CORE LOADING DESIGN FOR BUSHEHR PRESSURIZED WATER REACTOR

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Abstract The modified out-in fuel management strategy was applied to the core loading design for the first four cycles of the Bushehr (Iran-1) KWU designed Pressurized Water Reactor (PWR). The minimum peak-to-average power density was chosen as the objective function of the optimization process. Lattice homogenization and group constants generation were performed by using the LEOPARD computer code. For core calculations the ERUPT code was applied. The optimum core configurations were designed after several hand shufflings of fuel assemblies. For the equilibrium cycle, a satisfactory value of 2.73 was found for the peaking power factor. The average discharge burn-up of this cycle was determined to be around 33,700 MWD / MTU.

چکیده در این مقاله طراحی سوخت گذاری قلب راکتور اتمی بوشهر (واحد شماره ۱) ، برای اولین چهار سیکل سوخت آن و با استفاده از روش مدیریت سوخت خارج به داخل (out-in)، ارائه می گردد. این راکتور از نوع آب سبک تحت فشار(PWR) می باشد و توسّط شرکت آلمانی KWU طراحی شده است. در محاسبات انجام شده حداقل نسبت تراکم توان (نسبت مقدار حداکثر به مقدار متوسط) بعنوان تابع هدف در بهینه سازی طرح مورد توجه قرار گرفته است. دراین طراحی محاسبات مربوط به همگن سازی شبکه و تولید ثوابت گروهی بکمک برنامه کامپیوتری LEOPARD انجام شده و برای محاسبات نوترونیک قلب، ازبرنامه کامپیوتری دیگر بنام ERUPT استفاده گردید. ضمناً دستیابی به طرح بهینه سوخت گذاری با تعویض مکرّر محل مجموعه های سوخت با یکدیگر در داخل قلب و تکرار محاسبات مربوط صورت گرفته است. ضریب حداکثر توان (Peaking Power facter) برای سیکل تعادل برابر ۲/۷۳ محاسبه شده که مقدار قابل قبولی است همچنین بر مبنای محاسبات انجام شده متوسط میزان مصرف سوخت (Burnup) برای سوخت خارج شده در پایان سیکل تعادل، برابر ۳۳۷۰۰ مگاوات ـ روز به ازاء یک تن اورانیوم.

INTRODUCTION

In nuclear fuel management, like the more general program of energy management, the main objective of any optimization plan is to minimize the cost. In the out-of-core fuel management, which basically involves uranium procurement, enrichment, fabrication, re-processing, etc...., the minimum levelized cost is the only characteristic of an optimized program, Here, the enrichment as a variable parameter plays the prominent role. In the in-core fuel management, there exists a conservative strategy which prefers designs implying the flattest possible spatial power distribution during the cycle. This strategy leads to a higher leakage, shorter cycle, and consequently suboptimal fuel utilization. In this socalled «out-in» scheme, the fresh fuel assemblies are loaded at the core periphery, while once and twice - burned fuel assemblies are arranged in a «checkerboard» pattern towards the core center. Several attempts to develop and implement an automatic optimization of the loading configurations were undertaken during the last three decades. Not all of these optimization techniques were based on minimum power peaking. Wall and Fenech [1] first demonstrated that dynamic programming could be used to optimize burn - up as the objective function. Naft and Sesonsky [2] proposed an optimization loading technique that maximizes the average power while limiting the peak power. Stout and Robinson [3] chose the minimum peak - to - average power ratio as objective characteristic of the optimum loading. They introduced a computer program called «SHUFLE» which uses an iteration approach for searching the optimum loading configuration. Most of the recent fuel management optimization efforts are towards designs using low - leakage loading patterns. In this fuel loading strategy, sometimes called «in - out» scheme, the fresh fuel assemblies are loaded in the core center and in later cycles are moved towards periphery. This type of in - core fuel management has, of course, the disadvantage of increased power peaking and also possibly less negative moderator temperature coefficient (MTC). The reason is that the low leakage cores are usually operated for an extended cycle length, which requires increasing the beginning - of - cycle (BOC) soluble boron concentration. Some studies [4, 5] have used maximum cycle length or end - of - cycle (EOC) K_{eff} instead of minimal cost, as the objective functional. The result of these calculations has been to highlight low leakage cores as the optimum configuration.

Comes and Turinsky [6] developed an optimization methodology incorporated in a computer code named OCEON. Their methodology uses a zero dimensional reactor physics model and a rapid fuel cycle cost routine to select minimum cost cycling schemes that satisfy all constraints.

