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Conceptual Core Design of 1300MWe Reactor for Soluble Boron Free Operation Using a New Fuel Concept

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Abstract

A conceptual core design of the 1300MWe KNGR (Korean Next Generation Reactor) without using soluble boron for reactivity control was developed to determine whether it is technically feasible to implement SBF (Soluble Boron Free) operation. Based on the borated KNGR core design, the fuel assembly and control rod configuration were modified for extensive use of burnable poison rods and control rods. A new fuel rod, in which Pu-238 had been substituted for a small amount of U-238 in fuel composition, was introduced to assist the reactivity control by burnable poison rods. Since Pu-238 has a considerably large thermal neutron capture cross section, the new fuel assembly showed good reactivity suppression capability throughout the entire cycle burnup, especially at BOC (Beginning of Cycle). Moreover, relatively uniform control of power distribution was possible since the new fuel assemblies were loaded throughout the core. In this study, core excess reactivity was limited to 2.0 $\%\delta\rho$ for the minimal use of control rods. The analysis results of the SBF KNGR core showed that axial power distribution control can be achieved by using the simplest zoning scheme of the fuel assembly. Furthermore, the sufficient shutdown margin and the stability against axial xenon oscillations were secured in this SBF core. It is, therefore, concluded that a SBF operation is technically feasible for a large sized LWR (Light Water Reactor).

Key Words : LWR core design, SBF operation, 1300MWe KNGR, Pu-238

1. Introduction

The major impetus for considering the elimination of soluble boron reactivity control is the simplification of the design, operation, and maintenance of future pressurized water reactors. Plant design and operation are simplified by the elimination of fluid systems and components used to add and remove boric acid from the primary coolant and the need to monitor and adjust soluble boron during routine operational transients and shutdown. Plant maintenance is also simplified by the elimination of the need to handle borated water during fluid system maintenance and by the elimination of maintenance due to corrosion induced by boric acid. In terms of reactor control and safety, SBF (Soluble Boron Free) operation offers potential benefits through the presence of a strong, negative MTC (Moderator Temperature Coefficient) over the entire fuel cycle. Reactor transients and load-follow performance are improved through enhanced reactivity feedback in response to power changes. Thus, a rise in moderator temperature will immediately, and passively, add significant negative reactivity throughout the core cycle life.

The major modifications for SBF operation on the reactor core design are that the control rod requirements must be increased and larger amounts of BP (Burnable Poison) rods must be included in the core design. It is recognized that SBF operation is possible since boiling water reactors operate without soluble poisons, and some early PWRs (Pressurized Water Reactors) operated without soluble boron. The SBF concept is more practical for smaller nuclear power plants that can more easily accommodate lower core power densities and provide a higher degree of core power distribution stability than larger plants. In the feasibility studies on the core design of the 600MWe reactor, which had been performed without using soluble boron for reactivity control [1,2,3,4], SBF LWR is technically feasible. However, it is still questionable whether SBF operation can also be possible in a large-sized reactor in which power distribution control is more difficult than in smaller plants.

In this study, a conceptual core design of the 1300MWe KNGR (Korean Next Generation Reactor) for SBF operation was carried out to examine the feasibility of SBF operation, not in a 600MWe reactor, but in a larger reactor. Under the strategy of using BP rods and control rods extensively instead of soluble boron, the fuel assembly configuration in the borated KNGR was modified in order to increase the degree of freedom in selecting the number and type of BP rods [5,6,7,8]. The fuel rod design and composition, the BP rod design, and the RCCA (Rod Cluster Control Assembly) pattern were also changed to suit SBF operation. For the control of the bottom-shifted axial power distribution that is an inherent characteristic in SBF operation, the simplest form of fuel assembly axial zoning was developed to shift the power distribution toward the top of the core by using an enrichment zoning of Pu-238. The stability characteristics associated with xenon were evaluated, including xenon override capability in the return to power following a reactor trip.

The analyses in this study were performed by using the CASMO-3[9]/XFORM[10]/MASTER [11] code packages. MASTER code, which has been developed at KAERI (Korea Atomic Energy Research Institute) for a PWR core design, performs the depletion calculation using microscopic cross sections generated by CASMO-3 which is a multigroup two-dimensional transport theory code for assembly depletion calculations. XFORM has been developed at KAERI for the purpose of transferring cross section data from the CASMO-3 outputs into inputs of MASTER.

