DEVELOPMENT OF AXIALLY VARIABLE STRENGTH CONTROL RODS FOR THE POWER MANEUVERING OF PWRS

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ABSTRACT

In this research, lower shifted worth control rods (LSWCRs) are suggested to mitigate problems related to variation of axial power distribution during the power maneuvering of PWRs. These rods are classified into two types. The first type is 'multi-purpose control rod', and the other type is 'regulating control rod'. Two multi-purpose control rod banks(LSWCR1, LSWCR2) and three regulating control rod banks(LSWCR5, LSWCR4, LSWCR3) are suggested and developed. The moving characteristics of LSWCRs, related to variation of reactivity and the axial offset(AO), are analyzed and the operation strategy for LSWCRs are established. Then, an application of LSWCRs for the power maneuvering is performed using the developed strategy, and the reference daily load pattern is 100-50-100%, 2-6-2-14h pattern that is appropriate for operation of the electric grid in Korea. From the results, it is shown that the combinative use of multi-purpose control rods(LSWCR1, LSWCR2) makes it possible to control the AO within the target band during the power maneuvering. Also, the results show that the power maneuvering without reactivity compensation by change of boron concentration is accomplished, and consequently the minimization of boron concentration change is possible.

1. INTRODUCTION

The nuclear power plant has limited operation flexibility, compared with other power plant, due to special consideration of core safety. Therefore, in the present operation of electric grid in Korea, the nuclear power is used as only base load means, and change in electric power generation to follow load change is performed by other electric power sources, such as fossil power plants. However, as the share of the nuclear power in an electric power generation increases, there is a growing needs for nuclear power plants to be able to follow load changes on a utility's power system, therefore the load follow capability and operation of nuclear power plants becomes more important.

In a nuclear power plant, the reactor power change is caused by changes in reactivity. Two primary mechanisms for reactivity changes are control rods and soluble boron. Cylindrical control rodlets of neutron absorbing material are assembled into clusters and manipulated as groups(banks) of clusters in a reactor. Soluble boron control involves the use of a neutron absorber in the form of boric acid, dissolved in the coolant to compensate for slow reactivity change. A moderator temperature control is auxiliary means. To produce favorable steam generation characteristics, PWRs operate at a programmed average coolant temperature. However, it is desirable at times to allow coolant temperature to deviate from its programmed value and to utilize the reactivity feedback effects to produce a desired power change.[1]

During a load following operation of a nuclear power plant, the reactor core is in a transient state induced by transient effects of xenon, which is one of the fission product and is a very strong absorber of thermal neutrons.[2] The reactivity change makes variation of xenon concentration and axial distribution, and a change in xenon axial distribution causes xenon oscillation, which makes reactor be able to reach uncontrollable state or trip. Therefore, preventing a xenon oscillation is important. And to prevent a xenon oscillation, maintaining the axial power distribution within some prescribed range is required, during power maneuvering.

However, the reactivity change using the existing mechanisms has difficulties in maintaining this distribution within the prescribed range. Firstly, a motion of control rods in a reactor core involves variation of axial power distribution. In the top half of the core, a control rod insertion moves the power distribution to the negative direction, and withdrawal moves the power distribution to the positive direction. In the bottom half of the core, vice versa. Secondly, a power variation with boron concentration change involves change of axial power distribution. For instance, a power reduction with boration always tend to move the power distribution in the positive direction because of the negative moderator temperature coefficient.

In this study, axially variable strength control rods(lower shifted worth control rods) are suggested to mitigate variation of axial power distribution during power maneuvering, and a new power maneuvering strategy with suggested control rods is developed. In addition, minimizing boron concentration change is considered, to increase the efficiency of the axially variable strength control rods, on the new power maneuvering strategy.

2. BACKGROUND[3]

Power distributions are represented by a variable called axial offset(AO) or axial shape index(ASI).

$$AO(=ASI) = \frac{P_T - P_B}{P_T + P_B} \qquad (1)$$
$$\Delta I = P_T - P_B$$

where,

ΔI : power difference between top and bottom half of the core
P_T : power in top half of the core
P_B : power in bottom half of the core.

This is simply the normalized difference between the power in the top half of the core and the power in the bottom half of the core. The top and bottom core power indications needed to calculate the AO are obtained from top and bottom nuclear detectors that are located outside the reactor vessel.