In the present work, the objective was to design fuel loading of our reference reactor, the Bushehr KWU designed pressurized water reactor. Since the first core configuration was provided by the supplier [7], it was only necessary to analyze that core and determine the loading configuration of the first few cycles. Due to the limitation of access to modern computer codes and advanced machines, this study may not be recognized as a finalized and very accurate one, but it should be considered as a survey type of fuel management. We have used LEOPARD [8] and ERUPT [9] computer codes for lattice homogenization and core calculation. More rigorous results could be generated if the modified version of LEOPARD code, named PSUI - LEOPARD [10] and the more elaborate multi - dimensional fuel cycle codes such as SIMULATE-E [11] were available.

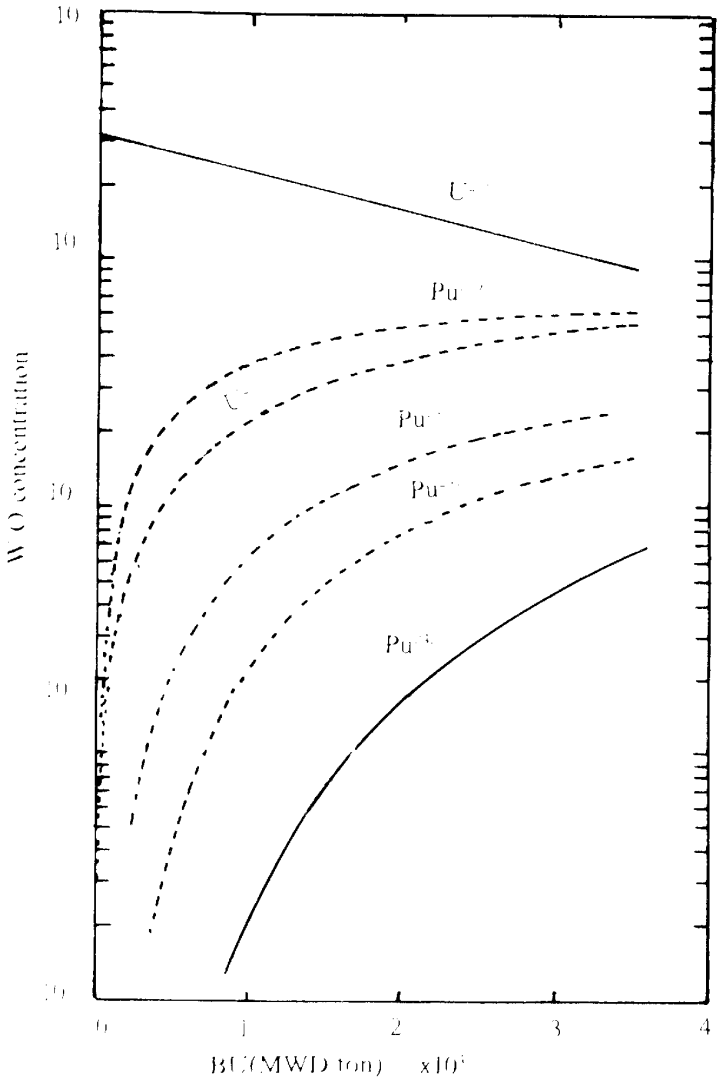

Figure 1. Concentration variation of fissil and fertile nuclides with burn - up in 3.2% enriched fuel assemblies of the 1st core.

LATTIC HOMOGENIZATION BY LEOPARD

The first step of the in - core fuel management is the generation of group constants by lattice homogenization. LEOPARD Code is capable of producing either 4-group or 2-group constants, but for the in - core fuel management calculations, the 2-group is quite satisfactory. In LEOPARD, the cell homogenization is performed over a so - called «suppercell». In this cell the effect of control and instrumentation cells and also lattice spaces is incorporated into an extra region. The volume percent of all materials and elements of the suppercell is calculated and used as the input to the code. The effective temperature necessary to calculate resonance integrals was evaluated from [11]:

$$T = 0.48\,T_c + 0.52\,T_s \qquad (1)$$

where, T_c and T_s denote the temperatures of the center and the surface of the fuel respectively.

Another input parameter is the geometric buckling which involves the reflector saving. For LWR's with Zr clad the reflector saving is almost independent of the core dimensions [13]. In the present work the value of 7 cm [14] was used for this parameter. The variation of weight percent of important isotopes such as ^{235}U, ^{236}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu with burn - up calculated by LEOPARD is shown in Figure 1.

The depletion calculation results were tabulated for later use by ERUPT. These tables contained the values of the group constants for three different enrichments (1.9%, 2.5%, and 3.2%) at 21 subsequent burn - up steps. In this article we have assumed that during normal operation of the reactor all control rods are out of the core. Also the soluble boron concentration necessary to compensate for the excess reactivity is treated seperately and will be discussed later in this paper. In fact, soluble boron is evenly dispersed through the core and has a minor effect on the power distribution.