2. Fuel Assembly Modifications

2.1. Fuel Assembly Lattice

Since BP rods are, in SBF core, mainly used for the compensation for long-term reactivity due to fuel depletion at nominal full power conditions, the selection and the use of BP rods suited to the SBF concept are very important. As stated early, the fuel assembly configurations of borated KNGR were modified in order to increase the degree of

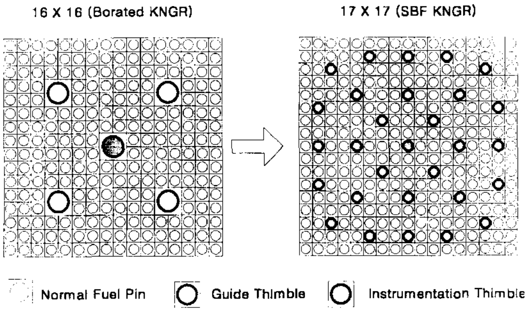
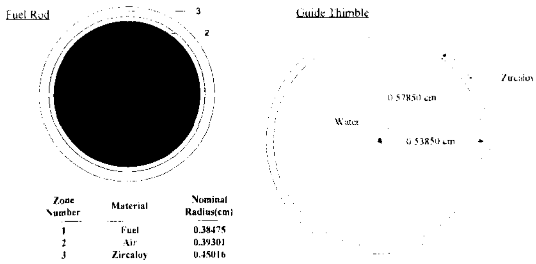


Fig. 1. Fuel Lattice Modification of KNGR



Zone Number	Material	Nominal Radius(cm)
1	Fuel	0.38475
2	Air	0.39301
3	Zircaloy	0.45016

Fig. 2. Dimensions of Fuel Pin and Guide Thimble

freedom in the selection of the number and type of BP rods. The (16 × 16) assembly size and (2 × 2) size guide thimble were changed to (17 × 17) and (1 × 1), respectively. With no change of fuel assembly pitch, fuel rod diameter was reduced so that the whole core diameter would not increase. The new (17 × 17) fuel lattice modified in this work is shown in Figure 1. It is recognized that 28 control rods were accommodated in the new fuel assembly to secure large control rod worth as compared to a 24 control rod configuration used in current standard designs. The fuel rod and guide thimble were newly designed as shown in Figure 2. It was based upon the fuel-to-moderator ratio of the borated KNGR core.

2.2. Fuel Rod Composition

Since reactivity is, as is generally known, an almost linear function of burnup for LWR lattices [12], considerable amounts of excess reactivity at BOC (Beginning of Cycle) are required to achieve the target cycle length. In SBF core, the excess reactivity must be compensated by BP and control rods. To limit the worth of control rod insertions necessary to adjust reactivity over a cycle, a large number of BP rods should be used to suppress the core reactivity. If all BP rods are loaded not in the guide thimbles but in the fuel location to reserve room for control rod insertion, linear power density (LPD) will be increased.

To improve the above problems, a new fuel rod, in which Pu-238 is substituted for a small amount of U-238 in fuel composition, was introduced to suppress the excess reactivity at BOC, and to avoid controlling the local reactivity by BP rods only. Since Pu-238 has a considerably large thermal neutron capture cross section in comparison to U-238, reactivity suppression at BOC can be large by just small amounts of Pu-238. In this study, infinite multiplication factor of the two different fuel assemblies that Pu-238 and Pu-240 among the plutonium isotopes having even mass number had been substituted for U-238 by 1 w/o, respectively, was calculated as a function of burnup. As shown in Figure 3, it was confirmed that excess reactivity at zero burnup could be suppressed considerably without BP rods, and, if the same amount of plutonium was substituted, Pu-240 was shown to be more effective than Pu-238. This is caused by the fact that the neutron capture capability of Pu-240 is better than that of Pu-238 over the whole neutron energy range.