The basic idea behind the Westinghouse power distribution control philosophy, called constant axial offset control (CAOC), is to keep the AO within a control band about a reference AO value(target ASI) that corresponds to the most stable axial power distribution possible for existing core conditions, that is, the power shape existing at full power with equilibrium xenon and no control rods in the core.

Then, the AO(ASI) target band is determined as follows: This target band must be sufficiently narrow such that the benefits of lowered peaking factors can be obtained, yet also must be sufficiently broad to allow the plant operator to make power change easily. The target power difference band and corresponding AO band around a typical target are chosen to meet these dual objectives. Typically the selected target boundaries are ±5%, as shown in Figure1.

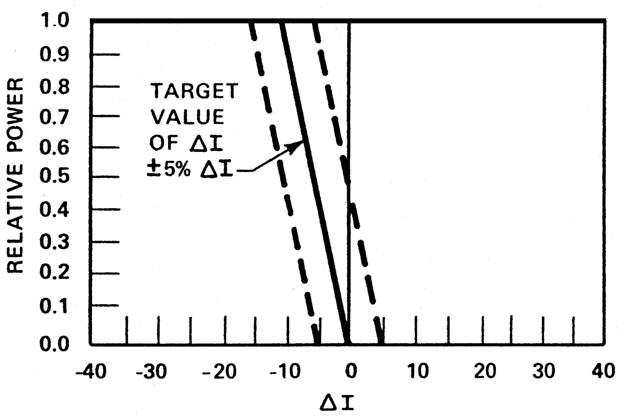

Figure 1. The target band of ΔI

The AO is calculated by dividing ΔI by relative power. Therefore, target boundary is ±5% at 100% power, but target bands broaden as the relative power decrease, as shown in Figure 2. And the AO(ASI) target band according to power variation is shown in Figure 3.

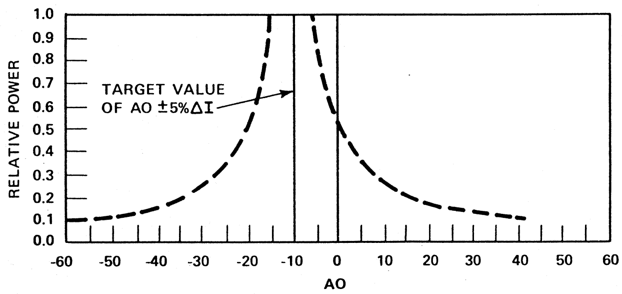

Figure 2. The target band of AO

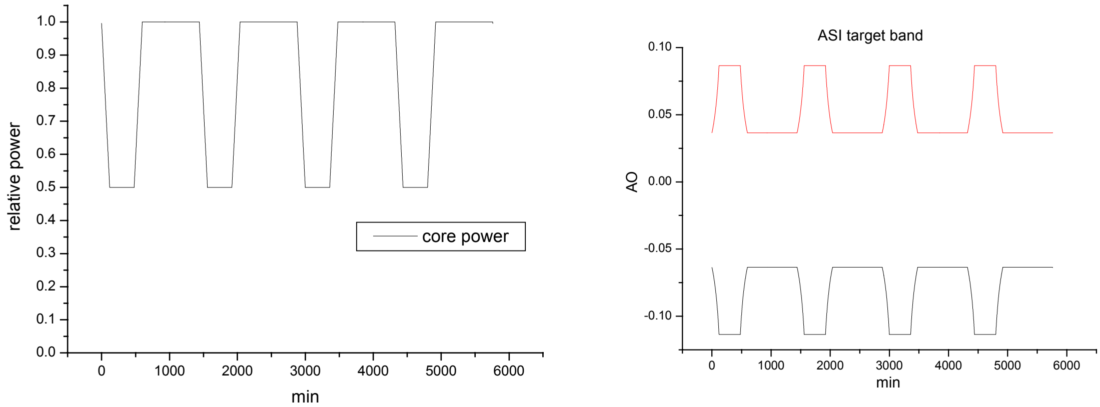

Figure 3. AO(ASI) target band according to power variation

In the CAOC operation, a power reduction without control rod insertion always tends to move the AO in the positive direction because of the negative moderator temperature coefficient. Therefore, a proper amount of full length control rod group insertion tends to move the AO back to the original target AO(negative direction). Thus, the full length rods are used for two purposes in this status-to absorb the reactivity insertion associated with the power reduction, and to maintain the AO at its original value. The prime factor in determining the degree of full length rod insertion should be AO control rather than reactivity control. In some case, the full length rod insertion necessary for CAOC is not enough to control the reactivity change associated with the power reduction. The balance of the reactivity change is then controlled through changes in the moderator boron concentration. Also, the degree of full length rod insertion during part power operation is not large enough to produce the reactivity required to return to full power, therefore boron dilution is necessary.

