Development of
a Nonlinear Reactivity Model
for BWR

Kaynar Sulu Reaktörlerde
Doğrusal Olmayan Reaktivite Modeli
Geliştirilmesi

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Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

in the Field of Nuclear Engineering

Hacettepe University

February, 1998

To the Institute for Graduate Studies in Pure and Applied Sciences,

This work has been approved by the Graduate Committee as partial fulfillment of the requirements for then degree of **Master of Science** in the field of **Nuclear Engineering**

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ABSTRACT

Linear Reactivity Model (LRM) is currently being used in fuel management calculation of Pressurized Water Reactors (PWR). A computer code Reload Power Mapping (RPM) which is based on LRM was developed by Driscoll et al[1]. However, in many commercial power reactor types, assembly reactivity is a nonlinear function of burnup. Moreover, there is a strong coupling between assembly power and assembly reactivity in Boiling Water Reactors (BWR).

In this study, RPM computer code is modified so that it can be applied in fuel management analyses of commercial reactor types other than PWRs. The modifications include the incorporation of piecewise linear reactivity model with reactivity feedback due to thermal hydraulic coupling, the implementation of an under-relaxation technique to improve accuracy and convergence characteristics of the code.

Thus developed computer code is shown to be applicable to fuel management calculations of BWRs and PWRs with burnable absorbers, in addition to PWRs which can be modelled by the original RPM code.

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[1] Driscoll M.J., Downar T.J., Pilat E.E., The Linear Reactivity Model for Nuclear Fuel Management, American Nuclear Society, La Grange Park, Illinois USA, 1990

ÖZET

Doğrusal Reaktivite Modeli (DRM), Basınçlı Su Reaktörlerinin (BSR) yakıt yönetim hesaplarında halen kullanılmaktadır. DRM metodunu kullanan Reload Power Mapping (RPM) bilgisayar kodu bu amaçla Driscoll ve çalışma arkadaşları tarafından geliştirilmiştir. Ne var ki, mevcut pek çok ticari reaktör tipinde yakıt demeti reaktivitesi yanma oranın doğrusal olmayan bir fonksiyonudur. Bunun da ötesinde, Kaynar Sulu Reaktörlerde (KSR) yakıt demeti gücüyle reaktivitesi ihmal edilemez bir ilişki vardır.

Bu çalışmada, RPM bilgisayar kodunda değişiklikler yapmak suretiyle BSR haricindeki ticari reaktörlerin yakıt yönetimi için de kullanılabilmesi sağlanmıştır.Bu değişiklikler, termal hidrolik geri beslemeleri de kapsayan kesikli doğrusal reaktivite modelinin koda uyarlanması ve kodun yakınsama ve duyarlılık özelliklerini iyileştirmek için under-relaxation metodu kullanılmasını içermektedir.

Böylece geliştirilen bilgisayar kodunun, orjinal RPM kodu ile modellenebilen BSR'ler haricinde, KSR ve yanabilen yutuculu BSR'lerinde yakıt yönetimi hesaplarında kullanabileceği gösterilmiştir.

ACKNOWLEDMENTS

I would like to thank my advisers, Dr. Üner Çolak and Dr. Mehmet Tombakoğlu for their patience, guidance and advice during this study. I would also like to thank Dr. Erol Çubukcu for proof reading the manuscript of this thesis.

I would also like to thank staff of Hacettepe University Nuclear Engineering Department and staff of Turkish Atomic Energy Authority Nuclear Safety Department for their patience and understanding.

Financial support provided by Hacettepe University Research Fund through the contract 95.01.010.011 is also appreciated

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CHAPTER 1

INTRODUCTION

Nuclear energy is one of the most significant technological achievements in this century. Currently, there are more than four hundred commercial nuclear power plants operated in the world. Three quarters of these nuclear power plants are Light Water Reactors (LWR). Two-thirds of these LWRs are Pressurized Water Reactors (PWR) and the rest are Boiling Water Reactors (BWR).

Nuclear fuel management plays a crucial role for reducing the cost of electricity generation of nuclear power plants. Safety is another major concern during the operation of a nuclear power plant which requieres the knowledge of fuel characteristics at any burnup step. This information is normally provided by nuclear fuel management calculations which depend on the type of the reactor. These calculations can be performed by using simple models for PWRs. However, such calculations are rather complicated in BWRs due to the strong thermal hydraulics and neutronics coupling. There are several general nuclear fuel management strategies dealing with the fuel loading patterns of the reactor cores.

1.1. Nuclear Fuel Management

Nuclear fuel management activities are classified in two main categories: "out-of-core" and "in-core" fuel management. Out-of-core fuel management deals with the front-end and back-end of nuclear fuel cycle. It also assesses the contribution of fuel supply, enrichment, and disposal to electricity generation cost.

In-core fuel management begins with the design of the fuel assembly. Operational parameters of the fuel and the reactor power history are also in the scope of in-core fuel management.

The primary objective of the fuel management activities is to minimize the fuel cost. This is achieved by adjusting fuel parameters and fuel loading patterns. However, this must be done without violating operational and safety constraints.

Multi-batch core loading is the preferred choice to minimize the cost of electricity generation. In multi-batch core loading, only a fraction of the core is removed and substituted by the fresh fuel during the refueling.

1.2. Fuel Loading patterns

The criterion for selecting the best fuel loading pattern is to extract the maximum energy from the fuel at a minimum cost without violating the safety and operational limits. This is achieved by keeping peak-to-average power ratio low and thus flattening the power distribution as much as possible.

Fuel management calculations are simplified by considering the core symmetry, resulting in reduction of computational time and cost. Typically, 1/8 or 1/4 core symmetry is used.

Out-In Loading

In this loading strategy, core is divided into N numbers of concentric annular sub-region. The fresh fuel is loaded into the outermost region of the core. At each refuelling, irradiated fuel batches are moved to the neighbouring inner regions, the batch at the central region is taken out of the core. Thus, central region always contains the fuel with the highest burnup. This pattern has the advantages of low power peaking. The primary disadvantage of this loading pattern is the requirement of greater fissile material inventory and therefore, higher initial fuel enrichment and higher fuel cost.

Scatter Loading

Scatter loading is also called the checkerboard scheme. In this scheme, the core is divided into many small regions. Each region consists of either four or six assemblies. This loading scheme has two major advantages; the first is the achievement of a nearly uniform power distribution and the second the relatively lower neutron leakage out of the core.

Low-Leakage Core Loading

Neutron leakage out of the core is an important consideration for the long-term safety criterion for pressure vessels as well as neutron economy. Low leakage core loading strategy is based on placement of the batch with the highest burnup at the periphery of the core. This scheme contributes to the reduction of radiation damage on the pressure vessel. Therefore, it extends the service lifetime of the pressure vessel resulting in an economical benefit.

1.3. History

In nuclear fuel management studies, the linear reactivity model (LRM) is applied to PWRs. LRM is a simplified model in order to solve 2-D in-core fuel management problems. Because of the simplifications in the model, the computational time and cost are low, whereas, the detailed fuel operational parameters are not provided.

Driscoll et al. [1] who developed and studied the history of the method note that:'...simple tutorial versions of this general approach can be traced back to the 1950s. However, with the notable exception of Egan's lengthy paper in the 1984 issue of *Progress in Nuclear Energy,* previous publications have been either limited in scope or focused on quite specialized aspects such as the convergence of refueling sequences'. In nuclear fuel management area, linear reactivity model became popular among scientists in the first half of 1980s.

1.4. The purpose of this thesis

In PWRs, the reactivity of each assembly can be approximated as a linear function of the burnup. Furthermore, the reactivity of the assembly does not depend on the location of the assembly in the core. Moreover, moderator density can be approximated to be independent of the assembly power.

In BWRs, however, the reactivity of the assembly is a strong function of the assembly power and burnup. Axial power profile depends on the assembly power and is bottom peaked. Thus, the moderator density varies with the power level of the assembly. For this reason, migration area becomes a function of the assembly power and therefore, cannot be treated as a constant as in the case of PWRs.

Reload Power Mapping (RPM) is a computer code which is based on the linear reactivity model developed by Sauer and Driscoll [2]. This program is intended to PWR fuel management analysis, hence has certain constraints such as constant migration area.

RPM computer code cannot be directly applied to BWR and CANDU fuel management analyses because of the non-linearity in the relationship between assembly reactivity and burnup. Moreover, there is a strong interdependency between thermal-hydraulics and neutronics in BWRs. Hence, migration area cannot be assumed constant and assembly reactivity also depends on power distribution.

The main objective of this thesis is to make necessary modifications on the RPM computer code to study the fuel management strategies for reactors in which the assembly reactivity is a nonlinear function of burnup. Among these reactors are BWRs, CANDUs, and PWRs with burnable absorbers. As a result of this study, piecewise linear reactivity model is implemented into the RPM computer code and a new computer code PLRM is developed.

This thesis consists of four chapters: this first chapter is dedicated to the introduction, review of the previous studies related to this work, and the statement of purpose.

Chapter two is devoted to the description of the RPM computer code and its algorithm. Governing equations of the linear reactivity model are also presented in this chapter.

Piecewise linear reactivity model is introduced in Chapter III. In this chapter, the modifications on the RPM computer code are also presented. In-core fuel management calculations for PWRs are carried out by using the RPM and the modified RPM computer codes. For BWRs, the modified RPM computer code is used to obtain 2-D beginning of cycle and end of cycle power map and end of cycle burnup distributions. The results are also presented and discussed in this chapter.

In the final chapter of this thesis, achievements of the study are summarized and recommendations for further studies are presented.

CHAPTER 2

LINEAR REACTIVITY MODEL

Reload Power Mapping (RPM) computer code, which is written in BASIC programming language, computes both power and burnup distributions at the beginning of cycle (BOC) and end of cycle (EOC) employing the linear reactivity model. The program is translated from BASIC to FORTRAN-77 and modified at Hacettepe University Nuclear Engineering Department. The program allows the user to specify up to 36 different types of fuel assemblies with 2-D calculations using 1/8 core symmetry. In the input description, the reactivity of each type of assembly is given as a linear function of burnup.

2.1. RPM Algorithm

To derive the governing equations of the LRM, we begin with two-group diffusion equations. Equation for Group 1 is given by

$$-D_1\nabla^2\phi_1 + \Sigma_{a1}\,\phi_1 + \Sigma_{12}\,\phi_1 - \frac{1}{k}(\nu\Sigma_{f1}\,\phi_1 + \nu\Sigma_{f2}\,\phi_2) = 0 \qquad \textbf{(2.1)}$$

for Group 2 by

$$-D_2\nabla^2\phi_2 + \Sigma_{a2}\,\phi_2 + \Sigma_{12}\,\phi_1 = 0 \qquad \textbf{(2.2)}$$

where,

D_i is the ith group diffusion coeficient,

∇^2 the Laplacian operator,

ϕ_i the ith group flux,

Σ_{ai} the ith group macroscopic absorption crossection,

ν the neutron yield per fission,

Σ_{fi} the ith group macroscopic fission crossection,

Σ_{ij} the macroscopic scattering crossection from ith to jth group,

and,

k the neutron multiplication factor.