In this study, Pu-238 was used instead of Pu-240, even though it is less effective at suppressing excess reactivity at zero burnup, because Pu-238 substitution shows more proper depletion

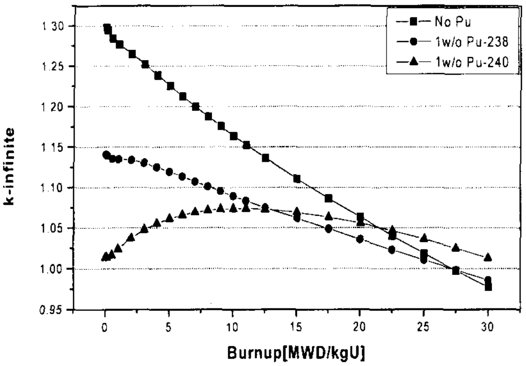
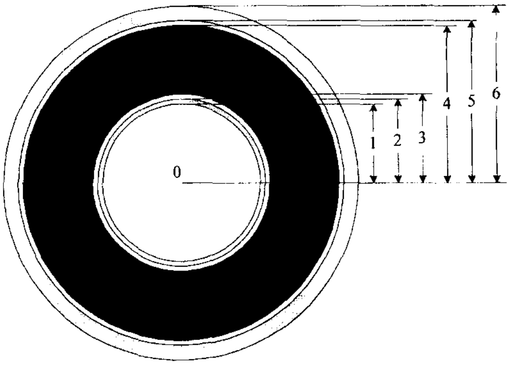


Fig. 3. Depletion Characteristic of Plutonium-Substituted Fuel Assembly



Zone Number	Material	Nominal Radius(cm)
0 - 1	Air	0.20280
1 - 2	Stainless Steel	0.21845
2 - 3	Air	0.22860
3 - 4	Al_2O_3-B_4C	0.40440
4 - 5	Air	0.41400
5 - 6	Stainless Steel	0.45016

Fig. 4. BP Rod Design

characteristics of fuel assembly than Pu-240 substitution for SBF core design. It comes from the fact that total macroscopic fission cross section of the fissile isotopes of plutonium induced by Pu-238 substituted is smaller than by Pu-240 at every burnup state. Therefore, when using Pu-240, large reactivity change over the burnup states is caused especially during 0 ~ 5 burnup as shown in Figure 3. The large reactivity ascension as the burnup proceeds is not desirable in SBF core, which causes the core reactivity and power shape control to be difficult. If Pu-238 is, however, substituted, excess reactivity decreases slowly as the fuel is depleted. If the excess reactivity is to be compensated by BP rods eligible for SBF core design, Pu-238 substitution shows an almost flat reactivity curve as a function of burnup.

2.3. Novel Burnable Poison Design

In order to find a BP rod, which can cause the core reactivity change be small as fuel is depleted, the depletion characteristics of various kinds of BP rods were analyzed without using soluble boron including integral and insertable BP rods currently being used. As a result, a novel BP rod, which can provide a proper reactivity hold-down at BOC with a relatively uniform rate of reactivity release, was introduced in this study. The BP rod having boron carbide admixed with alumina (B_4C-Al_2O_3) as an absorber material in the form of PYREX was used. Fuel rod OD (Outer Diameter) was employed as an OD of the BP rod to load the BP rod into the fuel rod location. Inner specifications of the BP rod are represented in Figure 4.

3. Analysis of Core Design for SBF Operation

3.1. Core Design

The evaluated fuel cycle design was based upon a 12-month equilibrium cycle with approximately one third of the fuel replacement in each cycle. The fuel management and BP loading scheme were designed to limit the requirement for control

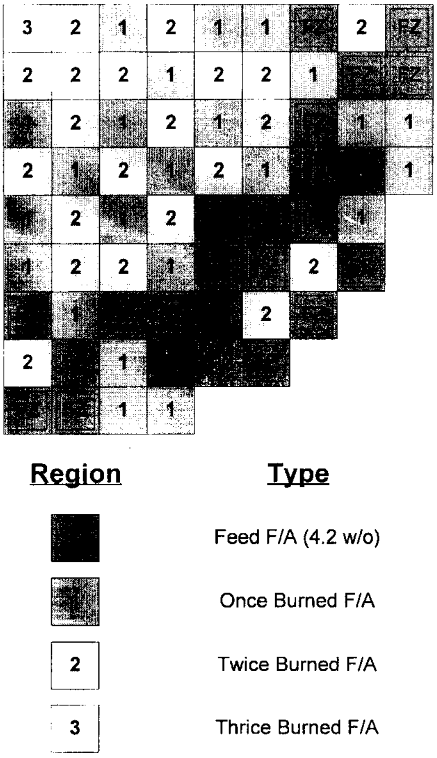


Fig. 5. Equilibrium Core Loading Pattern

rod reactivity adjustment over the cycle for nominal full power conditions to within a target value of 2.0 % reactivity. The target objective of F_{xy} was set to be 1.55, which is the value given for the borated KNGR.