3. DEVELOPMENT AND APPLICATION OF AXIALLY VARIABLE STRENGTH CONTROL RODS

A motion of control rods in a reactor core involves variation of axial power distribution. As shown in Figure 4, the AO moves linearly when control rod moves. And when control rod stops, the AO shows oscillation from xenon oscillation.[4] In the top half of the core, a control rod insertion moves the AO to the negative direction, and withdrawal moves the AO to the positive direction. In the bottom half of the core, vice versa.

However, the AO variation must be kept in the AO target band, as mentioned above. This characteristic makes it difficult to maneuver reactor power using control rods, and limits control rod motion. In this research, therefore, axially variable strength control rods are suggested to mitigate problems related to variation of axial power distribution during power maneuvering. The main purpose of axially variable strength control rods is lifting up the AO, and these rods cause reactivity change, of course, as normal control rods do.

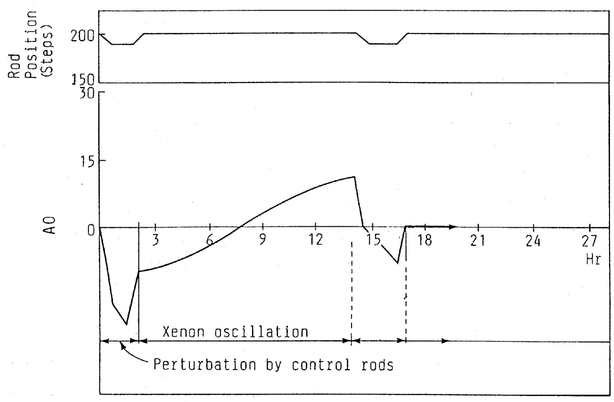

Figure 4. AO characteristics according to control rod motion

2.1 LOWER SHIFTED WORTH CONTROL RODS (LSWCRs)

In this research, lower shifted worth control rods(LSWCR) are suggested and developed. These rods are classified into two types. The first type is 'multi-purpose control rod', and the other is 'regulating control rod'. Two multi-purpose control rod banks(LSWCR1, LSWCR2) and three regulating control rod banks(LSWCR5, LSWCR4, LSWCR3) are suggested. The main tasks of the multi-purpose control rods are controlling the AO, providing relatively strong lifting-up tendency to the AO when these rods exist below the center of the core, and producing the required reactivity instead of a boron concentration change(boration/dilution). And the main purpose of the regulating control rods is producing reactivity change as existing normal control rods.

MULTI-PURPOSE CONTROL RODS (LSWCR1, LSWCR2)

Two multi-purpose LSWCRs are suggested in this work. The first multi-purpose control rod is the LSWCR1 of which worth shape is shown in Figure 5. The LSWCR1 moves mainly in the bottom half of the reactor core, and the AO approaches the upper AO target boundary at initial core state due to this LSWCR1. The requirements of the LSWCR1 are as follows: In respect of AO control, the role of the LSWCR1 is lifting up the AO, therefore the LSWCR1 should mitigate an AO distortion to the negative direction caused by the motion of the other control rods. Also, the LSWCR1 should cause the required reactivity change instead of boron concentration change. In addition, the LSWCR1 is used as an auxiliary means, in respect of reactivity change, compared with the LSWCR2 and moves within a narrow range because the most important purpose of the LSWCR1 is lifting up the AO, therefore, it alway exists in the bottom of the core.

The other multi-purpose control rod is the LSWCR2 and its worth shape is shown in Figure 6. The LSWCR2 moves in the whole range of the core differently from the LSWCR1. The requirement of the LSWCR2 are as follows: The LSWCR2 controls the AO to the negative or the positive direction, and mitigates an AO variation due to the motion of the other control rods. Another important role of the LSWCR2 is to cause the reactivity change needed for maintaining target reactor power instead of boron concentration change, when regulating rods are fully withdrawn.

