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Axial BP Zoning for the Soluble Boron Free Operation in Medium-Sized PWR

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ABSTRACT

Feasibility of soluble boron free operation for the medium-sized commercial reactors was investigated. Westinghouse advanced reactor, AP-600 was chosen as a design prototype. Design modification was applied for the assembly design with gadolinia burnable poison - high Gd enrichment and axial poison zoning. CASMO and NECTA-C code system checked axial offset and peaking factors as fuels burned up. A core with complex axial burnable poison zoning satisfied design goals - small excess reactivity for 18 month cycle. Therefore, critical bank positioning for three control rod banks was sought with ease. A.O. value and Fq value were kept within the safety limit.

I. INTRODUCTION

Elimination of soluble boron gives many benefits for PWR innovation. Soluble boron free operation will relieve plant manager from corrosion maintenance concerns and reduce volume of liquid radwaste as well as operational radiation dose. More negative MTC due to deborated moderator would improve reactor transient performance as well as operational safety. System simplification also can be achieved by elimination of CVCS.[1][2] By these reasons, SBFO (Soluble Boron Free Operation) option has been applied for small-sized reactors(less than 100MWt) especially for marine reactors of which high operational performance is more essential than economics. However, reactivity compensation and control became infeasible for large sized commercial reactors if soluble boron were eliminated from all operational modes. In this paper, feasibility of soluble boron free core design for the medium-sized commercial reactors was investigated. The generic principles were studied for design requirements of burnable poison rods and control rods within the framework of commercial PWR, AP-600.[3] However, effects on operational controllability, safety and costs were not investigated in this paper.

Core design was done for the assembly design with high enriched Gd BP (Burnable Poison) throughout the 18 month cycle. Calculation was done by a code system; CASMO-3 and NECTA-C (NESTLE updated version).[4]

II. DESIGN METHODOLOGY

II.1 Parametric Study

Excess reactivity of soluble boron free reactor should be compensated mainly by burnable poison materials. In this paper, gadolinia(Gd_2O_3) integral BP was chosen. As a first step, design of fuel assemblies with BP was performed with four design parameters - fuel enrichment, Gd enrichment, # of BP rods, and BP rod location.

Extensive parametric study was done for BP rod location. As a result, it is found that location of BP rods within an assembly does not change a lot the excess reactivity variations but affect pin peaking considerably. Figure 1 shows the effect of enrichments in fuel and Gd to the assemblywise reactivity. As the Gd enrichment goes up, reactivity variations become flat and this effect becomes strong when fuel enrichment is increased. Figure 2 shows effects of number of BP rod and that its sensitivity to K-inf. is monotonous and predictable.

II.2 Core Reactivity Balance

Total reactivity of core depends on the fuel loading pattern and core boundary condition, and it changes as fuel burns up. As a preliminary design for assemblies, a batch design was done for the reactivity balancing based on the following equation.

$$[\ K_\infty\ ]_{core}(BU) = \sum_1^{N_1} K_1(BU) + \sum_1^{N_2} K_2(BU) + \sum_1^{N_3} K_3(BU)$$

where N_1, N_2, N_3 are number of fresh, and once and twice burned fuel assemblies.

Design target at this stage is to find the best flat combination of three K(BU) curves among many combination of three variables; number of BP rods, enrichment of fuel and BP. Reactivity curve of fresh fuel assemblies can be easily found to be flat and linear by chosing proper parameter values. Therefore, reactivity balance search was done for once and twice burned fuels. An iteration search was performed for the best combination for small excess core reactivity with the following search conditions.

- Average K-infinite should be flat for the core.(Here, average of once and twice burned)
- Average excess reactivity should lie between 1% to 3%.
- Gd enrichment 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

2.55w/o fuel, 20 BP rods, 12w/o Gd

Reactivity balance for these assemblies are shown in Fig.3. The fresh fuel assemblies were determined by try & error method for the target of the 1% reactivity.

II.3 Axial BP Zoning

Due to high moderator temperature feedback, axial offset is shifted to be negative high in ARO condition. For the rodded core for the critical, A.O. would be more negative. With three kinds of batch fuels, three different axial BP zoning method were applied in order to minimize axial offset throughout the cycle.

At first, axial BP enrichment zoning was applied for every burnable poison rods. Enrichment zoning was designed for three axial regions; enrichment of Gd in the bottom half was increased by 2% and one in the top 5% region was reduced to 0%. As a result of core calculation using checkerboard and out-in core loading pattern, critical rod position was sought without difficulty. However, calculated axial offset was varied a lot during the cycle and increased above the +10% in EOC. The reason of failure in A.O. control came from Gd burnup characteristics of enrichment zoning. As shown in Figure 1, K-infinite peak was high in the middle of cycle. This made power shape distored upward skewed during the control rod withdrawal period for the criticality near the EOC.