CORE CALCULATION

The computer code ERUPT was used for flux and power density distribution calculation. This code is a two group two dimensional diffusion program suitable for cylindrical reactor cores.

The ability to iterate at subsequent time steps and calculation of important core characteristics such as Keff and burn - up of various core regions, give ERUPT some of the essential capabilities of an in - core fuel management code.

The calculated flux for each region at the beginning of a

time step is assumed to be constant during that period. From this flux the fluence (flux - time) of the region is determined and added to the previous accumulated value.

When the fluence is known, ERUPT can refer to the table of group constants to find the appropriate values by interpolation.The table should be made ready by a depletion code such as LEOPARD. In order to use ERUPT to analyze a core with a specific configuration, the core should be divided into several homogenous cylindrical concentric regions (rings). Each region would consist of a certain number of assemblies having the same enrichment, so that its group constants could be computed by LEOPARD.The equivalent radius of each region was so calculated that its volume equaled that of the entire assemblies it represented [15].

The code then proceeded to determine the flux, power density, and burn-up of each region at any desired moment of time.

Since in the process of loading configuration design the assemblies are the units which are shuffled, the EOC burn - up of individual assemblies was the real variable to be determined. This was calculated by first determining its volume fraction in any of the regions and then summing up the weighted burn - ups of those regions [15].

FUEL LOADING DESIGN

Among various core loading methods, the «scatter loading» is the most popular one for pressurized water reactors. Other less complex methods, obviously have their own disadvantages. The «zone - loading» gives better results compared with simple «batch - loading», but still is not satisfactory for large reactors. The reason is the sizable difference between flux and power density of individual zones.

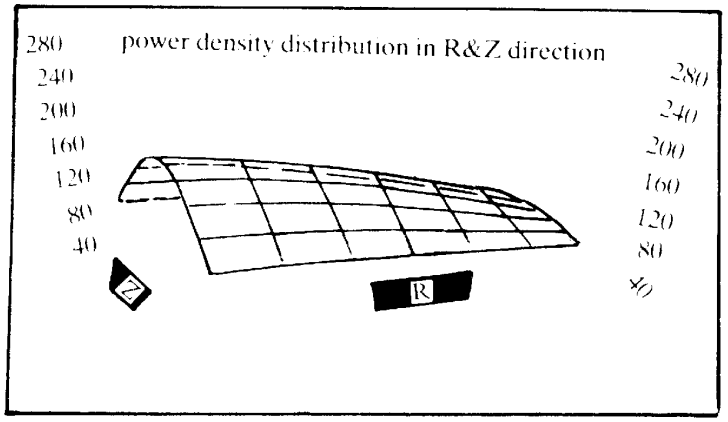

Figure 2. Power density distribution for a simple batch loading of the reference reactor.

The simple - batch method in which the core is loaded with uniformly enriched assemblies was tested for our reference reactor. The radial and axial power density distribution calculated by ERUPT (Figure 2), assuming a uniform enrichment value of 2.5% (average of the actual enrichements), showed the characteristic shape of Cosine (axially) and Bessel Function (radially). These undesirable power shapes make the batch - load impractical, not only for fuel economy reasons, but also because of the adverse effect of the reactivity change during the cycle. The unusual excess reactivity at the BOC requires a high concentration of chemical poisons, which could result in a positive temperature coefficient. In the «out - in scatter loading» method applied in this paper, the fuel assemblies with the highest enrichment are loaded at the core periphery and the rest is scattered in a checkerboard pattern in the central part of the core. Figure 3 shows the loading configuration of the first core of our reference reacter In order to make the power distribution as flat as possibile, each assembly with high reactivity (K_{∞}) is surrounded by four low reactivity assemblies.

The feed enrichment value is an important variable of in-core fuel management. This value is determined by a multistage total fuel cycle cost optimization process. For PWR cores with 3 zones and 1 year cycle length, the minimum fuel cycle cost occurs at an enrichment value of around 3.2% [16]. This value was also suggested by the manufacturer of our reference reactor [7]. However in the first core with entirely fresh fuels the assemblies of the two scattered central regions

