enrichment feed, the 4.0 percent feed enrichment was retained so that study of subsequent cycles could be expedited. Therefore, a reduction in the number of feed assemblies to 52 and increase in the number of reinserted assemblies to 13 was found to yield an acceptable arrangment.

The loading pattern for the first transition cycle is shown in

Figure 7 with one-eighth core symmetry assumed. Normalized power maps for BOC, the depletion step with highest peaking, and EOC are shown in Figures 8 through 10.

The only core location presenting difficulties for this cycle was point 14D where a fresh fuel assembly was inserted on the periphery. This position cannot support BP rods since control rods must be inserted in the assembly thimbles. Twelve poison rods were inserted in the adjacent assembly, 14E, to bring the peaking down to acceptable levels. In moving from BOL to xenon equilibrium, the power was found to increase by about 7 percent in the interior and be reduced by 7 percent on the periphery of the core. This effect was anticipated in planning the core management.

Second Transition Cycle

In the second transition cycle, assemblies of high reactivity are inserted into the interior of the core for the first time. Although the peaking is generally higher in the interior compared with the first transition cycle, the reinsertion of twenty-nine region 1 and four region 2 assemblies help provide an acceptable pattern as seen in Figures 11 through 14.

The feed batch size for this cycle is 48 assemblies, having an enrichment of 3.7 w/o U-235. The cycle length is a just acceptable 10.3 GWD/T. The region 9 assembly in position 9G caused peaking problems until it could be surrounded by highly exposed region 8 and 1 fuel. Fresh assemblies in positions 13C and 14D caused peaking concerns, but were brought under the limits by insertion of comparatively few BP rods and the placement of highly exposed fuel in their vicinity.

During this operating cycle the region 1 fuel assemblies achieved an average exposure of roughly 27,000 MWD/T, an increase of 8000 MWD/T. The four region 2 assemblies achieved an EOC

	H	G	F	E	D	C
8	1 0 –					
9	1 0 –	7 0 –				
10	7 0 –	8 0 –	7 0 –			
11	8 0 –	7 0 –	8 0 –	7 0 –		
12	7 0 –	8 0 –	7 0 –	8 0 –	7 0 –	
13	8 0 –	7 0 –	8 0 –	7 0 –	1 0 –	8 0 –
14	7 0 –	8 0 –	7 0 –	9 12 –	9 0 –	9 0 –
15	9 4 –	9 8 –	9 4 –	9 0 –		

LEGEND

XX	REGION NUMBER
Y	NUMBER OF BP RODS
ZZ	POSITION PREVIOUS CYCLE

Figure 7: First transition cycle (cycle 7), loading pattern.

	H	G	F	E	D	C
8	1 0.42 18.72					
9	1 0.56 18.72	7 0.80 20.37				
10	7 0.94 19.93	8 1.18 7.38	7 1.03 22.39			
11	8 1.17 10.04	7 1.06 20.37	8 1.20 9.64	7 1.02 22.17		
12	7 1.00 22.17	8 1.16 10.43	7 1.02 21.72	8 1.14 7.38	7 0.79 22.17	
13	8 1.10 10.26	7 0.96 22.84	8 1.16 7.38	7 0.86 24.86	1 0.65 18.72	8 0.79 11.81
14	7 0.89 23.96	8 1.05 11.81	7 0.91 24.64	9 1.24 0.00	9 1.11 0.00	9 0.78 0.00
15	9 1.08 0.00	9 1.04 0.00	9 1.05 0.00	9 0.94 0.00		

LEGEND

XX	REGION NUMBER
Y	POWER PEAKING
ZZ	EXPOSURE (GWD/T)

Figure 8: First transition cycle (cycle 7), beginning of life (BOC), boron PPM = 1129.

LEGEND

XX	REGION NUMBER	
YY	POWER PEAKING	

*MAXIMUM PEAKING

	H	G	F	E	D	C
8	1 0.56					
9	1 0.66	7 0.84				
10	7 0.93	8 1.11	7 0.97			
11	8 1.09	7 1.00	8 1.11	7 0.98		
12	7 0.96	8 1.09	7 0.99	8 1.12	7 0.86	
13	8 1.07	7 0.96	8 1.14	7 0.92	1 0.76	8 0.88
14	7 0.92	8 1.06	7 0.95	9 * 1.29	9 1.10	9 0.81
15	9 1.07	9 1.06	9 1.05	9 0.93		

Figure 9: First transition cycle (cycle 7), location of maximum peaking, core average exposure = 7.0 GWD/T.

