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Optimal Burnable Absorber Assignment for PWR Core Reload Design

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ABSTRACT

A new method has been developed to assign burnable poison loadings in the optimization of Pressurized Water Reactor core reload design. The method utilizes successive linear programming to determine the desired burnable poison loading. The optimum loading is selected after the evaluation of all candidate loadings close to the desired loading. The design method was implemented as a sub-program in the nodal core analysis code SIMULATE. The technique was applied to re-design Commonwealth Edison's Zion Unit-1 cycles 9 and 10. Significant improvements were achieved in cycle length, number of BP rods required, and power peaking. The present work completely automates the core reload design problem, significantly decreasing the time and effort required of the designer.

1. INTRODUCTION

1.1 Existing Method

A method for the optimization of core reload design has been developed and reported by previous researchers.[1] An algorithm based on this method was implemented as a sub-program within the LWR nodal core analysis computer program, SIMULATE-E.[2] The procedure was essentially divided into two separate optimization processes. The first is to determine the fuel loading pattern that yields the longest cycle. Secondly, the burnable poison (BP) loading is determined to control the core power peaking of the optimal pattern. The complete optimization procedure logic is shown in Figure 1. The optimization problem is made separable in this manner through the use of the Haling depletion.[3] By using this constant power depletion, the best loading pattern can be obtained totally independent of the control strategy.

The method used in the fuel loading optimization is a direct search technique which examines all possible two assembly exchanges from a user-input base loading pattern. Assembly exchanges are performed which yield an increase in the cycle length while still meeting peaking constraints. This procedure is repeated until the cycle length can no longer be increased by fuel shuffling. At this point, the direct search has been completed and the optimal loading pattern has been identified. The final loading pattern, and thus the 'optimum' cycle length, are

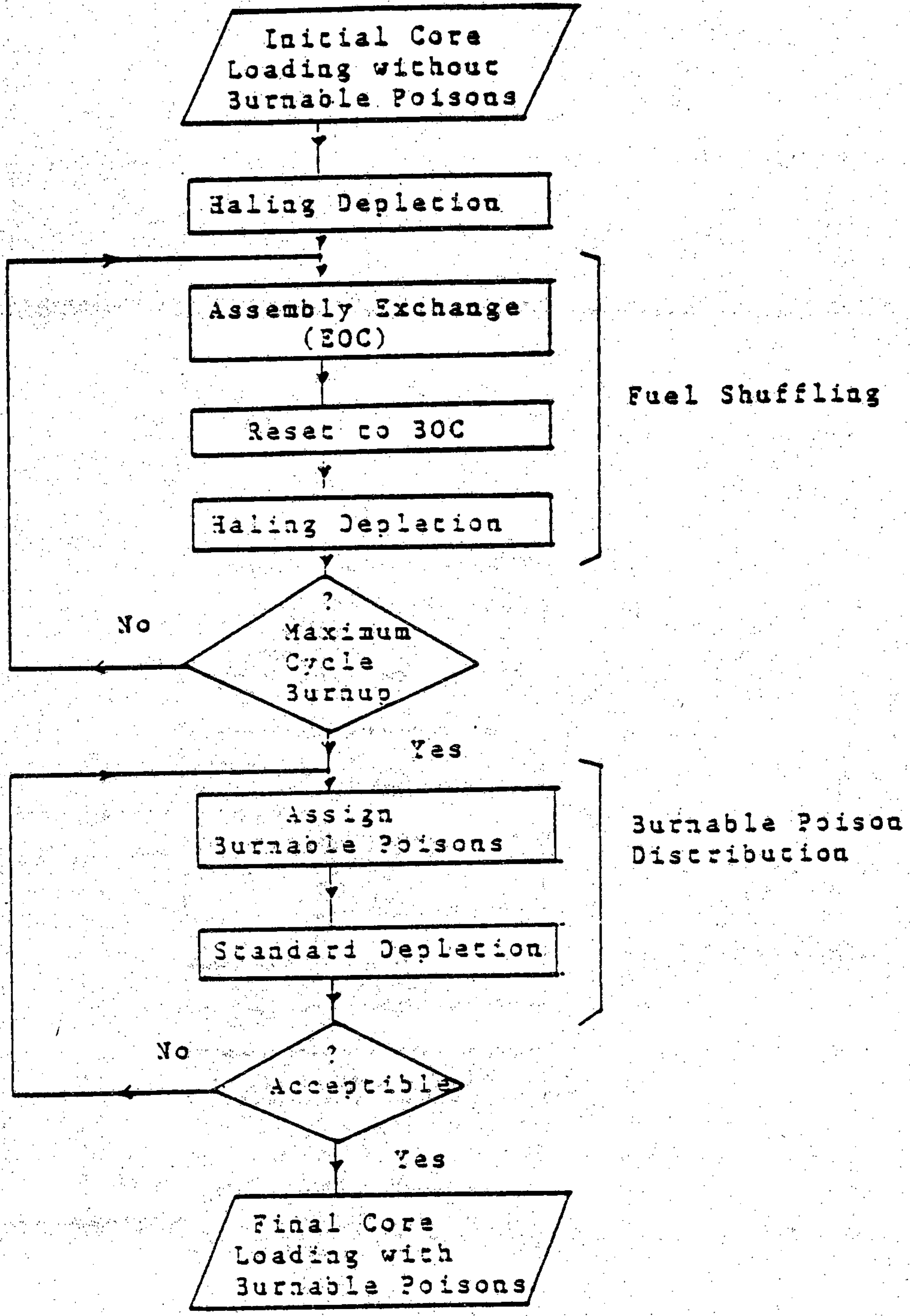


Figure 1. Optimization Procedure for Existing Reload Design Method

strongly influenced by the initial guess loading pattern because the search is not exhaustive, but only a subset of the complete factorial problem.

After the optimal fuel loading has been selected, it remains only to determine the required burnable poison power control. This task is accomplished through a linear programming solution to the second optimization problem. In the direct search algorithm, the objective function was the maximization of the cycle burnup. In this routine, however, the objective was to minimize the difference between the actual power distribution and some 'target' power distribution. For the control to be truly optimum, it would be necessary to have an optimum power shape as a target. This, however, is in itself a fairly significant problem and is not addressed in this work. Instead, the Haling power distribution from the previously determined optimal fuel loading pattern is utilized.

The solution method employs a successive linear programming technique in which the power distribution is represented as a linear function of the burnable absorber loading. This procedure is performed at each burnup step, giving an optimal BP trace throughout the depletion. Typical results of this procedure can be seen in Table 1. In the table, the assembly position is given in terms of the row and column indices of the assembly in the southeast octant of the reactor core (with position 1,1 being the core center). For the current work, as in most core design

TABLE 1. Optimal BP Loading Results from Existing Method

Cycle Burnup (GWD/MT)	Assembly Position								
	(2,2)	(4,1)	(4,3)	(5,4)	(6,5)	(6,6)	(7,2)	(7,3)	(7,4)
0.0	2.2	6.0	5.4	6.3	3.5	1.1	6.2	5.2	2.1
2.0	2.9	6.4	6.1	6.7	5.4	0.7	6.2	6.2	0.6
4.0	2.5	6.5	6.5	7.4	6.1	1.5	5.6	7.2	0.0
6.0	3.3	7.4	7.7	8.5	6.7	2.2	7.0	7.5	0.8
8.0	5.8	7.9	8.7	9.3	7.1	3.3	7.6	7.3	4.2
10.0	4.9	4.8	6.2	6.9	6.7	4.4	6.4	6.6	4.2
12.0	0.0	0.0	0.0	0.1	4.1	5.2	3.0	3.7	3.1

work, octant symmetry of the reactor core is assumed.

The major shortcoming of this present method is that the procedure is not completely automated. In fact, as it is now, the code requires a great deal of user interaction in the design process. This requires that the user possess a significant amount of insight into the core design problem. From data such as that in Table 1, the designer must select a BP distribution using available designs. Current design practice permits only multiples of four BP's per assembly. And, of course, this loading is held constant over the entire duration of the cycle. Thus the engineer is faced with the non-trivial task of selecting a BP loading which (subject to the above criteria) best fits the time varying non-realizable BP distributions returned by the code.

Even after this has been accomplished, the designer's work is far from over. To validate the core design loading, the engineer must perform a series of depletion calculations. If, at any point in the depletion, the core power peaking limits are violated, the BP loading must be adjusted and the procedure repeated. This step in the design process, which is basically a trial and error procedure, is by far the most time consuming and laborious. Finally, even when this manual iteration is complete and a BP loading which controls power peaking has been found, it still remains to be seen whether or not it is the 'optimal' BP distribution.

1.2 Objective of Current Work

Basically, the objective of the current work is to completely automate the burnable absorber assignment process. This would make the overall optimization procedure both faster and much easier for the core design engineer. Instead of the code returning a different, non realizable number of BP's for each burnup step, the updated code will return a single BP loading that *is* physically realizable. In addition, rather than simply accepting the first BP distribution that meets the core peaking constraints, the improved method selects the loading that gives the cycle of greatest length. Finally, the new code is totally automated, requiring no user interaction and a minimum of additional input.

2. BP ASSIGNMENT METHODOLOGY

2.1 Introduction

The existing BP assignment method requires the designer to perform a large portion of the design work manually and, therefore, achieves a final reload design which is less than optimal. There are basically two separate processes currently being done manually. The first is a selection of an initial BP loading from the linear programming results. The second is the depletion calculation and subsequent alterations to the initial loading due to power peaking violations. A methodology for automating these two problems and achieving a more nearly optimal design will be discussed in the following chapter. The complete logic flow diagram for the improved BP assignment method is given in Figure 2.

Previously, the core designer was required to use personal intuition to select the initial BP distribution from the non-integer linear programming results. One method used was averaging the BP values returned at the various burnup steps and using the closest available number of BP rods. Another method involved selecting the available BP loading closest to the desired BP loading at the point in the cycle requiring the greatest total number of BP rods. Typically, this occurred at the middle of the cycle, at a cycle burnup of approximately 8 GWD/MT. The basis for the current method is that the BP loading is best chosen from the beginning of the cycle (BOC) results.

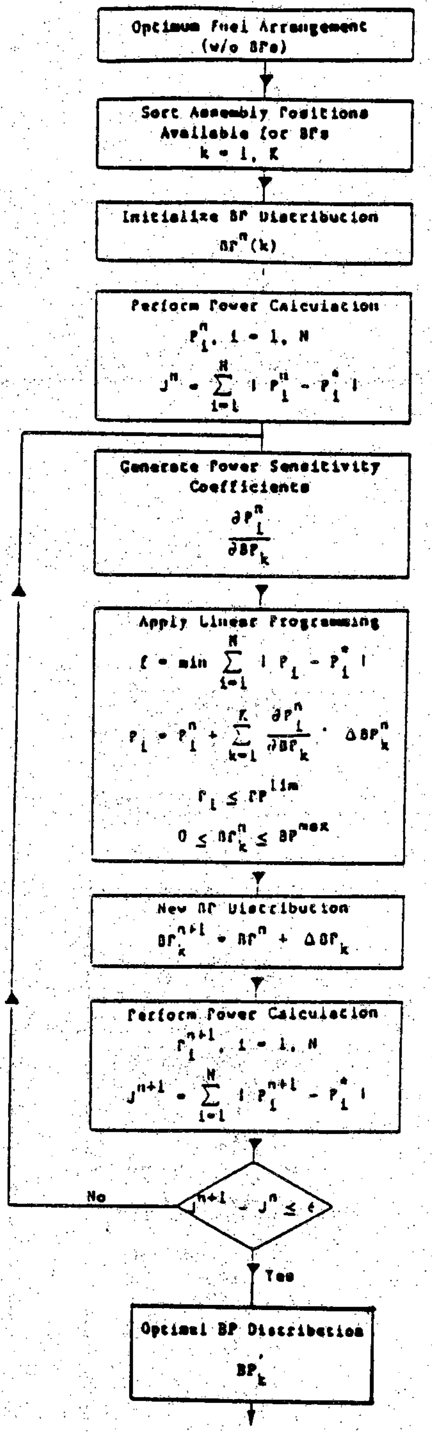
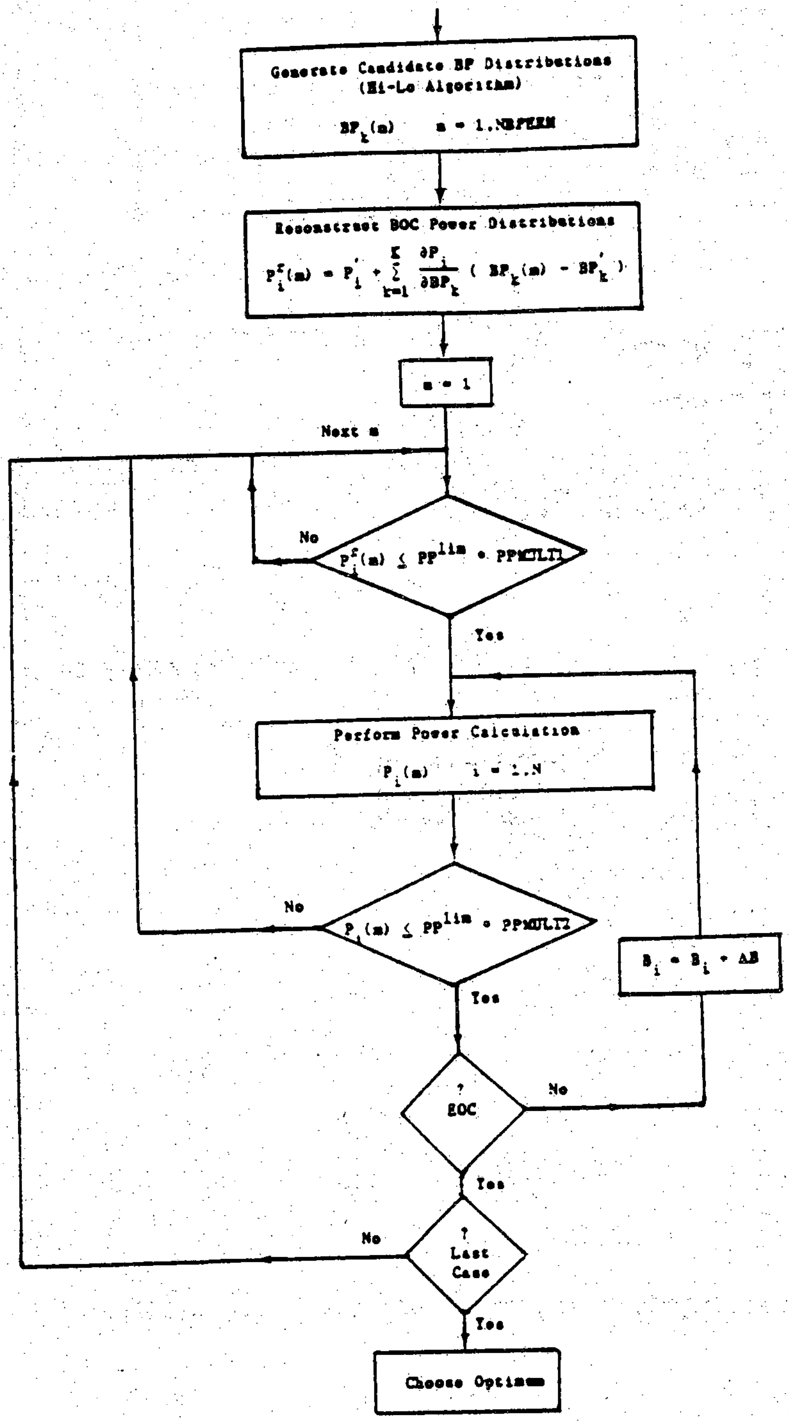

Optimum Fuel Arrangement
(w/o BPs)
Sort Assembly Positions
Available for BPs
k = 1, K
Initialize BP Distribution
$BP^n(k)$
Perform Power Calculation
P_i^n, i = 1, N
$J^n = \sum_{i=1}^{N} | P_i^n - P_i^* |$
Generate Power Sensitivity
Coefficients
$\frac{\partial P_i^n}{\partial BP_k}$
Apply Linear Programming
$f = \min \sum_{i=1}^{N} | P_i - P_i^* |$
$P_i = P_i^n + \sum_{k=1}^{K} \frac{\partial P_i^n}{\partial BP_k} \cdot \Delta BP_k^n$
$P_i \leq PP^{lim}$
$0 \leq BP_k^n \leq BP^{max}$
New BP Distribution
$BP_k^{n+1} = BP^n + \Delta BP_k$
Perform Power Calculation
P_i^{n+1}, i = 1, N
$J^{n+1} = \sum_{i=1}^{N} | P_i^{n+1} - P_i^* |$
No
$J^{n+1} - J^n \leq \epsilon$
Yes
Optimal BP Distribution
BP_k'

Figure 2. Improved Burnable Absorber Assignment Algorithm


Generate Candidate BP Distributions
(Hi-Lo Algorithm)
$BP_k(m)$ m = 1,NBPERM
Reconstruct BOC Power Distributions
$P_i^r(m) = P_i' + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} (BP_k(m) - BP_k')$
m = 1
Next m
No
$P_i^r(m) \leq PP^{lim} \cdot$ PPMULT1
Yes
Perform Power Calculation
$P_i(m)$ i = 1,N
No
$P_i(m) \leq PP^{lim} \cdot$ PPMULT2
Yes
$B_i = B_i + \Delta B$
? EOC
No
Yes
No
? Last Case
Yes
Choose Optimum

Legend:

P_i	= relative power in node i
P_i^*	= target power in node i
ΔBP_k	= burnable poison rod increment
J	= objective function
PP^{lim}	= nodal power peaking limit
N	= total number of fuel assemblies
K	= number of assemblies with BP rods
BP_k (m)	= BP loading in node k in combination m
NBPERM	= total number of candidate BP loadings identified
P_i^r (m)	= reconstructed power in node i with BP combination m
P_i'	= relative power in node i with optimal BP loading
P_i (m)	= relative power in node i with BP combination m
PPMULT1	= reconstructed power peaking tolerance
PPMULT2	= SIMULATE power peaking tolerance

Figure 2. Continued

This can not be proven rigorously because of the complicated physics of the problem, but rather the motivation for this assumption can be seen through the following 'heuristic' rules:

1. If the assembly power is too high throughout the cycle (thus the BOC power, P_o, is high), then the BP loading should be increased.

2. If the power is too low throughout the cycle (P_o is too low), the BP loading should be decreased.

3. If the power is too low at BOC (P_o- low) and thus too high at the middle of the cycle (MOC), the BP loading should be decreased

4. If the power is too high at BOC (P_o- high) and too low at MOC, the BP loading should be increased.

From the above implied correlation between the BOC power and the control requirements throughout the cycle, (P_o high -> increase, P_o low -> decrease), it appears that the BP assignment can effectively be performed at the beginning of the cycle. Thus, the linear programming procedure need only be executed at BOC, with the actual BP loading determined from these results.

At this point in the procedure, another major difference arises between the old and new methods. Instead of choosing a single initial guess BP loading, the improved code generates all possible BP distributions close to the optimal BP loading using a Hi-Lo algorithm. This algorithm will be discussed in more detail in following sections. Each of these loadings is then depleted to end-of-cycle. If, at any point in the depletion, power peaking constraints are violated, the case is terminated and the next case is depleted. Following the depletion of all cases, the BP loading yielding the greatest cycle length is chosen as the optimum.

2.2 BOC Linear Programming

The objective for the optimal BP loading search is the minimization of the absolute difference between the actual power distribution and the target power distribution. As mentioned previously, an 'optimum' power shape has yet to be determined. In the absence of an optimum shape, the Haling power shape from the optimal fuel loading is used as the target. This target power does possess some inherent advantages. Haling first proposed[3] that maintaining a constant power shape throughout the cycle would yield the minimum power peaking for a given fuel loading. Maintaining a constant power distribution throughout the cycle is referred to as the Haling depletion.

