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Nuclear Design Feasibility of the Soluble Boron Free PWR Core

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Abstract

A nuclear design feasibility of soluble boron free(SBF) core for the medium-sized(600MWe) PWR was investigated. The result conformed that soluble boron free operation could be performed by using current PWR proven technologies. Westinghouse advanced reactor, AP-600 was chosen as a design prototype. Design modification was applied for the assembly design with burnable poison and control rod absorber material. In order to control excess reactivity, large amount of gadolinia integral burnable poison rods were used and B4C was used as a control rod absorber material. For control of bottom shift axial power shape due to high temperature feedback in SBF core, axial zoning of burnable poison was applied to the fuel assemblies design. The combination of enrichment and rod number zoning for burnable poison could make an excess reactivity swing flat within around 1% and these also led effective control on axial power offset and peak pin power. The safety assessment of the designed core was performed by the calculation of MTC, FTC and shutdown margin. MTC in designed SBF core was greater around 6 times than one of Ulchin unit 3&4. Utilization of enriched B10(up to 50w/o) in B4C shutdown control rods provided enough shutdown margin as well as subcriticality at cold refueling condition.

1. Introduction

Elimination of soluble boron gives many benefits for PWR innovation[1]. Soluble Boron Free Operation(SBFO) will relieve plant manager from corrosion maintenance concerns and reduce volume of liquid radwaste as well as operational radiation dose. The strong, negative moderator temperature coefficient due to deborated moderator would improve reactor transient performance as well as operational safety. System simplication also can be achieved by eliminating the need to monitor and adjust soluble boron concentration during routine operation, transients and shutdown in a number of plant systems. Therefore, the costs assessment of CE[2][3] indicates that total power generation cost would be decreased by the system simplications achieved through elimination of soluble boron. From these standpoints, SBFO option has been widely applied for small-sized reactors (less than 100 MWt) especially for marine reactors of which system simplication is essential as well as economics. However, reactivity compensation and reactor control became infeasible for large sized commercial reactors if soluble boron were eliminated from all operational modes.

The purpose of this study is to evaluate a conceptual initial core design in a limited scope effort to determine feasibility of the soluble boron free operation in PWR; it is not intended to identify a complete, optimized design. As a result, feasibility of soluble boron free core design for the medium-sized commercial reactors was investigated. The generic principles as a parametric research were studied for design requirements of burnable poison rods and control rods within the framework of commercial PWR, AP-600[4]. Also, effects on axial burnable poison zoning in fuel assembly, operational controllablity and shutdown margin were investigated to meet safety requirements.

The soluble boron free core design was aimed with current PWR proven technologies. Therefore, geometrical data for fuel assemblies as well as system boundary conditions for a core design were set the same as AP-600. Stainless steel reflector assemblies in the radial reflector zones were counted around the core. Design requirements and goals are :

- Existing fuel and core design methodologies should be used.
- Reactor is to generate rated power of AP-600 for more than 18 months with three reloading batch.
- Maximum fuel pin peaking is to be no larger than in AP-600.
- Axial Offset should be controlled within ±10% throughout cycle.
- No more than half the fuel assemblies have control rod drive mechanisms.
- Reactivity change due to power defect and burnup will be compensated by burnable poisons and control rods.
- Safety margin would remain within the existing plant technical specifications.

2. Core Design Tools

An assembly code, CASMO-3[5] was linked with three dimensional nodal code NESTLE[6]. CASMO-3 is a multi-group two dimensional transport theory code for burnup calculations on PWR and BWR fuel assemblies. And, NESTLE is a few-group neutron diffusion equation solver utilizing the nodal expansion method for eigenvalue, adjoint, fixed-source steady state and transient problems. Validation of this code system was sought by the comparison with the results in Standard Safety Analysis Report(SSAR)[4].