	H	G	F	E	D	C
8	1 0.63 24.12					
9	1 0.71 25.23	7 0.88 28.84				
10	7 0.95 29.44	8 1.12 18.93	7 0.98 32.51			
11	8 1.09 21.41	7 1.00 30.76	8 1.11 21.25	7 0.98 32.26		
12	7 0.97 32.05	8 1.09 21.71	7 0.99 31.84	8 1.12 18.76	7 0.88 30.61	
13	8 1.07 21.15	7 0.96 32.47	8 1.12 18.87	7 0.92 33.83	1 0.78 26.01	8 0.90 20.24
14	7 0.92 32.99	8 1.05 22.28	7 0.95 33.92	9 1.26 12.40	9 1.09 10.80	9 0.81 7.83
15	9 1.06 10.47	9 1.05 10.25	9 1.03 10.18	9 0.91 9.03		

LEGEND

XX	REGION NUMBER
Y	POWER PEAKING
ZZ	EXPOSURE (GWD/T)

Figure 10: First transition cycle (cycle 7), end of cycle (EOC), core average exposure = 10.0 GWD/T.

	H	G	F	E	D	C
8	1 0 –					
9	8 0 13C	9 0 15G				
10	8 0 12E	8 0 13F	8 0 11D			
11	1 0 –	9 0 15F	1 0 –	9 0 14C		
12	9 0 14C	1 0 –	9 0 14D	8 0 14G	9 0 15G	
13	2 0 –	9 0 15E	8 0 10G	8 0 13H	1 0 –	10 4 –
14	9 0 15H	8 0 12G	8 0 11F	9 0 14E	10 0 –	10 0 –
15	10 8 –	10 4 –	10 4 –	10 0 –		

LEGEND

XX	REGION NUMBER
Y	NUMBER OF BP RODS
ZZ	POSITION PREVIOUS CYCLE

Figure 11: Second transition cycle (cycle 8), loading pattern.

	H	G	F	E	D	C
8	1 0.66 18.72					
9	8 0.89 20.24	9 1.23 10.25				
10	8 0.84 18.76	8 0.94 18.87	8 0.84 18.76			
11	1 0.80 18.72	9 1.17 10.18	1 0.82 18.72	9 1.28 7.83		
12	9 1.23 7.83	1 0.88 18.72	9 1.22 10.80	8 0.98 22.28	9 1.21 10.25	
13	2 0.82 29.80	9 1.26 9.03	8 0.98 18.93	8 0.88 21.15	1 0.81 18.72	10 1.28 0.00
14	9 1.23 10.47	8 0.94 21.71	8 0.88 21.25	9 1.16 12.40	10 1.14 0.00	10 0.92 0.00
15	10 1.00 0.00	10 0.99 0.00	10 0.93 0.00	10 0.83 0.00		

LEGEND

XX	REGION NUMBER
Y	POWER PEAKING
ZZ	EXPOSURE (GWD/T)

Figure 12: Second transition cycle (cycle 8), beginning of cycle (BOC), boron PPM = 1165.

	H	G	F	E	D	C
8	1 0.74					
9	8 0.97	9 1.30				
10	8 0.92	8 1.01	8 0.90			
11	1 0.86	9 1.22	1 0.87	9 *1.30		
12	9 1.26	1 0.92	9 1.24	8 1.00	9 1.20	
13	2 0.84	9 1.26	8 0.99	8 0.88	1 0.80	10 1.20
14	9 1.19	8 0.93	8 0.87	9 1.11	10 1.06	10 0.85
15	10 0.94	10 0.93	10 0.88	10 0.77		

LEGEND

XX	REGION NUMBER
YY	POWER PEAKING

*MAXIMUM CYCLE PEAKING

Figure 13: Second transition cycle (cycle 8), xenon equilibrium power map and location of maximum cycle peaking, boron PPM = 880, core average exposure = 0.1 GWD/T.