The key to the solution of the BP loading optimization problem is the accurate prediction of the nodal relative powers, P_i . If the power distributions were calculated by solving the nodal diffusion equation (which is the standard procedure), the required computation time would be prohibitive. In order to accelerate the solution procedure, a first order perturbation approximation is made of the nodal relative power. This permits the representation of the power as a linear function of the BP loading. This approximation is given below:

$$P_i = P_i^o + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \Delta BP_k$$

where,

P_i = relative power in node i

P_i^o = initial power in node i with base BP loading

$\frac{\partial P_i}{\partial BP_k}$ = first order approximation of the change in the power in node i due to addition of one BP rod in position k

ΔBP_k = difference between the searched BP loading and the base BP loading and

K = total number of BP positions in the core.

The first derivative, $\frac{\partial P_i}{\partial BP_k}$, is determined numerically by perturbing the BP loading and performing standard nodal power calculations. This linear approximation of the nodal relative power is actually a very good one. The core-averaged relative difference between the actual power and the estimated power is less than a percent. The accuracy of the first order approximation will be discussed in further detail in the following sections.

The objective function for the linear programming problem can be written as

$$f = \min \sum_{i=1}^{N} | P_i - P_i^* |$$

where,

P_i = actual power in node i

P_i^* = target power for node i

N = total number of nodes (assemblies) in the core.

The problem is subject to the following constraints:

$$P_i \leq P_{lim} \qquad i = 1,N$$

$$BP_k \geq 0 \qquad k = 1,K$$

where,

P_{lim} = core nodal power peaking limit

BP_k = number of rods in BP position k.

The above three relationship are a statement of the optimization problem for the burnable absorber assignment. However, the objective function requires modification for solution by linear programming methods. The transformation of the three equations into the 'standard LP form' is as follows:

By making use of the following substitution of an independent variable, d_i

$$d_i = | P_i - P_i^* |,$$

the objective function can be re-written as

$$f = \min \sum_{i=1}^{N} d_i.$$

Since it is standard practice to write an optimization problem in terms of the maximization of some quantity, the objective function for this problem can easily be transformed as follows:

$$f = \max \left(- \sum_{i=1}^{N} d_i \right).$$

Since P_i was previously defined as

$$P_i = P_i^o + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \Delta BP_k,$$

the independent variable d_i can be re-written by

$$d_i = \left| P_i^o + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \Delta BP_k - P_i^* \right|.$$

Re-arranging gives

$$d_i = \left| (P_i^o - P_i^*) + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \Delta BP_k \right|.$$

The absolute value in the objective function is not acceptable for LP solution because it is not a 'linear' function. The objective function needs to be re-formulated using additional inequality constraints. This re-formulation can be shown through the following simple example.

Suppose that the objective of a two region optimization problem is the minimization of the variable Y, subject to the constraint that $Y = |X|$. This is shown graphically in Figure 3.

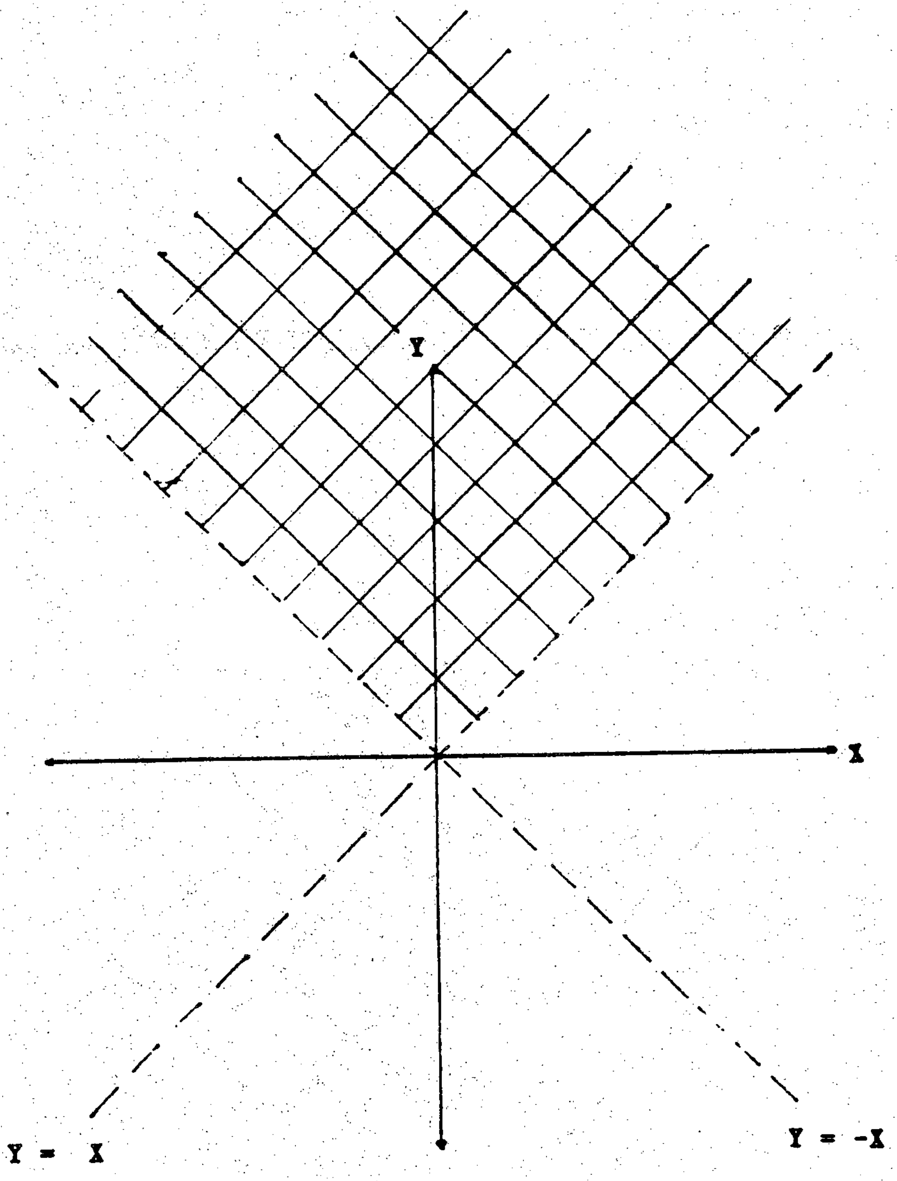


Figure 3. Simple Two Region Optimization Problem

In the figure, two functions are plotted; those being $Y = X$ and $Y = -X$. The function $Y = |X|$ can be represented as $Y = X$, for $X \geq 0$, and $Y = -X$, for $X \leq 0$. Even though these are equality constraints, this is still unsatisfactory for LP formulation. For a linear programming solution procedure, it is necessary to have the objective function (and constraints) in terms of relationships that are valid for <u>all</u> ranges of possible values. The shaded area of the figure is represented by the inequality constraints $Y \geq X$ and $Y \geq -X$. These two inequalities can actually be represented by the single inequality $Y \geq |X|$. Now this is not exactly the desired function, since it corresponds to the entire region above the curve $Y = |X|$. However, since the objective function is to minimize Y, the solution procedure would converge to a point <u>on</u> the curve. Thus, the two inequality constraints $Y \geq X$ and $Y \geq -X$ can be used to replace $Y = |X|$ in the LP formulation.

Returning now to the BP optimization problem, d_i can now be re-written as follows:

$$d_i \geq [\ (P_i^o - P_i^*) + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \Delta BP_k\ ]$$

and,

$$d_i \geq -\ [\ (P_i^o - P_i^*) + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \Delta BP_k\ ].$$

The peaking constraint can be re-written making use of the definition of the nodal power, P_i

$$P_i^o + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \Delta BP_k \leq P_{lim}.$$

Finally, by replacing the search variable ΔBP_k with

$$\Delta BP_k = BP_k^n - BP_k^{n-1},$$

the system of equations can be re-written in their final form (after some re-arranging) as

$$f = \max\ (- \sum_{i=1}^{N} d_i)$$

$$\sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} BP_k^n - d_i^n \leq (P_i^* - P_i^o) + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} BP_k^{n-1} \qquad \text{for } i = 1,N$$

$$- \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} BP_k^n - d_i^n \leq - (P_i^* - P_i^o) - \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} BP_k^{n-1} \qquad \text{for } i = 1,N$$

$$\sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} BP_k^n \leq (P_{lim} - P_i^o) + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} BP_k^{n-1} \qquad \text{for } i = 1,N$$

$$BP_k \geq 0 \qquad \text{for } k = 1,K.$$

The linear programming technique used to solve the above problem is the revised simplex method.[4] This method is currently employed by all commercial LP computer codes. The particular code used in this work is the IMSL library subroutine ZX3LP.

2.3 Hi-Lo Algorithm

The solution of the preceding mathematical programming problem prescribes the desired BP loading. However, this desired BP loading is not physically realizable and thus not of great value to the designer. A Hi-Lo algorithm is utilized to determine a practical BP loading closest to the optimal BP loading.

The first task performed by the Hi-Lo algorithm is the determination of the high and low values for the number of BP rods to be placed in each poisonable assembly. Since current design allows BP's to be used in multiples of four only, this corresponds to finding the two multiples of four that bracket the desired number of BP's. For example, if the desired number of BP's is 7.2 for a certain position, the high and low values would be four and eight, respectively.

The next step is the formation of all possible combinations of these high and low values at each BP position. Since this is simply a binary decision (high or low) at each BP position, the total number of these combinations would be 2^K , where K is the total number of BP positions. The identification of all possible combinations is facilitated by the above fact. To generate these combinations, all one has to do is convert the 2^K numbers from 0 to 2^K-1 from decimal to binary. This results in a K digit number consisting of nothing but 0's and 1's. In this representation, a 1 in the i'th position in the binary number corresponds to the placement of the high number of BP's in the i'th core BP position. Similarly, a 0 corresponds to the low number of BP's. Given below is an example of the transformation from decimal to binary to BP loading representation.

Decimal	Binary	BP Loading
100	1100100	Hi Hi Lo Lo Hi Lo Lo

The number of BP combinations formed is expanded when the desired number of BP's for any position is very close to an available loading. For example, if the desired number of BP's is 7.9 for a particular position, then loadings of 4,8 and 12 BP's in that position are investigated. These additional combinations are formed utilizing a variation of the binary transformation routine described above. Exactly how close the desired number of BP's and the available number of BP's must be is specified by the user. The tolerance used for all of this work and recommended for any subsequent analysis is 0.5 (one half of one BP rod). This tolerance may, however, be adjusted to values ranging from 0 to 2 in order to increase or decrease the number of BP loadings examined. In the instance where no acceptable BP loading is identified, the tolerance should definitely be relaxed. To the other extreme, if an unwieldy number of BP combinations are created, the tolerance may be tightened. The total number of BP combinations is given by

$$N = \sum_{l=0}^{n} \begin{bmatrix} n \\ l \end{bmatrix} 2^{K-l}$$

where,

$\begin{bmatrix} n \\ l \end{bmatrix}$ = number of combinations of n items taken l at a time

K = total number of BP positions in the core

n = number of positions in the core where 'extra' BP loadings are considered.

Utilizing basic statistical theory for the determination of $\begin{bmatrix} n \\ l \end{bmatrix}$, the above equation can be re-written as

$$N = \sum_{l=0}^{n} \frac{n!}{l!(n-l)!} 2^{K-l}.$$

If there are no 'extra' positions (n=0), the previous relationship reduces to 2^K , which is the base number of combinations discussed earlier in the section. On the other hand, if every BP position is an 'extra' position (n=K), then the number of combinations swells to 3^K . A graphical representation of this relationship is given by Figure 4. The upper limit shown in the figure is simply due to the declared array size in the coding itself. Realistically, this upper limit would probably never be approached due to the relatively high cost of depleting such a large number of cases.

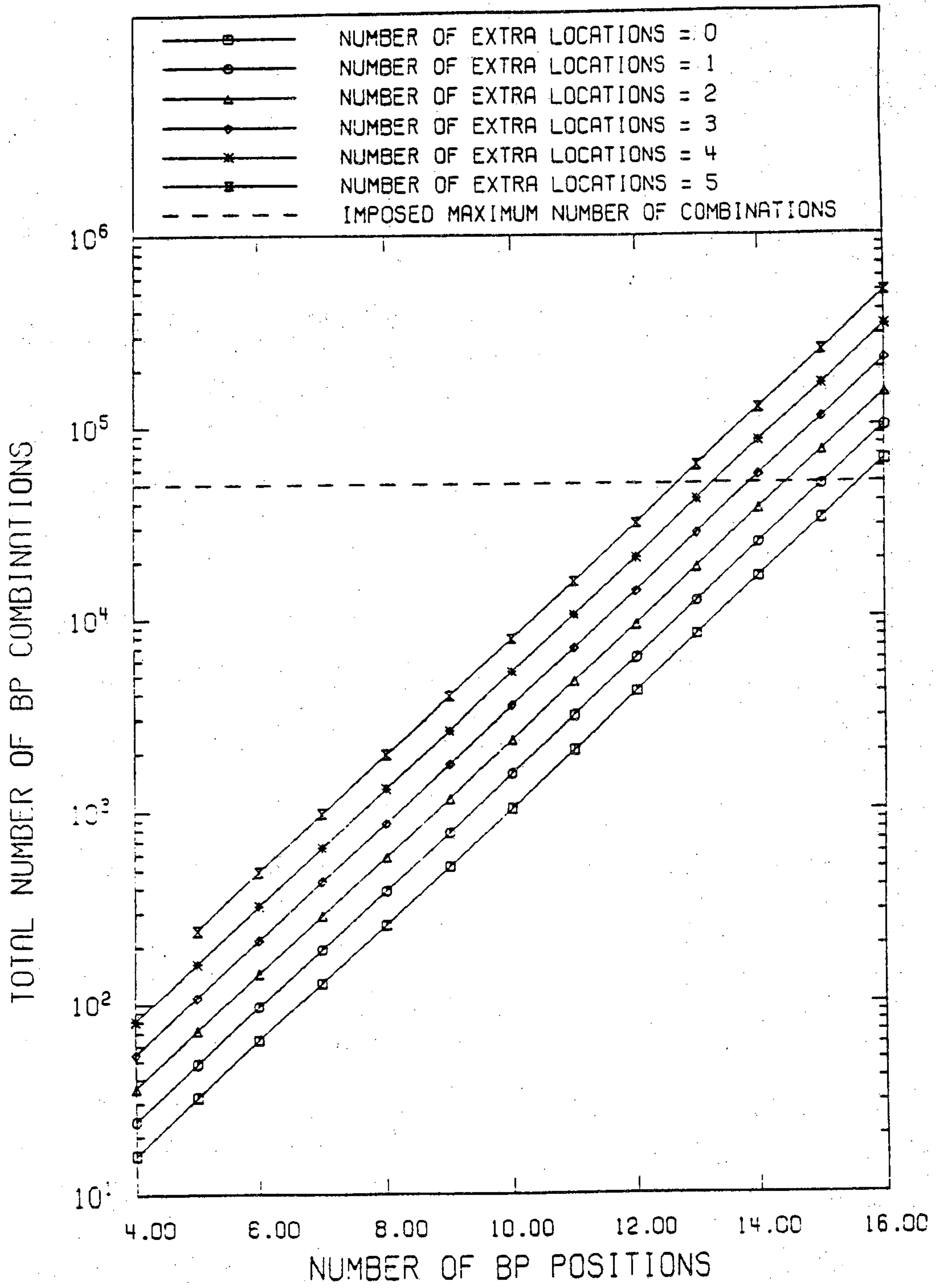


Figure 4. Number of BP Combinations Formed by Hi-Lo Algorithm

2.4 Power Reconstruction and Case Pruning

The first order perturbation approximation discussed in earlier sections was fundamental to the solution of the optimization problem using a linear programming technique. In the solution procedure, a matrix of linear sensitivity coefficients, $\frac{\partial P_i}{\partial BP_k}$, are calculated numerically. This sensitivity matrix is used to approximate the nodal power distribution, as the BP loading is iteratively modified. As an additional benefit this matrix may also be used to estimate the power distribution resulting from each of the candidate BP loadings identified by the Hi-Lo algorithm. Similarly to the relationship given in section 2.2, the nodal power is given by

$$P_i^r(m) = P_i' + \sum_{k=1}^{K} \frac{\partial P_i}{\partial BP_k} \left(BP_k(m) - BP_k' \right)$$

where,

$P_i^r(m)$ = reconstructed power in node i with BP combination m

P_i' = relative power in node i with optimal BP loading

BP_k' = optimal BP loading for node k

$BP_k(m)$= BP loading in node k in combination m

K = total number of BP positions in the core.

Thus, without a time consuming normal power calculation, a relatively accurate representation of the nodal power distribution may be obtained. A comparison of the reconstructed power and the SIMULATE calculated power for a particular BP loading is given in Figure 5. Of particular note is the relatively small average absolute difference of 0.9%.

In order to minimize computation time and thus cost, an excessive number of nodal power calculations should be avoided. This can be accomplished by eliminating infeasible cases before the normal power calculations are performed. The current method incorporates one such pruning procedure in its calculational scheme. The pruning parameter currently used is the nodal power peaking. If the maximum power peaking exceeds a preset limit, the case is discarded and the following case is examined.

The preset peaking limit is based on two multiplicative factors: a base nodal power peaking limit, PP_{lim}, and a power peaking tolerance multiplier, PPMULT1. The user input base limit, PP_{lim}, is derived from thermal hydraulic safety considerations and previous core operational data. For this work, a fairly typical value of 1.33 was implemented. The peaking tolerance multiplier is applied to relax the peaking limitations on the reconstructed power distributions. The motivation for this relaxation is the error introduced by the linear approximation made in the power reconstruction. Based on power distribution comparisons for several different burnable poison loadings such as the one given in Figure 5, the overall average percent difference is found to be approximately 0.5% with a standard deviation of about 0.5%. From basic statistical theory, it is 99.7% certain that all data points are

X.XXX	<- Reference Power
X.XXX	<- SIMULATE Power
+X.X	<- % Difference
+0.9	<- AVG % Diff

0.953 0.982 +3.0					
1.110 1.139 +2.6	1.249 1.278 +2.3				
1.020 1.040 +2.0	1.227 1.249 +1.8	1.034 1.045 +1.1			
1.217 1.228 +0.9	1.338 1.349 +0.8	1.174 1.173 -0.1	1.143 1.140 -0.3		
0.868 0.872 +0.5	1.276 1.279 +0.2	1.181 1.178 -0.3	1.285 1.278 -0.5	1.129 1.118 -0.9	
0.754 0.752 -0.3	1.077 1.074 -0.3	1.322 1.311 -0.8	1.089 1.081 -0.7	1.255 1.242 -1.0	1.006 0.994 -1.2
0.815 0.810 -0.6	1.194 1.187 -0.6	1.264 1.257 -0.6	1.179 1.179 +0.0	0.858 0.856 -0.2	0.345 0.341 -1.2
0.301 0.299 -0.7	0.387 0.384 -0.8	0.422 0.419 -0.7	0.311 0.309 -0.6		

Figure 5. BOC Power Distribution Comparison Cycle 9 - Case 2

within range of $\bar{x} + 3\sigma_x$. Thus, all reconstructed nodal powers should be within 0.5 + 3(0.5) or 2% of the actual nodal power calculated by SIMULATE. The peak powers ($P_i \geq 1.3$) that are of most interest here were predicted slightly more accurately, with all reconstructed peak powers expected to be within 1% of the SIMULATE powers.