As the second method, axial BP zoning was done by BP rod numbers instead of Gd enrichment because effect of number zoning to the k-infinite curve is more monotonous and predictable compared with enrichment zoning. 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 half without Gd. As a result of BP rod number zoning, core excess reactivity at the ARO has much smoother and flat shape. Also, critical rod position was sought without difficulty and axial offset was controlled within -15% & +10% which is a little wider band than conventional limit band. The reason of out of A.O. limit band (±10%) can be found in Fig 2. Reactivity gaps between K-inf. curves were reduced remarkably as fuels were burned up. Therefore, the margin of A.O. is reduced.

As the third method, two axial BP zoning method were combined for the merits of both sides. Therefore, this method used the merits of the number zoning at BOC and enrichment zoning near the EOC.

Final selection of axial BP zoning are :

Fuel Type 1 0 - 68% : 1.85w/o, 4 BP (12w/o Gd)
68 - 100% : 1.85w/o, 4 BP (4w/o Gd)
Fuel Type 2 0 - 5% : 2.55w/o, 24 BP (2w/o Gd)
5 - 68% : 2.55w/o, 24 BP (10w/o Gd)

68 - 95% : 2.55w/o, 24 BP (12w/o Gd)
95 - 100% : 2.55w/o, 12 BP (2w/o Gd), 12 BP (0w/o Gd)
Fuel Type 3 0 - 5% : 2w/o for all BP
5 - 68% : 12w/o for all BP
68 - 95% : In case of 16 BP, 12w/o for 12 BP, 0w/o for 4 BP
In case of 20 BP, 16w/o for 12 BP, 0w/o for 4 BP
In case of 32 BP, 28w/o for 12 BP, 0w/o for 4 BP
95 - 100% : 2w/o for 50% of all BP, 0w/o for 50% of all BP

With this BP zoning method, reactivity change of each assembly could be flat and smooth as shown in Figure 4. Core loading pattern with control bank location are shown Fig. 5. Depending on the excess reactivity shown in Fig. 6, critical control bank position of three banks were sought and shown in Fig. 7. Here, two control banks were inserted with overlapping principle for the core reactivity balance. One control bank(bank-2) was moved independently for the reactivity balance and A.O. control. In this case, variation of A.O. and Fq were kept within the conventional limit band as shown Fig. 8 and 9.

III. CONCLUSION

Designed core satisfied general requirements for SBFO in the aspect of nuclear design of the initial core. 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 in 17 assemblies out of 149 assemblies, core excess reactivity was compensated by virture of large amount of Gd BP loading. There would be no problem in shutdown margin because there are many possible locations in the core when we load control bank at every other fuel assemblies. Axial BP zoning method could be applied successfully unless complex fabrication might not cause any problems.

REFERENCES

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2. ABB-CE, "Soluble Boron Free Passive PWR Study Phase II Summary Report," EPRI Report, Nov. (1989)
3. "AP600 Standard Safety Analysis Report," Chap.4, Westinghouse, June (1992)
4. Jong-Chae Kim, et. al., "Feasibitity Test for the SBFO in Commercial PWR," Proceeding of the Korean Nuclear Society Spring Meetting (1996)