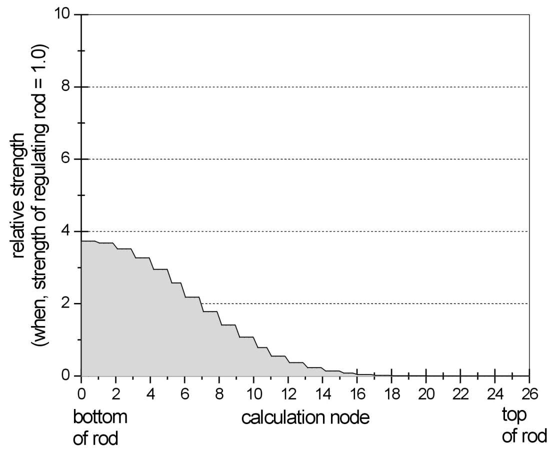

Figure 5. Worth shape of LSWCR1

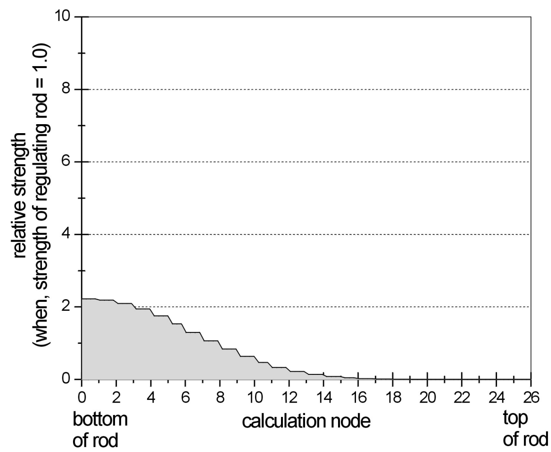

Figure 6. Worth shape of LSWCR2

REGULATING CONTROL RODS (LSWCR5～3)

Three regulating LSWCRs, named LSWCR5, LSWCR4, and LSWCR3 are suggested. Their worth shapes are identical and shown in Figure 7. These rods perform the same function as the existing normal control rods. These rods are fully withdrawn at initial state, and the main purpose of the regulating control rods is to cause reactivity change. In addition, these rods provide a strong AO change to the positive direction, compared with the existing normal control rods, after passing through the center of the core because of the lower shifted worth shape.

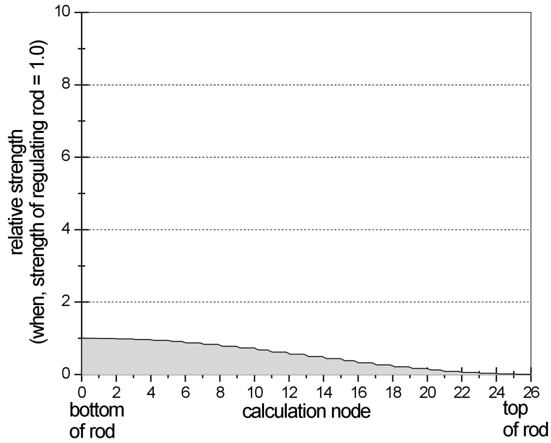

Figure 7. Worth shape of regulating LSWCRs

2.2 APPLICATION OF LSWCRS FOR THE POWER MANEUVERING

In respect of axial power distribution, a power variation with boron concentration change involves change in axial power distribution. For instance, a power reduction with boration always tend to move the AO in the positive direction because of the negative moderator temperature coefficient. Therefore, utilization of boron concentration change for reactivity compensation makes it difficult to solve AO related problems with axially variable strength rods during power maneuvering. For that reason, minimization of boron concentration change is necessary. However, the degree of control rod insertion during part power operation is not large enough to produce the reactivity required to return to full power, and boron dilution is necessary. Therefore, the other means that performs the above boron's role, instead of boron concentration change, is required.

In this research, boron concentration change is performed only for compensating fuel burn-up and limited on other case such as reactivity compensation, hence the change of boron concentration is minimized. And the multi-purpose lower shifted worth control rods(LSWCR1, LSWCR2) substitute for boron and are inserted in the core at the initial state(100% power equilibrium) in other to produce the required reactivity instead of changing boron concentration. For experiments, the ONED94 code is used for an application plant. The ONED94 code is an one-dimensional reactor core simulation code.[5]

INITIAL STATE OF THE CORE

Firstly, the initial positions of multi-purpose control rods are determined. The initial position of the LSWCR1 is determined as follows: The reactor power varies accordingly as a control rod moves from the bottom to the top of the core. In the case of the LSWCR1, from some experiments using the ONED94 code, it is shown that the position on which the reactor power is minimized is not the bottom of the core due to the lower shifted worth shape. The position exists in the lower part of the bottom half of the core, and this position is selected as the initial position of the LSWCR1. Then, the initial position of the LSWCR2 is determined as follow: From experiments changing the position of the LSWCR2, it is shown that the initial AO varies as shown in Figure 8, and the lower position that approaches the upper AO boundary is selected as the initial position of the LSWCR2.