In the case of $D_2\nabla^2\phi_2 << \Sigma_{a2}\phi_2$, which is a good approximation for LWRs, the diffusion equation for thermal group (Group 2) can be rewritten as

$$\Sigma_{a2}\,\phi_2 = \Sigma_{12}\,\phi_1$$

hence,

$$\phi_2 = \frac{\Sigma_{12}\,\phi_1}{\Sigma_{a2}} \qquad \textbf{(2.3)}$$

Reactivity is defined as

$$\rho = \frac{\text{neutron production - neutron consumption}}{\text{neutron production}} \qquad \textbf{(2.4)}$$

and therefore, given by

$$\rho = \frac{(\nu\Sigma_{f1}\phi_1 + \nu\Sigma_{f2}\phi_2) - (\Sigma_{a1}\phi_1 + \Sigma_{a2}\phi_2)}{(\nu\Sigma_{f1}\phi_1 + \nu\Sigma_{f2}\phi_2)} \qquad \textbf{(2.5)}$$

Using Equations (2.3) and (2.5), Equation (2.1) can be written as

$$\nabla^2\phi + \frac{\rho}{1-\rho}\frac{1}{M^2}\phi = 0 \qquad \textbf{(2.6)}$$

where, M^2 is the migration area, defined as

$$M^2 = \frac{D_1}{\Sigma_{12} + \Sigma_{a1}} \qquad \textbf{(2.7)}$$

The local power density expressed as function of the fast flux is

$$q = \kappa\,(\Sigma_{f1} + \Sigma_{f2}\frac{\Sigma_{12}}{\Sigma_{a2}})\,\phi_1 \qquad \textbf{(2.8)}$$

where,

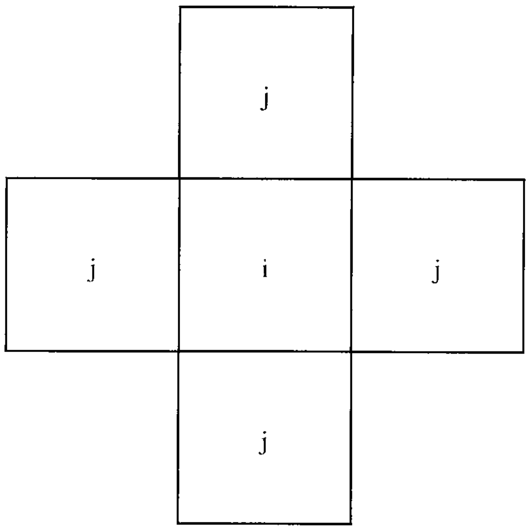
κ is the energy yield per fission.

Combining Equations (2.5), (2.6), and, (2.8), and finally, the result can be written as

$$\nabla^2[q(1-\rho)] + \frac{\rho q}{M^2} = 0 \qquad \textbf{(2.9)}$$

Sauer et al. [1] used these approximations and their results are presented as follows:

Coupling Relation



Adjacent face-to-face nodes in x-y geometry

$$f_i = \frac{\frac{1}{4-R}\sum_{j=1}^{4-R} f_j \left[1-\left(\frac{3-\theta}{2}\right)\rho_j\right]}{1-\left[\theta+\frac{R(R+1)}{4}(\theta-1)\right]\left[\rho_i - R\cdot\rho_L\right]}$$

where R is the number of neighbors that are reflector (i.e., nonfuel) nodes (e.g., R=0,1,2);f_i,f_j are the power levels (relative to the core-average assembly having $\bar{f}\equiv 1.0$) for assembly *i* and its face-to-face neighbors,j; and ρ_i, ρ_j are their corresponding reactivities

Coupling Constants for 3-D

$$\theta = 1+\frac{1}{6}\frac{h^2}{M^2}$$

where

h is the node (i.e,assembly) width

M^2 the migration area

ρ_L the leakage reactivity, can be related to albedo, but best determined empirically (typical value ~ 0.1).

Using these results, Driscoll et al. [1] developed two dimensional the power sharing relationship. They used geometric and material buckling and finite difference approximation. Their work produced the following relationship:

$$q_i = \frac{\frac{1}{S}\sum_{j=1}^{S} q_{sj}(1-\rho_{sj})}{1-\theta_R(\rho_i - \rho_{LR})} \qquad \textbf{(2.10)}$$

where R is the number of reflected faces, the remaining S interfaces are with fueled assemblies. In this algorithm the parameters take on the following values:

R	θ	ρ_L
0 (interior)	$\theta_0 = 1 + \frac{1}{4}\frac{h^2}{M^2}$	$\rho_{L0} = 0$
1	$\theta_1 = (4\theta_0 - \gamma)/3$ $\theta_1 = \frac{4\theta_0 - 1}{3(1-\rho_{L1})}$	$\rho_{L1} = \frac{1}{2}\frac{1-\gamma}{2\theta_0 - \gamma/2}$ $\rho_{L1} = \frac{1-\gamma}{3\theta_1}$
2	$\theta_2 = (2\theta_0 - \gamma)$ $\theta_2 = \frac{(2\theta_0 - 1)}{1-\rho_{L2}}$	$\rho_{L2} = \frac{1-\gamma}{2\theta_0 - \gamma}$ $\rho_{L2} = \frac{1-\gamma}{\theta_2}$

First, assembly power according to the nodal relation given by coupling relation is estimated by RPM computer code. Then, mean potential reactivity of the core is given by the power-weighted relation:

$$\overline{\rho_c} = \sum_{i=1}^{N} \frac{f_i(\rho_i - \rho_{BPi} - A_i \overline{f_i} B_c)}{\sum_{i=1}^{N} f_i} \qquad \textbf{(2.11)}$$

where, ρ is the burnable poison reactivity, B_c the core-average cycle burnup and f_i the cycle average power of assembly i:

$$\overline{f_i} = \frac{f_{i,BOC} + f_{i,EOC}}{2} \quad \textbf{(2.12)}$$

The leakage reactivity is given by

$$\overline{\rho_L} = \frac{\sum^{N} f_i \cdot NF \cdot RQ}{\sum_{i=1}^{N} f_i} \quad \textbf{(2.13)}$$

where, NF is the number of assembly faces to reflector and RQ the fraction of assembly-born neutrons leaking per reflected faces.

The soluable poison is given by

$$\rho_{SP} = \overline{\rho_c} - \overline{\rho_l} \quad \textbf{(2.14)}$$

The thermal leakage correction is applied converged powers at BOC and EOC.

The formula for the thermal leakage is

$$\frac{\Delta f_i}{f_i} = -TL \cdot \rho_i \quad \textbf{(2.15)}$$

where, the thermal leakage correction is $TL \approx 4L/h$.

Figure 2.1. shows the flow chart of the RPM computer code flow.

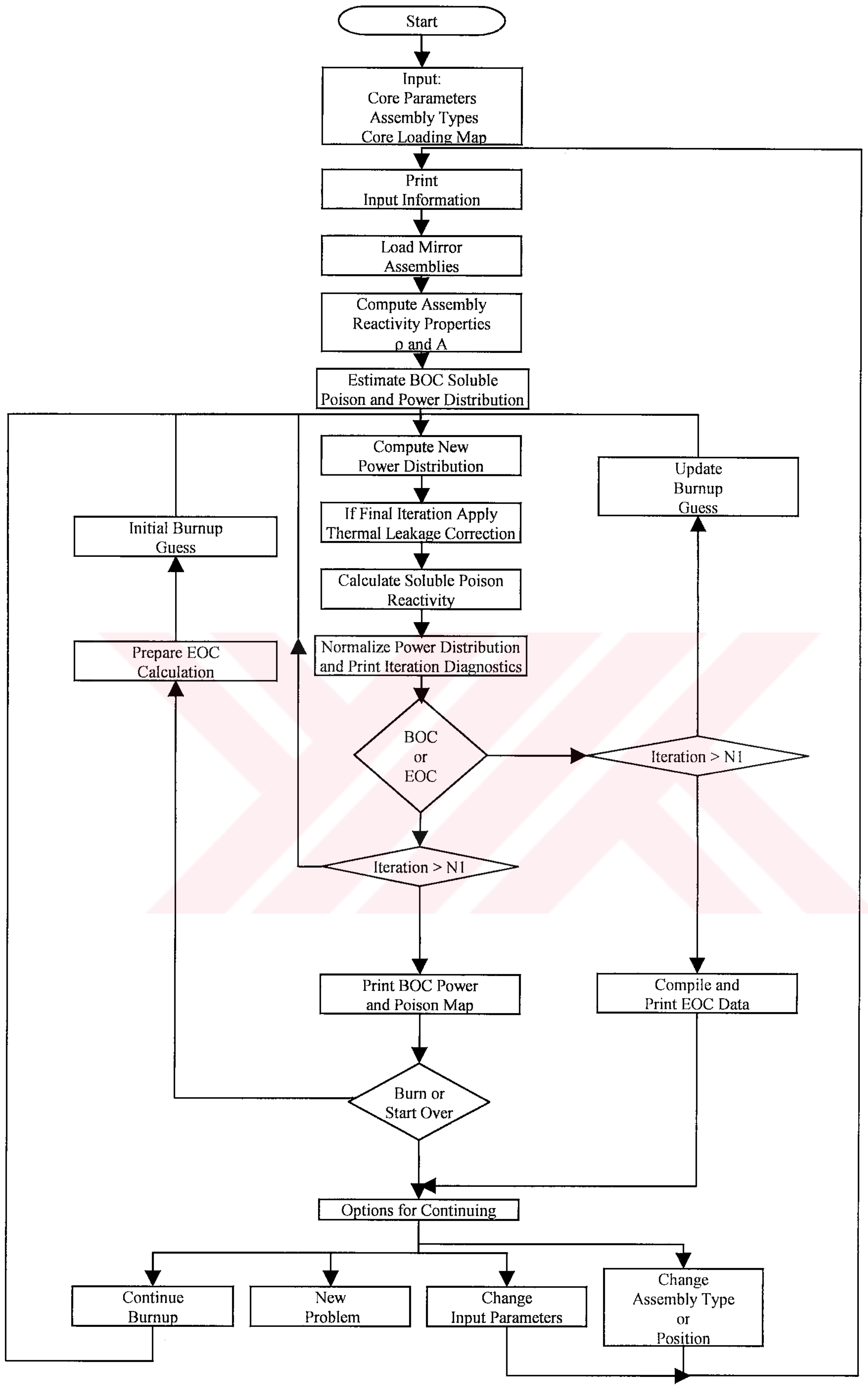


Figure 2.1. RPM flow chart.

2.2. Description of RPM and its input parameters

When RPM program is executed by user, it open two files. First one is the input file "RPM.INP" prepared by the user to manage program branching, the output file "RPM.OUT" created by the computer code itself.

Input file of RPM consists of several data cards. The number of cards is changed by user directive.

Card 1: Number of differen assembly Types: N

Card 2: Specified end of core ρ

Card 3: Power sharing factor

Card 4: Thermal Leakage Correction

Card 5: Radial Leakage Corection

Card 6: Number of iteration

N times

Card 7.1: Reactivity of assembly at beginning of cycle

Card 7.2: slope of ρ

Card 7.3: Burnable Poison reactivity

Card 8.1: Assembly type at first location

.