The equilibrium core loading pattern is shown in Figure 5. In the reload SBF core design, careful determination of the core loading pattern should be required in comparison to the loading pattern of a borated reactor, because reactivity release of the feed assembly is different from that of the burned fuel assembly. Since reactivity of the burned fuel assembly decreases rapidly during burnup due to the exhaustion of burnable absorbers, reactivity of the feed assembly should be increased rapidly to compensate for the decreasing reactivity of the burned fuel. However, fuel management becomes more difficult when the infinite multiplication factor rises steeply during burnup in the fresh fuel. In this study, feed enrichment and the number of BP rods were, therefore, determined for the slow increase of feed assembly reactivity during burnup to avoid higher radial and axial peaking. For the equilibrium core loading pattern, a pattern, which is similar to an out-in scheme, was used to minimize the effects of the feed assembly on core reactivity instead of the in-out scheme. The unrodded reactivity as a function of cycle burnup at nominal full power is shown in Figure 6. The maximum unrodded reactivity of about 1.9%$\delta\rho$ is within the target objective.

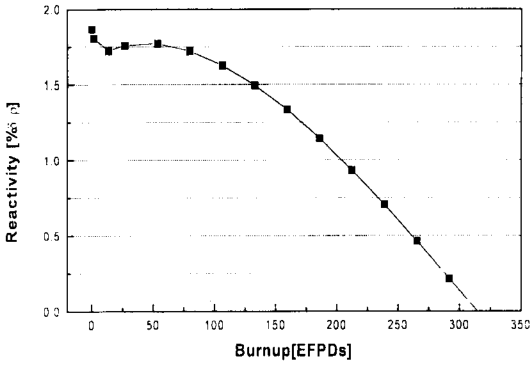


Fig. 6. Unrodded Reactivity Over Cycle

Axial zoning of the fuel assembly was used to control the bottom-shifted axial power distribution, which is an inherent characteristic in SBF operation due to the elimination of soluble boron. In all feed assemblies, the simplest form of axial zoning was adopted by using enrichment zoning of Pu-238 in the fuel composition as shown in Figure 7. Sixteen BP rods were loaded into all feed assemblies as shown in Figure 8. The BP rod location was determined for the minimum pin peaking factor through many assembly depletion calculations performed with the CASMO-3 code.

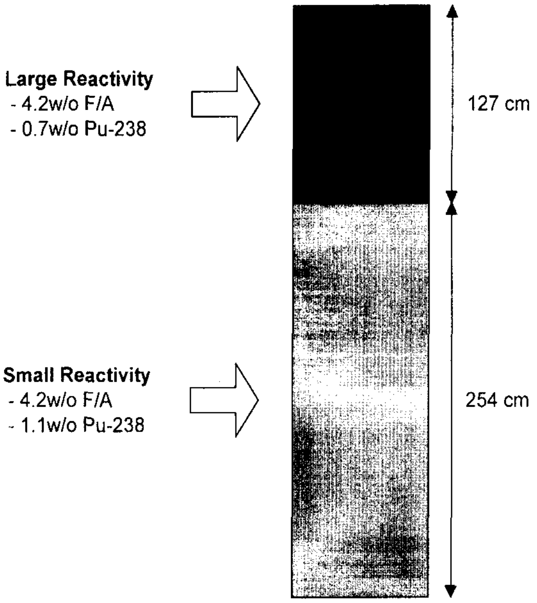


Fig. 7. Fuel Assembly Axial Zoning Pattern

The RCCA configuration was also modified to adjust long-term reactivity control over the cycle, and to secure a sufficient shutdown margin. The RCCAs were divided into two categories as shown in Figure 9: RCB for reactivity and power distribution control, and SDB for shutdown. RCB was divided into 5 banks : RCB1, RCB2, RCB3, RCB4, and RCB5, and SDB into 4 banks : SDB1, SDB2, SDB3, and SDB4. In selection of the control rod group, two nuclear design criteria were employed. First, the total reactivity worth must be adequate to meet the sufficient shutdown margin of the reactor. Second, in view of the fact that RCBs should be fully or partially inserted at power operation, the total power peaking factor should be low. RCBs were comprised of Silver-Indium-Cadnium absorber, and SDBs were modeled as strong absorbing rods consisting of B_4C absorber to secure a sufficient cold shutdown margin.