LEGEND

XX	REGION.NUMBER
Y	POWER PEAKING
ZZ	EXPOSURE (GWD/T)

	H	G	F	E	D	C
8	1 0.79 26.58					
9	8 0.96 30.04	9 1.21 23.02				
10	8 0.94 28.20	8 0.99 29.09	8 0.93 28.07			
11	1 0.89 27.73	9 1.17 22.43	1 0.89 27.79	9 1.22 20.75		
12	9 1.20 20.40	1 0.93 28.26	9 1.18 23.19	8 0.98 32.40	9 1.16 22.38	
13	2 0.86 38.75	9 1.20 21.66	8 0.98 29.08	8 0.91 30.33	1 0.85 27.29	10 1.18 12.36
14	9 1.18 22.74	8 0.95 31.42	8 0.91 30.42	9 1.09 23.80	10 1.02 10.78	10 0.84 8.71
15	10 1.03 10.25	10 1.01 10.09	10 0.95 9.49	10 0.81 8.16		

Figure 14: Second transition cycle (cycle 8), end of cycle (EOC), core average exposure = 10.3 GWD/T.

burnup of 39,000 MWD/T -- an increase of 9000 MWD/T. It should be noted that only 3 once-burned region 1 assemblies now remain in the spent fuel pool.

Third Transition Cycle

The third transition cycle, shown in Figures 15 through 18, was host to a substantial reinsertion of region 2 fuel (44 assemblies). Unlike region 1 fuel, which could be represented as one exposure, the twice-burned region 2 fuel varied greatly in individual exposures. This somewhat complicated the fuel management problem for this cycle. It was necessary to divide the available region 2 assemblies into several similar exposure groups and choose one assembly from each group for reinsertion into a quarter core. In this way approximate eighth-core symmetry could be maintained. The batch size, enrichment and burnable poison rod loadings are the same as in transition cycle 2. However, the cycle length is short by 500 MWD/T. Use of region 1 assemblies in this cycle and region 2 assemblies in the previous cycle could help alleviate this problem.

Fourth Transition Cycle

The fourth transition cycle is very similar to the past two cycles except that no reinserted assemblies were used to lower core reactivity. As a consequence, the cycle length for the first trial, designated as 10A, is very long at 11.3 GWD/T. The cycle length was shortened by the insertion of 8 depleted burnable poison rods (BP rods that have been depleted in the reactor for one cycle) into each region 11 (once burned) fuel assembly and a substantial insertion of fresh burnable poison rods into the fresh region 12 assemblies. Although reduced to 10.6 GWD/T, a substantial improvement, the cycle length is still long; also some re-shuffling was required to meet the constraints on F_Q. This clearly suggests the need for better fuel management in the earlier transition cycles.

	H	G	F	E	D	C
8	1 0 –					
9	9 0 11E	9 0 12H				
10	9 0 13G	2 0 –	10 0 15H			
11	9 0 12H	9 0 12F	9 0 11G	9 0 14H		
12	9 0 12D	10 0 14D	2 0 –	10 0 15E	2 0 –	
13	10 0 13C	2 0 –	10 0 15F	9 0 14E	2 0 –	11 0 –
14	9 0 9G	10 0 15G	2 0 –	10 0 14C	11 0 –	11 0 –
15	11 8 –	11 4 –	11 4 –	11 0 –		

LEGEND

XX	REGION NUMBER
Y	NUMBER OF BP RODS
ZZ	POSITION PREVIOUS CYCLE

Figure 15: Third transition cycle (cycle 9), loading pattern.

	H	G	F	E	D	C
8	1 0.62 18.72					
9	9 0.85 20.75	9 0.83 20.40				
10	9 0.87 21.66	2 0.67 27.92	10 1.11 10.24			
11	9 1.08 21.66	9 1.02 23.19	9 1.05 22.43	9 1.15 22.74		
12	9 1.21 22.38	10 1.22 10.78	2 0.77 30.14	10 1.23 8.15	2 0.63 30.89	
13	10 1.24 12.36	2 0.81 30.48	10 1.14 9.48	9 1.06 23.80	2 0.65 31.11	11 1.17 0.00
14	9 1.21 23.02	10 1.26 10.09	2 0.76 30.58	10 1.24 8.70	11 1.11 0.00	11 0.88 0.00
15	11 1.10 0.00	11 1.15 0.00	11 0.98 0.00	11 0.88 0.00		

LEGEND

XX	REGION NUMBER
Y	POWER PEAKING
ZZ	EXPOSURE (GWD/T)

Figure 16: Third transition cycle (cycle 9), beginning of cycle (BOC), boron PPM = 1113.