It follows, then, that a multiplier of 1.02 would effectively account for the uncertainty in the reconstructed power distributions. This multiplier is also user-input, and may be altered if necessary, but this value is recommended for any subsequent work.

This pruning procedure provides a significant reduction in the number of cases which must be evaluated using the normal power calculations. Equally important, however, is the fact that while many cases are discarded, no potentially successful cases are discarded. The relatively loose tolerance insures that all BP loadings that are even close to being acceptable are passed on to the next step in the selection process.

2.5 Case Depletion and Optimal Selection

The final step in the core design process is the depletion of all the cases that passed the pruning test described in the previous section. This is by far the most time consuming portion of the code, involving numerous power distribution calculations for each depletion. The optimum BP loading is selected after all cases have been depleted to EOC.

For a particular loading pattern to be acceptable, it must meet power peaking constraints throughout the cycle. Thus, in the core design process, the core power peaking must be checked at each step in the depletion. In addition, the burnup steps must be small enough to insure that power peaking violations do not occur between steps. This checking process is included in the code's depletion procedure. If, at any point in the depletion, the power peaking limits are exceeded, the depletion is terminated and depletion of the succeeding case is begun.

Just as in the power reconstruction pruning, the peaking constraint in the core depletion also includes a power peaking tolerance in the form of a multiplier. In this case, the multiplier, PPMULT2, accounts for the error in the SIMULATE power distribution calculations as compared to the actual power distribution. The quantitative evaluation of this error is beyond the scope of this work. For this reason and basic conservatism, a multiplier of 1.00 is used here and recommended in all subsequent work. As it applies here, conservatism means that while some potentially successful cases are discarded, the cases that are deemed acceptable by the code are much more likely to satisfy the requirements for loading into the reactor.

After all candidate BP loadings have been depleted, it remains only to select the optimum loading. This selection is based on the maximization of the cycle length. Thus, of those cases that deplete to EOC, the one yielding the longest cycle is selected as the optimum.

3. APPLICATION TO CORE RELOAD

3.1 Introduction

The improved core reload design method was employed for a re-design of Commonwealth Edison's Zion Unit-1 cycles 9 and 10. The actual loading patterns for both cycles are given in Figures 6 and 7, respectively. Note: The fuel type descriptor given for each assembly is simply a variable used internally by the program to differentiate between assemblies of different design and/or fuel enrichments. The re-design is done utilizing the original fuel assemblies (i.e. same enrichments) ; the difference between the new and the old designs is the loading pattern and the BP loading. Thus, the result of the optimization is the improvement in the cycle length for a given fuel loading. Conversely, the code could also be used to give a desired cycle length using a lower reload enrichment.

The nodal code SIMULATE has been benchmarked for both Zion-1 cycles 9 and 10, and has been shown to yield sufficiently accurate results for design work of this type. All current work has been performed utilizing the core model formulated through benchmarking procedure from previous work.[1] In addition, all core calculations are performed assuming that equilibrium Xenon and Samarium concentrations are present in the core. This approximation is valid at all burnup steps except BOC, at which point these two fission products have not yet reached their saturation

X	<- Fuel Type
X.XX	<- Enrichment
XX	<- # of BP
XX.XXX	<- BOC Burnup

1 2.90 20.620					
4 2.70 12.960	5 2.80 20 0.000				
3 2.80 25.880	6 3.20 11.410	4 2.70 13.100			
5 2.80 8 0.000	4 2.70 12.240	5 2.80 12 0.000	2 3.20 23.200		
3 2.80 25.890	6 3.20 7.910	2 3.20 23.770	5 2.80 4 0.000	2 3.20 21.220	
3 2.80 24.940	3 2.80 24.040	6 3.20 16 0.000	2 3.20 22.750	4 2.70 12.770	5 2.80 0.000
4 2.70 9.810	6 3.20 8 0.000	6 3.20 8.270	6 3.20 8 0.000	6 3.20 0.000	2 3.20 31.420
1 2.90 20.620	6 3.20 9.410	6 3.20 0.000	3 2.80 22.630		

Figure 6. Reference Loading Pattern for Cycle 9

X	<- Fuel Type
X.XX	<- Enrichment
XX	<- # of BP
XX.XXX	<- BOC Burnup

3 2.90 27.530					
6 2.80 27.200	4 3.20 8 0.000				
2 2.80 13.980	4 3.20 14.320	2 2.80 14.670			
4 3.20 12 0.000	1 2.70 25.060	4 3.20 12 0.000	1 2.70 24.600		
2 2.80 10.400	4 3.20 13.060	1 2.70 23.160	4 3.20 12 0.000	1 2.70 26.100	
4 3.20 14.990	2 2.80 14.950	4 3.20 10.110	4 3.20 22.080	4 3.20 8 0.000	5 3.60 4 0.000
4 3.20 14.990	5 3.60 16 0.000	4 3.20 21.570	5 3.60 8 0.000	4 3.20 17.960	4 3.20 25.290
1 2.70 20.730	4 3.20 10.200	5 3.60 0.000	2 2.80 15.200		

Figure 7. Reference Loading Pattern for Cycle 10

level. However, at BOC, the reactor is just beginning its ascent to full power. By a cycle burnup of 150 MWD/MT, the reactor has reached full power and the fission product inventories have attained their equilibrium values. In addition, at this small core burnup, the burnable poison concentration has not changed appreciably from its BOC value. Thus, performing the core design calculations at BOC while assuming equilibrium Xenon and Samarium is equivalent to designing the core reload at a cycle burnup of 150 MWD/MT. Since it is at just this burnup step that almost all core benchmarking is performed, this seems to be an acceptable approximation. The only possible drawback with this method is the lack of a representation of core behavior at the actual beginning-of-cycle conditions. Power peaking at the actual BOC should not pose a problem, however, since the reactor is operating at such a low power level.

The optimization process consists of two separate stages: the fuel loading search and the burnable poison search. Since only the latter has been altered in this work, only the BP assignment results will be discussed in detail. The results of the fuel loading search will be given for completeness. A more detailed analysis of the fuel loading optimization can be found in reference 1.

3.2 Optimization Results

In order to achieve the longest cycle for a given fuel loading, it is necessary to move as much of the fresh fuel as possible to the core interior. This both decreases neutron leakage by placing less reactive fuel on the core periphery and increases the worth of the fresh fuel by placing those assemblies in areas of 'high neutron importance'. The limiting factor in how much fresh fuel can be moved inboard is the imposed power peaking limit. This peaking can be partially controlled through the use of a proper burnable poison loading.

Figures 6 and 7 illustrate the loading patterns that were actually used in cycles 9 and 10, respectively. In both cycles, a fairly large percentage of the fresh fuel has been placed in the 56 core peripheral positions. In the cycle 9 loading, 28 of the 68 fresh fuel assemblies are on the periphery, while cycle 10 has 20 out of 60. In addition, the cycle 9 loading has 8 once-burned assemblies on the periphery and cycle 10 has 24. Clearly, there is a large amount of highly reactive fuel on the core periphery. Thus, there seems to be a great deal of room for improvement in the achievable cycle length for both cycles.

This presumption is supported by the results from the direct search procedure. By moving much of the reactive fuel away from the periphery, the shuffling procedure obtained an improvement in cycle length of over

1000 MWD/MT. The improved fuel loading patterns are given is Figures 8 and 9. In striking contrast to the actual loadings, the improved cycle 9 loading has 36 twice-burned fuel assemblies on the periphery and cycle 10 now has 44. This yields improvements in both cycle length and pressure vessel neutron fluence. The latter consideration has recently received a considerable amount of attention.

The next step in the optimal design process is the determination of a BP loading capable of controlling the power peaking in the new fuel loadings. Since so much highly reactive fuel was moved inboard, power peaking control becomes much more difficult. The direct search method did, however, apply a power peaking limit to the fuel loading optimization, so a feasible control strategy should exist. In fact, in the the cycle 9 BP search, 31 different loadings were found to be acceptable. Cycle 10, on the other hand, yielded only 2 acceptable BP loadings. The reason for this apparent discrepancy is that the cycle 9 optimal fuel loading had 10 poisonable positions in the octant while cycle 10 had only 9. Thus, many more candidate BP loadings were identified for cycle 9 than for cycle 10 (2304 compared to 1152). The optimal BP loading was selected from these acceptable loadings for both cycles. The optimal BP loadings determined by the code for cycles 9 and 10 are shown in Figures 10 and 11, respectively.

X X.XX XX.XXX	<- Fuel Type <- Enrichment <- BOC Burnup

1 2.90 20.620					
4 2.70 9.810	5 2.80 0.000				
1 2.90 20.620	6 3.20 11.410	2 3.20 23.200			
5 2.80 0.000	6 3.20 9.410	5 2.80 0.000	4 2.70 13.100		
3 2.80 25.890	6 3.20 7.910	4 2.70 12.770	6 3.20 8.270	2 3.20 21.220	
3 2.80 24.940	4 2.70 12.240	6 3.20 0.000	2 3.20 22.750	6 3.20 0.000	5 2.80 0.000
4 2.70 12.960	6 3.20 0.000	5 2.80 0.000	6 3.20 0.000	6 3.20 0.000	2 3.20 31.420
3 2.80 25.880	3 2.80 22.630	2 3.20 23.770	3 2.80 24.040		

Figure 8. Optimal Fuel Loading Pattern for Cycle 9

X <- Fuel Type
X.XX <- Enrichment
XX.XXX <- BOC Burnup

3 2.90 27.530					
2 2.80 13.980	5 3.60 0.000				
1 2.70 20.730	2 2.80 15.200	2 2.80 14.670			
4 3.20 0.000	4 3.20 17.960	4 3.20 0.000	1 2.70 24.600		
2 2.80 10.400	4 3.20 13.060	4 3.20 14.320	4 3.20 0.000	1 2.70 24.600	
4 3.20 14.990	4 3.20 10.110	2 2.80 14.950	4 3.20 10.200	5 3.60 0.000	4 3.20 0.000
4 3.20 14.990	5 3.60 0.000	5 3.60 0.000	4 3.20 0.000	4 3.20 21.570	1 2.70 25.060
6 2.80 27.200	4 3.20 22.080	4 3.20 25.290	1 2.70 23.160		

Figure 9. Optimal Fuel Loading Pattern for Cycle 10

X	<- Fuel Type
X.XX	<- Enrichment
XX	<- # of BP
XX.XXX	<- BOC Burnup

1 2.90 20.620					
4 2.70 9.810	5 2.80 12 0.000				
1 2.90 20.620	6 3.20 11.410	2 3.20 23.200			
5 2.80 12 0.000	6 3.20 9.410	5 2.80 20 0.000	4 2.70 13.100		
3 2.80 25.890	6 3.20 7.910	4 2.70 12.770	6 3.20 8.270	2 3.20 21.220	
3 2.80 24.940	4 2.70 12.240	6 3.20 12 0.000	2 3.20 22.750	6 3.20 8 0.000	5 2.80 0.000
4 2.70 12.960	6 3.20 0.000	5 2.80 4 0.000	6 3.20 0.000	6 3.20 0.000	2 3.20 31.420
3 2.80 25.880	3 2.80 22.630	2 3.20 23.770	3 2.80 24.040		

Figure 10. Optimal Design Pattern for Cycle 9

X X.XX XX XX.XXX	<- Fuel Type <- Enrichment <- # of BP <- BOC Burnup

3 2.90 27.530					
2 2.80 13.980	5 3.60 4 0.000				
1 2.70 20.730	2 2.80 15.200	2 2.80 14.670			
4 3.20 4 0.000	4 3.20 17.960	4 3.20 8 0.000	1 2.70 24.600		
2 2.80 10.400	4 3.20 13.060	4 3.20 14.320	4 3.20 8 0.000	1 2.70 24.600	
4 3.20 14.990	4 3.20 10.110	2 2.80 14.950	4 3.20 10.200	5 3.60 4 0.000	4 3.20 0.000
4 3.20 14.990	5 3.60 8 0.000	5 3.60 4 0.000	4 3.20 0.000	4 3.20 21.570	1 2.70 25.060
6 2.80 27.200	4 3.20 22.080	4 3.20 25.290	1 2.70 23.160		

Figure 11. Optimal Design Pattern for Cycle 10

Comparisons of three core loading alternatives: the reference (actual) design, the previous 'optimal' design, and the improved design are given in Tables 2 and 3. The superiority of both of the optimal designs as compared to the reference case is apparent. The length of cycle 9 was improved by over 1000 MWD/MT while cycle 10 saw an increase of over 1500 MWD/MT. Also, the number of BP rods necessary for peaking control was decreased. This decrease was quite drastic in the cycle 10 design, where the number of BP's was more than cut in half. The focus of this work, however, is the improvement of the optimization procedure, which is evident by comparison of the new and old 'optimal' results.

The new optimal design of cycle 9 gave a slight improvement in both the achievable cycle length and the number of BP's required as compared to the old optimal design. The cycle was lengthened by about 15 MWD/MT while using 32 fewer BP rods. This improvement also coincided with a small reduction in the cycle maximum power peaking. In fact, the old optimal design would not have been considered acceptable by the present design method due to peaking violations.

At first it may appear that the old optimal design for cycle 10 is superior to the newer design in that it results in an identical cycle length while using slightly fewer BP rods. However, while the old design does give an equal cycle length, the power peaking is significantly higher than the new optimal design.

TABLE 2. Comparison of Loading Patterns for Cycle 9

	Loading Pattern		
	Reference	OLD	NEW
Cycle Length (GWD/MT)	11.944	12.964	12.980
Total Number of BP's	496	480	448
Max. Power Peaking	1.3146	1.3342	1.3253

TABLE 3. Comparison of Loading Patterns for Cycle 10

	Loading Pattern		
	Reference	OLD	NEW
Cycle Length (GWD/MT)	11.638	13.241	13.241
Total Number of BP's	544	256	288
Max. Power Peaking	1.3420	1.3457	1.3295

A more detailed comparison of the power peaking for both cycles is given in Tables 4 and 5. The cycle 9 results show that the only peaking violation of the old optimal design occurs at the beginning-of-cycle. As was mentioned earlier, peaking is not an important consideration at BOC. This, coupled with the fact that the power peaking does not greatly exceed the limit, would lead to the conclusion that the old optimal design would, in fact, be acceptable. Even so, the peaking in the new design is superior to both the old optimal design and even the reference design.

From the cycle 10 results, it appears that the old optimal design exceeded power peaking limits for nearly half of the cycle. Clearly, this is an unacceptable design. Even the reference design violates the peaking limit of 1.33 , although this violation occurs at BOC (similar to the old optimal design of cycle 9). Just as in the cycle 9 design, the new optimal design for cycle 10 is far superior to the old optimal design, with a lower power peaking factor at nearly every burnup step.

TABLE 4. Maximum Power Peaking - Cycle 9

Cycle Burnup (GWD/MT)	Loading Pattern Reference	OLD	NEW
0.0	1.314	1.334	1.309
1.0	1.315	1.309	1.291
2.0	1.309	1.299	1.284
3.0	1.300	1.294	1.297
4.0	1.283	1.296	1.301
5.0	1.283	1.300	1.309
6.0	1.293	1.321	1.317
8.0	1.284	1.318	1.325
10.0	1.296	1.305	1.314

TABLE 5. Maximum Power Peaking - Cycle 10

Cycle Burnup (GWD/MT)	Loading Pattern		
	Reference	OLD	NEW
0.0	1.342	1.346	1.330
1.0	1.297	1.341	1.323
2.0	1.273	1.336	1.325
3.0	1.256	1.332	1.324
4.0	1.249	1.325	1.319
5.0	1.251	1.320	1.313
6.0	1.254	1.316	1.315
8.0	1.258	1.310	1.312
10.0	1.257	1.300	1.305

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

With the completion of the present work, there now exists a completely automated method for optimizing the burnable poison loading for a core reload design pattern. It should be stressed that the method is capable of performing reload design only. The code is not designed to be used for startup cycle design. This is due to the fact that in the startup core, all of the assemblies are 'fresh' and available for BP loading. The code is simply not capable of handling such a large number of poisonable assemblies.

The improved method will save the core designer a great deal of time and effort. Perhaps even more significantly, the design work can now be performed by individuals not having a tremendous amount of insight or experience in the core reload design problem. This makes the code ideal for utilities desiring to become vendor-independent in the designing of their own reload cores.

The major benefit of the improved BP assignment method is not in lengthening the cycle, for it is becoming more and more evident that the BP loading has very little effect on the achievable cycle length. Its greatest worth is in determining a burnable poison loading that makes possible the safe operation of the optimal fuel loading pattern. Also, the improved method investigates a far greater number of alternative loading strategies and therefore increases the likelihood that the safest and most economical scenario is chosen.

Recommendations

It has been shown in previous work[1] that the control strategy has but a minor effect on the achievable cycle length. This theory is further supported by the current work. The difference between the longest and the shortest cycles that were deemed as acceptable by the code is less than 40 MWD/MT for both cycles 9 and 10. This would seem to lead to the conclusion that the selection of the optimal BP loading on the basis of cycle length is not such a viable alternative. Other possible alternatives for the objective function include: the minimization of the total number of BP rods and the minimization of the power peaking. The minimization of the total number of BP rods in the core would obviously lower fuel cycle costs by reducing the cost of fuel fabrication. This would also lead to an lessening of the reactivity penalty due to BP residue. The minimization of the core power peaking gives no explicit benefit in terms of cycle length or fuel costs. It does, however, give rise to a larger margin of safety, which could ultimately outweigh either of the above benefits.

The entire foundation of the burnable absorber assignment method is based on the attempt to achieve some desired power distribution. Theoretically, this target power shape is the optimum power shape. Since this optimum is currently unknown, a Haling power distribution was used as a target in the present method. Unfortunately, however, this is most probably not the optimum power shape. The method would be improved if the true optimum power distribution could be determined. This task is currently being undertaken here at Purdue.

The current method provides an adequate tool for optimized reload design utilizing discrete burnable absorber rods. This is by far the most common means of power peaking control in today's reactors. However, the inherent advantages of other types of absorbers, such as gadolinia and IFBA may soon lead to the replacement of the discrete absorber rod. Therefore, it would be advisable to examine the possibility of incorporating the use of these other types of absorbers into the core reload design method.

LIST OF REFERENCES

1. Kim, Y./J., 'Optimization of Core Reload Design for Low-Leakage Fuel Management in Pressurized Water Reactors,' Ph. D. Thesis, Purdue University, 1986.

2. Ver Planck, D., 'SIMULATE-E: A Nodal Core Analysis Program for LWR's; Computer Code Users's Manual,' EPRI-NP-2792-CCM,1983.

3. Haling, R., 'Operating Strategy for Maintaining An Optimum Power Distribution Throughout Life,' Proc. ANS Topl. Mtg.; Nuclear Performance Power Reactor Cores, TID-7672, 1964.