Secondly, the equilibrium boron concentration on initial state is obtained by boron search using the ONED94 code, and then the boron concentration is fixed and does not vary according to time.

In this way, the initial state of the core is obtained and it is shown in Figure 9. The initial relative core power is 1.0(100% power) as shown in Figure 9(a). The initial positions of LSWCRs are determined as shown in Figure 9(b). The multi-purpose LSWCRs are in the bottom half of the core, and the regulating LSWCRs are fully withdrawn on initial state. Finally, the initial AO is shown in Figure 9(c). The AO transient starts with decreasing AO value in the power maneuvering, therefore, the initial AO exists beneath the upper AO target boundary.

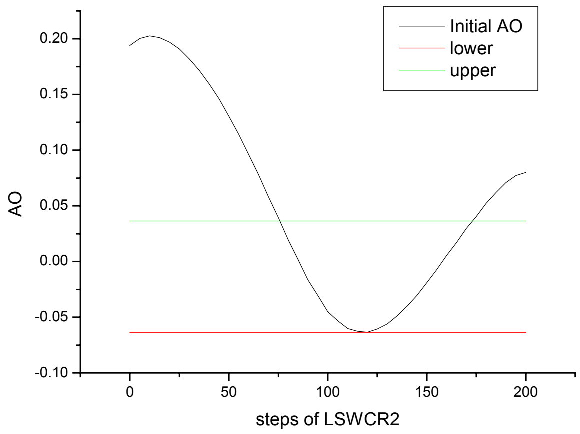

Figure 8. Initial AO vs. position of the LSWCR2

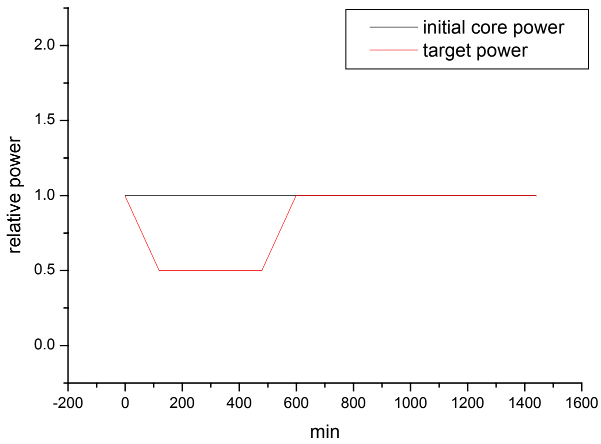

Figure 9(a). Initial relative core power

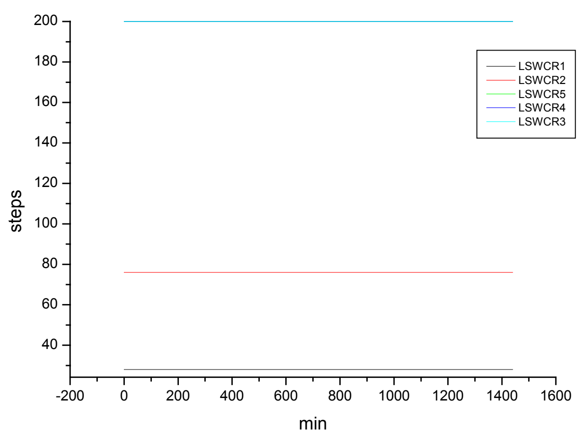

Figure 9(b). Initial positions of LSWCRs

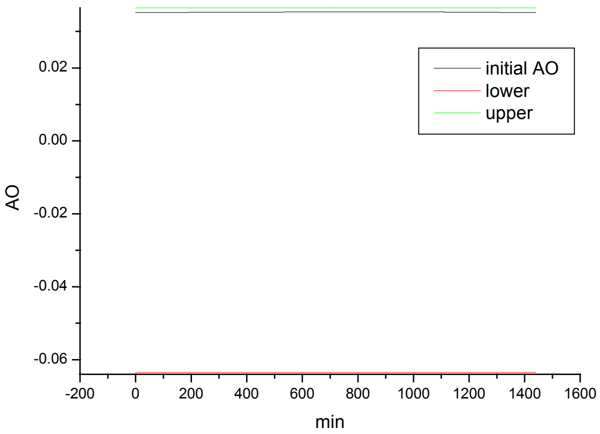

Figure 9(c). Initial axial offset

DEVELOPMENT OF OPERATION STRATEGY FOR LSWCRS AND ITS APPLICATION

Firstly, the moving characteristics of LSWCRs, related to variation of reactivity and the AO, are analyzed before establishing the operation strategy for LSWCRs. Experiment results are obtained on the conditions that the LSWCR1(or LSWCR2) moves from the initial position to the top of the core then moves to the bottom of the core, and the LSWCR1(or LSWCR2) moves from the initial position to the bottom of the core then moves to the top of the core. Analyzing the results provides the moving characteristics of LSWCRs. The both moving characteristics of LSWCR1 and LSWCR2 are identical each other and shown in TABLE Ⅰ.

● at initial position

LSWCR1, 2	*Reactivity*	*AO*
Insert	up	up
Withdraw	up	down

● above initial position

LSWCR1, 2	*Reactivity*	*AO*
Insert	down	down
Withdraw	up	down then up

● below initial position

LSWCR1,2	*Reactivity*	*AO*
Insert	up	up
Withdraw	down	down

TABLE Ⅰ Moving characteristics of LSWCR1 and 2