AP-600 was loaded with VANTAGE-5H with Wet Annular Burnable Absorber(WABA). Uncertainty of the core design calculation came from the special design feature in AP-600; stainless steel rods in radial reflector zones. At present, detail design data were not known and furthermore CASMO-3 can not handle the heterogeneity in reflector region. In this work,

1.048 1.005 −4.1	0.968 0.977 0.1	1.112 1.073 −3.5	1.054 1.071 1.6	1.149 1.117 −2.8	1.016 1.025 0.9	1.074 1.034 −3.7
	1.073 1.031 −3.9	1.014 1.028 1.4	1.287 1.248 −3.0	1.029 1.053 2.3	1.104 1.091 −1.2	0.957 0.952 −0.5
		1.109 1.072 −3.3	1.006 1.028 2.2	1.081 1.057 −2.2	1.022 1.067 4.4	0.938 0.922 −1.7
			1.065 1.042 −2.2	0.934 0.974 3.9	0.895 0.900 0.5	0.626 0.634 1.3
SSAR NESTLE Error(%)				1.153 1.172 1.6	0.712 0.739 3.8	

Fig. 1. Planar Power Distribution at BOC

core boundary fuel region was homogenized by color set calculations with reflector composition which was assumed to be a homogeneous mixture. Composition of mixture was obtained by volume weighting by stainless steel to water ratio of 4.

Core design calculation results from CASMO-3/NESTLE were acceptable compared with SSAR. Dissolved boron content for criticality was given in Table 1. Calculated cycle length was 16,000MWD/MTU by the difference of around 600MWD/MTU. Planar power distribution at BOC and EOC were given in Fig. 1 and Fig. 2. These results showed acceptable accuracy compared with SSAR except reflector region. Compared with radial power distribuation, root mean square error(at ARO, EQ. Xenon) was 2.65% at BOC and 2.89% at EOC. There were shown some deviations in control bank worths - from 12 pcm error in M2 bank to 52 pcm in M3 bank.

Table 1. Critical Boron Concentration and Control Rods Worth(pcm)

	SSAR	CASMO-3/NESTLE
Critical Boron Concentration(ppm)		
HFP, No Xenon	1020	1028
HFP, Equilibrium Xenon	742	755
Control Rods Worth(pcm)		
M0	509	481
M1	602	557
M2	835	847
M3	1141	1089
AO	1875	1913

3. Design Methodology

Existing PWR technology could be applied in a soluble boron free core design when there were no major engineering design changes. The designed core was loaded with the same AP-600 fuel assemblies which had the same fuel pin dimensions, spacer grids, guide tubes, etc. Conventional westinghouse finger-type control rod

0.992 1.005 1.3	1.083 1.095 1.1	1.008 1.028 2.0	1.112 1.137 2.2	1.016 1.041 2.5	0.977 0.984 0.7	0.865 0.842 −2.7
	0.999 1.015 1.6	1.101 1.121 1.8	1.108 1.159 4.6	1.118 1.141 2.6	0.986 0.993 0.7	0.874 0.840 −3.9
		1.025 1.047 2.2	1.131 1.153 1.9	1.044 1.061 1.6	1.138 1.146 0.7	0.863 0.829 −3.9
			1.050 1.066 1.5	1.124 1.124 0.0	0.923 0.900 −2.5	0.692 0.636 −8.1
SSAR NESTLE Error(%)				1.099 1.075 −2.2	0.781 0.728 −6.8	

Fig. 2. Planar Power Distribution at EOC

assemblies were also used with standard control rod drive mechanisms which were spaced once every other assemblies.

3.1. Burnable Poison

Excess reactivity should be compensated mainly by burnable absorber in a soluble boron free core. Boron, Gadolinium, or Erbium were used for burnable absorber material in commercial PWRs. The type of burnable absorber can be categorized as integral type and discrete type. Candidates for the latter type were Pyrex, WABA and those of the former were Gd_2O_3, Er_2O_3 and IFBA.

In general, characteristics of burnable absorber depends on the poison concentration, number and position of poison rods in shimmed assemblies. For the core of SBFO with over 18 month cycle, excess reactivity should be compensated by much more number of burnable absorbers. Therefore, with discrete type BP, it is expected that reactivity compensation could not be achieved due to the restriction in the number of poison rods in assembly. In this paper, considered for both nuclear characteristics in assembly and operation experience, gadolinia(Gd_2O_3) admixed with natural UO_2 integral burnable poison was chosen. Gadolinium is particularly good for long term reactivity compensation because its reactivity holddown capacity can make the reactivity rundown of the fuel with burnup nearly linear low, thereby limiting of the control rod insertion required to adjust excess reactivity throughout cycle[7][8]. Gadolinium burnable poisons have already been used widely in BWRs as well as in PWRs.