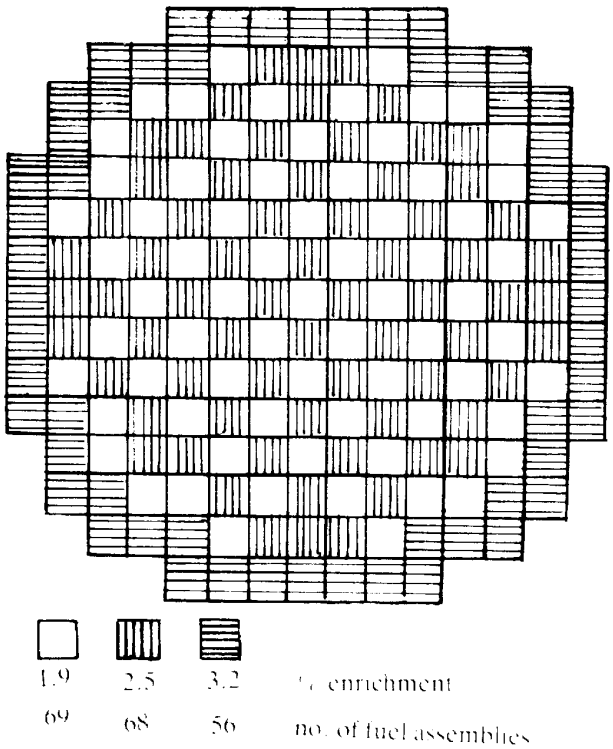

Figure 3. Loading configuration of the 1st core of the reference reactor.

should have lower enrichments (1.9% and 2.5%) in order to secure power shape uniformity. From now on we refer to the first core assemblies with initial enrichments of 1.9, 2.5, and 3.2 percent as L1, L2, and L3, respectively.

Another important variable is the cycle length. For the 1st cycle the cycle length is chosen to be longer than other cycles. The purpose of this is to gain more energy from the assemblies so that after being removed from the 1st core may never again have a chance of being loaded into the core. In this work, the length of the 1st cycle was about 420 days [7] and the length of the subsequent cycles was considered to be around 1 year. It is interesting to note that while American companies such as B & W are recently changing from 12 month to 18 and 24 month cycle lengths [17, 18] for economical reasons, the FR German companies have concluded that 12 month cycles work out cheaper for their country [18]. The longer cycle length, of course would demand higher feed enrichment and even could lead to larger batch sizes if the discharge burn- uplimit is not raised accordingly.

The burn - up distribution of the 1st core at the EOC calculated by ERUPT is demonstrated in Figure 4. Also the variation of the 1st cycle K_{eff} versus time is shown in Figure 5.

The transeint at the beginning of the exposure is due to the build - up of ^{135}Xe, which soon reaches equlibrium and lets the smooth variation start and continue. In Figure 6, least square fit to the radial power density

	A	B	C	D	E	F	G	H
A	14570 1.9	17137 2.5	14012 1.9	17143 2.5	13887 1.9	17927 2.5	17127 2.5	15973 2.5
B		14201 1.9	17249 2.5	14481 1.9	17396 2.5	14203 1.9	17137 2.5	15963 3.2
C			14569 1.9	17681 2.5	14335 1.9	17261 2.5	13093 1.9	15892 3.2
D				14081 1.9	17832 2.5	13725 1.9	18038 3.2	15782 3.2
E					17072 2.5	12896 1.9	15918 3.2	
F						16258 3.2	15738 3.2	
G								
H					Burn - up (MWD/MT) Enrichment (%)			B-U E

Figure 4. Burn - up distribution at the end of 1st cycle.

distribution data of the 1st core at the BOC and EOC is compared. The BOC power shape peaks at the center, while for the EOC a flatter distribution is observed. This is due to the spread of reactivity that occurs after one cycle of exposure. In fact, as shown in Figure 4, the regions with higher enrichment have produced more energy and thus have become less reactive. Similar behavior for the axial power density distribution of the central and buckling regions is seen in Figures 7 and 8.

The fuel loading design for subsequent cycles was not so straightforward as for the 1st cycle. In this segment of in - core fuel management the iterative approach is the most practical method of searching for optimum pattern. Actually, there is no argument about the peripheral zone of the core, because that section is always substituted by fresh fuel. On the contrary, for the central scattered zone, one has to decide which assemblies should be removed and which ones must be shuffled. Several heuristic search methods have been suggested (e. g. see references 10 and 19) for finding optimum reload configurations. These methods are not founded on exact rules of equations, but instead are based on some general guidelines resulting from experiences gained by trying hundreds of different configurations. A comperhenstive list of these general rules is given in reference 3. The authors have developed a computer code named SHUFLE, which applies these rules in an automatic shuffling effort to