4. Reklaitis, G. V. et. al., 'Engineering Optimization: Methods and Applications,' John Wiley and Sons, New York, 1983.

APPENDICES

APPENDIX A: SOURCE LISTING

The following partial source listing gives all of the major routines that were either created or altered in this work. Excluded are routines with minor or cosmetic changes.

```
      SUBROUTINE PARTB                                                  PARTB      2
       CHARACTER*8 ADATE,BDATE,IHTIME,JHTIME                            F200CPU    3
      DIMENSION JOBNAM(2)                                               BLOK4      6
      LOGICAL IVOID,ICNTRL,IFIRST,LEVELU,LEVELC                         OPUS      20
      LOGICAL DEPL(50000),KPFRST                                        OPUS      21
      DIMENSION IBP(50000,20),IROW(20),JCOL(20),EXP(8,8),CONC(6,8,8)    OPUS      22
      TEMP=0.0                                                          OPUS      23
      ITEMP=0                                                           OPUS      24
      NBPERM=1                                                          OPUS      25
      DEPL(1)=.TRUE.                                                    OPUS      26
      MOPTIM=A1(46)                                                     PARTB     15
      IMABWR=MODEB(2)                                                   PARTB     16
      IDEBUG=0                                                          PARTB     17
      IFIRST=.TRUE.                                                     SMCY1    102
       CALL QSSNDMDF('LEN=',16,'MSG=','** IN PARTB **')                 PARTB     19
      CALL TIMER (5HPARTB,2)                                            PARTB     21
      LAUSED(2)=LAUSED(1)                                               PARTB     22
C                                                                       PARTB     23
      INITIALIZATION                                                    PARTB     24
C                                                                       PARTB     25
      IEOL=0                                                            PARTB     26
      DEP=DE                                                            PARTB     27
      TIMXE=0.0                                                         PARTB     28
      NEC=0                                                             PARTB     29
      IBRN=IBURN                                                        PARTB     30
      ISTEP=0                                                           PARTB     31
      FIRST=1.0                                                         PARTB     32
      CALL PAGES (10)                                                   PARTB     33
      LINES=LINES-8                                                     PARTB     34
      WRITE (ITAPOT,10)                                                 PARTB     35
   10 FORMAT (/45X, 44HBEGIN COUPLED NUCLEAR - HYDRAULIC ITERATIONS)    PARTB     36
C                                                                       PARTB     37
      DETERMINE THE ITERATION LEVELS INVOLVED IN THS CASE.              PARTB     38
C                                                                       PARTB     39
      IVOID=.FALSE.                                                     PARTB     40
      IF (NUMAX.GT.0) IVOID=.TRUE.                                      PARTB     41
      ICNTRL=.FALSE.                                                    PARTB     42
      IF(MODEB(5).GE.3) ICNTRL=.TRUE.                                   PARTB     43
      IF (MODEB(5).GT.5) ICNTRL=.FALSE.                                 PARTB     44
C     THE HALING ITERATION USES THE CONTROL ITERATION LEVEL DURING      PARTB     45
C     THE END OF LIFE EXPOSURE SEARCH.                                  PARTB     46
      IF (MODEB(5).EQ.6.AND.MODEB(10).GT.0) ICNTRL=.TRUE.               PARTB     47
      NC=0                                                              PARTB     48
      NU=0                                                              PARTB     49
      NS=0                                                              PARTB     50
      XL=1.0                                                            PARTB     51
      ITERS=0                                                           PARTB     52
      ISRCH=0                                                           PARTB     53
      LPMEM = NPARTA                                                    PARTB     54
      LNEED=NMACRO*NDIM3D                                               PARTB     55
      IF (MODEB(1).EQ.0) LNEED=NDIM3D                                   PARTB     56
C     PUT ONLY THE SOURCE TO POWER CONVERSION FACTOR ON I/O FOR 1 GROUP PARTB     57
      CALL NEXTPT (LPMEM,10,LNEED,20HCROSS SECTION        )             PARTB     58
      LNEED = NSTATE*NDIM3D                                             PARTB     59
      CALL NEXTPT(LPMEM,18,LNEED,15HSTATE VARIABLES)                    PARTB     60
      CALL NEXTPT(LPMEM,24,NDIM3D,20HTHERMAL LEAKAGE       )            PARTB     61
      LPW=LPMEM                                                         OPUS      27
   21 CONTINUE                                                          XXX2       1
       NITERS=1                                                         PARTB     63
C     CONTROL ITERATION STARTS HERE                                     PARTB     64
   30 CONTINUE                                                          PARTB     65
      IOSC=0                                                            PARTB     66
      XLC=XKEFF                                                         PARTB     67
      LEVELC=.FALSE.                                                    XXX2       2
        IBPAS=0                                                         XXX2       3
        KSTEP=1                                                         PARTB     68
      NC=NC+1                                                           OPUS      28
      KPFRST=.TRUE.                                                     OPUS      29
      IF(MOPTIM .LT. 2) GO TO 40                                        XXX2       4
       CALL POWDIS (DEP,ICNTRL,IDEBUG,IOPTEX,IOSC,ISRCH,IVOID,          XXX2       5
     * LEVELC,LEVELU,LPAXLS,LPBU,NCOEFS,NCROSS,NEDITS,NEDTS,NEXPOS,     OPUS      30
     * NFLOW,NPOWER,NSOURC,NVOID,XPOLST,XT,IFIRST,KPFRST)               OPUS      31
      DO 60 I=1,IMAX                                                    OPUS      32
      CALL READX(CONC,LP12,ITAPH,I,ND,JD,KD,LPXTR(12))                  OPUS      33
      DO 60 J=1,JMX(I)                                                  OPUS      34
      EXP(I,J)=CONC(NC4,J,1)                                            OPUS      35
   60 CONTINUE                                                          XXX2       8
       CALL POISPUT(A(LPSRC),A(LPXBR),KSTEP,ID,JD,NITERS,IBPAS,         XXX2       9
     * DEP,ICNTRL,IDEBUG,IOPTEX,IOSC,ISRCH,IVOID,                       XXX2      10
     * LEVELC,LEVELU,LPAXLS,LPBU,NCOEFS,NCROSS,NEDITS,NEDTS,NEXPOS,
                                                                        OPUS    36
     * NFLOW,NPOWER,NSOURC,NVOID,XPOLST,XT,IFIRST,                      OPUS    37
     * KBPOS,NBPERM,IBP,DEPL,IROW,JCOL)                                 XXX2    12
        IF(IDEBUG.GT.0) GO TO 660                                       XXX2    13
       IF(IBPAS.EQ.0) THEN                                              XXX2    14
        NU=0                                                            XXX2    15
        NC=0                                                            XXX2    16
        GO TO 30                                                        XXX2    17
       ELSE                                                             XXX2    18
       ENDIF                                                            XXX2    19
 40    CONTINUE                                                         OPUS    38
      NODEP=0                                                           OPUS    39
      NODEP1=0                                                          OPUS    40
      IF(MOPTIM .EQ. 2) THEN                                            OPUS    41
      WRITE(6,50)                                                       OPUS    42
 50   FORMAT(1H1,1X,62H PERFORM DEPLETION OF ALL ACCEPTABLE INTEGRAL BP OPUS    43
     *COMBINATIONS:,/,3X,61(1H*))                                       OPUS    44
      ENDIF                                                             OPUS    45
      DO 665 KPOIS=1,NBPERM                                             OPUS    46
      PTEMP=0.0                                                         OPUS    47
      XTEMP=0.0                                                         OPUS    48
      IPEAK=0                                                           OPUS    49
      JPEAK=0                                                           OPUS    50
      IF(.NOT. DEPL(KPOIS)) THEN                                        OPUS    51
      NODEP=NODEP+1                                                     OPUS    52
      GO TO 665                                                         OPUS    53
      ENDIF                                                             OPUS    54
C                                                                       OPUS    55
C     INITIALIZATION                                                    OPUS    56
C                                                                       OPUS    57
      IEOL=0                                                            OPUS    58
      DEP=DE                                                            OPUS    59
      TIMXE=0.0                                                         OPUS    60
      NEC=0                                                             OPUS    61
      ISTEP=0                                                           OPUS    62
      FIRST=1.0                                                         OPUS    63
      IBRN=IBURM                                                        OPUS    64
C                                                                       OPUS    65
C     DETERMINE THE ITERATION LEVELS INVOLVED IN THS CASE.              OPUS    66
C                                                                       OPUS    67
      IVOID=.FALSE.                                                     OPUS    68
      IF (NUMAX.GT.0) IVOID=.TRUE.                                      OPUS    69
      ICNTRL=.FALSE.                                                    OPUS    70
      IF(MODEB(5).GE.3) ICNTRL=.TRUE.                                   OPUS    71
      IF (MODEB(5).GT.5) ICNTRL=.FALSE.                                 OPUS    72
C     THE HALING ITERATION USES THE CONTROL ITERATION LEVEL DURING      OPUS    73
C     THE END OF LIFE EXPOSURE SEARCH.                                  OPUS    74
      IF (MODEB(5).EQ.6.AND.MODEB(10).GT.0) ICNTRL=.TRUE.               OPUS    75
      NC=0                                                              OPUS    76
      NU=0                                                              OPUS    77
      NS=0                                                              OPUS    78
      XL=1.0                                                            OPUS    79
      ITERS=0                                                           OPUS    80
      ISRCH=0                                                           OPUS    81
      LPMEM = NPARTA                                                    OPUS    82
      LNEED=NMACRO*NDIM3D                                               OPUS    83
      IF (MODEB(1).EQ.0) LNEED=NDIM3D                                   OPUS    84
C     PUT ONLY THE SOURCE TO POWER CONVERSION FACTOR ON I/O FOR 1 GROUP OPUS    85
      CALL NEXTPT (LPMEM,10,LNEED,20HCROSS SECTION        )             OPUS    86
      LNEED = NSTATE*NDIM3D                                             OPUS    87
      CALL NEXTPT(LPMEM,18,LNEED,15HSTATE VARIABLES)                    OPUS    88
      CALL NEXTPT(LPMEM,24,NDIM3D,20HTHERMAL LEAKAGE      )             OPUS    89
      LPW=LPMEM                                                         OPUS    90
      IF(MOPTIM .EQ. 2) THEN                                            OPUS    91
      XPO=0.0                                                           OPUS    92
      A1(1)=0.0                                                         OPUS    93
      XT=0.0                                                            OPUS    94
      XPOLST=0.0                                                        OPUS    95
      NTOTBP=0                                                          OPUS    96
      DO 1 K=1,KBPOS                                                    OPUS    97
      I=IROW(K)                                                         OPUS    98
      J=JCOL(K)                                                         OPUS    99
      IF(J .EQ. 1) THEN                                                 OPUS   100
      IF(I .EQ. J) THEN                                                 OPUS   101
      NYY=1                                                             OPUS   102
      ELSE                                                              OPUS   103
      NYY=4                                                             OPUS   104
      ENDIF                                                             OPUS   105
      ELSEIF(I .EQ. J) THEN                                             OPUS   106
      NYY=4                                                             OPUS   107
      ELSE
```

```
          NYY=8                                                           OPUS      108
          ENDIF                                                           OPUS      109
          NBP(I,J)=IBP(KPOIS,K)*10+(NBP(I,J)/1000)*1000                   OPUS      110
          NTOTBP=NTOTBP+NYY*IBP(KPOIS,K)                                  OPUS      111
    1     CONTINUE                                                        OPUS      112
          ENDIF                                                           OPUS      113
   20     CONTINUE                                                        OPUS      114
    C     CONTROL ITERATION STARTS HERE                                   OPUS      115
          IOSC=0                                                          OPUS      116
          XLC=XKEFF                                                       OPUS      117
          LEVELC=.FALSE.                                                  OPUS      118
          NC=NC+1                                                         OPUS      119
          CALL POWDIS(DEP,ICNTRL,IDEBUG,IOPTEX,IOSC,ISRCH,IVOID,          OPUS      120
         *     LEVELC,LEVELU,LPAXLS,LPBU,NCOEFS,NCROSS,NEDITS,NEDTS,      OPUS      121
         *     NEXPOS,NFLOW,NPOWER,NSOURC,NVOID,XPOLST,XT,IFIRST,KPFRST)  OPUS      122
          IF(MOPTIM .EQ. 2) THEN                                          OPUS      123
          PPLIM=A1(39)                                                    OPUS      124
          PPMULT2=A2(52)                                                  OPUS      125
          IF(SMAX .GT. PPLIM*PPMULT2) THEN                                OPUS      126
          NODEP1=NODEP1+1                                                 OPUS      127
          KPFRST=.FALSE.                                                  OPUS      128
          GO TO 665                                                       OPUS      129
          ENDIF                                                           OPUS      130
          IF(SMAX .GT. PTEMP) THEN                                        OPUS      131
          PTEMP=SMAX                                                      OPUS      132
          IPEAK=MAXSI                                                     OPUS      133
          JPEAK=MAXSJ                                                     OPUS      134
          XTEMP=XPO                                                       OPUS      135
          ENDIF                                                           OPUS      136
          ENDIF                                                           OPUS      137
    C                                                                     PARTB     503
    C     END  BWR LIMITS CALCULATION                                     PARTB     504
    C                                                                     PARTB     505
    C                                                                     PARTB     506
    C     EDIT SEVERAL AXIAL AVERAGE DISTRIBUTIONS                        PARTB     507
    C                                                                     PARTB     508
          IF(MOPTIM .LT. 2) THEN                                          OPUS      138
          CALL EDT1 (8,MZ,MZ,MZ,MZ,MZ)                                    PARTB     509
          IF(MODEB(5).EQ.1.OR.MODEB(5).EQ.2) CALL HTBAL(2)                PARTB     510
          CALL PAGES(15+KMAX)                                             PARTB     511
          WRITE (ITAPOT,300)                                              PARTB     512
          WRITE (ITAPN,300)                                               PARTB     513
  300     FORMAT (/54X,27HAVERAGE AXIAL DISTRIBUTIONS,//,                 PARTB     514
        1 11X,4HNODE,8X,5HPOWER,8X,5HWATER,7X,8H SOURCE ,7X,7HTHERMAL,7X, PARTB     515
        2  7HCONTROL,11X,1HK,10X,6HBYPASS/                                PARTB     516
        3 35X,7HDENSITY,21X,7HLEAKAGE,20X,8HINFINITY,9X,4HVOID/           PARTB     517
        4  25X,1HP,13X,1HU,13X,1HS,13X,1HT,12X,2HCT,13X,1HK,12X,2HBU/)    PARTB     518
          CALL AXIALP (A(LPAXLS),KD,7,22H(12X,I2,7F14.4,12X,I2),ITAPOT)   PARTB     519
          CALL AXIALP (A(LPAXLS),KD,7,22H(12X,I2,7F14.4,12X,I2),ITAPN)    PARTB     520
          ENDIF                                                           OPUS      139
    C                                                                     PARTB     521
    C     APPLY THE CONTROL SEARCH CALLED FOR BY MODEB(5)                 PARTB     522
    C                                                                     PARTB     523
          NU=0                                                            PARTB     524
          IF (.NOT.ICNTRL) GO TO 390                                      PARTB     525
          IF (NC.GE.NCMAX) GO TO 390                                      PARTB     526
          IF (NC.LT.2) GO TO 310                                          PARTB     527
          IF (LEVELC) GO TO 390                                           PARTB     528
  310     CONTINUE                                                        PARTB     529
          M=MODEB(5)-3                                                    PARTB     530
          GO TO (340,350,370),M                                           PARTB     531
   340     CALL NHWORD(NAM,8HSEQUENCE,8)                                  SMCY1     113
          GO TO 360                                                       PARTB     533
   350     CALL NHWORD(NAM,8HPATTERN ,8)                                  SMCY1     114
  360     ANOTWT=NOTWT                                                    PARTB     535
           CALL NHWORD(NAM(13),8HPOSITION,8)                              SMCY1     115
           CALL SEARCH(SR(4),ANOTWT,NAM,NAM(13),XKEFF,XLMBDA,ISRCH)       SMCY1     116
          NOTWT=ANOTWT                                                    PARTB     538
          IF (NOTWT.LE.0) NOTWT=0                                         PARTB     539
          CALL RODMUV (A(LPR),A(LPNPCR),A(LPARAY),A(LPNTCH),ID,JD,IRMX,LIMRA PARTB  540
        1Y,LIMPAS)                                                        PARTB     541