LEGEND

XX	REGION NUMBER
YY	POWER PEAKING

*MAXIMUM CYCLE PEAKING

	H	G	F	E	D	C
8	1 0.72					
9	9 0.95	9 0.92				
10	9 0.96	2 0.74	10 1.17			
11	9 1.14	9 1.08	9 1.10	9 1.18		
12	9 1.24	10 *1.25	2 0.81	10 1.24	2 0.65	
13	10 1.24	2 0.83	10 1.14	9 1.06	2 0.65	11 1.10
14	9 1.17	10 1.21	2 0.75	10 1.19	11 1.04	11 0.81
15	11 1.02	11 1.06	11 0.91	11 0.82		

Figure 17: Third transition cycle (cycle 9), xenon equilibrium power map and location of maximum cycle peaking, boron PPM = 819, core average exposure = 0.1 GWD/T.

LEGEND

XX	REGION NUMBER	
Y	POWER PEAKING	
ZZ	EXPOSURE (GWD/T)	

	H	G	F	E	D	C
8	1 0.85 26.18					
9	9 1.04 30.13	9 1.01 29.52				
10	9 1.00 30.90	2 0.81 35.37	10 1.14 21.18			
11	9 1.08 32.13	9 1.04 33.19	9 1.06 32.61	9 1.11 33.54		
12	9 1.13 33.54	10 1.16 22.14	2 0.83 38.05	10 1.18 19.58	2 0.72 37.49	
13	10 1.15 23.64	2 0.84 38.50	10 1.12 20.19	9 1.04 33.71	2 0.73 37.75	11 1.16 10.71
14	9 1.11 33.84	10 1.16 21.37	2 0.80 38.08	10 1.15 19.76	11 1.03 9.81	11 0.84 7.86
15	11 1.06 9.95	11 1.08 10.21	11 0.97 8.94	11 0.84 7.86		

Figure 18: Third transition cycle (cycle 9), end of cycle (EOC), core average exposure = 9.5 GWD/T.

The power peaking for this cycle (10B) is shown in Figures 19 through 22.

The problem with cycle lengths encountered in the third and fourth transition cycles suggests reduction of the region 9 feed enrichment, better management of the reinserted fuel assemblies and the possible requirement of additional transition cycles. Any of these considerations, if implemented, would serve to reduce the potential severity of the power peaking in the reload core. The transition scheme developed in this preliminary study could therefore be considered as a "worst case" that yet meets peaking constraints. Thus, it appears power peaking problems should not be prohibitive to the development of a practical three-to-four batch transition scheme for Zion Unit 1.

Moderator Temperature Coefficient (MTC)

The moderator temperature coefficient was determined for each of the transition cycles. As shown in Table 7, all cycles meet the necessary constraints of a negative MTC at BOL, HZP; and an MTC more positive than -3.9×10^{-4} at EOC, HFP. Since the values are well behaved, it appears likely that MTC considerations should not interfere with the development of an acceptable three-to-four batch transition scheme.

7.0 URANIUM UTILIZATION AND ECONOMICS

Uranium Resource and Separative Work Utilization

By comparing the feed requirements and net energy production of the three-to-four batch transition cycles with those for a reference three-batch equilibrium cycle case, an estimate of the differences in uranium and separative work utilization can be made. Utilization is defined here as net energy production (either for a cycle or a group of cycles) divided by either the U_3O_8 feed

	H	G	F	E	D	C
8	1 0 –					
9	10 0 10F	11 0 13C				
10	9 0 11H	10 0 12G	10 0 13F			
11	9 0 12H	10 0 14E	10 0 14G	9 0 10F		
12	9 0 10H	11 8 15F	9 0 9H	11 8 14D	10 0 13F	
13	11 8 15H	9 0 11F	11 8 15E	10 0 12E	9 0 11G	12 8 –
14	10 0 13H	11 8 14C	9 0 13E	11 8 15G	12 0 –	12 8 –
15	12 8 –	12 8 –	12 4 –	12 4 –		

LEGEND

XX	REGION NUMBER
Y	NUMBER OF BP RODS
ZZ	POSITION PREVIOUS CYCLE

Figure 19: Fourth transition cycle (cycle 10B), loading.