.

.

Card 8.36: Assembly type at last location

Card 9: Continuing options

RPM program has five option for continuing.

1 Continue Burnup (Coastdown)

2 Start Totally New Problem

3 Change Selected Assemblies at BOC and Rerun

4 Change Control Parameters

5 Stop Program.

The user must specify the iteration number, power sharing factor, thermal and radial leakage correction factor, assembly reactivity and soluble poison reactivity at BOC for each assembly, slope of ρ and, number different assemblies. In RPM program, one-eighth core symmetric loading pattern can be modelled as shown in Figure 2.2.

1	2	4	7	11	16	22	29
	3	5	8	12	17	23	30
		6	9	13	18	24	31
			10	14	19	25	32
				15	20	26	33
					21	27	34
						28	35
							36

Figure 2.2. RPM fuel assembly locations.

Reflector must be shown '0' in the input of RPM. RPM has also capabilities of these:

1. Pincell Within an Assembly: set $\theta = Th = 1$ and $RQ = 0$

2. BWR Cores: BWR has four times assemblies comparing the PWR core. User must be pre-averaged BWR Assembly because RPM can be perform 193 assemblies.

CHAPTER 3

PIECEWISE LINEAR REACTIVITY MODEL

RPM is a compact computer code with great capabilities designed for the fuel management studies of PWRs using the linear reactivity model.

3.1. Modifications on RPM Computer Code

RPM computer code becomes inadequate in the case of nonlinear dependency of reactivity on burnup. In the fuel management of BWRs, due to nonlinear void reactivity feedback, reactivity is also coupled with the power generated in the assembly. As a result of these feedback mechanisms, RPM computer code needs to be modified. The first modification is that the piecewise linear reactivity model is imbedded in the modified diffusion equation to incorporate nonlinear reactivity dependency on burnup. The second one, the migration area is also the function of power generated in each assembly. However, in PWRs, there is not such a case. But, if we need to model the assemblies with burnable poisons , migreation area needs to be considered to be dependent on the assembly type, mainly on the location and the amount of burnable poison rod. Due to those reasons, modified diffusion equation is written as

$$\nabla^2\left[q(1-\rho)\right]+\frac{\rho q}{M^2}=0 \qquad \textbf{(3.1)}$$

where,

ρ is function of burnup and power peaking factor and,

M^2 is function of burnup, power peaking factor and, assembly type.

Piecewise Linear Reactivity Model (PLRM) is based on four main modifications on RPM. In the original RPM code, the migration area M^2 is assumed to be constant. Reactivity,i.e., ρ is also assumed to be function of burnup. This is a good aproximation in the case of PWR. However, a mixture of steam and water is present in BWR assemblies. Therefore, migration area becomes a function of both assembly power and axial location, because with increasing steam fraction, migration area increases. In this study, the first modification on the RPM algortihm is the inclusion of variable migration area.

The strategy of the RPM computer code is to search the EOC reactivity which is given as an input parameter. While the calculations of the EOC assembly power performed by the program, estimated burnup is used. Thus, the end of cycle reactivity is found by the formula

$$\rho=\rho_0-B\beta \qquad \textbf{(3.2)}$$

where,

ρ_0 is the initial reactivity,

B the end of cycle burnup,

β the slope of reactivity versus burnup.

While RPM is searching the EOC reactivity, it uses simple iteration algorithm. This algorithm has some advantages like the shorter runtime. But it has the disadvantage of lack of convergence. Under relaxation method is used in PLRM to overcome the convergence problem. It is the second modification on RPM. The convergence problem is overcomed using the under-relaxation method, thus, the ossilatory convergence behaviour of BWRs is also successfully handled. Under-relaxation is utilized at each burnup step calculation. Thus, it is given by

$$F=F^{old}+w(F^{new}-F^{old}) \qquad \textbf{(3.3)}$$

where,

F is normalized assembly power and,

w the weight factor.

PLRM utilizes two variables for the next step calculations. One of the two is the number of iteration. If the number of iteration exceeds the maximum iteration number given in the input file, the code terminates the current burnup step calculations and then passes to the next burnup step. The other control statement is the infinity norm of the difference of two succeding step power peaking vectors. The difference vector is defined as the error vector. If the infinity norm of the error vector is less than epsilon, i.e., 0.001, the code passes to the next burnup step calculations. When under-relaxation is used, it is observed that the code is successfully converges without exceeding the maximum number of iterations.

Radial leakage correction factor for the large reactor core is calculated using:

$$\rho_{LR} \approx \frac{2\pi R(\frac{M}{2})}{\pi R^2} = \frac{M}{R} \tag{3.4}$$

It is a good approximation for *R*>>*M*. Radial leakage correction factor for the fresh fuel assembly is less than that of the irradiated fuel assembly. This correction factor is used at the peripherial fuel assembly calculations. Moreover, the power peaking factor of the periperial fuel assembly is depend on the number of the faces of the assembly adjacent to reflector region. The correction factor is assumed to be constant in the RPM code and it is given as an input parameter. However, the variable correction factor can be supplied in the PLRM computer code.

The last modification in the RPM code is the burnup steps. At the start up of the reactor, the reactivity is decreased within a short time interval due to xenon build-up. Using a small initial burnup step, the initial transient due to poisonous fission products can be handled. It is also possible to investigate the effect of burnable poison on the power history of the nuclear reactor by adjusting the burnup and utilizing piecewise linear reactivity model.

3.2. Modification on RPM Input File

PLRM input file is similar with RPM input file. There are some additions to it before the card 1. These additions are related program branching and the under relaxation factor. Card 2, Card 3, Card 5 and, Card 7.x are dummy cards and are not use by PLRM computer code.

The additional cards are located before card 1 in the input file.

Card 0.1: Under relaxation weigth factor

Card 0.2: Initial burnup step

Card 0.3: Maximum Burnup

Card 0.4: Burnup step

3.3. Reload Pattern Calculation for PWR

Figure 3.3. shows the BOC assembly power peaking factors for PWR obtained by the RPM code. Figure 3.5. shows the results of PLRM. The results of the RPM and the PLRM computer codes are comparable with each other.

The EOC assembly power peaking factors and the assembly burnup obtained by the RPM and PLRM computer codes are given in Figure 3.4 and (3.6) respectively. In PLRM computer code, at each burnup step power peaking factor of each assembly is calculated and utilized in the next step calculations to obtain EOC assembly burnups and power peaking factors. Thus, the differences on the EOC power peaking factor and burnup of the assemblies between the RPM and PLRM codes occur.

Assembly Characteristics

Batch	BOC Reactivity	Number of Assemlies
1	0.1454	64 or 65
2	0.1733	64
3	0.1940	64 or 65
		193 Total

Other

Slope of $\rho(B)$, A= 9E-3 kg/MWd	1/8 core symmetry, all cases
Power-sharing factor, θ_i =2.83	Twenty iterations, all cases
Radial Leakage Factor, ρ_L=0.1	Zero EOC core Reactivity, all cases
Thermal Leakage correction, 4L/h=0.38	No burnable poison employed

Table 3.1. Input parameters for reload pattern calculations.

1 1.785	2 1.832	1 1.707	2 1.615	1 1.334	2 1.130	1 0.807	3 0.470
	1 1.759	2 1.782	1 1.534	2 1.366	1 1.066	3 0.857	3 0.465
		2 1.750	2 1.537	1 1.234	2 1.023	1 0.709	3 0.391
			1 1.304	2 1.139	1 0.861	3 0.642	3 0.270
				1 0.912	2 0.733	3 0.442	
					3 0.559	3 0.262	

Assembly Type

Relative BOC Power

1 2.128	3 2.214	1 1.984	3 1.816	1 1.384	3 1.068	1 0.630	2 0.312
	1 2.079	3 2.113	1 1.707	3 1.433	1 0.984	2 0.627	2 0.304
		3 2.092	3 1.740	1 1.273	3 0.963	1 0.554	2 0.262
			1 1.393	3 1.156	1 0.777	2 0.466	2 0.186
				1 0.867	3 0.644	2 0.333	
					2 0.425	2 0.193	

Assembly Type

Relative BOC Power

1 1.749	2 1.819	3 1.842	1 1.614	2 1.465	3 1.271	1 0.800	2 0.385
	1 1.720	2 1.768	3 1.712	1 1.374	2 1.167	3 0.840	1 0.365
		1 1.541	1 1.442	3 1.389	1 1.011	2 0.710	3 0.334
			2 1.371	2 1.198	3 0.952	1 0.542	2 0.216
				1 0.908	2 0.695	3 0.385	
					1 0.434	3 0.211	

Assembly Type

Relative BOC Power

3 2.350	2 2.234	3 2.114	2 1.827	3 1.542	2 1.112	3 0.688	1 0.282
	3 2.221	2 1.990	3 1.812	2 1.461	3 1.097	1 0.618	1 0.261
		2 1.796	2 1.610	3 1.367	2 0.975	3 0.590	1 0.233
			3 1.450	2 1.145	3 0.825	1 0.428	1 0.155
				3 0.912	2 0.585	1 0.269	
					1 0.336	1 0.141	

Assembly Type

Relative BOC Power

Figure 3.1. The location of the assembly type and the power factors for PWR at the BOC given by PLRM code. Top and Left: No.1, out-in(S). Top and Right: No.2, low-leakage. Bottom and Left: No. 3, Pure scatter. Bottom and Right: No.4, very low-leakage.