As a first step, design of fuel assemblies with gadolinia integral burnable poison was performed with four design parameters - fuel enrichment, Gd_2O_3 concentration, number of burnable poison rods, and their location. Extensive parametric study also was done for burnable poison rod location. As a result, it was found that location of burnable poison rods within an assembly does not change a lot the excess reactivity variations but affect pin power peaking considerably. Fig. 3

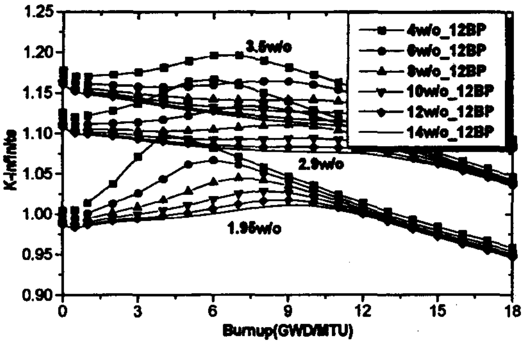


Fig. 3. Variation in K-inf. of Assembly to the Change of Fuel and Gd Enrichment

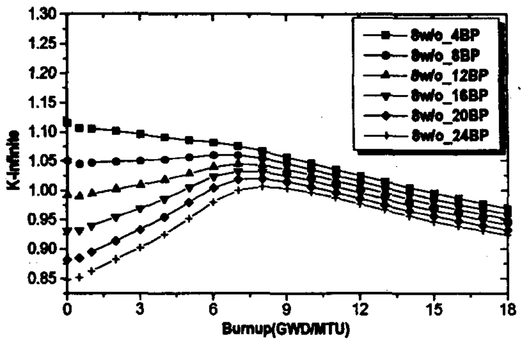


Fig. 4. Variation in K-inf. of Assembly to the Change of Number of BP Rods

showed the effects of enrichments in fuel and Gd to the assemblywise reactivity swing. In general, gadolinia integral burnable poison brought strong reactivity hold-down at beginning of cycle. However, as the Gd concentration went up, reactivity variations became flatter and this effect became stronger when fuel enrichment was increased. Also, Fig. 4 showed the effects of number of BP rod in assembly and that its sensitivity to K-infinite was monotonous and predictable compared with enrichment change.

3.2. Excess Reactivity Conrol

Excess reactivity control is achived in the SBF core through a combination of burnable poison rods and control rods. Burnable poisons provides the means of long-term reactivity compensation. However, control rod is used not only for control long-term excess reactivity but also for control of reactivity defects from HFP to HZP and shutdown during refueling.

Long-term excess reactivity compensation can be achived in this core with burnable poison and with partial insertion of regulation control banks within the A.O. criteria. The soluble boron free core design has a strong, negative moderator temperature defect over the entire cycle length. The reduction of moderator defect can be achieved using thinner fuel rod, increasing the fuel rod pitch or adding more water hole. However, in this paper, SBF core should be designed with existing PWR fuel features. Therefore, moderator to fuel ratio was maintained within current PWRs. Reactivity limit for current PWRs at mode 6(refueling mode) is 0.95. The subcriticality margin of 5% should be only with control rods. It is obvious, therefore, that the total control rod worth in SBFO should be much larger than in current PWRs.

The control rod worth can be increased in two ways on the base of current PWR control rod drive mechanism. The total number of control rod fingers can be increased, or strength of absorber materials can be increased. In this study, B_4C for the shutdown was used as absorber material because of its high rod worth and reasonable cost. And, westinghouse type gray rod was used for excess reactivity control.

3.3. Core Reactivity Balance

Movement of control rod tends to cause an adverse axial power shape resulting in a high peaking factor. Therefore, total core excess reactivity should be maintained as flat as possible throughout the entire cycle in order to minimize control rod movement in SBFO. Total reactivity of core depends on the fuel loading pattern and core boundary condition, and it changes as fuel burnup. As a preliminary design for assemblies without detail core caluation, a batch fuel assembly design was done for an ideal SBF core reactivity balance based on the following equation.

$$[\,K_\infty\,]_{core}(BU) = \frac{1}{N_1+N_2+N_3}\left(\sum_{1}^{N_1}K_1(BU) + \sum_{1}^{N_2}K_2(BU) + \sum_{1}^{N_3}K_3(BU)\right) \quad (1)$$

where N_1, N_2, N_3 are numbers of three batch fuel assemblies.