LEGEND

XX	REGION NUMBER
Y	POWER PEAKING
ZZ	EXPOSURE (GWD/T)

*MAXIMUM CYCLE PEAKING

	H	G	F	E	D	C
8	1 0.66 18.72					
9	10 0.90 21.18	11 1.08 10.71				
10	9 0.75 32.06	10 0.93 22.14	10 0.98 20.18			
11	9 0.77 33.51	10 1.00 19.75	10 0.98 21.35	9 0.92 33.54		
12	9 0.93 30.76	11 1.19 8.94	9 1.01 30.13	11 * 1.24 9.81	10 1.09 20.19	
13	11 1.17 9.95	9 0.99 32.61	11 1.24 7.86	10 1.15 19.60	9 0.90 33.19	12 1.09 0.00
14	10 1.03 23.64	11 1.17 7.86	9 0.90 33.71	11 1.12 10.21	12 1.08 0.00	12 0.69 0.00
15	12 0.92 0.00	12 0.94 0.00	12 0.89 0.00	12 0.73 0.00		

Figure 20: Fourth transition cycle (cycle 10B), beginning of cycle and location of maximum cycle peaking, boron PPM = 1127.

LEGEND

XX	REGION NUMBER
YY	POWER PEAKING

	H	G	F	E	D	C
8	1 0.74					
9	10 0.98	11 1.15				
10	9 0.83	10 1.00	10 1.04			
11	9 0.83	10 1.05	10 1.03	9 0.95		
12	9 0.96	11 1.21	9 1.03	11 1.24	10 1.09	
13	11 1.17	9 0.99	11 1.23	10 1.13	9 0.89	12 1.04
14	10 1.01	11 1.14	9 0.88	11 1.08	12 1.03	12 0.65
15	12 0.87	12 0.88	12 0.85	12 0.69		

Figure 21: Fourth transition cycle (cycle 10B), xenon equilibrium, boron PPM = 834, core average exposure = 0.1 GWD/T.

LEGEND

XX	REGION NUMBER	
Y	POWER PEAKING	
ZZ	EXPOSURE (GWD/T)	

	H	G	F	E	D	C
8	1 0.78 26.55					
9	10 0.95 31.16	11 1.10 22.44				
10	9 0.82 40.51	10 0.94 32.18	10 0.96 30.51			
11	9 0.81 41.96	10 0.98 30.27	10 0.95 31.58	9 0.89 43.11		
12	9 0.94 40.77	11 1.16 21.42	9 0.98 40.68	11 1.15 22.43	10 1.02 31.23	
13	11 1.16 22.39	9 0.99 43.10	11 1.20 20.71	10 1.07 31.20	9 0.90 42.54	12 1.14 11.40
14	10 1.06 34.61	11 1.21 20.35	9 0.93 43.28	11 1.10 21.78	12 1.01 10.71	12 0.75 7.30
15	12 1.03 10.04	12 1.04 10.18	12 0.96 9.55	12 0.78 7.72		

Figure 22: **Fourth transition cycle (cycle 10B), end of cycle (EOC), core average exposure = 10.6 GWD/T.**

TABLE 7

MTC Analysis Results

Cycle	BOC, HZP $(\frac{\Delta P}{^{\circ}F})$	EOC, HFP $(\frac{\Delta P}{^{\circ}F})$
7	-6.1×10^{-5}	-2.3×10^{-4}
8	-7.3×10^{-5}	-2.4×10^{-4}
9	-1.0×10^{-4}	-2.5×10^{-4}
10A	-5.8×10^{-5}	-2.4×10^{-4}
10B	-2.6×10^{-5}	-2.6×10^{-4}

requirements, i.e., GWD/lb U_3O_8, for the resource utilization, or divided by the feed separative work requirements, i.e., GWD/kg-SWU, for the separative work utilization.

As reference, a three-batch equilibrium cycle was selected with a 64 assembly, 3.20 w/o feed enrichment. The four reference case cycles are shown at the top of Table 8. An average cycle length of 10.6 GWD/T was chosen which is close to present Zion cycle lengths. Standard calculation approaches were used, except that no uranium or separated work requirements were charged to the reinserted assemblies.

The results for this relative uranium and separative work utilization study on both a cycle-by-cycle and an overall transition basis, are shown in Tables 8 and 9. An increase in uranium utilization is observed for all but the first transition cycle, cycle 7. The decrease found in cycle 7 is due to the high enrichment used and the relatively large feed batch size (52 assemblies). The significant increase in uranium utilization found in the other transition cycles, however, proves that despite the necessity of higher feed enrichments, extended assembly burnup and lower feed batch size requirements can lead to substantial (5-10 percent) uranium resource savings in a realistic reactor operating situation.