1	1	1	1	1	2	2	3
0.913	0.928	0.974	1.050	1.157	1.320	1.167	0.684
	1	1	1	1	2	3	3
	0.944	0.992	1.070	1.168	1.319	1.194	0.670
		1	1	1	2	2	3
		1.049	1.141	1.209	1.280	1.062	0.582
			2	2	2	3	3
			1.317	1.334	1.224	0.945	0.402
				2	2	3	
				1.267	1.050	0.649	
					3	3	
					0.813	0.385	

Assembly Type

Relative BOC Power

3	3	3	3	3	2	2	1
3.008	2.906	2.611	2.156	1.587	0.951	0.500	0.188
	3	3	3	3	2	1	1
	2.806	2.514	2.065	1.516	0.905	0.452	0.175
		3	3	3	2	2	1
		2.230	1.794	1.306	0.785	0.410	0.151
			2	2	2	1	1
			1.341	0.954	0.595	0.289	0.095
				2	2	1	
				0.664	0.404	0.172	
					1	1	
					0.222	0.086	

Assembly Type

Relative BOC Power

3	3	3	3	3	1	1	2
3.501	3.357	2.951	2.343	1.614	0.819	0.422	0.186
	3	3	3	3	1	2	2
	3.214	2.811	2.212	1.518	0.775	0.420	0.179
		3	3	3	1	1	2
		2.412	1.817	1.232	0.634	0.331	0.143
			1	1	1	2	2
			1.176	0.760	0.441	0.248	0.091
				1	1	2	
				0.477	0.283	0.145	
					2	2	
					0.176	0.075	

Assembly Type

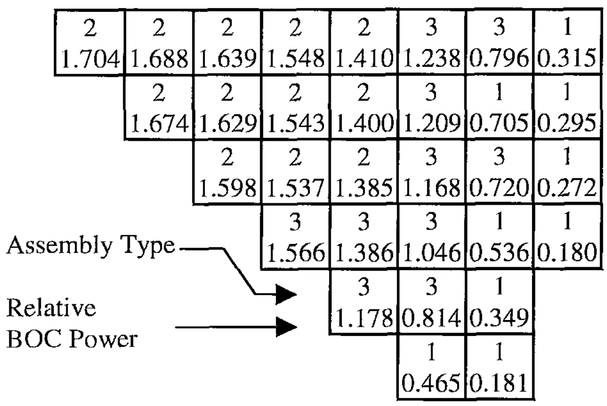
Relative BOC Power

1	1	1	1	2	2	3	2
0.824	0.844	0.911	1.043	1.292	1.426	1.232	0.636
	1	1	1	1	3	2	3
	0.862	0.922	1.036	1.212	1.443	1.162	0.632
		1	1	1	2	3	2
		0.971	1.067	1.202	1.337	1.107	0.539
			1	2	3	2	3
			1.162	1.316	1.323	0.904	0.378
				2	3	2	
				1.302	1.155	0.623	
					3	3	
					0.867	0.390	

Assembly Type

Relative BOC Power

Figure 3.1. ***con't.*** The location of the assembly type and the power factors for PWR at the BOC given by PLRM code. Top and Left: No.5, out - in(*Annular Arrangement*) - Central(*Annular Arrangement*). Top and Right: No.6, Central(*Annular Arrangement)* - in(*Annular Arrangement*) - out. Bottom and Left: No. 7, Central(*Annular Arrangement)* - out - in(*Annular Arrangement*). Bottom and Right: No.8, out(*scatter Arrangement*) - Central(*Annular Arrangement)*.



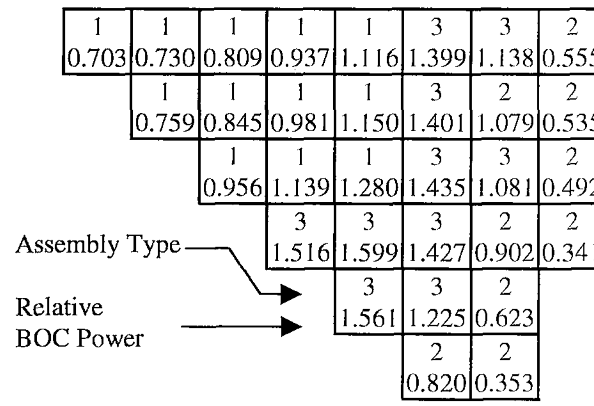


Figure 3.1. ***con't.*** The location of the assembly type and the power factors for PWR at the BOC given by PLRM code. Left: No.9, in(*Annular Arrangement*) - Central(*Annular Arrangement)* - out. Right: No. 10, in(*Annular Arrangement*) - out - Central(*Annular Arrangement)*.

Arrangement Number	**Description**	**Number of Assemblies in Batch #**			**Average Assembly Power in Batch #**			Peak Assembly	Leakage ρ
		1	2	3	1	2	3		
1	Out-In(S)	65	64	64	1.173	1.342	0.480	1.831	0.0107
2	Low Leakage	65	64	64	1.198	0.342	1.456	2.214	0.0079
3	Pure Scatter	65	64	64	1.041	1.034	0.923	1.842	0.0088
4	Very Low Leakage	64	64	65	0.302	1.406	1.286	2.350	0.0063
5	Out-In(A)-C(A)	65	64	64	1.076	1.225	0.696	1.334	0.0158
6	C(A)-In(A)-Out	64	64	65	0.203	0.722	2.057	3.008	0.0039
7	C(A)- Out -In(A)	64	64	65	0.583	0.185	2.212	3.501	0.0036
8	Out(S)-C(A)	65	64	64	1.038	1.026	0.934	1.443	0.0151
9	In(A)-C(A)-Out	64	65	64	0.363	1.536	1.091	1.703	0.0074
10	In(A)-Out-C(A)	65	64	64	1.001	0.626	1.371	1.599	0.0137

Table 3.2. PLRM results at the BOC.

1 1.053 16.25	2 1.090 16.99	1 1.046 16.43	2 1.071 17.16	1 1.021 16.52	2 1.019 17.16	1 0.932 15.65	3 0.847 12.15
	1 1.046 16.38	2 1.076 17.34	1 1.038 16.54	2 1.053 17.25	1 0.996 16.54	3 0.978 17.08	3 0.852 12.19
		2 1.070 17.82	2 1.072 17.48	1 1.038 16.57	2 1.055 17.00	1 0.985 15.11	3 0.840 11.05
			1 1.053 16.64	2 1.089 17.21	1 1.061 16.08	3 1.116 15.42	3 0.688 8.29
				1 1.074 16.24	2 1.142 16.07	3 0.961 12.13	
					3 1.156 14.84	3 0.740 8.45	

Assembly Type → Relative BOC Power → Cycle Burnup (MWd/kg)

1 0.898 16.48	3 0.936 17.82	1 0.938 16.82	3 0.981 18.11	1 0.983 16.80	3 1.036 17.52	1 1.052 14.14	2 0.903 9.72
	1 0.925 16.74	3 0.969 18.47	1 0.977 17.00	3 1.014 18.10	1 1.012 16.16	2 1.122 14.66	2 0.910 9.65
		3 0.994 19.33	3 1.018 18.70	1 1.023 16.93	3 1.078 17.39	1 1.067 13.63	2 0.863 8.82
			1 1.035 17.13	3 1.087 18.04	1 1.099 15.66	2 1.109 13.04	2 0.675 6.51
				1 1.127 16.33	3 1.279 16.04	2 0.956 10.30	
					2 1.165 12.99	2 0.716 6.88	

Assembly Type → Relative BOC Power → Cycle Burnup (MWd/kg)

1 0.966 16.05	2 1.003 17.00	3 0.998 18.35	1 0.999 16.91	2 1.054 17.58	3 1.084 18.37	1 1.089 15.03	2 0.885 9.86
	1 0.959 16.20	2 0.999 17.42	3 1.015 18.23	1 1.027 16.85	2 1.099 17.49	3 1.218 16.42	1 0.859 9.54
		1 0.950 16.07	1 0.975 16.52	3 1.044 18.30	1 1.048 16.35	2 1.158 15.08	3 0.928 9.83
			2 1.029 17.49	2 1.053 17.69	3 1.080 17.40	1 1.012 12.86	2 0.659 6.72
				1 1.047 15.92	2 1.118 15.19	3 0.951 10.84	
					1 0.997 11.78	3 0.713 7.18	

Assembly Type → Relative BOC Power → Cycle Burnup (MWd/kg)

3 1.234 19.45	2 1.226 18.92	3 1.207 19.53	2 1.181 19.15	3 1.151 19.64	2 1.123 18.23	3 1.214 15.99	1 0.817 8.73
	3 1.217 19.46	2 1.198 18.85	3 1.170 19.67	2 1.136 19.04	3 1.101 18.61	1 1.071 14.38	1 0.784 8.36
		2 1.175 18.60	2 1.142 18.99	3 1.102 19.51	2 1.066 17.90	3 1.152 15.27	1 0.745 7.92
			3 1.100 19.61	2 1.048 18.59	3 1.005 17.50	1 0.915 12.12	1 0.532 5.52
				3 0.993 18.12	2 0.983 14.83	1 0.704 8.63	
					1 0.836 10.74	1 0.496 5.35	

Assembly Type → Relative BOC Power → Cycle Burnup (MWd/kg)

Figure 3.2. The location of the assembly type and the power factors for PWR at the EOC given by PLRM code. Top and Left: No.1, out-in(S). Top and Right: No.2, low-leakage. Bottom and Left: No. 3, Pure scatter. Bottom and Right: No.4, very low-leakage.

1 1.207 14.49	1 1.185 14.48	1 1.137 14.54	1 1.067 14.76	1 0.999 15.45	2 1.002 17.51	2 0.939 17.02	3 0.820 12.33
	1 1.164 14.49	1 1.118 14.57	1 1.055 14.85	1 0.995 15.54	2 1.004 17.60	3 0.940 17.65	3 0.820 12.25
		1 1.082 14.78	1 1.044 15.33	1 1.008 15.96	2 1.043 17.50	2 1.027 16.48	3 0.825 11.25
			2 1.094 17.15	2 1.085 17.63	2 1.086 17.51	3 1.104 15.88	3 0.670 8.35
				2 1.106 17.65	2 1.125 16.47	3 0.940 12.15	
					3 1.132 14.78	3 0.721 8.31	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

3 1.279 21.17	3 1.267 21.25	3 1.241 21.31	3 1.203 21.19	3 1.151 20.44	2 1.090 17.84	2 1.083 14.71	1 0.759 8.46
	3 1.254 21.31	3 1.229 21.34	3 1.191 21.16	3 1.140 20.38	2 1.078 17.71	1 1.010 13.82	1 0.737 8.23
		3 1.205 21.25	3 1.169 20.81	3 1.119 20.01	2 1.065 17.53	2 1.045 14.14	1 0.698 7.73
			2 1.134 19.26	2 1.088 18.35	2 1.061 16.47	1 0.909 11.83	1 0.515 5.49
				2 1.060 17.16	2 1.033 14.66	1 0.717 8.71	
					1 0.864 10.90	1 0.506 5.52	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

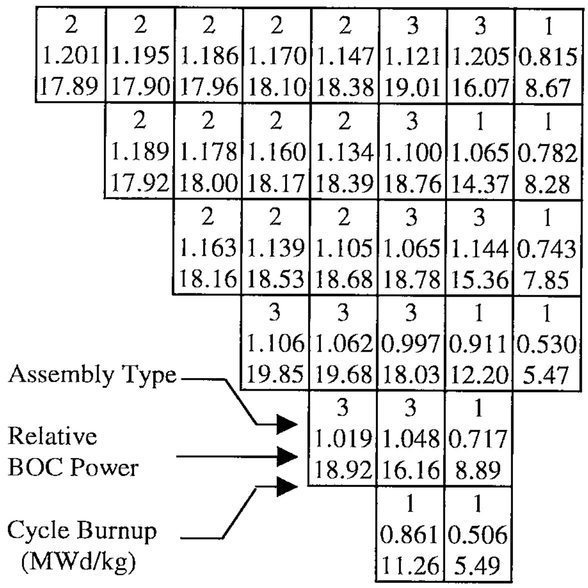
3 0.997 21.10	3 1.001 21.14	3 1.006 21.10	3 1.011 20.75	3 1.018 19.55	1 1.011 15.55	1 1.091 13.75	2 0.934 9.76
	3 1.005 21.16	3 1.009 21.05	3 1.013 20.61	3 1.024 19.43	1 1.029 15.60	2 1.165 14.48	2 0.941 2 9.75
		3 1.009 20.70	3 1.008 19.77	3 1.023 18.62	1 1.043 15.10	1 1.100 13.18	2 0.890 8.88
			1 0.964 16.52	1 1.009 15.41	1 1.083 14.13	2 1.131 12.60	2 0.692 6.54
				1 1.064 14.23	1 1.099 12.90	2 0.931 9.53	
					2 1.108 11.58	2 0.700 6.48	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

1 1.564 14.26	1 1.520 14.26	1 1.417 14.34	1 1.277 14.81	2 1.186 16.72	2 1.058 17.99	3 0.951 17.33	2 0.780 11.11
	1 1.477 14.24	1 1.377 14.31	1 1.236 14.66	1 1.097 15.75	3 1.039 18.41	2 0.965 16.61	3 0.815 11.32
		1 1.288 14.39	1 1.163 14.76	1 1.043 15.72	2 1.000 17.61	3 0.964 16.63	2 0.734 10.07
			1 1.072 15.46	2 1.021 17.22	3 0.932 18.10	2 0.892 14.45	3 0.585 7.56
				2 0.942 17.57	3 0.874 17.12	2 0.702 10.96	
					3 0.884 14.67	3 0.563 7.85	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

Figure 3.2. ***con't.*** The location of the assembly type and the power factors for PWR at the BOC given by PLRM code. Top and Left: No.5, out - in(*Annular Arrangement*) - Central(*Annular Arrangement*). Top and Right: No.6, Central(*Annular Arrangement)* - in(*Annular Arrangement*) - out. Bottom and Left: No. 7, Central(*Annular Arrangement)* - out - in(*Annular Arrangement*). Bottom and Right: No.8, out(*scatter Arrangement*) - Central(*Annular Arrangement)*.