Design target is to find the most flat letdown curve as a combination of three $K_i(BU)$ curves which have three variables; number of BP rods, enrichment of fuel and concentration of BP material. As a result of experience, reactivity curve of most reactive fuel batch(batch 1) can be easily found to be flat and linear. Therefore, reactivity balance search was done for batch 2(less reactive fuel) and 3(least reactive fuel) fuel assemblies. An iterative search based on data was performed for the best combination for small excess core reactivity with the following search conditions.

- Average K-infinite should be flat through the cycle length (as an average of batch 2 and 3 fuels).
- Average excess reactivity should lie as low as possible (between 1% to 3% excess reactivity).
- Gd concentration in BP should be less than 12w/o.

Final selection of two fuel assemblies are :

1.85w/o fuel, 4 BP rods, 12w/o Gd, and
2.55w/o fuel, 20 BP rods, 12w/o Gd.

The result of core reactivity balance search is shown in Fig. 5. This result will not be used to core design as it is because batch 1 fuel assemblies should be added. The batch 1 fuel assembly was determined by intuitive method in order to reduce total core excess reactivity less than 1%.

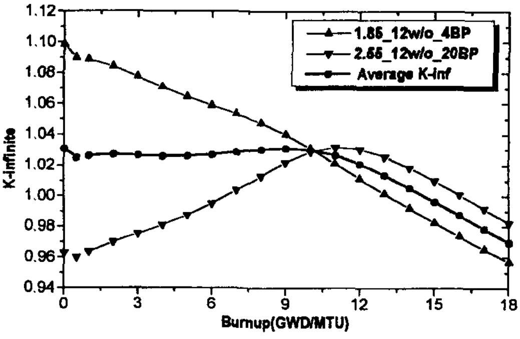


Fig. 5. Average K−infinite Change vs. Burnup

3.4. Axial BP Zoning

One of the major benefits of the SBF feature is a strong negative MTC at all time in life. This makes routine reactor control response easy. As first, the core exihibits a strong, natural load-follow characteristics due to high moderator temperature feedback. Secondly, the reactivity parameters which determine the core response characteristics do not change significantly. As a result, relatively simple control strategies for load-follow are possible in SBFO. However, high moderator temperature feedback makes axial power shape tilted to the bottom of core even in ARO condition, and this bottomward shift is increased when control rods are inserted for the excess reactivity control in SBFO. Three kinds of different axial burnable poison zoning method were applied in order to minimize axial offset throughout the cycle.

At first, axial burnable absorber enrichment zoning was applied for every burnable poison rods. Axial burnable poison enrichment zoning was designed for three axial regions; enrichment of gadolinium in the bottom half was increased by 2% and no enrichment at the top 5%. Remaining part of rod are designed as a base to fit total core excess reactivity as written above. As a result of core calculation using classical checkerboard and out-in core loading pattern, critical rod position could be sought. However, calculated axial offset varied a lot during the cycle, dropped to negative at BOC and increased above the +10% at EOC. The cause of failure in axial offset control came from Gd burnup characteristics in enrichment zoning as shown in Fig. 3. For the rodded core in BOC, variation of K-infinite to the change of burnable absorber concentration is not large enough to control axial offset. Because excess reactivity is high in the middle of cycle as shown in Fig. 6, control banks should remain inserted for long period of time for the reactivity compensation. This made power shape distorted upward skewed at the EOC. Axial Offset change for critical rod positions is shown in Fig. 7. Therefore, in order to control the A.O. within design target throughout the cycle, excess reactivity should be lowered and flattened a little more.