Then, the operation strategy for LSWCRs are established from the analysis results. And other rules used in order to establish the strategy are as follows: The LSWCR1 moves mainly in the bottom half of the reactor core, and the LSWCR1 is used as an auxiliary means, in respect of reactivity change, compared with the LSWCR2 and moves within a narrow range because the most important purpose of the LSWCR1 is lifting up the AO, therefore, it alway exists in the bottom of the core. The LSWCR2 moves in the whole range of the core differently from the LSWCR1. The operation strategy for the LSWCR1, the LSWCR2, and the regulating LSWCRs is shown in TABLE Ⅱ.

1) when time < 600 min,

● moving condition of the LSWCR1

① required rodspeed > 0
② all regulating rods are withdrawn
when ① & ②, LSWCR1 moves with -1.0*rodspeed/30.
otherwise, LSWCR1 stops.
③ required rodspeed < 0
④ steps of LSWCR1 < initial position
when ③ &④ , LSWCR1 moves with -1.0*rodspeed/30.
otherwise, LSWCR1 stops.

● moving condition of the LSWCR2

① required rodspeed > 0
② all regulating rods are withdrawn
when ① &② , LSWCR2 moves with rodspeed.
otherwise, LSWCR2 stops.
③ required rodspeed < 0
④ steps of LSWCR2 > initial position

when ③ &④ , LSWCR2 moves with rodspeed.
otherwise, LSWCR2 stops.

- moving condition of the regulating LSWCRs

① required rodspeed > 0
when ① , LSWCR5 moves with rodspeed and others move according to the existing overlap rule.
② required rodspeed < 0
③ steps of LSWCR2 > initial position
when ② &③ , LSWCR3 stops.
otherwise, LSWCR3 moves with rodspeed and others move according to the existing overlap rule.

2) when time > 600 min,

- moving condition of the LSWCR1

① required rodspeed > 0
② AO < AO_lower
when ① & ②, LSWCR1 moves with -1.0*rodspeed/20.
otherwise, LSWCR1 stops.
③ AO_lower < AO < AO_upper
when ① & ③, LSWCR1 moves with -1.0*rodspeed/30.
otherwise, LSWCR1 stops.
④ AO > AO_upper
when ① &④ , LSWCR1 moves with -1.0*rodspeed/30.
otherwise, LSWCR1 stops.
⑤ required rodspeed < 0
⑥ steps of LSWCR1 < initial position
when ⑤&⑥, LSWCR1 moves with -1.0*rodspeed/30.
otherwise, LSWCR1 stops.

- moving condition of the LSWCR2

① required rodspeed > 0
② AO < AO_lower
when ① &② , LSWCR2 moves with rodspeed.
otherwise, LSWCR2 stops.
③ AO_lower < AO < AO_upper
when ① &③ , LSWCR2 moves with rodspeed.
otherwise, LSWCR2 stops.
④ AO > AO_upper
when ① &④ , LSWCR2 moves with -1.0*rodspeed.
otherwise, LSWCR2 stops.
⑤ required rodspeed < 0
⑥ steps of LSWCR2 > initial position
⑦ AO > AO_upper
when ⑤&⑥&⑦, LSWCR2 moves with rodspeed.
otherwise, LSWCR2 stops.