          GO TO 380                                                       PARTB     542
  370     CONTINUE                                                        PARTB     543
    C     HALING SEARCH (SEE SIGCAL/SIGDAT)                               PARTB     544
           IF (MODEB(10).EQ.0) GO TO 380                                  PARTB     545
           CALL NHWORD(NAM,8HHALING D,8)                                  SMCY1     117
           CALL NHWORD(NAM(13),8HEXPOSURE,8)                              SMCY1     118
           CALL SEARCH(SR(5),DEP,NAM,NAM(13),XKEFF,XLMBDA,ISRCH)          SMCY1     119
  380     CONTINUE                                                        PARTB     549
          GO TO 30                                                        PARTB     550
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                                                                        PARTB    551
  390 CONTINUE                                                          PARTB    552
      NC=0                                                              PARTB    553
C                                                                       PARTB    554
C     END OF CONTROL LEVEL ITERATION                                    PARTB    555
C                                                                       PARTB    556
      LPSTAT=NFLOW                                                      PARTB    557
      LPMEM = LPSTAT + NSTATE*JD*KD                                     PARTB    558
      LNEED = LIST*NDAT*LIMNFT                                          PARTB    559
      CALL FINDPT(LPMEM,LPDAT,16,LNEED)                                 PARTB    560
      LNEED = KDIM*LMKNFT                                               PARTB    561
      CALL FINDPT(LPMEM,LPKTAB,17,LNEED)                                PARTB    562
      LPSIG = LPMEM                                                     PARTB    563
      LPCON = LPSIG + NMACRO*JD*KD                                      PARTB    564
      LPCNLD = LPCON + ND*JD*KD                                         PARTB    565
      LPWF = LPCNLD + ND*JD*KD                                          PARTB    566
      LPTKN = LPWF + KD*LIMNFT                                          PARTB    567
      LPTKN2 = LPTKN + KD*LIMNFT                                        PARTB    568
      NEXPOS = LPTKN2 + KD*LIMNFT                                       PARTB    569
      CALL CLSIZE(NEXPOS,LAUSED(2),20HEXPOSURE/EDITS      )             PARTB    570
C                                                                       PARTB    571
C     FUEL DEPLETION CONTROL                                            PARTB    572
C                                                                       PARTB    573
C                                                                       PARTB    574
C     USAGE OF IEOL AND IBURN                                           PARTB    575
C     INPUT 0 LT IEOL LT 99 TO INITIATE SEARCH FOR EOL EXPOSURE BY EOLEX PARTB    576
C     EOLEXP SETS IEOL=99 WHEN IT SEES EOFPL ON NEXT STEP.              PARTB    577
C     IEOL=999 WHEN NO MORE EXPOSURE CALCULATIONS ARE TO BE MADE        PARTB    578
C     IBURN=0 WHEN AFINAL SOURCE CALCULATION IS TO BE MADE.             PARTB    579
C     IBURN=1 IF NO MORE SOURCE CALCULATIONS ARE TO BE MADE             PARTB    580
C                                                                       PARTB    581
      IF (DE.EQ.0.0) IEOL=999                                           PARTB    582
      IF (DE.GT.0.0.AND.XPO.GE.XPOMAX) IEOL=999                         PARTB    583
      IF (DE.LT.0.0.AND.XPO.LE.XPOMAX) IEOL=999                         PARTB    584
      IF (IEOL.EQ.999) IBRN=1                                           PARTB    585
      IF (MODEB(5).NE.6) GO TO 400                                      PARTB    586
      IBRN=1                                                            PARTB    587
      IEOL=999                                                          PARTB    588
  400 CONTINUE                                                          PARTB    589
      DEP=DE                                                            PARTB    590
      IF (IEOL.EQ.999) GO TO 600                                        OPUS     140
      IF(MOPTIM .LT. 2) THEN                                            PARTB    591
      CALL PAGES (MAXLIN)                                               OPUS     141
      ENDIF                                                             PARTB    592
      LINES=4                                                           PARTB    593
      IOPTEX=1                                                          PARTB    594
      ISTEP=ISTEP+1                                                     PARTB    595
      MD12=ISTEP/2                                                      PARTB    596
      IF (MODEB(12).NE.0.AND.MD12*2.NE.ISTEP) GO TO 490                 PARTB    597
      IEOL=MODEB(10)                                                    PARTB    598
      IF (MODEB(5).GT.5) GO TO 470                                      PARTB    599
      IF (IEOL.LE.0) GO TO 470                                          PARTB    600
C                                                                       PARTB    601
C     FOLLOWING LOGIC CONTROLS THE END OF LIFE EXPOSURE SEARCH          PARTB    602
C     FOR XKEFF=XLMBDA                                                  PARTB    603
C                                                                       PARTB    604
C     ASSIGN CONTROL SEARCH PARAMETER                                   PARTB    605
      MM=MODEB(5)                                                       PARTB    606
      IF (MM.EQ.0) GO TO 410                                            PARTB    607
      GO TO (420,430,440,450,450,460), MM                               PARTB    608
  410 DUMY=0.0                                                          PARTB    609
      CALL EOLEXP (XKEFF,DE,XPO,XLMBDA,DEP,DUMY,IEOL,FIRST)             PARTB    610
      GO TO 470                                                         PARTB    611
  420 CALL EOLEXP (XKEFF,DE,XPO,XLMBDA,DEP,POI,IEOL,FIRST)              PARTB    612
      GO TO 470                                                         PARTB    613
  430 CONTINUE                                                          PARTB    614
      GO TO 470                                                         PARTB    615
  440 CONTINUE                                                          PARTB    616
      GO TO 470                                                         PARTB    617
  450 SRCH=NOTWT                                                        PARTB    618
      CALL EOLEXP (XKEFF,DE,XPO,XLMBDA,DEP,SRCH,IEOL,FIRST)             PARTB    619
      NOTWT=SRCH                                                        PARTB    620
      GO TO 470                                                         PARTB    621
  460 CONTINUE                                                          PARTB    622
  470 CONTINUE                                                          PARTB    623
      IF (DEP.LT.0.0.AND.XPO+DEP.LT.XPOMAX) DEP=XPOMAX-XPO              PARTB    624
      IF (DEP.GT.0.0.AND.XPO+DEP.GT.XPOMAX) DEP=XPOMAX-XPO              PARTB    625
C                                                                       PARTB    626
C     SIGCAL DOES THE FUEL DEPLETION WHEN IOPTEX=1                      PARTB    627
C                                                                       PARTB    628
      XPO=A1(1)+DEP
      IF (MODEB(12).GT.0.AND.MD12*2.EQ.ISTEP) GO TO 480                 PARTB    629
      GO TO 510                                                         PARTB    630
  480 IOPTEX=3                                                          PARTB    631
      GO TO 510                                                         PARTB    632
  490 CONTINUE                                                          PARTB    633
      WRITE (ITAPOT,500)                                                PARTB    634
  500 FORMAT (/10X,87HTHIS IS THE FIRST STEP IN THE STEP AVERAGE DEPLETI PARTB    635
     1ON PROCEDURE CONTROLLED BY MODEB(12).)                            PARTB    636
  510 CONTINUE                                                          PARTB    637
      CALL SIGCAL(A(LPSTAT),A(LPDAT),A(LPCON),A(LPCNLD),A(LPSIG),       PARTB    638
     1  A(LPNFT),A(LPTKN),A(LPTKN2),A(LPWF),A(LPKTAB),A(LPXK),          PARTB    639
     2  A(LPYY),A(LPCNLD),ID,JD,KD,ND,NMACRO,NSTATE,LIMNFT,KDIM,LIST,   PARTB    640
     3  NDAT,IOPTEX,DEP,XT,XPOLST,KPFRST)                               OPUS     142
      A1(1)=XPO                                                         PARTB    642
      IF (IOPTEX.NE.3) GO TO 530                                        PARTB    643
      LINES=LINES+2                                                     PARTB    644
      WRITE (ITAPOT,520) EBAR                                           PARTB    645
      WRITE (ITAPN,520) EBAR                                            PARTB    646
  520 FORMAT (/10X,57HTHIS IS THE REDEPLETION TIMESTEP CONTROLLED BY MOD PARTB    647
     1EB(12)./10X,34HTHE CORE AVERAGE EXPOSURE REMAINS ,F10.4)          PARTB    648
      GO TO 550                                                         PARTB    649
  530 CONTINUE                                                          PARTB    650
      IF(MOPTIM .LT. 2) THEN                                            OPUS     143
      WRITE (ITAPOT,540) EBAR                                           PARTB    651
      WRITE (ITAPN,540) EBAR                                            PARTB    652
  540 FORMAT (/10X,63HTHE AVERAGE EXPOSURE OF THE FUEL IN CORE HAS BEEN PARTB    653
     1INCREASED TO ,F10.4)                                              PARTB    654
      ENDIF                                                             OPUS     144
  550 CONTINUE                                                          PARTB    655
      IF(MOPTIM .LT. 2) THEN                                            OPUS     145
      CALL PAGES (2)                                                    PARTB    656
      WRITE (ITAPOT,560) DEP                                            PARTB    657
      WRITE (ITAPN,560) DEP                                             PARTB    658
  560 FORMAT (/10X,42HTHE (ADJUSTED) EXPOSURE INTERVAL USED WAS ,F10.4) PARTB    659
      ENDIF                                                             OPUS     146
      IF (MODEB(3).EQ.2.OR.MODEB(3).EQ.4) GO TO 570                     PARTB    660
      GO TO 590                                                         PARTB    661
  570 CONTINUE                                                          PARTB    662
      CALL PAGES (1)                                                    PARTB    663
      IF(MODEB(12).GT.0.AND.MD12*2.EQ.ISTEP) GO TO 575                  PARTB    664
      TIMXE1=TIMXE                                                      PARTB    665
      TIMXE=TIMXE+XT/3600.                                              PARTB    666
      XETIME=XETIME+XT/3600.                                            PARTB    667
  575 CONTINUE                                                          PARTB    668
      WRITE (ITAPOT,580) ISTEP,TIMXE1,TIMXE,XETIME                      PARTB    669
      WRITE (ITAPN,580) ISTEP,TIMXE1,TIMXE,XETIME                       PARTB    670
  580 FORMAT (10X,10HTIME STEP ,I4,10H BEGAN AT ,F10.4,20H HOURS AND END PARTB    671
     1ED AT ,F10.4,7H HOURS.,/10X,32HTOTAL TIME SINCE INITIALIZATION ,  FTN200F    8
     2  18H OF CONCENTRATIONS,8H IS NOW ,F10.4,7H HOURS.)               PARTB    673
  590 CONTINUE                                                          PARTB    674
  600 CONTINUE                                                          PARTB    675
C                                                                       PARTB    676
C     EDIT AXIAL AVERAGE EXPOSURE, VOID HISTORY AND CONCENTRATIONS      PARTB    677
C                                                                       PARTB    678
      IF(MOPTIM .LT. 2) THEN                                            OPUS     147
      CALL CLEAR(A(LPAXLS),7*KD,0.0)                                    PARTB    679
      CALL REWND (ITAPH,12)                                             PARTB    680
      DO 620 I=1,IMAX                                                   PARTB    681
      CALL READX (A(LPCON),LP12,ITAPH,I,ND,JD,KD,LPXTR(12))             PARTB    682
      CALL AXIALC(A(LPCON),A(LPYY),ID,JD,KD,ND,A(LPAXLS),NC4,1,7,I)     PARTB    683
      IF(ISET1.EQ.0)                                                    PARTB    684
     1CALL AXIALC(A(LPCON),A(LPYY),ID,JD,KD,ND,A(LPAXLS),NC5,2,7,I)     PARTB    685
      IF(ISET2.EQ.0)                                                    PARTB    686
     1CALL AXIALC(A(LPCON),A(LPYY),ID,JD,KD,ND,A(LPAXLS),NC6,3,7,I)     PARTB    687
      NCSM=NC5-1                                                        PARTB    688
      IF (NCSM.LT.1) GO TO 620                                          PARTB    689
      DO 610 NZ=1,NCSM                                                  PARTB    690
      CALL AXIALC(A(LPCON),A(LPYY),ID,JD,KD,ND,A(LPAXLS),NZ,NZ+3,7,I)   PARTB    691
  610 CONTINUE                                                          PARTB    692
  620 CONTINUE                                                          PARTB    693
      CALL PAGES(15+KMAX)                                               PARTB    694
      WRITE (ITAPOT,630)                                                PARTB    695
      WRITE (ITAPN,630)                                                 PARTB    696
  630 FORMAT(/54X,27HAVERAGE AXIAL DISTRIBUTIONS,//,                    PARTB    697
     1 11X,4HNODE,5X,8HEXPOSURE,9X,4HVOID, 8X,7HCONTROL,5X,             PARTB    698
     2 51H- - - - - - C O N C E N T R A T I O N S - - - - - - -,/       PARTB    699
     3 35X,7HHISTORY, 7X,7HHISTORY,7X,6HIODINE,8X,5HXENON,              PARTB    700
     47X,10HPROMETHIUM,5X,8HSAMARIUM,/)                                 PARTB    701
      CALL AXIALP(A(LPAXLS),KD,7,29H(12X,I2,3F14.4,4E14.4,12X,I2),ITAPOT PARTB    702
     1)                                                                 PARTB    703
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      CALL AXIALP(A(LPAXLS),KD,7,29H(12X,I2,3F14.4,4E14.4,12X,I2),ITAPN) PARTB     704
C     GET 3D EDITS OF CONCENTRATION FILE ARRAYS, E,V,I,XE,PM,SM          PARTB     705
      LPMEM=NFLOW                                                        PARTB     706
      CALL FINDPT(LPMEM,LPSRC,11,NDIM3D)                                 PARTB     707
      LPE=LPMEM                                                          PARTB     708
      LPXE = LPE + NDIM3D                                                PARTB     709
      LPV = LPXE + NDIM3D                                                PARTB     710
      LPCON = LPV + NDIM3D                                               PARTB     711
      LPTKN = LPCON + ND*JD*KD                                           PARTB     712
      LPTKN2 = LPTKN + KD*LIMNFT                                         PARTB     713
      LPWF = LPTKN2 + KD*LIMNFT                                          PARTB     714
      LPMAP1 = LPWF + KD*LIMNFT                                          PARTB     715
      LPMAP2=LPMAP1+MAX0(JD*KD,576)                                      PARTB     716
      NEDTS=LPMAP2+KD*16                                                 PARTB     717
      CALL CLSIZE (NEDTS,LAUSED(2),17HTARGET FILE EDITS)                 PARTB     718
      CALL FZONES(A(LPTKN),A(LPTKN2),A(LPWF),ID,JD,KD,                   PARTB     719
     1 LIMNFT)                                                           PARTB     720
      CALL EDITB3 (A(LPSRC),A(LPE),A(LPV),A(LPXE),A(LPCON),A(LPNFT),A(LP PARTB     721
     1NFID),A(LPMAP1),A(LPMAP2),A(LPBATF),A(LPYY),ID,JD,KD,ND,           PARTB     722
     2A(LPTKN),A(LPTKN2),A(LPWF),LIMNFT)                                 PARTB     723
      ENDIF                                                              OPUS      148
      IF (DE.GT.0.0.AND.XPO.GE.0.99999*XPOMAX) IEOL=999                  PARTB     724
      IF (DE.LT.0.0.AND.XPO.LE.1.00001*XPOMAX) IEOL=999                  PARTB     725
C                                                                        PARTB     726
C     SHOULD ANOTHER SOURCE CALCULATION BE INITIATED                     PARTB     727
C                                                                        PARTB     728
      IF (IBRN.EQ.0.AND.IEOL.GE.99) GO TO 640                            PARTB     729
      IF (IEOL.EQ.999) GO TO 650                                         PARTB     730
      GO TO 20                                                           PARTB     731
  640 IEOL=999                                                           PARTB     732
      IBRN=1                                                             PARTB     733
      GO TO 20                                                           PARTB     734
  650 IEOL=999                                                           PARTB     735
      IF (MODEB(15).EQ.0) GO TO 660                                      PARTB     736
      A1(4)=PTH                                                          PARTB     737
      A1(5)=WT                                                           PARTB     738
      A1(10)=POI                                                         PARTB     739
      A1(11)=NOTWT                                                       PARTB     740
      IF(MODEB(5).NE.6) GO TO 660                                        PARTB     741
C                                                                        PARTB     742
C       CONTINUATION MODE FOR COMPLETED HALING DEPLETIONS                PARTB     743
C                                                                        PARTB     744
      XPO=XPOMAX                                                         PARTB     745
      A1(1)=XPO                                                          PARTB     746
  660 CONTINUE                                                           PARTB     747
C                                                                        OPUS      149
C     DEPLETION COMPLETED - PRINT OUT RESULTS                            OPUS      150
C                                                                        OPUS      151
      IF(MOPTIM .EQ. 2) THEN                                             OPUS      152
      WRITE(6,664) KPOIS                                                 OPUS      153
  664 FORMAT(10(/),1X,5HCASE ,I5,10H COMPLETED,/,1X,20(1H=))             OPUS      154
      WRITE(6,667) (IBP(KPOIS,J),J=1,KBPOS)                              OPUS      155
  667 FORMAT(/,10X,11HBP LOADING ,20I4)                                  OPUS      156
      WRITE(6,668) NTOTBP                                                OPUS      157
  668 FORMAT(10X,25HTOTAL NUMBER OF BP RODS  ,I4)                        OPUS      158
      WRITE(6,654) PTEMP,XTEMP,IPEAK,JPEAK                               OPUS      159
  654 FORMAT(/,1X,21HMAX POWER PEAKING OF ,F7.5,4H AT ,F6.3,             OPUS      160
     *21H GWD/MT AT POSITION (,I1,1H,,I1,1H))                            OPUS      161
      WRITE(6,655) XPO                                                   OPUS      162
  655 FORMAT(///,1X,25HCYCLE LENGTH ACHIEVED    ,F7.3,8H  GWD/MT)        OPUS      163
      IF(XPO .GT. TEMP) THEN                                             OPUS      164
      TEMP=XPO                                                           OPUS      165
      ITEMP=KPOIS                                                        OPUS      166