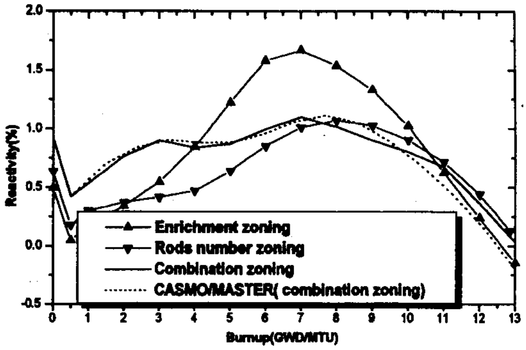


Fig. 6. Excess Core Reactivity Change vs. Burnup

The design methodology shown above has some limitations: Because Gd enrichment was limited to 10~12w/o with fixed burnable absorber rod number, enough reactivity compensation was not capable. Furthermore, because excess reactivity variations of all assemblies were sought to be flat, selection of assemblies was restricted and average core excess reactivity variation was not favorable. As a new method, fuel assembly axial zoning was done by BP rod numbers[3] instead of Gd enrichment because effect of number zoning to the K-infinite curve is more monotonous and predictable compared with enrichment zoning as shown in Fig. 3 and 4. Gd enrichment was set to be the maximun 12w/o. Axial BP zoning was applied to four axial regions; bottom 5% has all BP rod number with 2w/o Gd, next 74% length has also all number of BP rods but with 12w/o Gd, next 16% length at the top section has 4 BP rods without Gd and the others with 12w/o, and the last section at the top 5% length has half with 2w/o and the other half without Gd. As a result of BP rod number zoning, core excess reactivity at the ARO has much smoother and flat shape than enrichment zoning as shown in Fig. 6. Also, critical rod position was sought without difficulty and axial offset was controlled within (−15%, +10%) band which is a little wider band than conventional limit band. Variation of A.O. and F_Q are shown in Fig. 7 and Fig. 8. Fig. 4 shows the reason why A.O. is out of ±10% limit band. Reactivity gap between K-infinite curves was reduced remarkably as fuels were burned up. Therefore, the margin of A.O. is reduced in EOC.

As the third method, above two axial zoning method are combined for core design in order to get the benefits of both rods number zoning at BOC and enrichment zoning near the EOC. Enrichment axial zoning method was applied to batch 2 and 3 fuel assemblies. Rods number zoning method was applied to batch 1. With this axial zoning method, reactivity change of each assembly could be flat and smooth as shown in Figure 6.

Core loading pattern with control bank location are shown in Fig. 9. Depending on the excess reactivity, critical control bank position of three

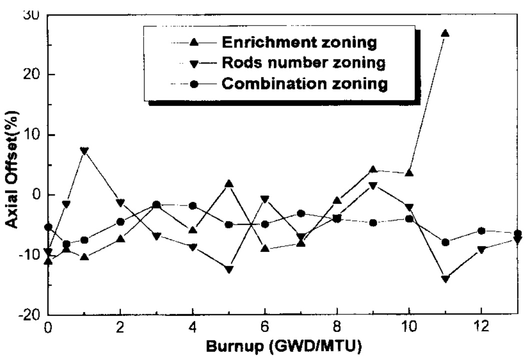


Fig. 7. Axial Offset Change for Critical Rod Positions

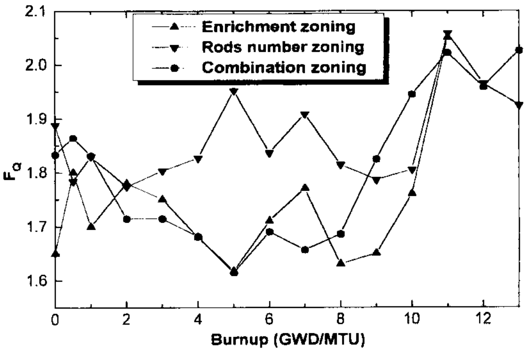
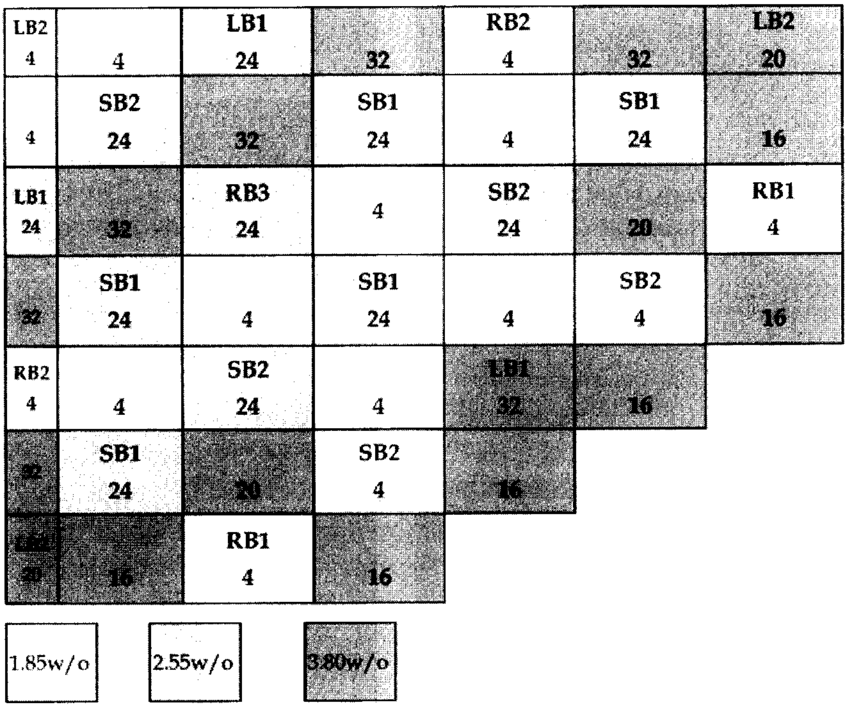