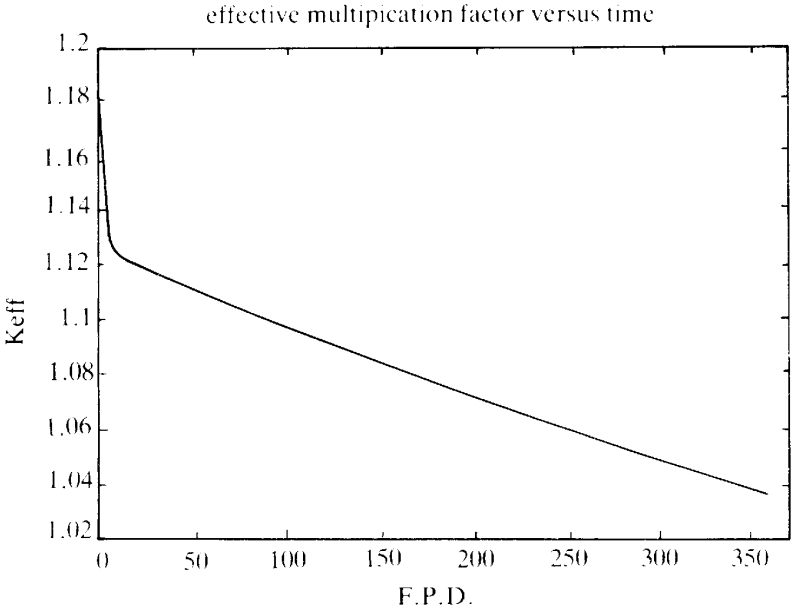

Figure 5. Variation of Keff with time during the 1st cycle.

determine the optimum loading configuration. In the present work, we only had a chance to use ERUPT computer code as our tool for analyzing the core. This code had no provisions for automatic shuffling. Therefore, we had to set the configurations and run the code in an iterative manner, in order to find the

optimum pattern. Since our objective function of optimization (minimum peak - to - average power density) was the same as reference 3, we employed their general rules as the main guideline in our manual shuffling. The core of our reference reactor contained 193 fuel assemblies (FA), so at each refueling we replaced 64 FA's (almost one third of the core) with fresh FA's with 3.2% enrichment. The out - line of the changes at the end of the 1st cycle is as follows:

- 64 FA's with highest burn - up were selected from the 69 FA's of the L1 and were discharged.
- The entire 56 L3 FA's were moved from periphery into the central zone and replaced by fresh FA's (L4).
- The 5 remaining assemblies of L1 were mixed with FA's of L2 (68 assemblies) and the 8 fresh FA's from L4, and shuffled to reach the optimum configuration.

The loading configuration at the beginning of the 2nd cycle and the burn - up distribution of the end of this cycle are shown in Figures 9 and 10. The burn - ups in Figure 10 are given in terms of Mwd/MTU. At the end of the 2nd cycle we had the following changes:

- 5 FA's from L1 remained from the 1st cycle together with 59 FA's from L2 were removed.
- The 9 remaining FA's from the L2 which were selected to have the lowest burn - up were moved to new positions.
- 64 fresh FA's (L5) were charged to the peripheral zone.

Therefore the third core consisted of 64 fresh FA's (L5), 64 assemblies of L4, 56 FA's from L3 and 9 FA's from L2. The shuffling of the FA's in the scattered zone was repeated many times, until no improvement of the peaking power factor (PF), defined as the peak - to - average power density, could result from further trials.

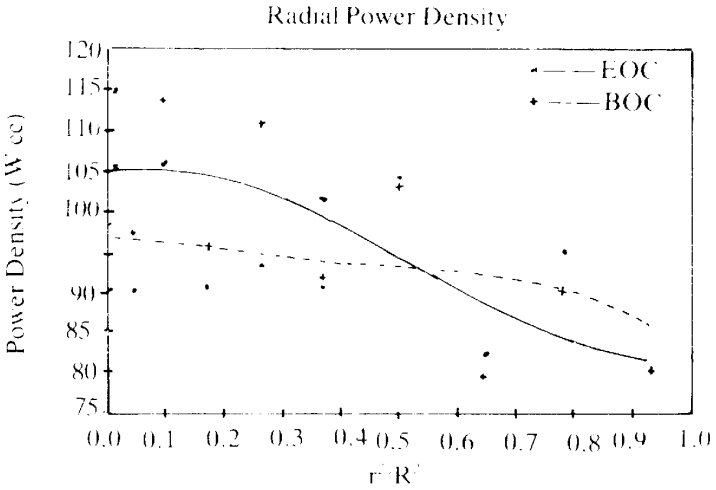

Figure 6. Radial power density distribution at the beginning(BOC) and end of (EOC) of the 1st core.