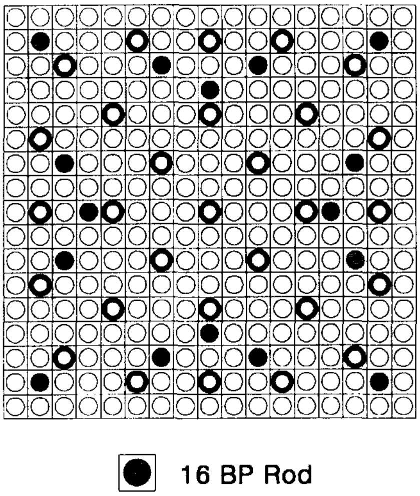
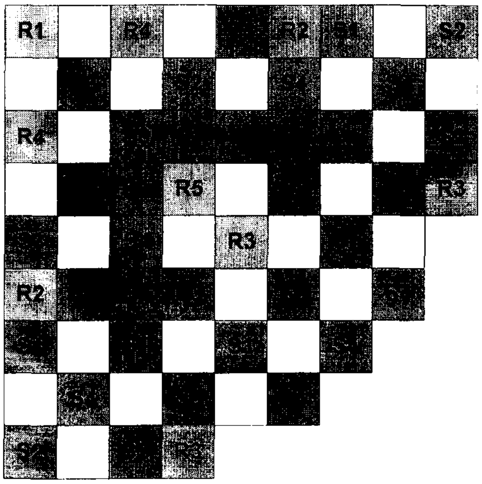


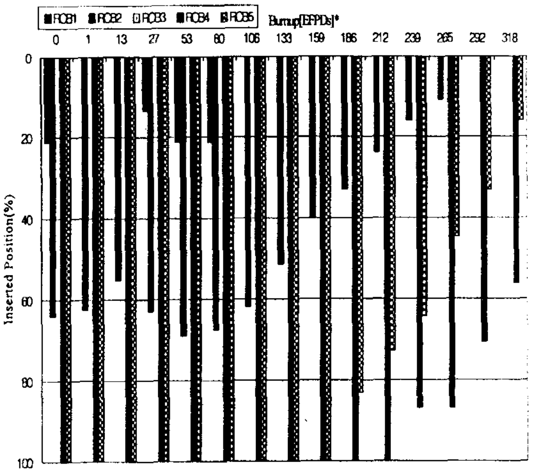
Fig. 8. BP Rod Loading Pattern



Index	Control Bank Name	Material
R1, R2, R3, R4, R5	RCB 1, 2, 3, 4, 5	Ag-In-Cd
S1, S2, S3, S4	SDB 1, 2, 3, 4	B_4C

Fig. 9. Rod Cluster Control Assembly Pattern

Control rod adjustment for long term reactivity control over the cycle was analyzed for the RCBs. The insertion history over the cycle, to provide a core k-effective of 1.0, is shown in Figure 10. RCB4 and RCB5 were fully inserted for reactivity



* : Effective Full Power Day

Fig. 10. Critical Control Rod Position Over Cycle

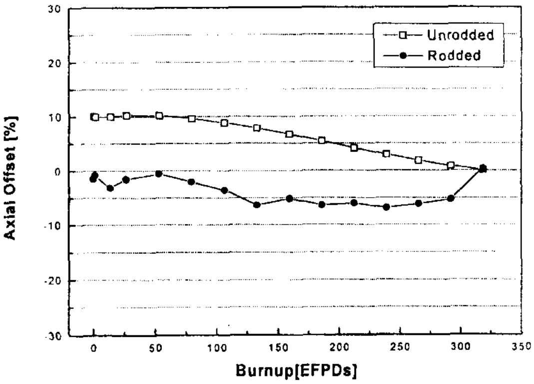


Fig. 11. Axial Offet Over Cycle (Critical CR Position)

control until about 70% EOC, and RCB1 and RCB2 were partially inserted to control the top and bottom reactivities in the core until MOC, respectively. RCB2 and RCB5 were in charge of top and bottom reactivities in the core, respectively, after MOC. The rodded AO (Axial Offset) and F_{xy} are shown in Figures 11 and 12, respectively, together with unrodded one. By showing that AO values ranged from -7.0% to 0.4%, and F_{xy} is