Fig. 8. FQ Change for Critical Rod Positions



LB2 4	4	LB1 24	32	RB2 4	32	LB2 20
4	SB2 24	32	SB1 24	4	SB1 24	16
LB1 24	32	RB3 24	4	SB2 24	20	RB1 4
32	SB1 24	4	SB1 24	4	SB2 4	16
RB2 4	4	SB2 24	4	LB1 32	16	
32	SB1 24	20	SB2 4	16		
LB2 20	16	RB1 4	16			

1.85w/o 2.55w/o 3.80w/o

LB(Gray Bank), RB(Regulating Bank), SB(Shutdown Bank)
Number in the Box : number of BP rod

Fig. 9. Loading Pattern of Fuel Assemblies and Control Banks

banks were sought and shown in Fig. 10. Also, axial power distribution for rodded core was shown in Fig. 11. Here, two control banks were inserted with overlapping principle for the core reactivity balance. One control bank(LB2) was moved independently for excess reactivity control and also for A.O. control. In this case, variation of A.O. and F_Q was kept within the conventional limit

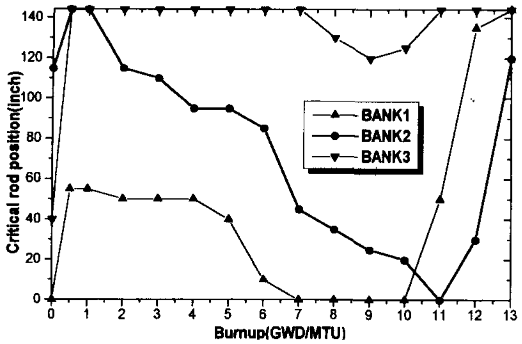


Fig. 10. Critical Control Bank Position at HFP Condition

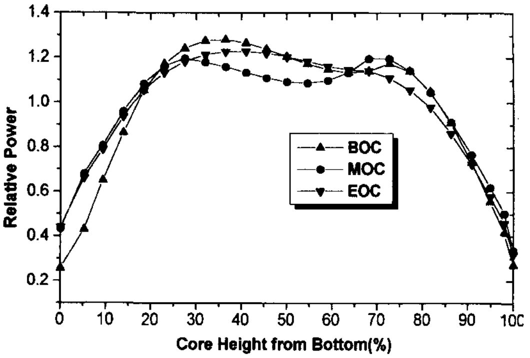


Fig. 11. Axial Power Distribution for Rodded Core, HFP Condition

band as shown Fig. 7 and 8.

As a summary, it is highly recommended that number zoning of BP rod method should be used as an axial zoning method for SBF core design. The appropriate combination of enrichment and number zoning of BP rod would give the maximum benefit in terms of axial offset control.

4. Shutdown Margin Assessment

In soluble boron free core, it is important to evaluate an impact on safety for reactivity induced accident such as SLBA (Steam Line Break Accident) and REA (Rod Ejection Accident). More negative MTC in SLBA would give more reactivity to core at cooldown stage. Rodded operation for full power condition in SBFO could reduce shutdown margin in case of rod ejection. Both hazard can be compensated only if enough control rod banks are provided for safe shutdown. Therefore, the safety assessment for the designed core was done as a comparison of significant parameters of designed core with those of current PWR design, such as MTC, FTC and shutdown margin.

Calculated values of MTC as well as FTC compared with current PWR (Ulchin unit 3&4)[9] were given in Table 2. The result indicates that negative MTCs in SBFO were larger about 6 times at HFP condition than those of conventional PWR, but FTC is almost the same.