Due to the high enrichment need of cycle 7 and the short length of cycle 9, the separative work requirements for the transition scheme are increased as a whole. As can be seen from Table 9, the separative work savings in transition cycles 8 and 10A or 10B cannot quite make up for the significant decrease found in cycles 7 and 9. The overal effect is a one to two percent decrease in separative work utilization.

As can be seen from Table 10, a reduction in feed enrichment of only 0.1 w/o produces an increase of 2 to 3 percent in uranium resource utilization, and a 4 to 6 percent increase in separative work utilization provided all other parameters are the same. This

TABLE 8

Uranium Resource Utilization Results

Cycle by Cycle Basis:

Cycle	Cycle Ore Requirement (ST U_3O_8)*	Net Cycle** Energy (GWD)	Resource Utilization (GWD/ST U_3O_8)	Relative to Reference
Ref.	226.1	934.1	4.13	1.00
7	232.7	881.2	3.79	1.09
8	197.7	907.6	4.59	0.90
9	197.7	837.1	4.23	0.98
10A	197.7	995.7	5.04	0.82
10B	197.7	934.1	4.72	0.87

Overall Basis:

Case	Cycle Ore* Requirements (ST U_3O_8)	Net Scenario** Energy (GWD)	Resource Utilization (GWD/ST U_3O_8)	Relative to Reference
Reference Scheme	904.4	3736.3	4.13	1.00
Transition with 10A	825.8	3621.6	4.38	0.94
Transition with 10B	825.8	3560.0	4.31	0.96

*Includes a 1.5% loss factor

**A total core tonnage of 88.12 was assumed

TABLE 9

Separative Work Utilization Results

Cycle by Cycle Basis:

Cycle	Cycle SWU* Requirement (kg)	Net Cycle** Energy (GWD)	SWU (GWD/kg-SWU) Utilization	Comparison to Reference
Ref.	182.8	934.1	5.11	1.00
7	204.8	881.2	4.30	1.19
8	169.4	907.6	5.35	0.95
9	169.4	837.1	4.94	1.03
10A	169.4	995.7	5.88	0.87
10B	169.4	934.1	5.51	0.93

Overall Basis:

Case	Scenario SWU* Requirements (kg)	Net Scenario Energy (GWD)	SWU (GWD/kg-SWU) Utilization	Comparison to Reference
Ref. Scheme	731.2	3736.4	5.11	1.00
Transition with 10A	713.0	3621.6	5.08	1.01
Transition with 10B	713.0	3560.0	4.99	1.02

*Includes a 1.5% loss faction

**A total core tonnage of 88.12 was assumed

TABLE 10

Uranium Resource and Separative Work
Utilization Results for a 0.1 w/o Reduction in
Transition Cycle Feed Enrichment

Cycle by Cycle Basis:

Cycle	Resource Utilization (GWD/ST - U_3O_8)	Comparison to Reference	SWU Utilization (GWD/kg-SWU)	Comparison to Reference
Ref.	4.13	1.00	5.11	1.00
7	3.89	1.06	4.46	1.15
8	4.72	0.88	5.57	0.92
9	4.36	0.95	5.14	0.99
10A	5.18	0.78	6.11	0.84
10B	4.86	0.85	5.74	0.89

Overall Basis:

Case	Resource Utilization (GWD/ST - U_3O_8)	Comparison to Reference	SWU Utilization (GWD/kg-SWU)	Comparison to Reference
Reference Scheme	4.13	1.00	5.11	1.00
Transition with 10A	4.51	0.92	5.27	0.97
Transition with 10B	4.43	0.93	5.19	0.98

suggests that if the core reactivity can be kept constant with an enrichment reduction, greater resource and economic gains can be realized. Experience with the EPRI-NODE-P simulation of the transition cycles has shown that this should be possible by removing burnable poison rods from the reactor while decreasing the enrichment. Follow-on efforts in this area are in progress.

Fuel Cycle Cost Estimation

Fuel cycle costs for the transition cycle were compared with those for a reference three-batch fuel scheme with a discharge burnup of 31.8 GWD/T. For the transition cycles, the discharge burnup of each feed batch was assumed to be four times its first resident cycle length. Fuel cycle cost data were taken from Reference 5 and are listed in Table 11. No escalation was applied.