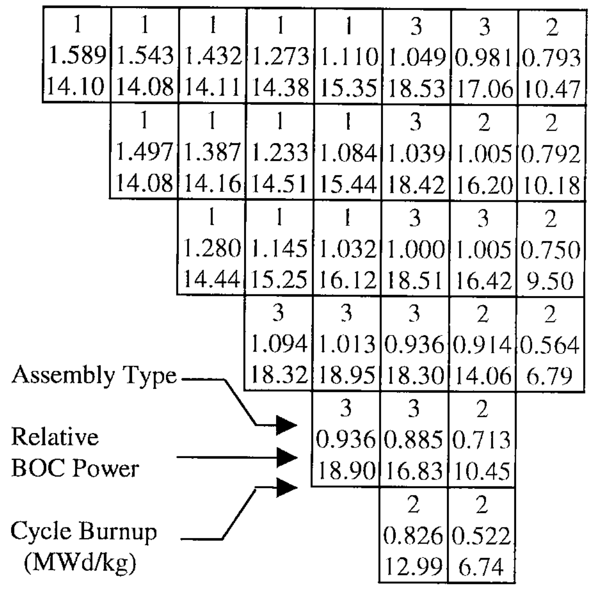


Figure 3.2. ***con't.*** The location of the assembly type and the power factors for PWR at the EOC given by PLRM code. Left: No.9, in(*Annular Arrangement*) - Central(*Annular Arrangement*) - out. Right: No. 10, in(*Annular Arrangement*) - out - Central(*Annular Arrangement*).

Arrangement Number	**Description**	**Batch Burnup MWd/kg**			**Average Assembly Power in Batch #**			**Core Average Cycle Burnup MWd/kg**	Leakage ρ
		1	2	3	1	2	3		
1	Out-In(S)	15.73	16.51	13.38	1.037	1.088	0.873	15.21	0.0239
2	Low Leakage	15.40	13.22	15.80	1.035	0.901	1.062	14.71	0.0247
3	Pure Scatter	14.85	14.97	14.62	1.004	1.010	0.984	14.81	0.0234
4	Very Low Leakage	11.50	17.05	17.05	0.753	1.122	1.121	15.21	0.0191
5	Out-In(A)-C(A)	16.65	15.36	12.69	1.123	1.026	0.847	14.91	0.0232
6	C(A)-In(A)-Out	11.46	16.63	18.39	0.736	1.069	1.191	15.51	0.0189
7	C(A)- Out -In(A)	15.65	13.65	15.42	1.049	0.913	1.036	14.91	0.0243
8	Out(S)-C(A)	17.99	13.44	12.35	1.238	0.916	0.841	14.61	0.0206
9	In(A)-C(A)-Out	11.36	17.70	16.23	0.745	1.183	1.068	15.11	0.0191
10	In(A)-Out-C(A)	17.70	11.26	14.52	1.231	0.768	0.996	14.51	0.0202

Table 3.3. PLRM results at the EOC.

Assembly Type / Relative BOC Power

1	2	1	2	1	2	1	3
1.858	1.889	1.743	1.613	1.334	1.112	0.800	0.476
	1	2	1	2	1	3	3
	1.811	1.794	1.545	1.351	1.059	0.835	0.471
		2	2	1	2	1	3
		1.750	1.527	1.230	1.005	0.703	0.396
			1	2	1	3	3
			1.302	1.121	0.854	0.625	0.284
				1	2	3	
				0.904	0.718	0.448	
					2	3	
					0.544	0.275	

Assembly Type / Relative BOC Power

1	3	1	3	1	3	1	2
2.168	2.252	2.013	1.833	1.387	1.062	0.621	0.306
	1	3	1	3	1	2	2
	2.113	2.140	1.721	1.435	0.977	0.617	0.298
		3	3	1	3	1	2
		2.112	1.748	1.271	0.953	0.545	0.256
			1	3	1	2	2
			1.393	1.148	0.766	0.456	0.182
				1	3	2	
				0.856	0.631	0.325	
					2	2	
					0.414	0.189	

Assembly Type / Relative BOC Power

1	2	3	1	2	3	1	2
1.868	1.932	1.986	1.670	1.452	1.228	0.778	0.383
	1	2	3	1	2	3	1
	1.822	1.839	1.721	1.371	1.134	0.803	0.366
		1	1	3	1	2	3
		1.584	1.452	1.351	0.989	0.683	0.340
			2	2	3	1	2
			1.347	1.164	0.911	0.525	0.223
				1	2	3	
				0.885	0.667	0.381	
					1	2	
					0.420	0.217	

Assembly Type / Relative BOC Power

3	2	3	2	3	2	3	1
2.395	2.275	2.146	1.844	1.546	1.105	0.678	0.276
	3	2	3	2	3	1	1
	2.259	2.018	1.826	1.462	1.088	0.609	0.256
		2	2	3	2	3	1
		1.815	1.618	1.363	0.965	0.579	0.228
			3	2	3	1	1
			1.449	1.136	0.813	0.419	0.151
				3	2	1	
				0.900	0.574	0.263	
					1	1	
					0.327	0.137	

Figure 3.3. The location of the assembly type and the power factors for PWR at the BOC given by RPM code. Top and Left: No.1, out-in(S). Top and Right: No.2, low-leakage. Bottom and Left: No. 3, Pure scatter. Bottom and Right: No.4, very low-leakage.

1 0.911	1 0.926	1 0.972	1 1.048	1 1.156	2 1.309	2 1.159	3 0.702
	1 0.941	1 0.990	1 1.068	1 1.168	2 1.308	3 1.178	3 0.688
		1 1.047	1 1.140	1 1.209	2 1.270	2 1.055	3 0.598
			2 1.303	2 1.322	2 1.215	3 0.933	3 0.429
				2 1.256	2 1.042	3 0.666	
					3 0.802	3 0.411	

Assembly Type

Relative BOC Power

3 2.986	3 2.885	3 2.593	3 2.144	3 1.583	2 0.956	2 0.501	1 0.197
	3 2.785	3 2.497	3 2.055	3 1.512	2 0.909	1 0.458	1 0.183
		3 2.218	3 1.789	3 1.303	2 0.789	2 0.411	1 0.157
			2 1.348	2 0.958	2 0.597	1 0.292	1 0.103
				2 0.666	2 0.405	1 0.180	
					1 0.225	1 0.092	

Assembly Type

Relative BOC Power

3 3.448	3 3.310	3 2.917	3 2.323	3 1.606	1 0.829	1 0.426	2 0.193
	3 3.173	3 2.783	3 2.200	3 1.514	1 0.785	2 0.421	2 0.186
		3 2.401	3 1.828	3 1.234	1 0.644	1 0.335	2 0.149
			1 1.201	1 0.774	1 0.447	2 0.249	2 0.098
				1 0.485	1 0.287	2 0.150	
					2 0.177	2 0.080	

Assembly Type

Relative BOC Power

1 0.823	1 0.843	1 0.910	1 1.043	2 1.281	2 1.416	3 1.216	2 0.657
	1 0.861	1 0.921	1 1.035	1 1.213	3 1.423	2 1.156	3 0.649
		1 0.970	1 1.066	1 1.204	2 1.328	3 1.093	2 0.557
			1 1.163	2 1.306	3 1.304	2 0.898	3 0.403
				2 1.293	3 1.139	2 0.644	
					3 0.856	3 0.416	

Assembly Type

Relative BOC Power

Figure 3.3. ***con't.*** The location of the assembly type and the power factors for PWR at the BOC given by RPM code. Top and Left: No.5, out - in(*Annular Arrangement*) - Central(*Annular Arrangement*). Top and Right: No.6, Central(*Annular Arrangement)* - in(*Annular Arrangement*) - out. Bottom and Left: No. 7, Central(*Annular Arrangement)* - out - in(*Annular Arrangement*). Bottom and Right: No.8, out(*scatter Arrangement*) - Central(*Annular Arrangement)*.

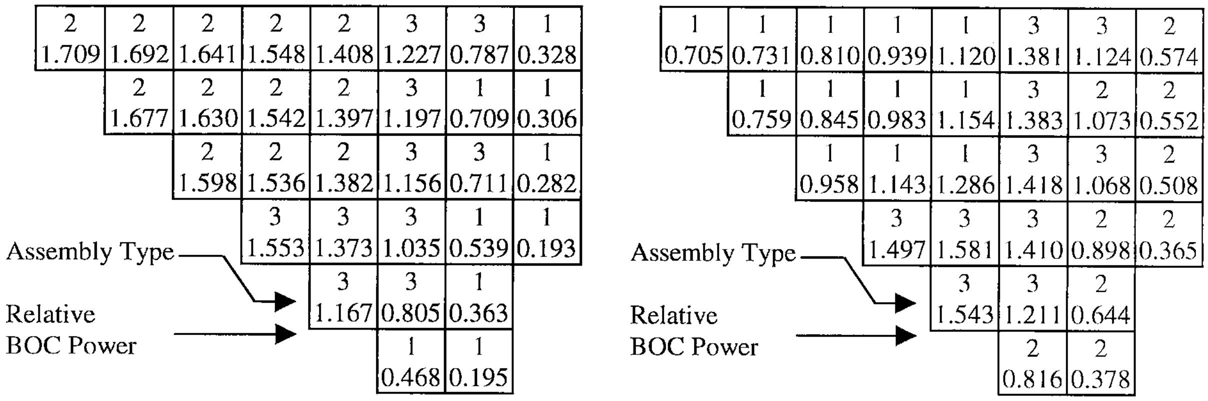


Figure 3.3. ***con't.*** The location of the assembly type and the power factors for PWR at the BOC given by RPM code. Left: No.9, in(*Annular Arrangement*) - Central(*Annular Arrangement)* - out. Right: No. 10, in(*Annular Arrangement*) - out - Central(*Annular Arrangement)*.

