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Proposal of Part Power Control Rod for Minimizing Axial Power Shape Change

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1. Introduction

Recently, renewable energy generation is rapidly increasing to achieve carbon neutrality. For electric grid stability, the load-following (LF) capability of nuclear power plants becomes more important to accommodate intermittent and fluctuating renewable energy.

The strategy of the LF operation is to reduce the power level from full-power to target-low-power, operate at low power for a period of time, and then return to full-power. In the commercial pressurized light water reactors (PWRs), the power level is controlled by both the soluble boron concentration control and the control element assemblies (CEAs) drive while the axial shape index (ASI) is kept within the operation limit.

The control rods (CRs) generally consist of neutron absorbers such as Boron, Cadmium, and Hafnium [1]. In OPR1000, boron carbide (B_4C) is used for the regulating CRs that can be used to control the power level, where ^{10}B in B_4C is a very strong neutron absorber. Since ^{10}B produces helium gas by the (n, alpha) reaction, the B_4C control rod can suffer from the irradiation swelling problem. Therefore, the operation limit is specified for the cumulative insertion time of the regulating CRs, which restricts the use of regulating CRs for the LF operation.

This paper presents a new design concept for the control rod named the part-power control rod (PPCR). The purposes of the PPCRs are to control the power level for the LF operation, provide better ASI control, and maintain structural integrity under irradiation conditions.

2. Control Rod in Typical PWR

The OPR1000 has CEAs with full-strength and part-strength CRs. The neutron absorber material of the full-strength CR is B_4C, and Inconel-625 is used as the absorber material for the part-strength CR. The full-strength CRs are used for regulating CEA or shutdown CEA, and the part-strength CRs are used for axial power distribution control. The absorber material B_4C includes ^{10}B having a very large neutron absorption cross section (3850 barns) and has excellent mechanical characteristics at high temperatures.

$$^{10}B + n \rightarrow {}^{7}Li + {}^{4}He \qquad (1)$$

However, helium gas is produced during irradiation of ^{10}B as shown in Equation (1). Most of the gases remain in B_4C pellets and it can cause radiation-induced swelling, cracking, or fragmentation [2].

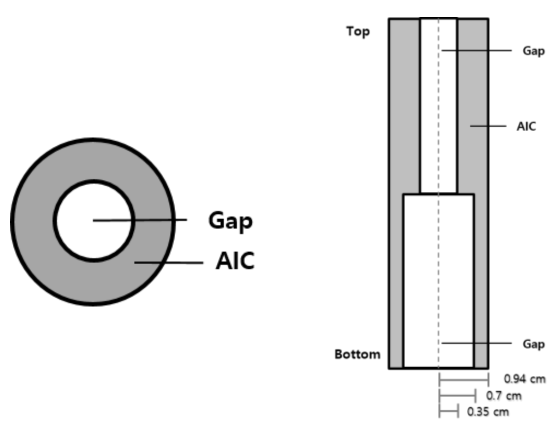
Another typical PWR, the Westinghouse reactor, uses Ag-In-Cd (AIC) alloys and SS304(Stainless Steel 304) as a neutron absorber and cladding material of CRs. The AIC alloys have proven to be superior structural stability and corrosion resistance. The AIC alloy does not generate gases from radiation exposure and has better compatible with cladding materials under neutron irradiation.

In general, CRs of the PWR are inserted from the top of reactor core. When CRs are inserted, power in the upper part of the core decrease compared to the lower part. In addition, neutron flux, moderator temperature, and concentrations of fission products are also changed by control rod drive. The power change causes unexpected flux oscillation due to xenon oscillation and power defects.

The power defect refers to changes in reactivity that occurs when the power changes. The reactor has an opposite effect on the power change due to the inherent characteristics during operation. The power defect further increases at the end of cycle.

The xenon oscillation makes power distribution control more difficult during LF operation. Xenon (^{135}Xe) is one of the main fission products and has a very large absorption cross-section. The xenon oscillation generates large power shift and occurs alternately at the top and bottom of the core.