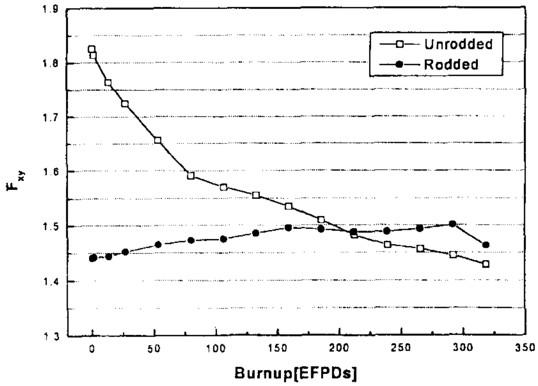


Fig. 12. Radial Peaking Factor Over Cycle (Critical CR Position)

within the target objective of 1.55, it is confirmed that power distribution control was well performed without using soluble boron.

MTC with burnup, and MTC and FTC (Fuel Temperature Coefficient) with temperature variation were calculated, and one of the results is shown in Figure 13. As a result of the calculations, it is confirmed that the inherent safety of the SBF KNGR designed in this work is secured as the cycle proceeds due to a strong negative MTC.

3.2. Shutdown Margin Calculation

The most limiting design consideration with respect to reactivity control is cold shutdown. Further, the removal of any one control rod (i.e., N-1 condition) should not cause the core to become critical. In practice, the N-1 limit is usually the design limiting condition for reactivity control. In general, the largest reactivity control requirement is demanded at EOC (End of Cycle), because the effect on power defect is biggest at the state when MTC has the most negative value. In SBF core, the most negative MTC occurs, however, at BOC owing to the absence of soluble boron. Therefore, the cold shutdown margin at

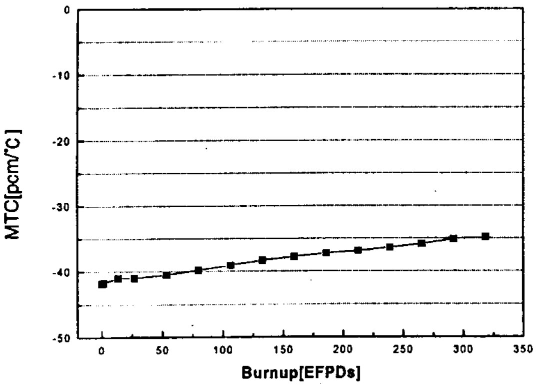


Fig. 13. MTC Values Over Cycle (Critical CR Position)

Table 1. Cold Shutdown Margin Calculation Results (BOC, Equilibrium Core)

Requirements (%)	
A. Control Rod Requirements [(a)+(b)+(c)+(d)+(e)]	10.8667
(a) Power Defect	2.1191
(b) Xenon Burnout	2.3643
(c) Isothermal Defect	4.0190
(d) Rod Insertion Allowance	1.8643
(e) Redistribution	0.5000
B. Control Rod Scram (N-1) Worth [(f)-(g)]	15.5138
(f) All Full-length Assemblies Inserted	17.8844
(g) Stuck Rod Worth	2.3706
C. 10 % Uncertainty Less [B × 0.9]	13.9624
D. Shutdown Margin [C-A]	3.0957

BOC was calculated and is summarized in Table 1. For an effect by redistribution, the usual value in common borated reactors was employed to calculate the reactor shutdown margin. When the rod worth at N-1 rod condition was calculated and reactivity insertion due to the power and temperature changes was offset, the net shutdown margin with 10 % adjustment to accommodate uncertainties was about 3.1 $\%\Delta\rho$ which is thought to be sufficient.