- moving condition of the regulating LSWCRs

① required rodspeed > 0

when ① , LSWCR5 moves with rodspeed and others move according to the existing overlap rule. ② required rodspeed < 0 ③ steps of LSWCR2 > initial position ④ AO > AO_upper when ② &③ &④ , LSWCR3 stops. otherwise, LSWCR3 with rodspeed and others move according to the existing overlap rule.

TABLE Ⅱ Operation strategy of LSWCRs for power maneuvering

In this table, the value of 'rodspeed' is obtained from a simple fuzzy logic with the value of power deviation from target power and the change rate of the value of power deviation. The parameter 'rodspeed' means the moving speed of regulating control rods. When a reactivity insertion is needed, the value of 'rodspeed' becomes positive then regulating control rods move up. And when a reactivity withdrawal is needed, the value of 'rodspeed' becomes negative.
Then, an application of LSWCRs for the power maneuvering is performed using the above strategy. A typical 100-50-100%, 2-6-2-14h pattern of daily load-follow power maneuvering is adopted based on the demand pattern in Korea. The power varies from 100 to 50% in 2h, holds at 50% for 6h, then rise to 100% in 2h.[6] And the burn-up state of the reactor core is BOC. The application results are shown in Figure 10.
Figure 10(a) shows the variation of the relative core power according to time. The calculated core power approximately corresponds with the reference target power, and some small deviation shown in this figure will be decreased through some tuning the algorithm to calculate control rod speed.
The boron concentration change shown in Figure 10(b) is fixed to the value on the initial state, and the boron concentration does not vary according to time.
The motions of LSWCRs, during the power maneuvering, are shown in Figure 10(c). And the above operation strategy will be continuously developed to satisfy the followings: After one-day cycle, the regulating LSWCRs are fully withdrawn, and the LSWCR1 and the LSWCR2 return to the initial positions. Finally, the variation of the AO according to time is shown in Figure 10(d). This result shows that the AO is regulated within the AO target band, by multi-purpose LSWCRs, during the power maneuvering.