Arrangement Number	**Description**	**Number of Assemblies in Batch #**			**Average Assembly Power in Batch #**			Peak Assembly	Leakage ρ
		1	2	3	1	2	3		
1	Out-In(S)	65	64	64	1.178	1.337	0.481	1.889	0.0110
2	Low Leakage	65	64	64	1.199	0.336	1.461	2.252	0.0073
3	Pure Scatter	65	64	64	1.048	1.033	0.916	1.932	0.0089
4	Very Low Leakage	64	64	65	0.295	1.411	1.287	2.395	0.0060
5	Out-In(A)-C(A)	65	64	64	1.075	1.216	0.707	1.322	0.0165
6	C(A)-In(A)-Out	64	64	65	0.210	0.725	2.047	2.986	0.0042
7	C(A)- Out -In(A)	64	64	65	0.593	0.190	2.197	3.448	0.0038
8	Out(S)-C(A)	65	64	64	1.038	1.027	0.933	1.423	0.0158
9	In(A)-C(A)-Out	64	65	64	0.373	1.536	1.081	1.709	0.0078
10	In(A)-Out-C(A)	65	64	64	1.004	0.639	1.355	1.581	0.0144

Table 3.4. RPM results at the BOC.

1 0.568 18.39	2 0.611 18.94	1 0.664 18.24	2 0.806 18.33	1 0.933 17.18	2 1.123 16.93	1 1.162 14.87	3 1.008 11.25
	1 0.615 18.38	2 0.715 19.01	1 0.803 17.78	2 0.984 17.69	1 1.106 16.40	3 1.239 15.72	3 1.015 11.26
		2 0.802 19.34	2 0.902 18.41	1 1.010 16.97	2 1.180 16.56	1 1.176 14.23	3 0.957 10.25
			1 0.973 17.23	2 1.134 17.09	1 1.198 15.54	3 1.212 13.92	3 0.768 7.97
				1 1.188 15.85	2 1.270 15.06	3 1.041 11.28	
					3 1.215 13.32	3 0.795 8.11	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

1 0.425 19.76	3 0.471 20.75	1 0.546 19.50	3 0.738 19.59	1 0.930 17.65	3 1.197 17.21	1 1.229 14.10	2 1.018 10.09
	1 0.482 19.77	3 0.600 20.88	1 0.735 18.71	3 0.992 18.49	1 1.161 16.29	2 1.286 14.50	2 1.018 10.03
		3 0.705 21.46	3 0.853 19.82	1 1.020 17.46	3 1.259 16.86	1 1.231 13.53	2 0.952 9.20
			1 0.958 17.91	3 1.181 17.74	1 1.259 15.43	2 1.228 12.84	2 0.749 7.10
				1 1.250 16.05	3 1.352 15.11	2 1.043 10.43	
					2 1.230 12.53	2 0.775 7.34	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

1 0.567 18.51	2 0.612 19.34	3 0.696 20.39	1 0.776 18.59	2 0.976 18.46	3 1.177 18.28	1 1.166 14.78	2 0.925 9.94
	1 0.612 18.50	2 0.712 19.39	3 0.838 19.45	1 0.962 17.74	2 1.177 17.57	3 1.251 15.61	1 0.900 9.62
		1 0.741 17.68	1 0.874 17.68	3 1.085 18.52	1 1.171 16.42	2 1.242 14.63	3 0.940 9.73
			2 1.044 18.18	2 1.189 17.89	3 1.295 16.77	1 1.128 12.57	2 0.710 7.09
				1 1.214 15.96	2 1.276 14.77	3 1.022 10.67	
					1 1.099 11.55	3 0.762 7.44	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

3 0.506 22.64	2 0.539 21.97	3 0.650 21.82	2 0.814 20.75	3 1.033 20.13	2 1.222 18.17	3 1.259 15.12	1 0.863 8.89
	3 0.579 22.15	2 0.683 21.08	3 0.855 20.93	2 1.054 19.64	3 1.246 18.22	1 1.191 14.04	1 0.842 8.57
		2 0.788 20.32	2 0.949 20.03	3 1.148 19.60	2 1.294 17.63	3 1.267 14.41	1 0.812 8.11
			3 1.102 19.91	2 1.248 18.61	3 1.343 16.83	1 1.106 11.90	1 0.613 5.96
				3 1.351 17.57	2 1.285 14.51	1 0.883 8.95	
					1 1.050 10.75	1 0.619 5.90	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

Figure 3.4. The location of the assembly type and the power factors for PWR at the EOC given by RPM code. Top and Left: No.1, out-in(S). Top and Right: No.2, low-leakage. Bottom and Left: No. 3, Pure scatter. Bottom and Right: No.4, very low-leakage.

1 1.044 14.73	1 1.033 14.76	1 1.008 14.92	1 0.983 15.31	1 0.990 16.17	2 1.095 18.12	2 1.102 17.04	3 0.888 11.98
	1 1.023 14.81	1 1.001 15.00	1 0.980 15.44	1 0.991 16.27	2 1.101 18.16	3 1.121 17.33	3 0.885 11.86
		1 0.987 15.32	1 0.988 16.03	1 1.011 16.73	2 1.114 17.96	2 1.103 16.27	3 0.844 10.87
			2 1.067 17.86	2 1.105 18.29	2 1.139 17.73	3 1.071 15.10	3 0.669 8.28
				2 1.139 18.05	2 1.119 16.29	3 0.896 11.76	
					3 1.039 13.87	3 0.678 8.20	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

3 0.287 25.88	3 0.330 25.41	3 0.465 24.18	3 0.700 22.48	3 1.004 20.45	2 1.260 17.51	2 1.295 14.20	1 0.903 8.70
	3 0.374 24.97	3 0.512 23.79	3 0.748 22.15	3 1.045 20.21	2 1.276 17.27	1 1.245 13.46	1 0.885 8.44
		3 0.657 22.72	3 0.889 21.17	3 1.165 19.51	2 1.356 16.96	2 1.307 13.59	1 0.849 7.96
			2 1.085 19.23	2 1.305 17.89	2 1.405 15.82	1 1.167 11.54	1 0.647 5.92
				2 1.424 16.52	2 1.373 14.05	1 0.942 8.87	
					1 1.125 10.67	1 0.662 5.96	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

3 0.195 28.40	3 0.237 27.65	3 0.374 25.65	3 0.622 22.95	3 0.941 19.85	1 1.146 15.39	1 1.298 13.44	2 1.089 10.00
	3 0.281 26.92	3 0.423 24.99	3 0.674 22.39	3 0.988 19.50	1 1.185 15.35	2 1.373 13.98	2 1.093 9.96
		3 0.574 23.19	3 0.812 20.57	3 1.099 18.19	1 1.242 14.70	1 1.312 12.83	2 1.023 9.13
			1 0.947 16.74	1 1.163 15.09	1 1.311 13.71	2 1.321 12.23	2 0.808 7.06
				1 1.285 13.80	1 1.323 12.55	2 1.096 9.72	
					2 1.275 11.31	2 0.819 7.01	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

1 1.118 14.61	1 1.103 14.65	1 1.066 14.87	1 1.029 15.59	2 1.064 17.65	2 1.096 18.91	3 1.096 17.40	2 0.855 11.38
	1 1.089 14.68	1 1.054 14.87	1 1.014 15.42	1 1.010 16.73	3 1.102 19.00	2 1.087 16.88	3 0.866 11.41
		1 1.029 15.04	1 1.005 15.59	1 1.015 16.70	2 1.104 18.31	3 1.096 16.47	2 0.809 10.28
			1 1.018 16.41	2 1.094 18.06	3 1.135 18.36	2 1.024 14.47	3 0.650 7.92
				2 1.128 18.22	3 1.115 16.97	2 0.849 11.23	
					3 1.022 14.13	3 0.658 8.08	

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

Figure 3.4. ***con't.*** The location of the assembly type and the power factors for PWR at the EOC given by RPM code. Top and Left: No.5, out - in(*Annular Arrangement*) - Central(*Annular Arrangement*). Top and Right: No.6, Central(*Annular Arrangement)* - in(*Annular Arrangement*) - out. Bottom and Left: No. 7, Central(*Annular Arrangement)* - out - in(*Annular Arrangement*). Bottom and Right: No.8, out(*scatter Arrangement*) - Central(*Annular Arrangement)*

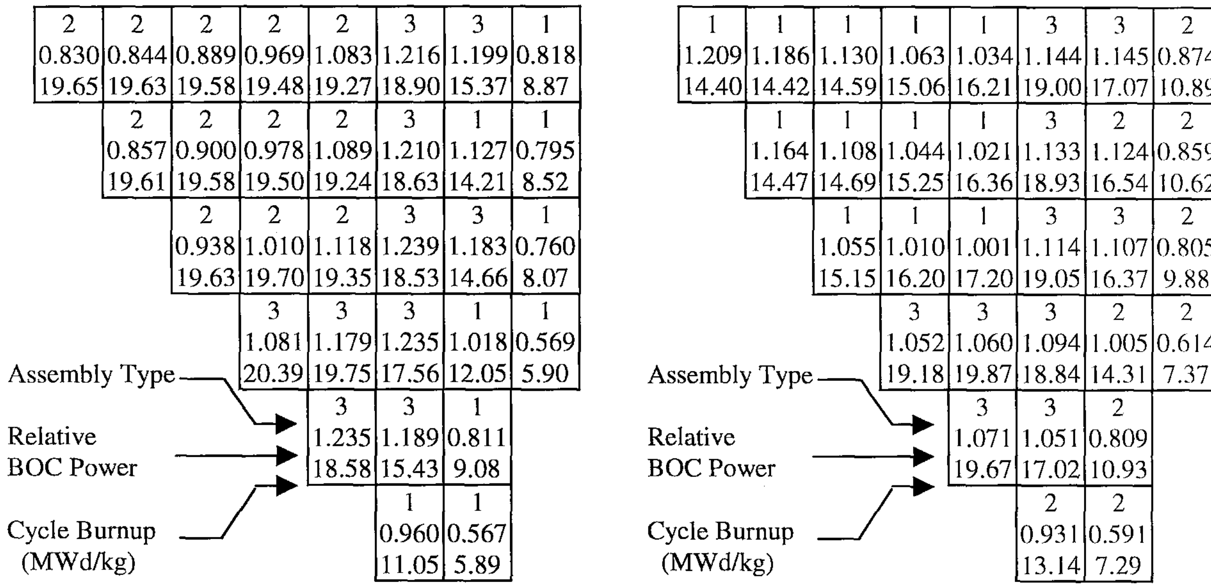


Figure 3.4. ***con't.*** The location of the assembly type and the power factors for PWR at the EOC given by RPM code. Left: No.9, in(*Annular Arrangement*) - Central(*Annular Arrangement)* - out. Right: No. 10, in(*Annular Arrangement*) - out - Central(*Annular Arrangement)*.