3. Design of PPCR



(a) (b)

Figure 1. Conceptual design of the PPCR

This section introduces the design of PPCRs with material and shapes. The neutron absorber of PPCR is AIC which has been proven to have high integrity in a lot of LF operation experiences. The PPCR is an annular control rod with an internal gap. Figure 1 depicts a conceptual design of the PPCR.

Figure 1.(a) shows the radial plane of the PPCR, which consists of a combination of a neutron absorber and a gap. The control rod reactivity is inverse proportion to the inner radius of the annulus. In order to compensate for the power distribution imbalance, the rod worth of the upper part of PPCR was designed to be larger than the lower part. Figure 1.(b) shows the axial plane of the PPCR. The outer radius of the neutron absorber was 0.94 cm, the inner radius of the upper part was 0.35cm, and the inner radius of the lower part was 0.7cm. Therefore, the percentage of AIC and reactivity on the upper part of the rod were higher than on the lower part.

Table 1. Rod worths by control rod types

	PS	R5	Part power	Comparison Target
Rod worth(pcm)	224	330	511	509

Table 1 shows integral rod worth by control rod types. The integral rod worth is total reactivity caused by fully insertion. The PS is part-strength CEAs and the R5 is a leading regulating bank in the OPR1000. The comparison target is a control rod having the same rod worth as PPCR and uniform axial reactivity. The total rod worth of the PPCR was greater than R5 and PS.

Operation simulation was performed to verify the PPCR has sufficient reactivity for power control and that the axial sectored design was effective during the LF operation. To evaluate the performance of the PPCR, the 3-D quasi-static load-following operation was simulated by RAST-K v2 [3].

The operating scenario was 100-70-100%P within 2 days, considering load-following operation over the weekend or holiday off-peak time. The simulation was performed under the end-of-cycle condition with large power defect and instability of xenon oscillations to assume worse case.

The PPCR and the comparison target CR assumed that rods replace the position of PSCEA to retain shutdown margin while some CEAs are inserted. The two types of CRs can reach the target power, but the axial power distribution control performance was significantly different. The changes in axial shape index (ASI) of the operation result is shown in Figure 3. ASI refers to the power deviation between the upper and lower portion of the reactor core and is calculated by Equation (2). P_B and P_T are lower and upper core power based on the center.

$$\mathrm{ASI} = \frac{[\mathrm{P_B} - P_T]}{[\mathrm{P_B} + P_T]} \tag{2}$$

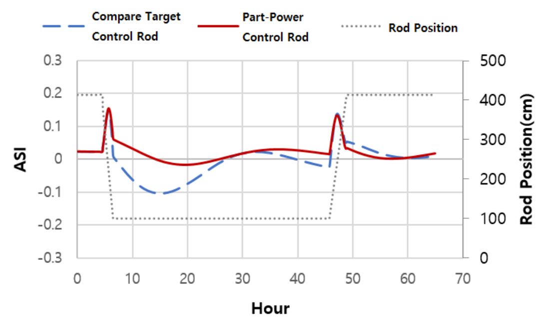


Figure 2. ASI variation during LF operation simulation

In Figure 2, the ASI temporarily increases during the insertion or the withdrawal of CRs. However, when the control rods are kept inserted, the ASI tendency of PPCR is flat as against the comparison target CR.

The ASI damping effect of the PPCR design was shown through the comparison of the control rod with uniform axial rod worth. When the PPCR was fully inserted to reduce the power level from 100%P to 70%P, the positive reactivity in the core upper part by the MTC effect was almost compensated by the stronger neutron absorption of the PPCR.

3. Conclusions

A new design control rod for the load-following operation was proposed. The PPCR used AIC alloy as a neutron absorber that has structural stability and corrosion resistance. The PPCR showed the better performance to control ASI due to its unique design feature of axially non-uniform rod worth (stronger rod worth in the core upper part). Furthermore, the rod worth of the PPCR is optimized as around 500 pcm to control the reactivity during the LF operation using only one control rod bank. The PPCR design leads to better control performance of ASI compared to the conventional uniform rod design.

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