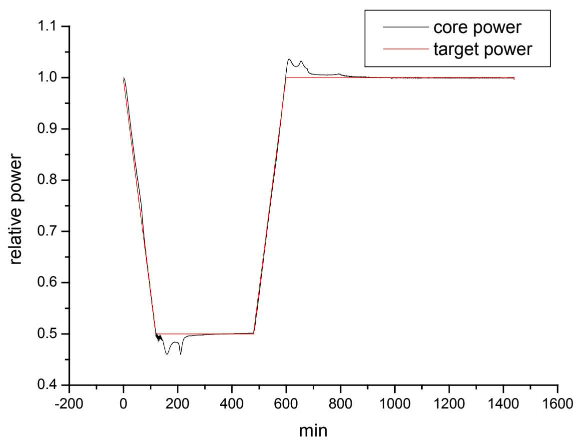

Figure 10(a). Core power

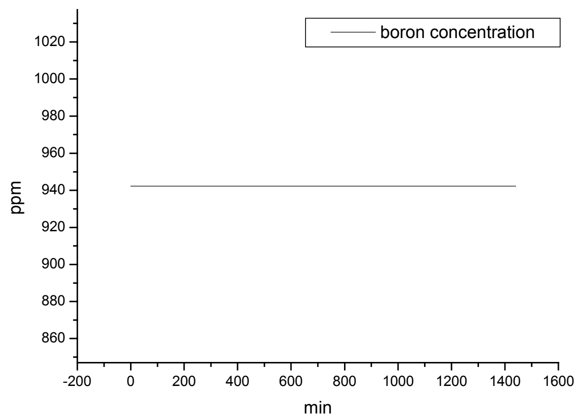

Figure 10(b). Boron concentration

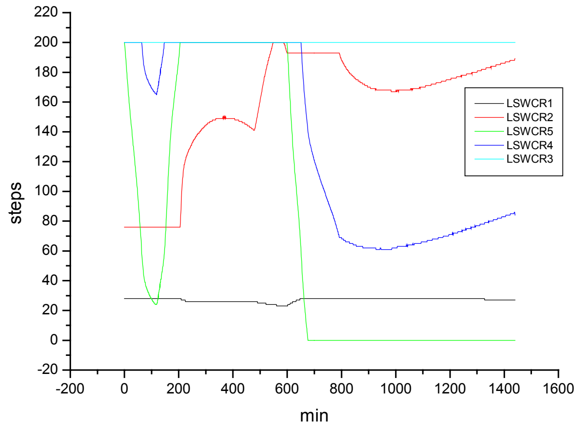

Fig.10(c). The motions of LSWCRs

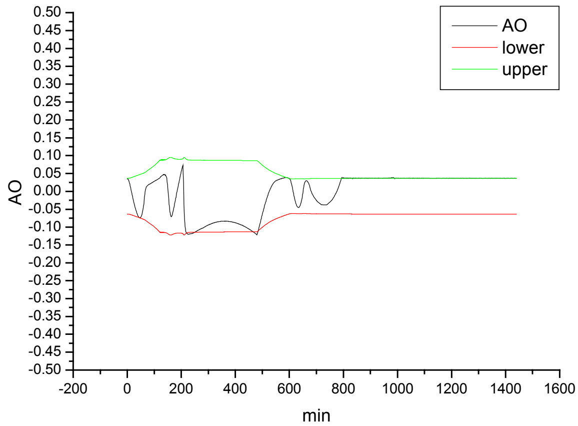

Fig.10(d). Axial offset

From the above results, it is shown that LSWCRs have good characteristics for controlling the AO and the combinative use of multi-purpose control rods(LSWCR1, LSWCR2) makes it possible to control the AO within the target band during the power maneuvering of PWRs. Also, the results show that the power maneuvering without reactivity compensation by change of boron concentration is accomplished, and consequently the minimization of boron concentration change is possible.

CONCLUSIONS

In this research, lower shifted worth control rods(LSWCR) are suggested and developed to mitigate problems related to variation of axial power distribution during the power maneuvering of PWR. These rods are classified into two types. The first type is 'multi-purpose control rod', and the other type is 'regulating control rod'. Two multi-purpose control rod banks(LSWCR1, LSWCR2) and three regulating control rod banks(LSWCR5, LSWCR4, LSWCR3) are suggested and developed. The main tasks of the multi-purpose control rods are controlling the AO, providing relatively strong lifting-up tendency to the AO when these rods exist below the center of the core, and causing the required reactivity change instead of changing boron concentration (boration/dilution). The main purpose of the regulating control rods is producing reactivity change as existing normal control rods do. The first multi-purpose control rod is the LSWCR1, and moves mainly in the bottom half of the reactor core. The role of the LSWCR1 is lifting up the AO, therefore the LSWCR1 should mitigate an AO distortion to the negative direction due to the motion of the other control rods. Also, the LSWCR1 should cause the required reactivity change instead of boron concentration change. The other multi-purpose control rod is the LSWCR2 and moves in the whole range of the core differently from the LSWCR1. The LSWCR2 controls the AO to the negative or the positive direction, and mitigates an AO variation due to the motion of the other control rods. Another important role of the LSWCR2 is to cause the reactivity change needed for maintaining target reactor power instead of boron concentration change, when regulating rods are fully withdrawn. Three regulating LSWCRs, named LSWCR5, LSWCR4, and LSWCR3, perform the same function as the existing normal control rods, and the main purpose of the regulating control rods is to cause reactivity change.

Then, the moving characteristics of LSWCRs, related to variation of reactivity and the AO, are analyzed and the operation strategy for LSWCRs are established. The ONED94 code is used for an application plant, and an application of LSWCRs for the power maneuvering is performed using the developed strategy.

From the results, it is shown that the insertion of multi-purpose control rods, at 100% power equilibrium state, can produce the required reactivity to return to full power, and a boron concentration change is minimized. Also, It is shown that the combinative use of multi-purpose control rods(LSWCR1, LSWCR2) controls the AO within the target AO band during the power maneuvering

Through this work, the utilities of the axially variable strength control rods(lower shifted worth control rods) are identified such that LSWCRs have good characteristics for controlling the AO during the power maneuvering of PWRs and the power maneuvering without reactivity compensation by change of boron concentration is accomplished. However, the safety analyses required in order to implement this approach have not been performed yet. Hence, the safety analyses will be performed in further research. In this work, the time in core life of the power maneuvers is BOC. Therefore, improving the operation strategy for axially variable strength control rods covering whole burn-up states (BOC, MOC, EOC) shall be considered also. Additionaly, the optimization of the worth shape of axially variable strength control rods, in order to provide these rods with the optimal performance for the power maneuvering, remains as a future work, considering several constraints such as regulation guides, shutdown margin, and etc.

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