Arrangement Number	**Description**	**Batch Burnup MWd/kg**			**Average Assembly Power in Batch #**			**Core Average Cycle Burnup MWd/kg**	Leakage ρ
		1	2	3	1	2	3		
1	Out-In(S)	16.51	17.58	11.35	1.000	0.981	1.017	15.15	0.0275
2	Low Leakage	16.79	10.35	18.56	1.003	1.021	0.974	15.23	0.0272
3	Pure Scatter	15.37	15.54	14.69	0.973	1.010	1.016	15.20	0.0259
4	Very Low Leakage	9.16	19.02	18.61	0.877	1.024	1.096	15.61	0.0225
5	Out-In(A)-C(A)	15.63	17.53	12.05	0.998	1.110	0.890	15.07	0.0238
6	C(A)-In(A)-Out	8.98	16.17	22.18	0.926	1.319	0.758	15.81	0.0238
7	C(A)- Out -In(A)	14.24	9.97	22.44	1.234	1.089	0.681	15.58	0.0290
8	Out(S)-C(A)	15.61	15.29	14.25	1.034	1.004	0.960	15.05	0.0230
9	In(A)-C(A)-Out	9.22	19.50	17.65	0.817	0.983	1.199	15.47	0.0209
10	In(A)-Out-C(A)	15.57	11.12	18.45	1.064	0.838	1.095	15.04	0.0220

Table 3.5. RPM results at the EOC.

3.4. Data evaluation for BWR

There is a study in the field of thermal hydraulic and neutronic calculations in BWR. 1-D BWR assembly is modelled. Converged axial power profile in this study is obtained. Then, using these results, a code, which performs radial power distribution calculations in BWR, and its interface programs was developed. The code was named "COUPLE".

In this Thesis, 1-D BWR assembly model was used. Previous study in H.U. Nuclear Energy Dept.[5] only dealed with axial power shape and Multiplication factor. It's aim was achieved. But it hasn't burnup capability.

To do it, A new program (namely "CBU") is developed, so that it has burnup capability. Figure 3.7 shows that this program has algorithm. Converged power profile is used at the each burnup step. Figure 3.8 show that program output.

Using developed program, 18 different power peaking is evaluated with 3 MWd/kg burnup step up to 30 MWd/kg.

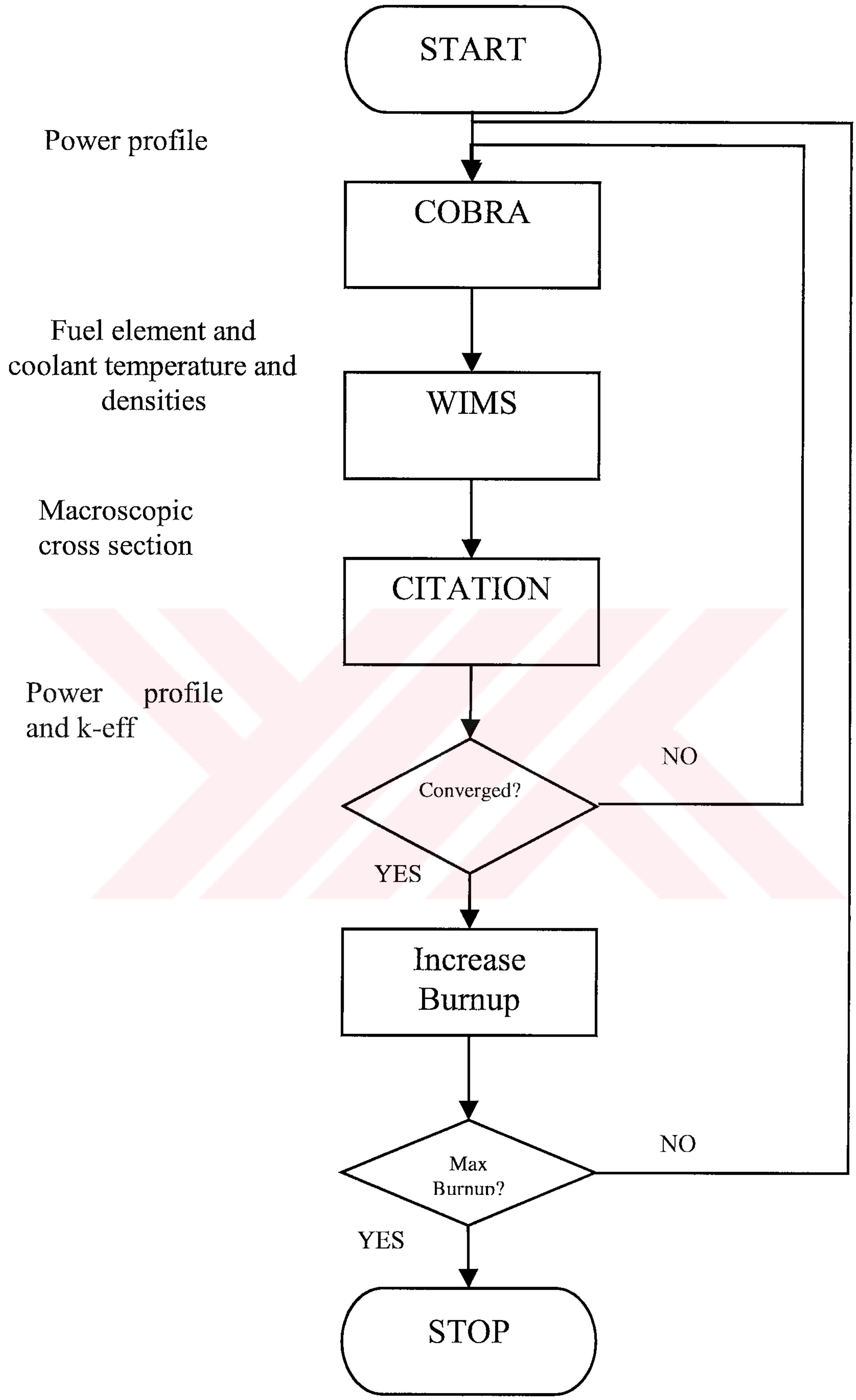


Figure 3.5. Flow chart of neutronics and thermalhydraulics coupling for BWR

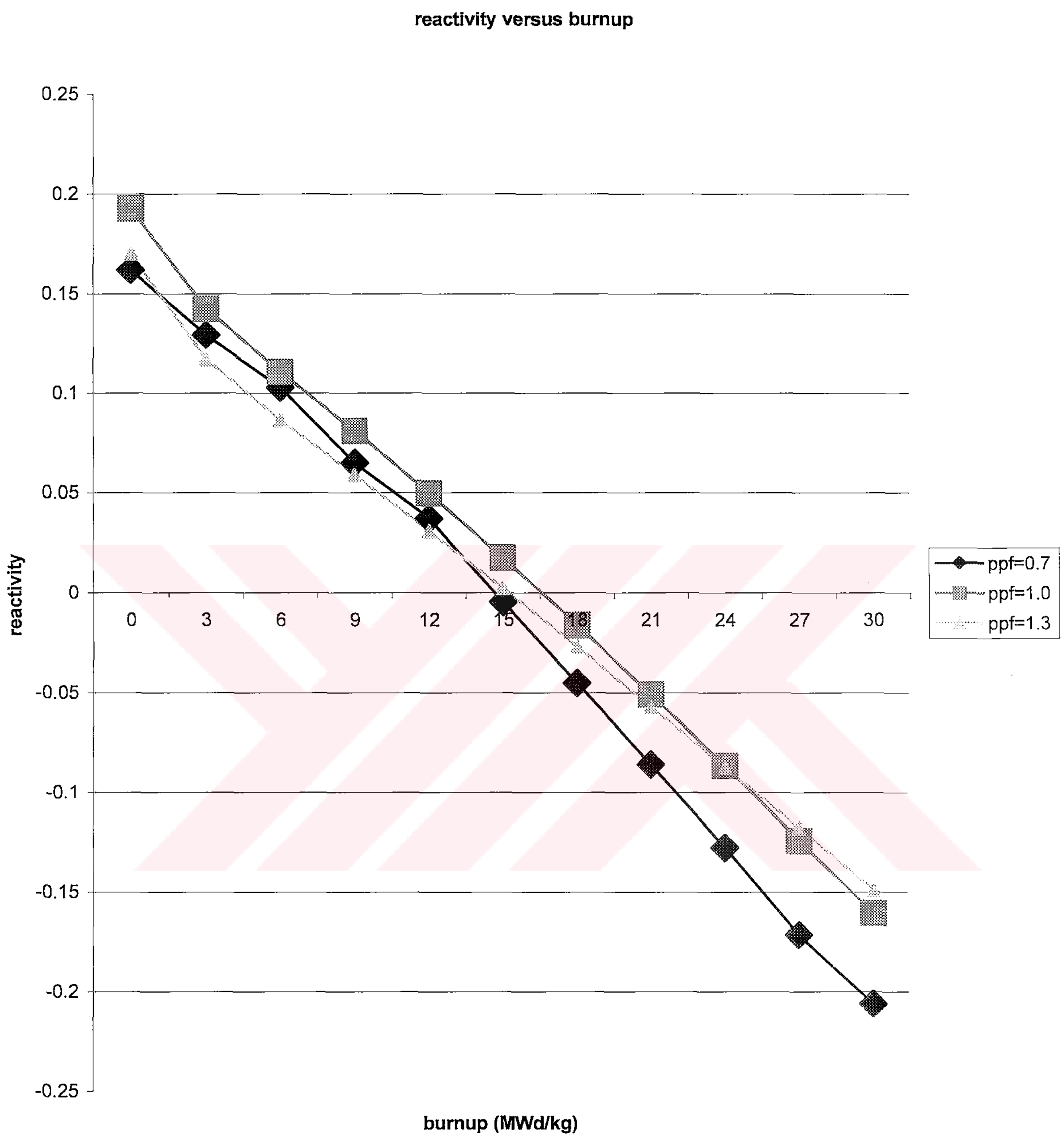


Figure 3.6. 1-D BWR results. The variation of reactivity as a function of burnup for three different power peaking factors. ppf=0.7, 1.0, and, 1.3.