      ENDIF                                                              OPUS      167
      ENDIF                                                              OPUS      168
      KPFRST=.FALSE.                                                     OPUS      169
C                                                                        PARTB     748
C     SET SEARCH EIGENVALUE FOR THE NEXT (SERIES OF )CASES               PARTB     749
C                                                                        PARTB     750
      IF(MODEB(21).EQ.0) GO TO 665                                       PARTB     751
      A1(19)=XKEFF                                                       PARTB     752
      XLMBDA=A1(19)                                                      PARTB     753
      MODEB(21)=0                                                        PARTB     754
  665 CONTINUE                                                           PARTB     755
      ENDPTH=PTH                                                         PARTB     756
      NORIGN=LWA-IBIAS                                                   PARTB     757
      CALL PAGES(18)                                                     PARTB     758
      IF(MOPTIM .EQ. 2) THEN                                             OPUS      170
      DO 675 K=1,KBPOS                                                   OPUS      171
      I=IROW(K)                                                          OPUS      172
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                                                                  OPUS     173
      J=JCOL(K)                                                   OPUS     174
      NBP(I,J)=IBP(ITEMP,K)*10+(NBP(I,J)/1000)*1000               OPUS     175
  675 CONTINUE                                                    OPUS     176
      NBP1=NBPERM-NODEP                                           OPUS     177
      NBP2=NBP1-NODEP1                                            OPUS     178
      CALL OPRES(NBP,NBPERM,NBP1,NBP2,TEMP,ITEMP,EXP,JMX)         OPUS     179
      ENDIF                                                       PARTB    759
      WRITE(ITAPOT,670) LWA,NORIGN,NPARTA,NFLOW,NVOID,NCROSS,NCOEFS,  PARTB    760
     1 NSOURC,NPOWER,NEDITS,NEXPOS,NEDTS                          OPUS     180
  670 FORMAT(1H1,10X,26HMEMORY BOUNDARIES IN PARTB,               PARTB    762
     A/10X,I8,30H INSTRUCTIONS (LWA)                              PARTB    763
     B/10X,I8,30H ORIGIN OF CONTAINER ARRAY                       PARTB    764
     1/10X,I8,30H INPUT DATA BOUNDARY                             PARTB    765
     2/10X,I8,30H FLOW ITERATION BOUNDARY                         PARTB    766
     3//10X,I8,30H VOID CALCULATION                               PARTB    767
     4/10X,I8,30H CROSS SECTION CALCULATION                       PARTB    768
     A/10X,I8,30H COEFFICIENTS CALCULATION                        PARTB    769
     5/10X,I8,30H SOURCE ITERATION                                PARTB    770
     6/10X,I8,30H POWER CALCULATION                               PARTB    771
     7/10X,I8,30H EDIT SECTION 1                                  PARTB    772
     8/10X,I8,30H EXPOSURE CALCULATION                            PARTB    773
     9/10X,I8,30H EDIT SECTION 2                                  PARTB    774
      CALL TIMER (5HPARTB,3)                                      PARTB    775
      RETURN                                                      PARTB    776
      END
      SUBROUTINE POISPUT(POW,XBR,KSTEP,IU,JU,NITERS,IBPAS,
     * DEP,ICNTRL,IDEBUG,IOPTEX,IOSC,ISRCH,IUOID,LEVELC,LEVELU,
     * LPAXLS,LPBU,NCOEFS,NCROSS,NEDITS,NEDTS,NEXPOS,NFLOW,NPOWER,
     * NSOURC,NUOID,XPOLST,XT,IFIRST,KBPOS,NBPERM,IBP,DEPL,IROW,JCOL)
CC
      COMMON/BLOK1/IBLOK1(1),ID,JD,KD,IX1,JX1,KX1,IX2,JX2,KX2,ISET1,
      CHARACTER*8 ADATE,BDATE,IHTIME,JHTIME
      DIMENSION JOBNAM(2)
C
      DIMENSION POW(IU,JU),XBR(IU,JU)
      DIMENSION IROW(20),JCOL(20),NBPBAS(15,15),PDERIU(15,15,20),
     *          NUMBP(20),RHS(120),ACY(120,50),T(100),DET(2)
     *         ,PBASE(15,15),COST(50),PSOL(120),DSOL(120),RW(15000),
     *          IW(400),DUM(120),BPLIM(20),IBP(50000,20)
      LOGICAL IUOID,ICNTRL,IFIRST,LEVELU,LEVELC,DEPL(50000),KPFRST
C
C
C  AT FIRST STEP OF DEPLETION, FIND FRESH FUEL POSITIONS IN WHICH
C  BP REQUIREMENTS WILL BE SEARCHED FOR
C
      JBPSOL=IROUND(A1(47))
      PPLIM=A1(39)
      BPDEL=A2(50)
      PPMULT1=A2(51)
      PPMULT2=A2(52)
      PPLIM=PPLIM*PPMULT2
      JBPEDIT=IROUND(A1(48))
      IF(JBPEDIT.EQ.0) NSTEP=1
      K=1
      NODES=0
      DO 20 I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 20 J=JL,JR
      INBP=NBP(I,J)-(NBP(I,J)/10000)*10000
      IF(INBP.LE.0) GO TO 30
      IROW(K)=I
      JCOL(K)=J
      K=K+1
 30   CONTINUE
       NODES=NODES+1
 20   CONTINUE
       KBPOS=K-1
C
C  AT EACH OUTER STEP, KEEP BASE POWER DISTRIBUTION IN ORDER TO GET
C  FIRST ORDER DERIVATIUE, D(POW(I,J))/D(BPNUM)
C
      DO 10  I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 10  J=JL,JR
      PBASE(I,J)=POW(I,J)
      NBPBAS(I,J)=NBP(I,J)
 10   CONTINUE
      KLCON=0
      DO 180 KPP=1,KBPOS
 170  I=IROW(KPP)
      J=JCOL(KPP)
      TTNBP=NBPBAS(I,J)-(NBPBAS(I,J)/1000)*1000
      BPLIM(KPP)=TTNBP/10.
      LDIFF=ABS(NUMBP(KPP))-KLCON
      IF(LDIFF.GT.0) KLCON=ABS(NUMBP(KPP))
 180  CONTINUE
C
C  COMPUTE THE LEAST SQUARE DIFFERENCE, (XBR(I,J)-PBASE(I,J))**2
C
      TOTAL=0.
      TOTAL1=0.0
      IF(JBPSOL.EQ.0) THEN
      DO 120 KK=1,KBPOS
      I=IROW(KK)
      J=JCOL(KK)
      TOTAL=TOTAL+ABS(XBR(I,J)-PBASE(I,J))/XBR(I,J)
 120  CONTINUE
      NTOTL=KBPOS
      DO 65 I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 65 J=JL,JR
      TOTAL1=TOTAL1+ABS(XBR(I,J)-PBASE(I,J))/XBR(I,J)
 65   CONTINUE
      AVGDIFF=100*TOTAL1/NODES
      ELSE
      DO 85 I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 85 J=JL,JR
      TOTAL=TOTAL+ABS(XBR(I,J)-PBASE(I,J))/XBR(I,J)
 85   CONTINUE
      NTOTL=NODES
      ENDIF
C
C  TEST CONVERGENCE
C
      OBSQ=100*TOTAL/NTOTL
      WRITE(6,3000) OBSQ
 3000 FORMAT(//,3X,'*** AVERAGE ABSOLUTE PERCENT DIFFERENCE =',F10.5,
     *  '  PERCENT')
      IF(JBPSOL.EQ.0) THEN
      WRITE(6,3060) AVGDIFF
      ENDIF
 3060 FORMAT(//,3X,'=== CORE AVERAGE PERCENT DIFFERENCE =',F10.5,
     *  ' PERCENT')
      IBPAS=0
C
C
      IF(NITERS.EQ.1) GO TO 130
      IF( NITERS .GT. 7 .OR. OBSQ .LE. 0.2 .OR.
     *     (ABS(OBSQ-OLDSQ) .LE. 0.1 .AND. KLCON .LT. 5) ) THEN
      IBPAS=1
      GO TO 999
      ENDIF
 130  OLDSQ=OBSQ
C
C  GET SENSITIVITY COEFFICIENT HERE, INCREMENT OF BPNUM IS 1
C
      WRITE(6,4545)
 4545 FORMAT(//,120(1H*),//)
      WRITE(6,4550) NITERS
 4550 FORMAT(///,2X,101(1H=),/,2X,'(',I2,')=',' OUTER ITERATION STEP'
     * ,/,2X,101(1H=),/)
      IF(OBSQ.LE.3.0) THEN
      IF(NITERS.EQ.1) GO TO 600
      WRITE(6,3050)
 3050 FORMAT(//,3X,55(1H-),/,3X,' NO MORE EVALUATION OF POWER ',
     * 'COEFFICIENTS HEREAFTER ',/,3X,55(1H-),/)
      GO TO 900
      ENDIF
 600  CONTINUE
      MDELBP=2
      IF(JBPEDIT.EQ.0) THEN
      IEDIT(2)=1
      IEDIT(3)=1
      IEDIT(5)=1
      ENDIF
      WRITE(6,4560)
 4560 FORMAT(///,3X,'=== GET SENSITIVITY COEFFICIENTS ===',//)
      DO 50 K=1,KBPOS
      DO 40 I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 40 J=JL,JR
 40   NBP(I,J)=NBPBAS(I,J)
      IP=IROW(K)
      JP=JCOL(K)
      WRITE(6,4570) K,IP,JP
 4570 FORMAT(//,3X,'(KSTEP)=',I3,'  ** POWER SENSITIVITY ARRAY DUE TO',
     *  ' INSERTION OF 1 BP IN (',I2,',',I2,') POSITION **')
      NBP(IP,JP)=NBP(IP,JP)+10*MDELBP
      NU=0
      KPFRST=.TRUE.
      CALL  POWDIS(DEP,ICNTRL,IDEBUG,IOPTEX,IOSC,ISRCH,IVOID,
     * LEVELC,LEVELU,LPAXLS,LPBU,NCOEFS,NCROSS,NEDITS,NEDTS,NEXPOS,
     * NFLOW,NPOWER,NSOURC,NVOID,XPOLST,XT,IFIRST,KPFRST)
      CALL REWND(ITAPU,11)
      CALL READX(POW,LP11,ITAPU,1,IU,JU,KD,LPXTR(11))
      DO 60 II=1,IMAX
      JL=JMN(II)
      JR=JMX(II)
      DO 61 JJ=JL,JR
      PDERIU(II,JJ,K)=(POW(II,JJ)-PBASE(II,JJ))/MDELBP
 61   CONTINUE
      WRITE(6,1000) (PDERIU(II,JH,K),JH=1,JR)
 1000 FORMAT(3X,15F8.5)
 60   CONTINUE
 50   CONTINUE
 900  CONTINUE
C
C   SOLVE LINEAR EQUATION, AC(I,J)*BPNUM(J)=RHS(J)  WHERE
C       I=J=1,KBPOS,  RHS(J)=XBR-PBASE
C   HERE SUBROUTINE LEQIF IN IMSL LIBRARY IS USED
C
C     OR.
C  APPLY LINEAR PROGRAMMING TECHNIQUE HERE,
C            F = MAX(- SUM(D(J)))
C
C            SUBJECT TO
C
C                AC(I,J)*X(J) .LE. RHS(J)
C
C                  WHERE I=1,(3*NODES)
C                        J=1,KBPOS+NODES
C
C    (X(J),J=1,KBPOS+NODES)=(NUMBP(1)..NUMBP(KBPOS),D(1)..D(NODES))
C
C    SUBROUTINE  ZX3LP IN IMSL LIBRARY IS UTILIZED
C
C
C
      IF(JBPSOL.EQ.0) GO TO 700
      N=KBPOS+NODES
      NODE2=2*NODES
      NODE3=3*NODES
      M2=0
      WRITE(6,5000) (BPLIM(L),L=1,KBPOS)
 5000 FORMAT(//,4X,'BPLIM(K) =',10F8.3)
C
      DO 76 I=1,NODES
 76   DUM(I)=0.0
      KY=1
      DO 77 I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 78 J=JL,JR
      DO 79 K=1,KBPOS
 79   DUM(KY)=DUM(KY)+PDERIU(I,J,K)*BPLIM(K)
 78   KY=KY+1
 77   CONTINUE
      KX=1
      DO 70 I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 70 J=JL,JR
       DO 71 K=1,KBPOS
        ACY(KX,K)=PDERIU(I,J,K)/XBR(I,J)
         ACY(KX+NODES,K)=-PDERIU(I,J,K)/XBR(I,J)
 71       ACY(KX+NODE2,K)=PDERIU(I,J,K)
      ACY(KX,KX+KBPOS)=-1.0
       ACY(KX+NODES,KX+KBPOS)=-1.0
      RHS(KX)=(XBR(I,J)-PBASE(I,J)+DUM(KX))/XBR(I,J)
       RHS(KX+NODES)=(PBASE(I,J)-XBR(I,J)-DUM(KX))/XBR(I,J)
        RHS(KX+NODE2)=PPLIM-PBASE(I,J)+DUM(KX)
      COST(KX+KBPOS)=-1.0
       KX=KX+1
 70   CONTINUE
C
      DO 75 J=1,KBPOS
 75   COST(J)=0.0
C
       WRITE(6,4440)
 4440  FORMAT(///,3X,65(1H=),/,3X,'??? LINEAR PROGRAMMING SOLVER:'
     * ,' SUBROUTINE ZX3LP IS CALLED ???',/,3X,65(1H=),/)
       TIME1=SECOND()
      CALL ZX3LP(ACY,120,RHS,COST,N,NODE3,M2,S,PSOL,DSOL,RW,
     $   IW,IER)
      TIME2=SECOND()
       TOTT=TIME2-TIME1
      DO 500 I=1,KBPOS
 500  NUMBP(I)=(PSOL(I)-BPLIM(I))*10.
       SOBQ=S/NODES*100
       GO TO 800
```

```
  700   CONTINUE
C
        KK=1
   80   CONTINUE
        II=IROW(KK)
        JJ=JCOL(KK)
        RHS(KK)=XBR(II,JJ)-PBASE(II,JJ)
        DO 90 K=1,KBPOS
        ACY(KK,K)=PDERIU(II,JJ,K)
   90   CONTINUE
         IF(KK.EQ.KBPOS) GO TO 95
         KK=KK+1
         GO TO 80
   95    CONTINUE
         WRITE(6,4449)
 4449    FORMAT(///,3X,65(1H=),/,3X,'??? LINEAR EQUATION SOLVER:'
     * ,' SUBROUTINE LEQIF IS CALLED ???',/,3X,65(1H=),/)
         TIME1=SECOND()
         CALL LEQIF(ACY,120,KBPOS,1,RHS,120,1,0,T,IER)
         TIME2=SECOND()
         TOTT=TIME2-TIME1
         DO 100 KI=1,KBPOS
  100    NUMBP(KI)=RHS(KI)*10
  800    CONTINUE
         WRITE(6,4011) TOTT
 4011    FORMAT(/,3X,'(CPU TIME CONSUMED IN EITHER LP OR LINEAR ',
     *     'EQUATION SOLVER) =',F10.6,' SECONDS',/)
          IF(JBPSOL.NE.0) THEN
          WRITE(6,4000) SOBQ
 4000    FORMAT(//,3X,'OBJECTIVE FUNCTION =',F10.5,'  PERCENT',/)
         ENDIF
         WRITE(6,2000) (NUMBP(KM),KM=1,KBPOS)
 2000    FORMAT(/4X,' ( INCREMENT OF BP DISTIBUTION )*10',/,4X,15I5)
C
C   ASSIGN SEARCHED BP DISTRIBUTION AT THIS PLACE
C
         DO 160 KL=1,KBPOS
  150    I=IROW(KL)
         J=JCOL(KL)
         LNBP=NBPBAS(I,J)-(NBPBAS(I,J)/1000)*1000
         MTBP=LNBP+NUMBP(KL)
         IF(MTBP.LE.0) NUMBP(KL)=-LNBP
         NBP(I,J)=NBPBAS(I,J)+NUMBP(KL)
  160    CONTINUE
         WRITE(6,4120)
 4120    FORMAT(///,3X,'*** CONSTRUCTED POWER USING LINEAR',
     *   ' APPROXIMATION IN SEARCHED BP DISTRIBUTION ***',//)
         DO 400 I=1,IMAX
          JL=JMN(I)
          JR=JMX(I)
         DO 410 J=JL,JR
         PPBAS=PBASE(I,J)
         DO 420 K=1,KBPOS
  420    PPBAS=PPBAS+PDERIU(I,J,K)*NUMBP(K)/10
         POW(I,J)=PPBAS
  410    CONTINUE
         WRITE(6,3020) (POW(I,JK),JK=1,JR)
 3020    FORMAT(3X,8F8.3)
  400    CONTINUE
          WRITE(6,3030)
 3030    FORMAT(///,3X,65(1H-),/,3X,' NORMAL POWER CALCULATION USING',
     *   ' REESTIMATED BP DISTRIBUTION',/,3X,65(1H-),/)
         KSTEP=KSTEP+1
         NITERS=NITERS+1
  999    CONTINUE
         IF(JBPEDIT.EQ.0) THEN
         IEDIT(2)=5
         IEDIT(3)=5
         IEDIT(5)=5
         ENDIF
         IF (IBFAS .EQ. 1) THEN
         CALL INT3P(IROW,JCOL,NBPBAS,PBASE,PDERIU,IMAX,JMN,JMX,KBPOS,
     *                 XBR,IU,JU,NBPERM,IBP,DEPL,PPLIM,BPDEL,PPMULT1)
         IEDIT(2)=1
         IEDIT(3)=1
         IEDIT(5)=1
         ENDIF
         RETURN
         END
```

```
      SUBROUTINE INTBP(IROW,JCOL,NBPBAS,PBASE,PDERIV,IMAX,JMN,JMX,
     *            KBPOS,XBR,IU,JU,NBPERM,IBP,DEPL,PPLIM,BPDEL,PPMULT1)
      LOGICAL DEPL(50000)
      DIMENSION IBPERM(50000),NDISBP(20),NLOBP(20),NHIBP(20),
     *            RNBP(20),NXBP(20),IROW(20),JCOL(20),NBPBAS(15,15),
     *            JMN(34),JMX(34),PBASE(15,15),PDERIV(15,15,20),
     *            IBPX0(20),LOCX(5),IPOINT(50000,20),
     *            PPOW(15,15),XBR(IU,JU),IBPEX(50000),IBP(50000,20)
C
      PARAMETER(INTMAX=6)
      DATA (NDISBP(I),I=1,7) /0,4,8,12,16,20,24/
C
C  DETERMINE THE HIGH AND LOW INTEGRAL NUMBER OF BP'S
C  CORRESPONDING TO THE POISPUT RESULTS
C
      DO 100 K=1,KBPOS
      I=IROW(K)
      J=JCOL(K)
      RNBP(K)=FLOAT( NBPBAS(I,J) - (NBPBAS(I,J)/1000)*1000 )/10.0
      IF(RNBP(K) .GT. NDISBP(INTMAX)) THEN
      WRITE(6,150) I,J
150   FORMAT(/,3X,'BP LIMIT EXCEEDED AT POSITION (',I2,',',I2,')')
      NHIBP(K)=NDISBP(INTMAX)
      NLOBP(K)=NDISBP(INTMAX-1)
      ENDIF
      DO 200 L=2,INTMAX
      IF(RNBP(K) .LE. NDISBP(L) .AND. RNBP(K) .GE. NDISBP(L-1)) THEN
      NHIBP(K)=NDISBP(L)
      NLOBP(K)=NDISBP(L-1)
      ENDIF
200   CONTINUE
      NMAX=NDISBP(INTMAX)
      IF((NHIBP(K)-RNBP(K)).LE. BPDEL .AND. NHIBP(K) .NE. NMAX) THEN
      NXBP(K)=NHIBP(K)+4
      ELSEIF((RNBP(K)-NLOBP(K)).LE. BPDEL .AND. NLOBP(K) .NE. 0)THEN
      NXBP(K)=NLOBP(K)-4
      ELSE
      NXBP(K)=-1
      ENDIF
100   CONTINUE
C
C  PRODUCE ALL POSSIBLE COMBINATIONS OF INTEGRAL BP LOADINGS
C
      NBPERM=2**KBPOS
      CALL COMBO(KBPOS,NBPERM,IBPERM)
      DO 205 K=1,KBPOS
      IPOINT(1,K)=K
205   CONTINUE
C  INCLUDE COMBINATIONS WITH 'EXTRA' BP POSSIBILITIES
      NUMX=0
      DO 210 K=1,KBPOS
      IF(NXBP(K) .GE. 0) THEN
      NUMX=NUMX+1
      LOCX(NUMX)=K
      ENDIF
210   CONTINUE
      NBPX=2**NUMX
      CALL COMBO(NUMX,NBPX,IBPX0)
      NUPERM=0
      DO 220 I=2,NBPX
      DO 225 II=1,KBPOS
      IPOINT(I,II)=II
225   CONTINUE
      NUM=IBPX0(I)
      NSUM=0
      DO 230 J=1,NUMX
      JJ=NUMX-J
      JJJ=NUM/10**JJ
      NUM=NUM-JJJ*10**JJ
      IF(JJJ .EQ. 1) THEN
      NSUM=NSUM+1
      IPTEM=IPOINT(I,NSUM)
      JPOS=LOCX(J)
      IPOINT(I,NSUM)=IPOINT(I,JPOS)
      IPOINT(I,JPOS)=IPTEM
      ENDIF
230   CONTINUE
      NUMEX=KBPOS-NSUM
      NBPEX=2**NUMEX
      CALL COMBO(NUMEX,NBPEX,IBPEX)
      DO 250 M=1,NBPEX
      NUPERM=NUPERM+1
      IBPERM(NBPERM+NUPERM)=INT((2.0/9.0)*10**NSUM)*10**(KBPOS-NSUM)
     1+IBPEX(M)
      DO 255 K=1,KBPOS
      IPOINT(NBPERM+NUPERM,K)=IPOINT(I,K)
  255 CONTINUE
  250 CONTINUE
  220 CONTINUE
      DO 245 M=1,NBPERM
      DO 245 K=1,KBPOS
      IPOINT(M,K)=IPOINT(1,K)
  245 CONTINUE
      NBPERM=NBPERM+NUPERM
  270 CONTINUE
C
      DO 300 M=1,NBPERM
      DEPL(M)=.TRUE.
C
C  DETERMINE THE ACTUAL BP LOADING FROM THE BP IDENTIFIER 'IBPERM'
C
      NOLDBP=IBPERM(M)
      DO 350 KK=KBPOS-1,0,-1
      K=IPOINT(M,KBPOS-KK)
      IBPID=NOLDBP/10**KK
      NOLDBP=NOLDBP-IBPID*10**KK
      IF(IBPID .EQ. 0) THEN
      IBP(M,K)=NLOBP(K)
      ELSEIF(IBPID .EQ. 1) THEN
      IBP(M,K)=NHIBP(K)
      ELSEIF(IBPID .EQ. 2) THEN
      IBP(M,K)=NXBP(K)
      ENDIF
  350 CONTINUE
C
C  CONSTRUCT POWER DISTRIBUTION USING LINEAR APPROXIMATION
C  COMPUTE THE DIFFERENCE, (XBR(I,J)-PBASE(I,J))
C
      TOTAL=0.
      DO 400 I=1,IMAX
      JL=JMN(I)
      JR=JMX(I)
      DO 410 J=JL,JR
      PPBAS=PBASE(I,J)
      DO 420 K=1,KBPOS
      PPBAS=PPBAS+PDERIV(I,J,K)*(IBP(M,K)-RNBP(K))
  420 CONTINUE
      PPOW(I,J)=PPBAS
      IF(PPBAS .GT. (PPLIM*PPMULT1)) DEPL(M)=.FALSE.
  410 CONTINUE
  400 CONTINUE
  300 CONTINUE
      RETURN
      END
      SUBROUTINE OPRES(NBP,NBPERM,NBP1,NBP2,TEMP,ITEMP,EXP,JMX)
      DIMENSION NBP(15,15),EN(8),NOBP(8),EXP(8,8),JMX(34)
      CALL FACE
      WRITE(6,50)
 50   FORMAT(1H1,15H OPUS RESULTS  ,/,15(1H*))
      WRITE(6,100) NBPERM, NBP1, NBP2
 100  FORMAT(///,5X,45H TOTAL NUMBER OF INTEGRAL BP COMBINATIONS      ,
     *I5,/,5X,45H NUMBER OF DEPLETABLE BP COMBINATIONS        ,I5,
     */,5X,45H NUMBER OF ACCEPTABLE BP COMBINATIONS       ,I5,///)
      WRITE(6,150) ITEMP,TEMP
 150  FORMAT(///,1X,5HCASE ,I5,23H GIVES LONGEST CYCLE AT,F7.3,
     *7H GWD/MT,//,1X,15H FUEL LOADING: ,/,1X,15(1H-))
      WRITE(6,200)
 200  FORMAT(/,25X,16(1H*),/,25X,16H* ENRICHMENT   *,/,25X,
     *16H* BP LOADING    *,/,25X,16H* BOC EXPOSURE *,/,25X,16(1H*))
      DO 300 I=1,8
      DO 350 J=1,JMX(I)
      NOBP(J)=MOD(NBP(I,J),1000)/10
      EN(J)=(MOD(NBP(I,J),10000000)/10000)/100.0
 350  CONTINUE
      GO TO (355,360,365,370,375,380,385,390) I
 355  WRITE(6,356)
 356  FORMAT(1X,10(1H*))
      GO TO 395
 360  WRITE(6,361)
 361  FORMAT(1X,19(1H*))
      GO TO 395
 365  WRITE(6,366)
 366  FORMAT(1X,28(1H*))
      GO TO 395
 370  WRITE(6,371)
 371  FORMAT(1X,37(1H*))
      GO TO 395
 375  WRITE(6,376)
 376  FORMAT(1X,46(1H*))
      GO TO 395
 380  WRITE(6,381)
 381  FORMAT(1X,55(1H*))
      GO TO 395
 385  WRITE(6,386)
 386  FORMAT(1X,55(1H*))
      GO TO 395
 390  WRITE(6,391)
 391  FORMAT(1X,55(1H*))
 395  CONTINUE
      WRITE(6,400) (EN(J),J=1,JMX(I))
 400  FORMAT(1X,1H*,8(F7.2,2H *))
      GO TO (405,410,415,420,425,430,435,440) I
 405  WRITE(6,406)
 406  FORMAT(1X,1H*,8X,1H*)
      GO TO 445
 410  WRITE(6,411)
 411  FORMAT(1X,1H*,2(8X,1H*))
      GO TO 445
 415  WRITE(6,416)
 416  FORMAT(1X,1H*,3(8X,1H*))
      GO TO 445
 420  WRITE(6,421)
 421  FORMAT(1X,1H*,4(8X,1H*))
      GO TO 445
 425  WRITE(6,426)
 426  FORMAT(1X,1H*,5(8X,1H*))
      GO TO 445
 430  WRITE(6,431)
 431  FORMAT(1X,1H*,6(8X,1H*))
      GO TO 445
 435  WRITE(6,436)
 436  FORMAT(1X,1H*,6(8X,1H*))
      GO TO 445
 440  WRITE(6,441)
 441  FORMAT(1X,1H*,4(8X,1H*))
 445  CONTINUE
      DO 450 J=1,JMX(I)
      IF(NOBP(J) .LE. 0) GO TO 450
      GO TO (500,550,600,650,700,750) J
 500  WRITE(6,525) NOBP(J)
 525  FORMAT(1H+,1X,I7)
      GO TO 450
 550  WRITE(6,575) NOBP(J)
 575  FORMAT(1H+,10X,I7)
```

```
      GO TO 450
600   WRITE(6,625) NOBP(J)
625   FORMAT(1H+,19X,I7)
      GO TO 450
650   WRITE(6,675) NOBP(J)
675   FORMAT(1H+,28X,I7)
      GO TO 450
700   WRITE(6,725) NOBP(J)
725   FORMAT(1H+,37X,I7)
      GO TO 450
750   WRITE(6,775) NOBP(J)
775   FORMAT(1H+,46X,I7)
450   CONTINUE
      WRITE(6,800) (EXP(I,J),J=1,JMX(I))
800   FORMAT(1X,1H*,8(F7.3,2H *))
300   CONTINUE
      WRITE(6,850)
850   FORMAT(1X,37(1H*))
      RETURN
      END
      SUBROUTINE COMBO(X,Y,A)                                           COMBO   2
      INTEGER X,Y,A(Y)                                                  COMBO   3
      DO 50 M=1,Y                                                       COMBO   4
      NUMBER=M-1                                                        COMBO   5
      IX=0                                                              COMBO   6
      DO 60 KK=1,X                                                      COMBO   7
      K=X-KK                                                            COMBO   8
      IDELX=NUMBER/2**K                                                 COMBO   9
      IX=IX+IDELX*10**K                                                 COMBO  10
      NUMBER=NUMBER-IDELX*2**K                                          COMBO  11
   60 CONTINUE                                                          COMBO  12
      A(M)=IX                                                           COMBO  13
   50 CONTINUE                                                          COMBO  14
      RETURN                                                            COMBO  15
      END                                                               COMBO  16
```