3.3. Xenon Stability Analysis

For the flexibility in plant maneuverability and ease of operation, it is desired that the core be inherently stable toward xenon-induced flux oscillation or else controllable by an operator response. Moreover, one of the design basis is that the core be controllable against axial oscillation. Two principle parameters that describe the flux oscillation are the time period between successive oscillation peaks and the attenuation of successive peak amplitudes. The attenuation factor, i.e., stability index, is the more important parameter from an operational standpoint, because it is a measure of the degree to which a particular core is stable or unstable to free-running xenon-induced oscillations. By convention, if the index of stability is negative, the core is stable, and otherwise positive, the core is unstable.

The stability characteristics of the SBF KNGR designed in this study were evaluated by using a 3-D core model to excite a xenon oscillation and then observing the changes in the AO as a function of time. The results, summarized in Table 2, demonstrates that even for a core height of 150 inches, the SBF KNGR was xenon stable early in cycle, and the core was still stable against xenon oscillation late in cycle when the most positive stability index occurs and xenon control is most difficult. The stability index at BOC was approximately -0.02409 hr^{-1}, and at EOC, -0.01047 hr^{-1}. Thus, it is noted that xenon oscillations in this SBF core are less severe than those in conventional PWR cores.

The capability of the SBF KNGR core to override xenon reactivity following reactor shutdown was evaluated by using the 3-D core model to simulate a reactor trip from full power

Table 2. Axial Stability Index Calculation Results (Equilibrium Core)

Burnup	Oscillation Period (hr)	Axial Stability Index (hr-1)
BOC (0 EFPD*)	32	-0.02409
85 % EOC (265 EFPDs)	28	-0.02044
EOC (318 EFPDs)	31	-0.01047

* : Effective Full Power Day

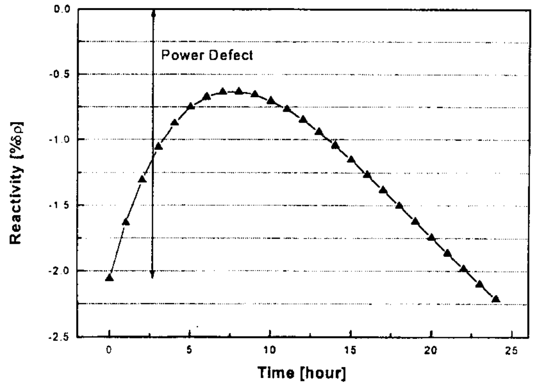


Fig. 14. Excess Reactivity Required After Reactor Trip (EOC)

and then following the xenon reactivity as a function of time. The result of the simulation that had been performed at EOC is shown in Figure 14. The result shows that no excess reactivity was required to return to power following the reactor trip at any times. The positive reactivity resulting from the power defect was sufficient to allow a return to power without excess reactivity. Therefore, xenon override can be accomplished, and a return to power following a reactor trip was easily obtainable for the SBF KNGR core.

4. Conclusions

A conceptual core design of the 1300MWe KNGR for SBF operation was carried out to examine the practicality of SBF operation in a large-sized PWR with limited optimizations under the strategy of extensive use of BP rods and control rods instead of using soluble boron. The fuel assembly configuration was modified including the core components of fuel rod and composition, and BP rods. The RCCA pattern was also changed to provide long term reactivity control over the cycle and a sufficient shutdown margin without soluble boron.

The new fuel rod introduced in this study was very effective to suppress excess reactivity at BOC by substituting Pu-238 for a small amount of U-238 in fuel composition, because Pu-238 has a large thermal neutron capture cross section compared to U-238. Therefore, the number of BP rods to control the long-term reactivity can be reduced considerably. Furthermore, axial and radial power distribution control were relatively well carried out uniformly throughout the whole core just as the use of soluble boron by avoiding local control by BP rods only. Since the bottom-shifted axial power distribution was well controlled by the simplest form of fuel assembly axial zoning by using a method of Pu-238 enrichment zoning, AO with burnup can be ranged in a relatively narrow band.

The analysis results of the SBF KNGR core show that power distribution can be controlled to within a target objective of 1.55, and the net shutdown margin requirement for cold conditions was sufficiently obtained. In xenon stability analysis, it is concluded that xenon oscillations can be less severe even in large-sized SBF cores. Though an 18/24-month cycle length was not achieved because feed assemblies can not be loaded into the SBF core center region for power peaking control, longer cycle lengths seem to be expected if optimization of the fuel management schemes is performed.

Acknowledgement

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