0.85	0.83	0.80	0.75	0.68	0.58									
0.92	0.91	0.88	0.84	0.77	0.67	0.55								
0.98	0.97	0.95	0.92	0.87	0.78	0.67	0.54							
1.03	1.02	1.01	0.98	0.94	0.88	0.80	0.69	0.57	0.45					
1.07	1.07	1.06	1.04	1.00	0.95	0.90	0.82	0.71	0.59	0.45				
1.11	1.11	1.10	1.08	1.06	1.02	0.97	0.91	0.84	0.72	0.59	0.45			
1.15	1.14	1.14	1.12	1.10	1.07	1.03	0.98	0.91	0.84	0.71	0.57			
1.17	1.17	1.17	1.16	1.14	1.12	1.08	1.03	0.98	0.91	0.82	0.69	0.54		
1.20	1.20	1.19	1.18	1.17	1.14	1.12	1.08	1.03	0.97	0.90	0.80	0.67	0.55	
1.22	1.22	1.21	1.20	1.19	1.17	1.14	1.12	1.07	1.02	0.95	0.88	0.78	0.67	0.58
1.23	1.23	1.22	1.22	1.20	1.18	1.17	1.14	1.10	1.06	1.00	0.94	0.87	0.77	0.68
1.24	1.24	1.23	1.23	1.22	1.20	1.18	1.16	1.12	1.08	1.04	0.98	0.92	0.84	0.75
1.24	1.24	1.24	1.23	1.22	1.21	1.19	1.17	1.14	1.10	1.06	1.01	0.95	0.88	0.80
1.25	1.25	1.24	1.24	1.23	1.22	1.20	1.17	1.14	1.11	1.07	1.02	0.97	0.91	0.83
1.25	1.25	1.24	1.24	1.23	1.22	1.20	1.17	1.15	1.11	1.07	1.03	0.98	0.92	0.85

Figure 3.7. Radial power distribution for BWR. [5]

1.250	1.245	1.235	1.210	1.160	1.090	1.005	0.885
	1.243	1.230	1.205	1.155	1.080	0.987	0.855
		1.218	1.185	1.130	1.045	0.928	0.760
			1.143	1.075	0.960	0.783	0.600
				0.975	0.820	0.600	
					0.588		

Figure 3.8. Pre-averaged radial power distribution for BWR. [5]

Assembly Type / Relative BOC Power

1 1.367	1 1.360	1 1.345	1 1.314	1 1.254	1 1.142	1 0.934	1 0.678
	1 1.354	1 1.337	1 1.304	1 1.240	1 1.122	1 0.897	1 0.658
		1 1.317	1 1.277	1 1.203	1 1.065	1 0.805	1 0.602
			1 1.225	1 1.130	1 0.955	1 0.710	1 0.517
				1 1.004	1 0.772	1 0.582	
					1 0.606		

Assembly Type / Relative BOC Power

1 1.535	1 1.524	1 1.502	1 1.455	1 1.363	1 1.187	1 0.837	1 0.488
	1 1.514	1 1.490	1 1.441	1 1.346	1 1.164	1 0.805	1 0.470
		1 1.462	1 1.405	1 1.298	1 1.101	1 0.739	1 0.419
			1 1.333	1 1.200	1 0.959	1 0.612	1 0.314
				1 1.022	1 0.705	1 0.400	
					1 0.428		

Assembly Type / Relative BOC Power

1 1.367	1 1.361	1 1.346	1 1.318	1 1.268	1 1.182	1 1.041	1 0.796
	1 1.354	1 1.337	1 1.306	1 1.250	1 1.154	1 1.000	1 0.758
		1 1.315	1 1.272	1 1.196	1 1.066	1 0.837	1 0.632
			1 1.207	1 1.109	1 0.898	1 0.675	1 0.490
				1 0.916	1 0.693	1 0.487	
					1 0.487		

Assembly Type / Relative BOC Power

1 1.390	1 1.368	1 1.326	1 1.267	1 1.191	1 1.103	1 1.006	1 0.902
	1 1.346	1 1.303	1 1.243	1 1.165	1 1.073	1 0.969	1 0.860
		1 1.258	1 1.192	1 1.107	1 1.005	1 0.876	1 0.763
			1 1.117	1 1.018	1 0.886	1 0.751	1 0.660
				1 0.888	1 0.744	1 0.627	
					1 0.624		

Figure 3.9. The location of the assembly type and the power factors for BWR at the EOC given by PLRM code. **Top and Left**: No.1Radial leakage=0.04 & Power sharing=2.0. **Top and Right**: No.2 Radial leakage=0.1&Power sharing=2.0. **Bottom and Left**: No. 3, Radial leakage is variable & Power sharing=2.0. **Bottom and Right**: No.4, Radial leakage is variable &Power sharing is variable

1 0.658 16.42	1 0.668 16.39	1 0.706 16.38	1 0.794 16.37	1 0.958 16.30	1 1.074 15.98	1 1.123 15.08	1 1.077 12.65
	1 0.679 16.37	1 0.722 16.35	1 0.816 16.34	1 0.978 16.24	1 1.082 15.89	1 1.128 14.92	1 1.079 12.46
		1 0.776 16.34	1 0.889 16.29	1 1.026 16.12	1 1.106 15.63	1 1.139 14.39	1 1.077 11.87
			1 1.000 16.16	1 1.079 15.81	1 1.128 15.01	1 1.128 13.22	1 1.020 10.59
				1 1.117 15.12	1 1.117 13.56	1 1.077 11.14	
					1 1.017 11.24		

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

1 1.123 16.85	1 1.121 16.79	1 1.124 16.73	1 1.130 16.62	1 1.134 16.33	1 1.122 15.58	1 1.045 13.69	1 0.758 9.16
	1 1.118 16.72	1 1.122 16.66	1 1.128 16.53	1 1.132 16.21	1 1.118 15.40	1 1.039 13.43	1 0.749 8.95
		1 1.125 16.57	1 1.130 16.38	1 1.131 15.94	1 1.110 14.92	1 1.018 12.55	1 0.717 8.23
			1 1.132 16.06	1 1.121 15.34	1 1.070 13.82	1 0.916 10.64	1 0.597 6.41
				1 1.076 14.04	1 0.947 11.27	1 0.655 7.33	
					1 0.662 7.52		

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

1 1.029 16.87	1 1.028 16.83	1 1.032 16.81	1 1.040 16.77	1 1.049 16.68	1 1.058 16.44	1 1.056 15.89	1 1.016 14.68
	1 1.028 16.80	1 1.032 16.77	1 1.040 16.72	1 1.050 16.59	1 1.057 16.29	1 1.051 15.61	1 1.004 14.14
		1 1.037 16.72	1 1.045 16.61	1 1.053 16.37	1 1.054 15.84	1 1.030 14.66	1 0.923 12.30
			1 1.052 16.39	1 1.053 15.89	1 1.035 14.85	1 0.961 12.81	1 0.785 10.15
				1 1.033 14.85	1 0.955 12.77	1 0.762 9.85	
					1 0.760 11.31		

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

1 1.179 18.07	1 1.170 17.89	1 1.155 17.56	1 1.134 17.09	1 1.104 16.47	1 1.065 15.69	1 1.015 14.77	1 0.948 13.58
	1 1.161 17.70	1 1.145 17.37	1 1.123 16.88	1 1.092 16.24	1 1.051 15.43	1 0.998 14.43	1 0.924 13.17
		1 1.128 17.01	1 1.102 16.47	1 1.066 15.75	1 1.018 14.84	1 0.949 13.57	1 0.857 12.03
			1 1.071 15.85	1 1.027 15.01	1 0.962 13.81	1 0.878 12.33	1 0.779 10.87
				1 0.965 13.88	1 0.880 12.39	1 0.772 10.76	
					1 0.772 10.78		

Assembly Type
Relative BOC Power
Cycle Burnup (MWd/kg)

Figure 3.10. The location of the assembly type and the power factors for BWR at the EOC given by PLRM code. **Top and Left**: No.1Radial leakage=0.04 & Power sharing=2.0. **Top and Right**: No.2 Radial leakage=0.1&Power sharing=2.0. **Bottom and Left**: No. 3, Radial leakage is variable & Power sharing=2.0. **Bottom and Right**: No.4, Radial leakage is variable &Power sharing is variable

The power peaking factors of fuel assemblies of the BWR core are given in Figure 3.8 and 3.9. The infinity and L_1 norms of the error is minimized when radial leakage correction and power sharing, e.g., variable migration area are used as a function of power generated in each assembly. The infinity norm of the error of the power peaking factor is about 11.2% at the central region of the BWR core and it is shown in Table 3.6. The L_1 norm of the error in the power peaking factor is also given in Table 3.6. as 4.35%. The results show that the nonlinear feedback due to void formation in BWRs must be taken into account in the fuel management calculations by means of variable migration area as well as including piecewise linear reactivity model.

Arrangement Number	Description	Peak Assembly	Leakage ρ	The Max. point error (%)	Integral error (%)
1	Radial leakage=0.04 Power sharing=2.0	1.367	0.0076	30.0	9.3
2	Radial leakage=0.1 Power sharing=2.0	1.535	0.0129	47.6	21.0
3	Radial leakage corrected Power sharing=2.0	1.367	0.0080	18.8	9.2
4	Radial leakage corrected Power sharing is variable	1.390	0.0101	**11.2**	**4.35**

Table 3.6. PLRM results at the BOC for BWR.

Arrangement Number	Description	Core Average Cycle Burnup MWd/kg	Leakage reactivity
1	Radial leakage=0.04 Power sharing=2.0	14.71	0.0134
2	Radial leakage=0.1 Power sharing=2.0	13.41	0.0216
3	Radial leakage corrected Power sharing=2.0	14.91	0.0122
4	Radial leakage corrected Power sharing is variable	14.61	0.0120

Table 3.7. PLRM results at the EOC for BWR.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Estimating the reactivity of fuel assemblies as a function of burnup provides an important imformation for developing fuel management strategies in nuclear reactors. Different reactors have their own characteristic relations between the reactivity of the fuel assemblies and the burnup. For instance, the reactivity in PWRs can be charecterized by a linear function of the assembly burnup. However, the reactivity of the assemblies in other type of commercial reactors is not only the function of burnup, but also the function of the power peaking factor of the assembly. Especially, the reactivity in BWRs must be modelled as a nonlinear function of the burnup and power peaking factor due to the reactivity feedback effect of the void.

In this study, the PLRM computer code based on the RPM code power sharing relationship algorithm was developed. The PLRM code generates the BOC power map and the EOC power map and the assembly burnup using a piecewise linear model. The code uses the variable migration area in the calculation of assembly power peaking factors. The migration area in the BWRs is also changed with the assembly power. Thus, the migration area is related to the assembly power.

In RPM code, a simple iterative scheme is applied using the linear reactivity model. In this scheme, the code initially calculates the BOC and the EOC power peaking factors and assembly burnups are calculated with these power peaking factors. However, in the PLRM code,the calculation of the BOC and the EOC converged power peaking factors are performed by the inclusion of the nonlinear model. Thus, these calculations are performed at a number of given burnup steps, and the EOC assembly burnup is obtained considering the power peaking factor of the assembly at each burnup steps. An under-relaxation method is applied at each burnup step calculation to improve the convergence characteristics of the code. As a result, the converged power map in the PLRM computer codc is used during the next step of the calculation as an initial condition. This concept is especially important in the fuel management of BWRs due to void reactivity feedback.

The PLRM computer code can perform fuel management calculations in 2-D. Only radial power peaking factors are generated by the code. However, the axial power distribution may be an important factor to be taken into account as in the case of BWRs. Normally, the axial power profile of a BWR assembly is function of the assembly power history and it is normally bottom peaked. This effect should not be ignored in the fuel management analysis of such reactors. In this study, this effect is taken into account by coupling the neutronics and thermal hydraulics characteristics for each fuel assembly in the axial direction for different power peaking factors and power histories. The current study may be extended for 3-D calculations to analyze BWRs and to obtain more realistic and accurate results for full core geometry.

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