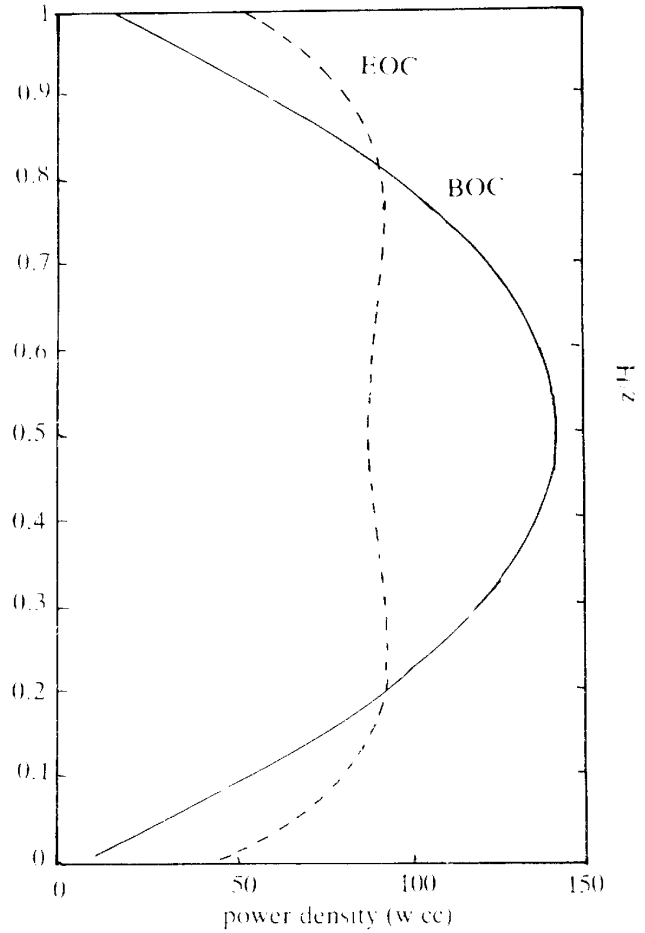

Figure 7. Axial power density distribution at central region of the 1st core

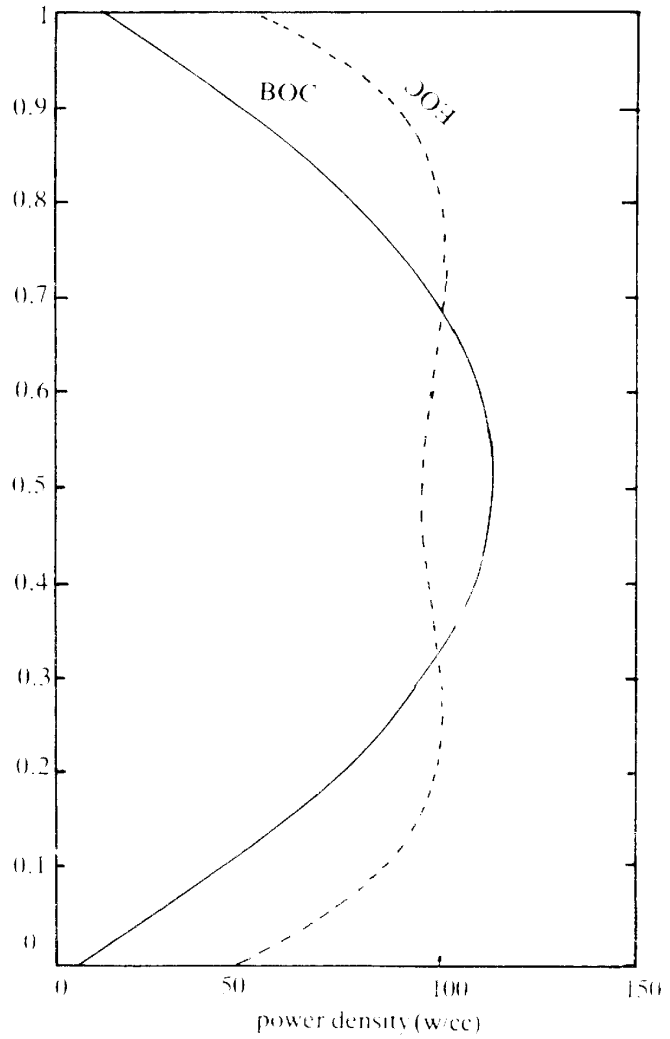

Figure 8. Axial power density distribution at peripheral region of the 1st core.

In Figures 11 and 12 the final BOC core configuration and the EOC burn - up distribution of the 3rd cycle are shown. The PF for this configuration was calculated to be 3.08.To form the core configuration for the 4th cycle the following steps were taken:

- The 9 remaining FA's from L2 together with the 56 FA's of L3 were discharged.
- One of the FA's from L2 (BD in Figure 10), discharged at the end of 2nd cycle was charged back and loaded in the center of the core.
- 64 FA's from the L5 were moved into the central zone and replaced by 64 fresh FA's (L6).