The capability of the designed soluble boron free core to load follow operation is investigated by estimating the required reactivity to reduce 50% power. Control rod for load follow operation was based on westinghouse type gray rod except that B4C was used as a absorber material instead of Ag-In-Cd; Bank LB1 and LB2 as shown in Fig. 9. Simulation of daily load following operation for this core was done in Ref. 10 and showed a feasibility.

The most limiting design consideration with respect to reactivity control is the magnitude of shutdown margin and possibility of cold shutdown in conjunction with refueling cooldown mode. As shown in Table 3, the calculated shutdown margin based on natural B10 shutdown bank (SB1, 2 in Fig. 9) is 3.35% at BOC and 4.80% at EOC, and subcriticality at the refueling cold standby condition is 0.9853 and 0.9753 in k. In order to have enough shutdown margin, design change for shutdown bank was done as an enrichment of B10 in the B4C up to 50w/o. With these new shutdown banks, shutdown margin is increased upto 10.71% at BOC and 11.99% at EOC. In this case, subcriticality at the refueling cold standby

Table 2. MTC & FTC at HFP, EQ. Xe Condition

	BOC		EOC	
	Designed Core	Ulchin 3&4	Designed Core	Ulchin 3&4
MTC (10-4/°F)	−3.37	−0.56	−3.92	−62.3
FTC (10-5/°F)	−1.05	−1.5	−1.38	−1.5

Table 3. Calculated Shutdown Margin of SBF Designed Core

		Nat. B10			Enriched B10(50w/o)	
		BOC		EOC	BOC	EOC
		NESTLE	MASTER	NESTLE	NESTLE	
(N-1) RCCA Worth	①	8.95%	10.79%	11.15%	17.13%	19.14%
with 10% uncertainty from rodded position	②	8.06%	9.71%	10.04%	15.42%	17.23%
Power Defect (HFP-HZP)						
Fuel Temp. Defect	③	1.89%	2.09%	2.21%	1.89%	2.21%
Moderator Temp. Defect	④	2.82%	3.19%	3.03%	2.82%	3.03%
Shutdown Margin	⑤=②-③-④	3.35%	4.43%	4.80%	10.71%	11.99%
Temperature Defect(HZP-CZP)	⑥	1.85%	2.53%	1.96%	1.85%	1.96%
Refueling Standby Subcriticality	⑤-⑥	0.9853	0.9753	0.9808	0.9187	0.9069

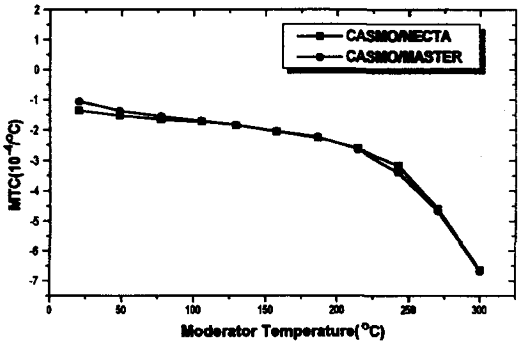


Fig. 12. Change of MTC vs. Moderator Temperature

condition is assured with large margin. k-value at BOC is 0.9187 and k at EOC is 0.9069.

Benchmark for the designed core using combination axial BP zoning method was done by CASMO-3/MASTER[11] code system. Excess reactivity, MTC and shutdown margin calculated by two code systems were coincident each other as shown in Table 3, Fig. 6 and Fig. 12.

5. Conclusions

The core designed in this study satisfied general requirements for SBFO in the aspect of nuclear design of initial core. The fuel assembly investigation study indicates that current design features are feasible to apply soluble boron free core design. The current burnable absorber design did compensate for excess fuel reactivity in the reference 18 month fuel cycle when large quantity and high concentration of burnable absorber was used.

Even though maximum core excess reactivity(1.1%) was a little more than target limit(1%), A.O. and FQ were kept within the safety limit. With three control rod banks at 65 assembly locations out of 149 assemblies, core excess reactivity was compensated with enough shutdown margin. In addition, because of strong negative moderator reactivity coefficients in entire cycle length, the safety performance of the soluble boron free operation was expected to be better than conventional PWR safety performance. For a real-world application of SBFO, safety analysis and economic evaluation for reload cycles should be done in detail.

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