APPENDIX B: ADDITIONAL INPUT REQUIREMENTS

A. Card Type 1

A1(39) PPLIM Nodal power peaking limit

A1(46) MOPTIM Control of optimization flow:
=1 - direct search only
=2 - BP search only
=3 - combined (currently unavailable)

A1(47) JBPSOL BP search method.
=0 fresh fuel search only
=1 linear programming

A1(48) JBPEDIT Output edit control
=0 normal operation
=1 for debugging purposes

B. Card Type 2

A2(50) BPDEL Burnable poison tolerance
(0.5 is recommended)

A2(51) PPMULT1 Reconstructed power peaking tolerance
(1.02 is recommended)

A2(52) PPMULT2 SIMULATE power peaking tolerance
(1.00 is recommended)

C. Card Type 17

XBR(i,j) Target power distribution

D. Card Type 32

NBP(i,j) Burnable poison identifier array,
of the form ABBBCDDD.
where,
A = fuel type (1 - 15x15 std,
2 - 15x15 ofa)
BBB= enrichment (e.g. 2.7 w/o - 270)
C = BP type (1 - glass, 2 - WABA)
DDD= number of BP's (e.g. 12 BP - 120)

In the highly unlikely situation that none of the candidate BP loadings successfully depletes to end-of-cycle, several courses of action are available. Corrective actions should be pursued in the following order:

1. increasing the BP tolerance, BPDEL, to create more candidate BP loadings to be evaluated

2. increasing the reconstructed power peaking tolerance, PPMULT1, to allow more cases to be passed on to the normal power calculation / depletion

3. increasing the SIMULATE power peaking tolerance, PPMULT2, to allow a higher power peaking to be acceptable for a final design pattern

It is much more likely that the opposite situation would occur, that too many cases reach the depletion stage such that the computation costs become excessive. In this case, the above actions should be reversed (i.e. instead of increasing tolerances, decrease them). However, the same order still applies to these alternatives.

APPENDIX C: SAMPLE INPUT LISTING

```
15411,BBL,CY,L10000.
RESOURCE(JCAT=S2)
ATTACH,SIMTRN.
SIMTRN.
  8  8  1  6  1  1                                      47 23  6
  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
I      *** ZION-1 CYCLE 9 SIMULATION (2-D MODEL, FALRE OPTION)
            0     ****************************************************
            0     *  ZION-1 CYCLE-9 2-D SIMULATION, MODERATOR FEEDBACK*
            0     *  INCLUDED,  FLARE OPTION USED WITH 1NODE/1 ASSEM  *
            0     *  BUILT-IN BPMODEL USED, SO EVERY XS IS FOR 0 BP   *
            0     *  FUEL TYPE      MAR.17,1986                       *
            0     *  FUEL SHUFFLING USING DIRECT SEARCH METHOD        *
            0     ****************************************************
            1      0.0   11.5 11.5 12.01  16.875 178.6 2250. 0
            1      S1  0.0  S3 82.17 S2
            1       .981  .981 1.0  21.608  10.804
            1      S1 -1  -1  0  0  3  12.01  16.875  99.56  0
            1      0  1  1  13.563  0  2250.  .73634  1.33  3  4
            1      2  10  11  1  1  1  0  5  1.27
            2     0  3  1  0  20  0  2  .0005  4  .00005  12
            2      .00005  4  .0001  1  0  0  0  0  1.0
            2      1.0  0.6  0  1.0  4 1.2 .6 S2  .35 1.0  0
            2       5  7  18  1  0 0 0 0 4  6 15 0 0  0  0  0 20.0
            3   1 S6 0.455 S2  1 30.48 S13 S9 6.241E+18  2.679 S2 4 0.0   .06404
            3   1 S2 .288E-4    .00633 S2 .211E-4   .01255 S2 .385E-5 0.0 S2 0.0
            3   2 S6 0.455 S2  2 30.48 S13 S9 6.241E+18  2.672 S2 4 0.0   .06405
            3   2 S2 .288E-4    .00626 S2 .211E-4   .01255 S2 .385E-5 0.0 S2 0.0
            3   3 S6 0.455 S2  3 30.48 S13 S9 6.241E+18  2.721 S2 4 0.0   .06420
            3   3 S2 .288E-4    .00670 S2 .211E-4   .01277 S2 .385E-5 0.0 S2 0.0
            3   4 S6 .455 S2  4 30.48 S13 S9 6.241E+18
            3   4  2.4428E+00  1.4184E-02 -1.3229E-04 4 0.0
            3   4  6.3547E-02  1.2444E-05  2.4107E-07 .288E-4
            3   4  2.7119E-03  2.2301E-04 -2.6877E-06 .211E-4
            3   4  1.1340E-02  6.2331E-05 -4.5984E-07 .385E-5 0.0 S2 0.0
            3   5 S6 .455 S2  5 30.48 S13 S9 6.241E+18
            3   5  2.4421E+00  1.3728E-02 -1.2446E-04 4 0.0
            3   5  6.3550E-02  1.1127E-05  2.5762E-07 .288E-4
            3   5  2.6939E-03  2.1710E-04 -2.5757E-06 .211E-4
            3   5  1.1336E-02  6.0015E-05 -4.2172E-07 .385E-5 0.0 S2 0.0
            3   6 S6 .455 S2  6 30.48 S13 S9 6.241E+18
            3   6  2.4396E+00  1.2124E-02 -9.8852E-05 4 0.0
            3   6  6.3561E-02  6.8125E-06  3.0254E-07 .288E-4
            3   6  2.6363E-03  1.9567E-04 -2.1907E-06 .211E-4
            3   6  1.1321E-02  5.1940E-05 -2.9976E-07 .385E-5 0.0 S2 0.0
            4   1     1  4  3  5  3  3  4  1
            4   2     4  5  6  4  6  3  6  6
            4   3     3  6  4  5  2  6  6  6
            4   4     5  4  5  2  5  2  6  3
            4   5     3  6  2  5  2  4  6
            4   6     3  3  6  2  4  5  6
            4   7     4  6  6  6  6  6
            4   8     1  6  6  3
           5 1 1      1 1 0 0 1 20 3
           5 1 1             0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
           5 1 1 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
           5 1 1 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
           5 1 1 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
           5 1 1 2.3604E-01 2.3593E-01 2.3584E-01 2.3561E-01 2.3534E-01
           5 1 1 2.3499E-01 2.3467E-01 2.3443E-01 2.3396E-01 2.3346E-01
           5 1 1 2.3297E-01 2.3253E-01 2.3217E-01 2.3222E-01 2.3322E-01
           5 1 1 2.3408E-01 2.3489E-01 2.3563E-01 2.3640E-01 2.3704E-01
           5 2 1      2 1 0 0 1 20 3
           5 2 1             0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
           5 2 1 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
           5 2 1 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
           5 2 1 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
           5 2 1 8.9364E-03 8.9471E-03 8.9775E-03 9.0403E-03 9.1868E-03
           5 2 1 9.3689E-03 9.5361E-03 9.6798E-03 9.8195E-03 9.9477E-03
           5 2 1 1.0064E-02 1.0172E-02 1.0272E-02 1.0454E-02 1.0619E-02
           5 2 1 1.0769E-02 1.0909E-02 1.1041E-02 1.1189E-02 1.1326E-02
           5 3 1      3 1 0 0 1 20 3
           5 3 1             0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
           5 3 1 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
           5 3 1 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
           5 3 1 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
           5 3 1 1.7108E-02 1.7157E-02 1.7138E-02 1.7117E-02 1.7035E-02
           5 3 1 1.6924E-02 1.6822E-02 1.6724E-02 1.6682E-02 1.6661E-02
           5 3 1 1.6650E-02 1.6645E-02 1.6642E-02 1.6655E-02 1.6677E-02
           5 3 1 1.6710E-02 1.6745E-02 1.6781E-02 1.6819E-02 1.6849E-02
```

```
             5 8 6 1.3776E-01 1.3571E-01 1.3351E-01 1.2874E-01 1.2370E-01
             5 8 6 1.1861E-01 1.1361E-01 1.0885E-01 1.0375E-01 9.3153E-02
             5 9 6     9 1 0 0 1 20 3
             5 9 6          0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
             5 9 6 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
             5 9 6 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
             5 9 6 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
             5 9 6 1.1007E+01 1.0985E+01 1.1075E+01 1.1148E+01 1.1222E+01
             5 9 6 1.1214E+01 1.1151E+01 1.1048E+01 1.0906E+01 1.0742E+01
             5 9 6 1.0562E+01 1.0371E+01 1.0172E+01 9.7534E+00 9.3264E+00
             5 9 6 8.9043E+00 8.4972E+00 8.1147E+00 7.7077E+00 7.3458E+00
3.20  0 BP 510 6  7.22  1 0 0 1  20   3  (XE2       )
           510 6           0  1.0000E-01  1.0000E+00  2.0000E+00  4.0000E+00
           510 6  6.0000E+00  8.0000E+00  1.0000E+01  1.2000E+01  1.4000E+01
           510 6  1.6000E+01  1.8000E+01  2.0000E+01  2.4000E+01  2.8000E+01
           510 6  3.2000E+01  3.6000E+01  4.0000E+01  4.4000E+01  4.8000E+01
           510 6  1.4554E+06  1.4460E+06  1.4562E+06  1.4599E+06  1.4680E+06
           510 6  1.4785E+06  1.4911E+06  1.5011E+06  1.4825E+06  1.4928E+06
           510 6  1.4999E+06  1.5132E+06  1.5256E+06  1.5167E+06  1.5367E+06
           510 6  1.5552E+06  1.5662E+06  1.5758E+06  1.5852E+06  1.5929E+06
3.20  0 BP 511 6  7.24  1 0 0 1  20   3  (SM2       )
           511 6           0  1.0000E-01  1.0000E+00  2.0000E+00  4.0000E+00
           511 6  6.0000E+00  8.0000E+00  1.0000E+01  1.2000E+01  1.4000E+01
           511 6  1.6000E+01  1.8000E+01  2.0000E+01  2.4000E+01  2.8000E+01
           511 6  3.2000E+01  3.6000E+01  4.0000E+01  4.4000E+01  4.8000E+01
           511 6  4.2382E+04  4.2674E+04  4.2901E+04  4.2981E+04  4.3166E+04
           511 6  4.3413E+04  4.3719E+04  4.3958E+04  4.3471E+04  4.3721E+04
           511 6  4.3889E+04  4.4219E+04  4.4530E+04  4.4291E+04  4.4787E+04
           511 6  4.5254E+04  4.5527E+04  4.5770E+04  4.6008E+04  4.6204E+04
3.20       512 6 7 8 1 0 0 1 2  (BORON2)
           512 6 0 0 0   1.4544E-05  1.5523E-08 -1.5057E-10
3.20       513 6 2 3 1 0 0 2 3  (DOP1)
           513 6 0 0 0 0 0 0 0 0
           513 6 -4.1533E-05  1.3450E-06 -8.1371E-08  1.3755E-09
3.20       514 6 2 3 1 0 0 1 3 (DOP2)
           514 6 0 0 0 0   3.1933E-04 -9.7971E-06  6.3531E-07 -1.1467E-08
3.20       515 6 2 1 0 0 0 3 0 (DOP3)
           515 6 -2.7780E-04  8.4521E-06 -5.5394E-07  1.0092E-08
 3.20      516 6 2 4 0 0 0 1 0   -1.5051E-04  2.0440E-04  (DEL AB1)
 3.20      517 6 7 4 0 0 0 1 0   -5.4028E-03  7.3374E-03  (DEL AB2)
 3.20      518 6 1 4 0 0 0 1 0   -1.1836E-01  1.6074E-01  (DEL TR1)
 3.20      519 6 6 4 0 0 0 1 0   -7.0851E-01  9.6220E-01  (DEL TR2)
 3.20      520 6 3 4 0 0 0 1 0   -2.0335E-02  2.7620E-02  (DEL REMU)
 3.20      521 6 2 8 0 0 0 1 0.0  0.0   2.8985E-07 (BORON1)
 3.20      522 6 2.22 0 0 0 0 0 0.0    1.0340E+02           ( XE1 )
 3.20      523 6 2.24 0 0 0 0 0 0.0    7.9930E+01           ( SM1 )
           7   1   0.0  R6   -.20
           7   2   0.0  R6   -.15
           7   3   0.0  R6   -.15
           7   4   0.0  R6   -.15
           7   5   0.0  R5   -.15
           7   6   0.0  R5   -.15
           7   7   0.0  R3   -.15   -.15
           7   8   -.20    -.15    -.15     -.15
          10 1    1A7 1B8 1C7 1D9 1E7 1F7 1G8 1H7
          10 2    1B8 2B9 2C8 2D8 2E8 2F7 2G9 2H8
          10 3    1C7 2C8 3C8 3D9 3E7 3F9 3G8 3H9
          10 4    1D9 2D8 3D9 4D7 4E9 4F7 4G9 4H7
          10 5    1E7 2E8 3E7 4E9 5E7 5F8 5G9
          10 6    1F7 2F7 3F9 4F7 5F8 6F9 6G6
          10 7    1G8 2G9 3G8 4G9 5G9 6G6
          10 8    1H7 2H8 3H9 4H7
          10 1 1        20.620
          10 1 2        12.960
          10 1 3        25.880
          10 1 4             0
          10 1 5        25.890
          10 1 6        24.940
          10 1 7         9.870
          10 1 8        20.620
          10 2 1        12.960
          10 2 2             0
          10 2 3        11.410
          10 2 4        12.240
          10 2 5         7.910
          10 2 6        24.040
          10 2 7             0
          10 2 8         9.410
          10 3 1        25.880
          10 3 2        11.410
```

```
10 3 3        13.100
10 3 4             0
10 3 5        23.770
10 3 6             0
10 3 7         8.270
10 3 8             0
10 4 1             0
10 4 2        12.240
10 4 3             0
10 4 4        23.200
10 4 5             0
10 4 6        22.750
10 4 7             0
10 4 8        22.630
10 5 1        25.890
10 5 2         7.910
10 5 3        23.770
10 5 4             0
10 5 5        21.220
10 5 6        12.770
10 5 7             0
10 6 1        24.940
10 6 2        24.040
10 6 3             0
10 6 4        22.750
10 6 5        12.770
10 6 6             0
10 6 7        31.420
10 7 1         9.810
10 7 2             0
10 7 3         8.270
10 7 4             0
10 7 5             0
10 7 6        31.420
10 8 1        20.620
10 8 2         9.410
10 8 3             0
10 8 4        22.630
12         -.0001  S3   .008
13         0.59582  -0.49396  -0.20215
14     1    1.0  0.0
15     1    1  1  1  1  1  1  1  1
15     2    1  1  1  1  1  1  1  1
15     3    1  1  1  1  1  1  1  1
15     4    1  1  1  1  1  1  1  1
15     5    1  1  1  1  1  1  1
15     6    1  1  1  1  1  1  1
15     7    1  1  1  1  1  1
15     8    1  1  1  1
19         1 R39 1 R40
20         0 1 S6 0 0 S1 0 S3 1 S7 0
21         1  1  3  0  6  0  0 S3 0 S2  0   1  1  S6  0
32     1   20000000  20000000  20000000  22802080  20000000
32     1   20000000  20000000  20000000
32     2   20000000  22802200  20000000  20000000  20000000
32     2   20000000  23202080  20000000
32     3   20000000  20000000  20000000  22802120  20000000
32     3   23202160  20000000  20000000
32     4   22802080  20000000  22802120  20000000  22802040
32     4   20000000  23202080  20000000
32     5   20000000  20000000  20000000  22802040  20000000
32     5   20000000  20000000
32     6   20000000  20000000  23202160  20000000  20000000
32     6   20000000  20000000
32     7   20000000  23202080  20000000  23202080  20000000
32     7   20000000
32     8   20000000  20000000  20000000  20000000
42     1    1  0  1  0  1  0  1  0
42     2    0  0  0  0  0  1  0  0
42     3    1  0  1  0  1  0  1  0
42     4    0  0  0  0  0  1  0  0
42     5    1  0  1  0  1  0  1
42     6    0  1  0  1  0  0  0
42     7    1  0  1  0  1  0
42     8    0  0  0  0
43     1    4  2  2  2  2  2  2  2
43     2    2  1  3  3  3  3  3  3
43     3    2  3  1  3  3  3  3  3
43     4    2  3  3  1  3  3  3  3
43     5    2  3  3  3  1  3  3
```