As for previous cycles, trial shufflings based on the mentioned guidelines continued until the final optimum loading pattern (Figure 13) was found. In this core the entire FA's had initial enrichment of 3.2%, and a value of 2.73 was calculated for the PF of the core. It appeared that the fuel loading of future cycles would be very similar to that of the 4th cycle, so we assumed this cycle to be the start of the equlibrium in - core fuel

	A	B	C	D	E	F	G	H
A	12896 9	13093 1.9	17249 2.5	16258 3.2	17143 2.5	15973 3.2	17072 2.5	0 3.2
B		17927 2.5	18038 3.2	17137 2.5	15918 3.2	17681 2.5	15782 3.2	0 3.2
C			17249 2.5	15963 3.2	17832 2.5	0 3.2	17261 2.5	0 3.2
D				17137 2.5	15892 3.2	17396 5.5	0 3.2	0 3.2
E					17122 2.5	15389 3.2	0 3.2	
F						0 3.2	0 3.2	
G								
H					Burn - up (MWD/MT) Enrichment (%)		B-U E	

Figure 9. Loading configuration of the beginning of the 2nd cycle.

	A	B	C	D	E	F	G	H
A	18193	18923	24903	28947	26472	27299	28280	12358
B		25135	27427	26279	27699	28411	29140	12256
C			26418	27327	28017	13240	28208	11979
D				27011	28837	28485	12893	11524
E					28086	28816	12138	
F						12309	11398	
G								
H					Burn - up (MWD/MT)		B-U	

Figure 10. Burn - up distribution at the end of 2nd cycle.

	A	B	C	D	E	F	G	H
A	26279 2.5	12358 3.2	25135 2.5	12309 3.2	27327 3.2	12138 3.2	28947 3.2	0 3.2
B		24903 2.5	11524 3.2	28837 3.2	11398 3.2	28816 3.2	12256 3.2	0 3.2
C			27299 3.2	11979 3.2	27424 3.2	0 3.2	29140 3.2	0 3.2
D				27327 3.2	12893 3.2	27699 3.2	0 3.2	0 3.2
E					12138 3.2	13240 3.2	0 3.2	
F						0 3.2	0 3.2	
G								
H					Burn - up (MWD/MT) Enrichment (%)		B-U E	

Figure 11. The final core configuration at the beginning of the 3rd cycle.

	A	B	C	D	E	F	G	H
A	32823	20891	32810	22447	39339	24631	41244	11346
B		31980	21396	39411	23410	41374	24507	11052
C			37442	23473	39597	12585	41196	10628
D				39436	25396	40079	11661	10305
E					24591	25250	10793	
F						10919	10175	
G								
H					Burn - up (MWD/MT)		B-U	

Figure 12. Burn - up distribution at the end of 3rd cycle.

mangement. The PF values of several reactors [20] are given in Table 1. These values are in good agreement with our value of 2.73 for the equilibrium cycle PF. Figure 14 demonstrates the burn - up distribution at the end of the 4th cycle. The average discharge burn - up for this cycle was 33690 Mwd/MTU. This burn - up is in very good agreement with the supplier design value.

SOLUBLE BORON CONCENTRATION

The excess reactivity control required to assure criticality during the cycle energy production may be compensatedby burnable poison (BP) rods or soluble boron or a combination of them. In this work no BP rods have been considered, meaning that the full control of excess reactivity was given to soluble boron. A simple computer program was written to calculate the critical boron concentration as a function of burn - up for a homogeneousreactor core. It is assumed that boron only affects the absorption cross section of the coolant. The macroscopic absorption cross section for soluble boron can be written as:

$$\Sigma_{aB} = a C_B \qquad (2)$$

where C_B is the boron concentration in ppm, and a is a constant value determined by the volume ratio and density of water in the coolant, and also the microscopic absorptoion cross section of boron. For our reference reactor a value of 1.686×10^{-5} was found for this constant.

The program iteration scheme is based on the following relations:

$$S_n = [\delta k / \delta C_B]^{(n)} \qquad (3)$$

$$\Delta K^{(n)} = K^{(n)} - 1 \qquad (4)$$

$$C_B^{(n)} = C_B^{(n-1)} + \Delta K^{(n)} / S_n \qquad (5)$$

	A	B	C	D	E	F	G	H
A	26275 2.5*	10919	22447	10175	24591	10175	24631	0
B		20981	10305	21369	11661	24507	11052	0
C			23473	10628	23410	0	25396	0
D				23473	10793	25250	0	0
E					11346	12585	0	
F						0	0	
G								
H					Burn - up (MWD/MT)			B–U

* the only FA with 2.5% enrichment

Figure 13. The final loading configuration of the 4th core.

where $K^{(n)}$ is the K_{eff} calculated from the two group difussion formalism. First, an initial guess for C_B ($C_B^{(0)}$) is considered and the value of $K^{(1)}$ is calculated; if $K^{(1)}$ is not equal to 1 the program uses equation 3 through 5 to find a new value for C_B. The iteration continues until the criticality is reached. The procedure is then repeated for all burn - up steps of each cycle. Figure 15 shows the variation of boron concentration as a function of burn - up for the first core of our reference reactor assuming a homogeneous core with an average 2.5% enrichment. As expected, this variation shows the same behaviour as the K_{eff} variation of Figure 5. The concentration values are comparable, but slightly less than values provided by KWU [7].