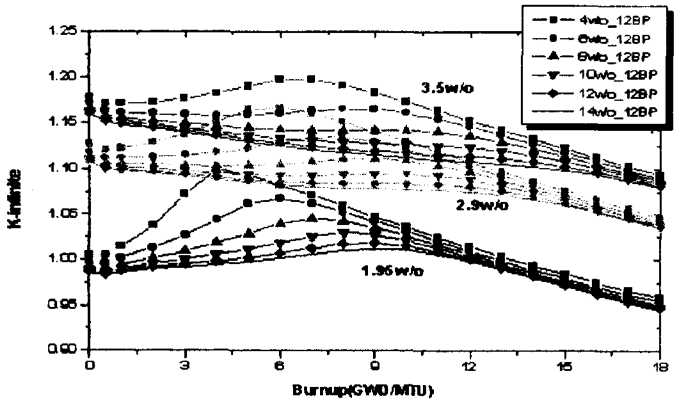

Fig.1 Variation in K-inf. of Assembly for Change of Fuel and Gd Enrichment

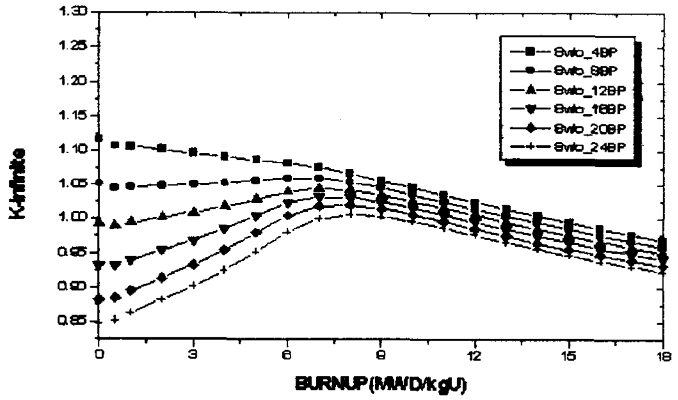

Fig.2 Variation in K-inf. of Assembly for the Change of Number of BP Rods

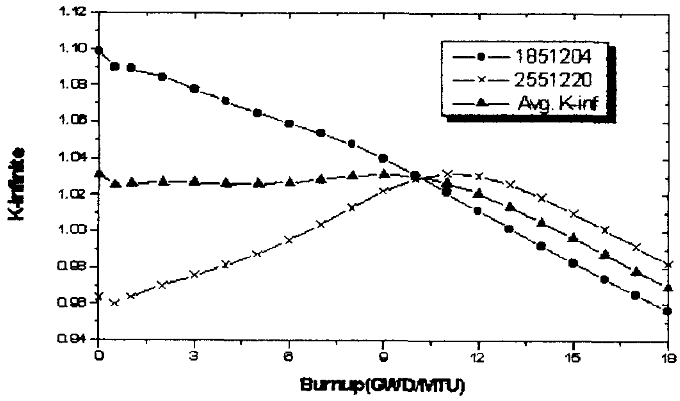

Fig.3 K-infinite Change vs. Burnup

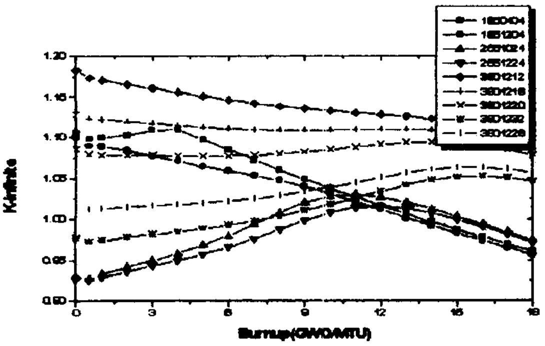

Fig.4 K-inf. variations of Fuel Assemblies

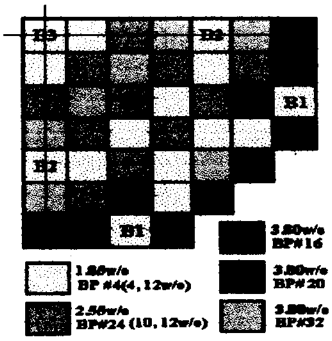

Fig.5 Core fuel loading pattern

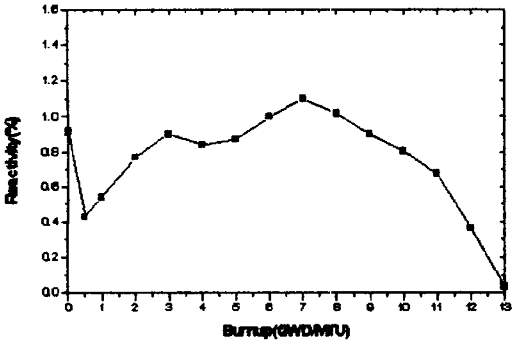

Fig.6 Core excess reactivity change

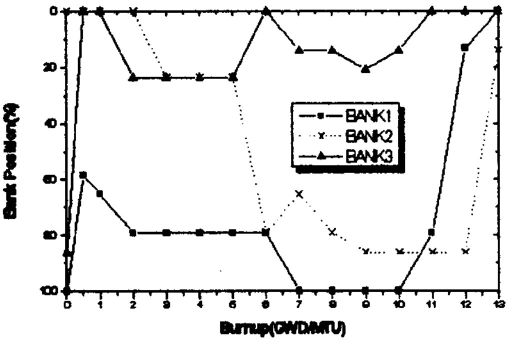

Fig.7 Critical control bank positions

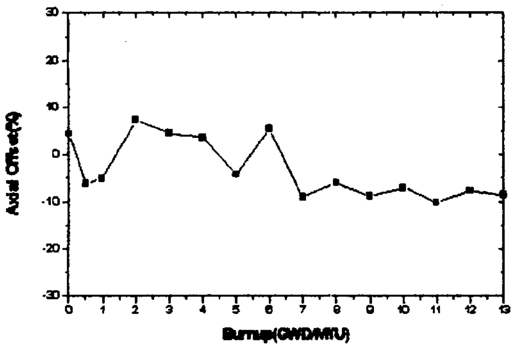

Fig.8 Axial Offset change for critical rod position

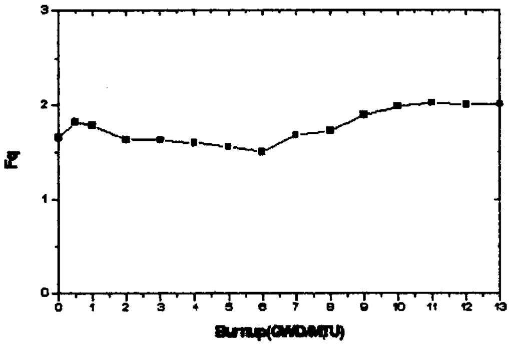

Fig.9 Variation of Fq vs. Burnup