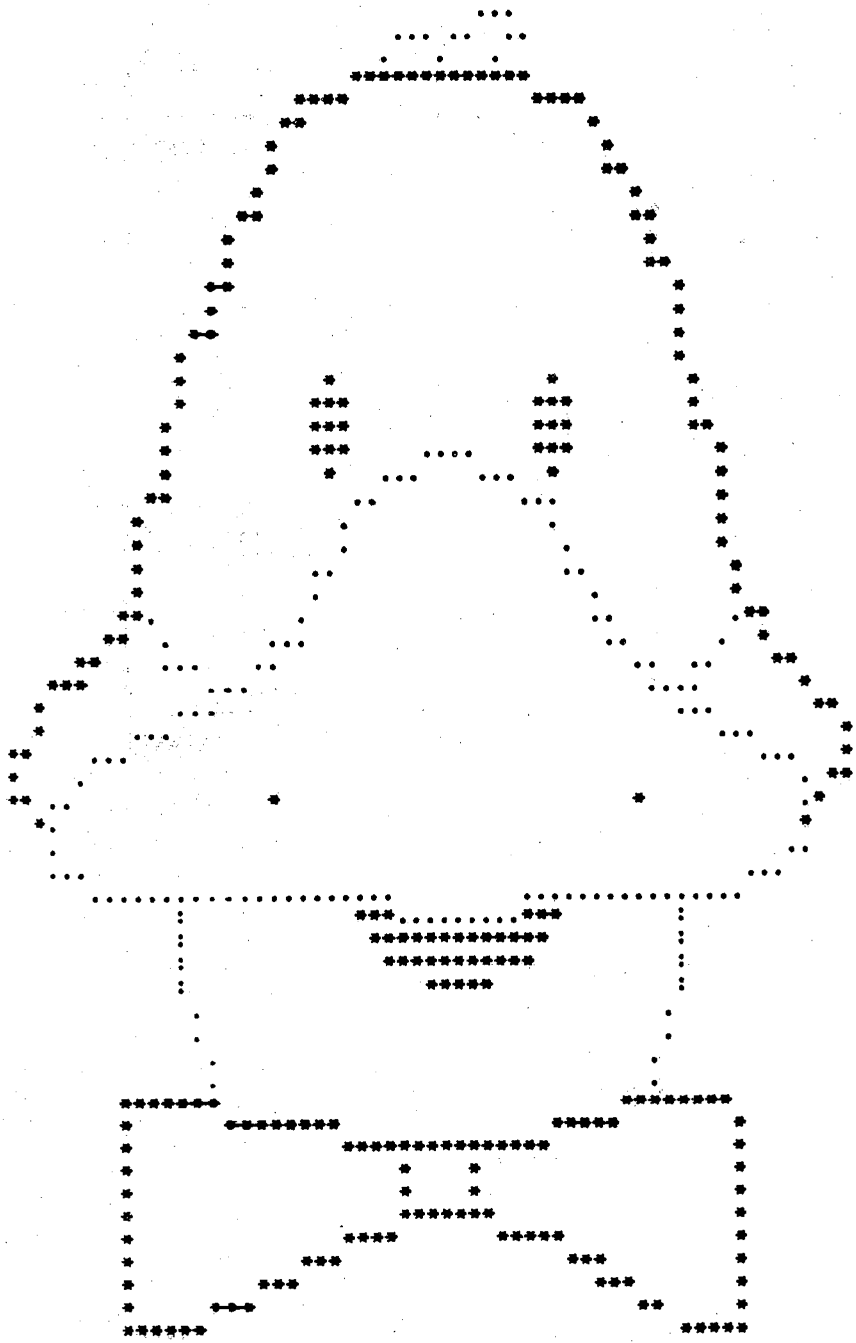
```
          43  6  2  3  3  3  3  1  3
          43  7  2  3  3  3  3  3
          43  8  2  3  3  3
          99
ILAST
```

```
15411,BBL,CY,L10000.
RESOURCE(JCAT=S3)
ATTACH,ZZSYM.
ATTACH,SIMTRN.
SIMTRN.
  8  8  1  6  1  1                                          47 23  6
   2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
I       *** ZION-1 CYCLE 9 SIMULATION (2-D MODEL, FLARE OPTION)
          0      ****************************************************
          0      *  ZION-1 CYCLE-9 2-D SIMULATION, MODERATOR FEEDBACK*
          0      *  INCLUDED,  FLARE OPTION USED WITH 1NODE/1 ASSEM  *
          0      *  BUILT-IN BPMODEL USED, SO EVERY XS IS FOR 0 BP   *
          0      *  FUEL TYPE       DEC.14,1986                      *
          0      *  BP SEARCH - PATTERN 2B                            *
          0      ****************************************************
          1        0.0   18.0 2.0 12.01  16.875 178.6 2250. 0
          1        S1  1000.  S3 82.17 S2
          1         .981  .981 1.0  21.608  10.804
          1        S1 -1  -1  0  0  3  12.01  16.875  99.56  0
          1        0  1  1  13.563  0  2250.  .73634  1.33  3  4
          1        2  5  6  0  2  1  0  5  1.33
          2       0  3  1  0  20  0  2  .0005  4  .00005  12
          2        .00005  4  .0001  1  0  0  0  0  1.0
          2        1.0  0.6  0  1.0  4 1.2 .6 S2  .35 1.0  0
          2         5 7 18 1 0 0 0 0 4 6 15 0 0 0 0 0 20.0
          2         0.50 1.020 1.000
          3    1 S6 0.455 S2  1 30.48 S13 S9 6.241E+18  2.679 S2 4 0.0   .06404
          3    1 S2 .288E-4    .00633 S2 .211E-4   .01255 S2 .385E-5 0.0 S2 0.0
          3    2 S6 0.455 S2  2 30.48 S13 S9 6.241E+18  2.672 S2 4 0.0   .06405
          3    2 S2 .288E-4    .00626 S2 .211E-4   .01255 S2 .385E-5 0.0 S2 0.0
          3    3 S6 0.455 S2  3 30.48 S13 S9 6.241E+18  2.721 S2 4 0.0   .06420
          3    3 S2 .288E-4    .00670 S2 .211E-4   .01277 S2 .385E-5 0.0 S2 0.0
          3    4 S6 .455 S2  4 30.48 S13 S9 6.241E+18
          3    4  2.4428E+00  1.4184E-02 -1.3229E-04 4 0.0
          3    4  6.3547E-02  1.2444E-05  2.4107E-07 .288E-4
          3    4  2.7119E-03  2.2301E-04 -2.6877E-06 .211E-4
          3    4  1.1340E-02  6.2331E-05 -4.5984E-07 .385E-5 0.0 S2 0.0
          3    5 S6 .455 S2  5 30.48 S13 S9 6.241E+18
          3    5  2.4421E+00  1.3728E-02 -1.2446E-04 4 0.0
          3    5  6.3550E-02  1.1127E-05  2.5762E-07 .288E-4
          3    5  2.6939E-03  2.1710E-04 -2.5757E-06 .211E-4
          3    5  1.1336E-02  6.0015E-05 -4.2172E-07 .385E-5 0.0 S2 0.0
          3    6 S6 .455 S2  6 30.48 S13 S9 6.241E+18
          3    6  2.4396E+00  1.2124E-02 -9.8852E-05 4 0.0
          3    6  6.3561E-02  6.8125E-06  3.0254E-07 .288E-4
          3    6  2.6363E-03  1.9567E-04 -2.1907E-06 .211E-4
          3    6  1.1321E-02  5.1940E-05 -2.9976E-07 .385E-5 0.0 S2 0.0
          4    1      1
          4    2      4  5
          4    3      1  6  2
          4    4      5  6  5  4
          4    5      3  6  4  6  2
          4    6      3  4  6  2  6  5
          4    7      4  6  5  6  6  2
          4    8      3  3  2  3
          5 1 1       1 1 0 0 1 20 3
          5 1 1             0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
          5 1 1 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
          5 1 1 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
          5 1 1 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
          5 1 1 2.3604E-01 2.3593E-01 2.3584E-01 2.3561E-01 2.3534E-01
          5 1 1 2.3499E-01 2.3467E-01 2.3443E-01 2.3396E-01 2.3346E-01
          5 1 1 2.3297E-01 2.3253E-01 2.3217E-01 2.3222E-01 2.3322E-01
          5 1 1 2.3408E-01 2.3489E-01 2.3563E-01 2.3640E-01 2.3704E-01
          5 2 1       2 1 0 0 1 20 3
          5 2 1             0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
          5 2 1 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
          5 2 1 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
          5 2 1 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
          5 2 1 8.9364E-03 8.9471E-03 8.9775E-03 9.0403E-03 9.1868E-03
          5 2 1 9.3689E-03 9.5361E-03 9.6798E-03 9.8195E-03 9.9477E-03
          5 2 1 1.0064E-02 1.0172E-02 1.0272E-02 1.0454E-02 1.0619E-02
          5 2 1 1.0769E-02 1.0905E-02 1.1041E-02 1.1189E-02 1.1326E-02
          5 3 1       3 1 0 0 1 20 3
          5 3 1             0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
          5 3 1 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
          5 3 1 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
          5 3 1 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
          5 3 1 1.7108E-02 1.7157E-02 1.7138E-02 1.7117E-02 1.7035E-02
          5 3 1 1.6924E-02 1.6822E-02 1.6724E-02 1.6682E-02 1.6661E-02
```

```
             5 8 6 1.3701E-01 1.3657E-01 1.3835E-01 1.3992E-01 1.4203E-01
             5 8 6 1.4288E-01 1.4294E-01 1.4239E-01 1.4117E-01 1.3960E-01
             5 8 6 1.3776E-01 1.3571E-01 1.3351E-01 1.2874E-01 1.2370E-01
             5 8 6 1.1861E-01 1.1361E-01 1.0885E-01 1.0375E-01 9.9153E-02
             5 9 6     9 1 0 0 1 20 3
             5 9 6            0 1.5000E-01 1.0000E+00 2.0000E+00 4.0000E+00
             5 9 6 6.0000E+00 8.0000E+00 1.0000E+01 1.2000E+01 1.4000E+01
             5 9 6 1.6000E+01 1.8000E+01 2.0000E+01 2.4000E+01 2.8000E+01
             5 9 6 3.2000E+01 3.6000E+01 4.0000E+01 4.5000E+01 5.0000E+01
             5 9 6 1.1007E+01 1.0985E+01 1.1075E+01 1.1148E+01 1.1222E+01
             5 9 6 1.1214E+01 1.1151E+01 1.1048E+01 1.0906E+01 1.0742E+01
             5 9 6 1.0562E+01 1.0371E+01 1.0172E+01 9.7534E+00 9.3264E+00
             5 9 6 8.9043E+00 8.4972E+00 8.1147E+00 7.7077E+00 7.3458E+00
3.20    0 BP 510 6  7.22  1 0 0 1  20   3  (XE2       )
             510 6              0  1.0000E-01  1.0000E+00  2.0000E+00  4.0000E+00
             510 6  6.0000E+00  8.0000E+00  1.0000E+01  1.2000E+01  1.4000E+01
             510 6  1.6000E+01  1.8000E+01  2.0000E+01  2.4000E+01  2.8000E+01
             510 6  3.2000E+01  3.6000E+01  4.0000E+01  4.4000E+01  4.8000E+01
             510 6  1.4554E+06  1.4460E+06  1.4562E+06  1.4599E+06  1.4680E+06
             510 6  1.4785E+06  1.4911E+06  1.5011E+06  1.4825E+06  1.4928E+06
             510 6  1.4999E+06  1.5132E+06  1.5256E+06  1.5167E+06  1.5367E+06
             510 6  1.5552E+06  1.5662E+06  1.5758E+06  1.5852E+06  1.5929E+06
3.20    0 BP 511 6  7.24  1 0 0 1  20   3  (SM2       )
             511 6              0  1.0000E-01  1.0000E+00  2.0000E+00  4.0000E+00
             511 6  6.0000E+00  8.0000E+00  1.0000E+01  1.2000E+01  1.4000E+01
             511 6  1.6000E+01  1.8000E+01  2.0000E+01  2.4000E+01  2.8000E+01
             511 6  3.2000E+01  3.6000E+01  4.0000E+01  4.4000E+01  4.8000E+01
             511 6  4.2382E+04  4.2674E+04  4.2901E+04  4.2981E+04  4.3166E+04
             511 6  4.3413E+04  4.3719E+04  4.3958E+04  4.3471E+04  4.3721E+04
             511 6  4.3889E+04  4.4219E+04  4.4530E+04  4.4291E+04  4.4787E+04
             511 6  4.5254E+04  4.5527E+04  4.5770E+04  4.6008E+04  4.6204E+04
3.20         512 6 7 8 1 0 0 1 2  (BORON2)
             512 6 0 0 0   1.4544E-05  1.5523E-08 -1.5057E-10
3.20         513 6 2 3 1 0 0 2 3  (DOP1)
             513 6 0 0 0 0 0 0 0 0
             513 6 -4.1533E-05  1.3450E-06 -8.1371E-08  1.3755E-09
3.20         514 6 2 3 1 0 0 1 3 (DOP2)
             514 6 0 0 0 0   3.1933E-04 -9.7971E-06  6.3531E-07 -1.1467E-08
3.20         515 6 2 1 0 0 0 3 0 (DOP3)
             515 6 -2.7780E-04  8.4521E-06 -5.5394E-07  1.0092E-08
 3.20        516 6 2 4 0 0 0 1 0   -1.5051E-04  2.0440E-04  (DEL AB1)
 3.20        517 6 7 4 0 0 0 1 0   -5.4028E-03  7.3374E-03  (DEL AB2)
 3.20        518 6 1 4 0 0 0 1 0   -1.1836E-01  1.6074E-01  (DEL TR1)
 3.20        519 6 6 4 0 0 0 1 0   -7.0851E-01  9.6220E-01  (DEL TR2)
 3.20        520 6 3 4 0 0 0 1 0   -2.0335E-02  2.7620E-02  (DEL REMU)
 3.20        521 6 2 8 0 0 0 1 0.0  0.0   2.8985E-07 (BORON1)
 3.20        522 6 2.22 0 0 0 0 0 0.0     1.0340E+02          ( XE1 )
 3.20        523 6 2.24 0 0 0 0 0 0.0     7.9930E+01          ( SM1 )
             7   1   0.0  R6   -.20
             7   2   0.0  R6   -.15
             7   3   0.0  R6   -.15
             7   4   0.0  R6   -.15
             7   5   0.0  R5   -.15
             7   6   0.0  R5   -.15
             7   7   0.0  R3   -.15   -.15
             7   8   -.20    -.15    -.15    -.15
             10 1 1       20.620
             10 1 2        9.810
             10 1 3       20.620
             10 1 4            0
             10 1 5       25.890
             10 1 6       24.940
             10 1 7       12.960
             10 1 8       25.880
             10 2 1        9.810
             10 2 2            0
             10 2 3       11.410
             10 2 4        9.410
             10 2 5        7.910
             10 2 6       12.240
             10 2 7            0
             10 2 8       22.630
             10 3 1       20.620
             10 3 2       11.410
             10 3 3       23.200
             10 3 4            0
             10 3 5       12.770
             10 3 6            0
             10 3 7            0
             10 3 8       23.770
```

```
10 4 1             0
10 4 2         9.410
10 4 3             0
10 4 4        13.100
10 4 5         8.270
10 4 6        22.750
10 4 7             0
10 4 8        24.040
10 5 1        25.890
10 5 2         7.910
10 5 3        12.770
10 5 4         8.270
10 5 5        21.220
10 5 6             0
10 5 7             0
10 6 1        24.940
10 6 2        12.240
10 6 3             0
10 6 4        22.750
10 6 5             0
10 6 6             0
10 6 7        31.420
10 7 1        12.960
10 7 2             0
10 7 3             0
10 7 4             0
10 7 5             0
10 7 6        31.420
10 8 1        25.880
10 8 2        22.630
10 8 3        23.770
10 8 4        24.040
12        -.0001  S3   .008
13        0.59582  -0.49396  -0.20215
14    1    1.0  0.0
15    1    1  1  1  1  1  1  1  1
15    2    1  1  1  1  1  1  1  1
15    3    1  1  1  1  1  1  1  1
15    4    1  1  1  1  1  1  1  1
15    5    1  1  1  1  1  1  1
15    6    1  1  1  1  1  1  1
15    7    1  1  1  1  1  1
15    8    1  1  1  1
17    1    0.983
17    2    1.115  1.296
17    3    1.032  1.176  1.081
17    4    1.261  1.264  1.299  1.143
17    5    0.899  1.172  1.149  1.175  1.081
17    6    0.806  1.051  1.326  1.067  1.241  1.025
17    7    0.849  1.133  1.188  1.124  0.921  0.416
17    8    0.387  0.461  0.486  0.364
19        1 5 5 1 5 1 R60
20         0 0 S6 0 1 S1 1 S3 1 S7 0
21         1  1  3  0  1  0  1 S2 1 1 S2  0   1  1  S6  0
32    1    22900000
32    2    22700000  22802080
32    3    22900000  23200000  23200000
32    4    22802080  23200000  22802080  22700000
32    5    22800000  23200000  22700000  23200000  23200000
32    6    22800000  22700000  23202080  23200000  23202080  22802080
32    7    22700000  23202080  22802080  23202080  23202080  23200000
32    8    22800000  22800000  23200000  22800000
99
:LAST
```

APPENDIX D: SAMPLE OUTPUT



OPUS SAYS...

```
 OPUS RESULTS
***************


     TOTAL NUMBER OF INTEGRAL BP COMBINATIONS      1152
     NUMBER OF DEPLETABLE BP COMBINATIONS            39
     NUMBER OF ACCEPTABLE BP COMBINATIONS             2


CASE   373 GIVES LONGEST CYCLE AT 13.240 GWD/MT

 FUEL LOADING:
----------------

                           *****************
                           * ENRICHMENT    *
                           * BP LOADING    *
                           * BOC EXPOSURE  *
                           *****************
**********
*   2.90 *
*        *
* 27.530 *
*******************
*   2.80 *   3.60 *
*        *      4 *
* 13.980 *  0.000 *
****************************
*   2.70 *   2.80 *   2.80 *
*        *        *        *
* 20.730 * 15.200 * 14.670 *
*************************************
*   3.20 *   3.20 *   3.20 *   2.70 *
*      4 *        *      8 *        *
*  0.000 * 17.960 *  0.000 * 26.100 *
**********************************************
*   2.80 *   3.20 *   3.20 *   3.20 *   2.70 *
*        *        *        *      8 *        *
* 10.400 * 13.060 * 14.320 *  0.000 * 24.600 *
*******************************************************
*   3.20 *   3.20 *   2.80 *   3.20 *   3.60 *   3.20 *
*        *        *        *        *      4 *        *
* 14.990 * 10.110 * 14.950 * 10.200 *  0.000 *  0.000 *
*******************************************************
*   3.20 *   3.60 *   3.60 *   3.20 *   3.20 *   2.70 *
*        *      8 *      4 *        *        *        *
* 14.990 *  0.000 *  0.000 *  0.000 * 21.570 * 25.060 *
*******************************************************
*   2.90 *   3.20 *   3.20 *   2.70 *
*        *        *        *        *
* 27.200 * 22.080 * 25.290 * 23.160 *
*************************************
```