CONCLUSION

While there are previous reports on analysis of the first core of our reference reactor [21, 22] and fuel cycle calculations [23], this work was the first attempt to core configuration design for a PWR in Iran. The highest credit was given to the safety parameter, by considering the minimum peak - to - average power density as the objective function of the optimization. The core loading patterns for the first 4 cycles were designed and analyzed. Since the ERUPT code had no fuel assembly automatic shuffling feature, we had to run the code many times to find the optimum core configuration for each cycle. The peaking power factor of the equlibrium cycle (4th cycle) was determined to be equal to 2.73, which is comparable to the values for some other working PWR's. Also, the average dischage burn - up of the 4th cycle was calculated to be around 33,700 MWD/MTU, a value close to the design figure for the reference reactor.

	A	B	C	D	E	F	G	H
A	35683	22645	34360	22394	36940	22387	36083	10005
B		32556	22377	33618	24010	36700	22393	9854
C			35692	22941	35713	12144	36332	9416
D				35864	22999	36903	10494	9115
E					23175	23492	9586	
F						9722	8994	
G								
H					Burn - up (MWD/MT)			B–U

average discharge burn-up = 33690 MWD/MT

Figure 14. Burn - up distribution at the end of 4th cycle.

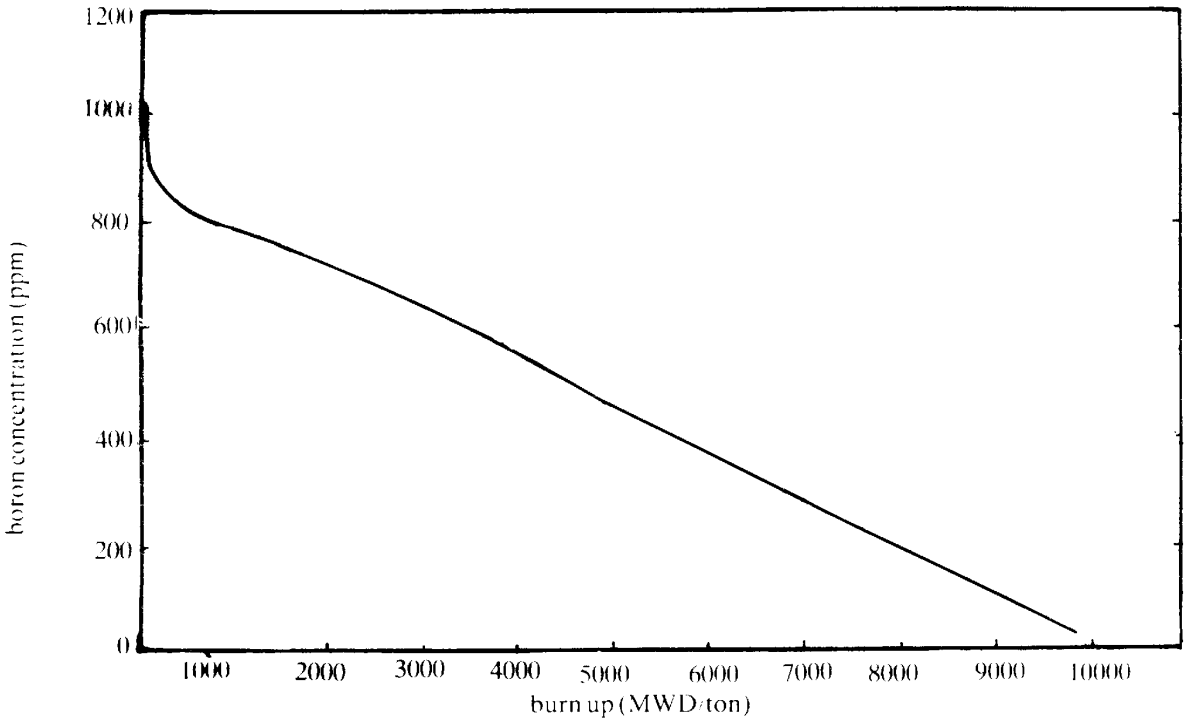

Figure 15. Critical soluble boron concentration variation with burn up.

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