Calculations were performed for each of two different backend scenarios. The first assumes the spent fuel will be shipped to Federal AFR (away from reactor) storage sites and permanently disposed there. The other assumes that the spent fuel will remain in the reactor pool for at least five years and then shipped to final disposal (as yet undetermined). Reinserted assemblies incurred only disposal costs.

The levelized cash flow and percentage cost breakdown results are shown in Tables 12 through 14. Fuel cycle costs for the transition cycles are lower by about 6 percent than those for the reference equilibrium, three-batch scheme. It must be emphasized that because of uncertainties in the various cost assumptions, these results are only intended to provide relative values. Other assumptions as may be appropriate for a given utility are likely to affect the comparison somewhat.

The calculations were performed using PINCAS, a modification of the fuel cycle code CINCAS.[6]

TABLE 11

Assumed Cost Data (in 1979 Dollars)
(Taken from Reference 27)

Annual Present Worth Rate			4%
Direct Cost Data:			
Uranium Ore	$/lb U_3O_8		$ 43.25
Uranium Conversion	$/lb-U		2.70
Separative Work	$/kg-SWU		98.00
Fabrication	$/kg-U		120.00
Shipping, Storage and Final Disposal of Spent Fuel	$/kg	with AFR	268.00
		w/o AFR	158.00
Losses			
U_3O_8 Conversion to UF_6			0.5%
Fabrication			1.0%
Tails			0.2 w/o
Lead Time			
Uranium Ore and Conversion			10 Months
Enrichment			6 Months
Fabrication			3 Months
Lag Time			
With AFR			5 Months
Without AFR			65 Months

TABLE 12

Levelized Cash Flow -- Overall
Transition Scheme Comparison

Case	With AFR		Without AFR	
	Mills/kwh(e)	Percent Decrease Over References Case	Mills/kwh(e)	Percent Decrease Over Reference Case
Reference	6.65	--	6.02	--
Transition with 10A	6.15	7.5	5.58	7.3
Transition with 10B	6.25	6.0	5.67	5.8

TABLE 13

Levelized Cash Flow Per Cycle

With AFR

Case	Mills/kwh(e) per cycle			
	7	8	9	10
Reference	6.65	6.65	6.65	6.65
Transition with 10A	6.66	5.99	6.49	5.46
Transition with 10B	6.66	5.99	6.49	5.82

Without AFR

Case	Mills/kwh(e) per cycle			
	7	8	9	10
Reference	6.02	6.02	6.02	6.02
Transition with 10A	6.25	5.60	5.67	4.77
Transition with 10B	6.25	5.60	5.67	5.08

TABLE 14

Cost Percentage Breakdown -- Overall Comparison

Equilibrium 3-Batch Scheme

Case	Ore + Conversion + Enrichment	Fabrication	Backend
With AFR	75%	8%	17%
Without AFR	81%	8%	11%

Transition Scheme (The same for both the 10A and 10B Case)

Case	Ore + Conversion + Enrichment	Fabrication	Backend
With AFR	79%	7%	15%
Without AFR	84%	7%	9%

8.0 CONTINUTING TASKS

Work is continuing in meeting program objectives through several immediate task efforts.

Calculational methods are being improved so that follow-on studies will be reliable. Emphasis is being given to LBP modeling.

The preliminary PWR transition cycles described in this report are being refined with the identification of a minimum feed enrichment as one objective. Associated with this effort is a study of extended burnup equilibrium cycles.

Low-leakage PWR cycles and the transition to them are being studied.

REFERENCES

1. The ARMP system was developed for the Electric Power Research Institute (EPRI) by Nuclear Associates International Corporation. The documentation, which is proprietary, is distributed by EPRI.

2. S. E. Marlett, "Analysis of Transition Cycles Leading to Extended Burnup in a Pressurized-Water Reactor," M.S. Thesis, Purdue University, 1980.

3. "Standardized Technical Specifications for Westinghouse PWRs," US NRC Report, NUREG-0452, 1978.

4. T. A. Rieck, "Effects of Refueling Decisions and Engineering Constraints on Fuel Management for a PWR," Ph.D. Thesis, Massachusetts Institute of Technology, 1974.

5. L. L. Clark and A. D. Chockie, "Fuel Cycle Cost Projections," Battelle Pacific Northwest Laboratories, NUREG/CR-1041, 1979.

6. T. W. Craig, P. J. Fulford and R. Swanson, Trans. Am. Nucl. Soc., 10, 438 (1967), (CINCAS is available through the ANL Code Center).

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