A Study on the Safety of Reactor Coolant System of Hanbit Units 5&6 According to Zinc Injection

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1. Introduction

From the 17th cycle of Hannul Unit 1 in Korea, zinc injection operation was first applied to reduce the reactivity exposure of workers when replacing the steam generator.

As a result of measuring the effect of reducing the system dose rate of 40 % or more compared to the entire cycle before injection and measuring the thickness of the oxide film on the fuel rod coating pipe. As the soundness of the fuel rod is maintained without negative effects, based on this successful experience.

It is promoting the application of zinc injection to light-water reactor nuclear power plants to contribute to safe operation of the power plant by reducing the primary system radiation dose and improving corrosion resistance of structural materials.

2. Evaluation and Results

2.1. Effects on fuel and primary system main materials

Figure 2-1 shows the result of comparing the oxide film thickness of ZIRLO^{TM} cladding tube measured after zinc injection at the 13th and 14th cycles of the Callaway nuclear power plant with data from other power plants. As shown in the figure, the thickness of the cladding pipe oxide film after zinc injection at the Callaway nuclear power plant is included in the measurement result range of other power plants, so it can be confirmed that the zinc injection operation did not affect the integrity of the cladding pipe even at Callaway nuclear power plant.

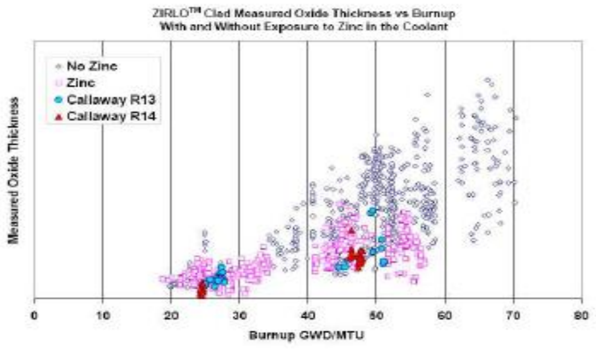

Fig. 2-1 Callaway 13 and 14 cycles zinc injection and oxide thickness vs. Combustion

Figure 2-2 shows the result of comparing the oxide film thickness of the ZIRLO^{TM} cladding tube measured after the 15th and 16th cycles of the operation of Vandellos Unit 2 with zinc injected and the oxide film thickness measured after 14 cycles of combustion without zinc injection According to Figure 2-2, it can be seen that the thickness of the oxide film measured after zinc injection and the thickness of the oxide film measured after 14 cycles of combustion without zinc injection show similar distributions. That is, in the case of the Vandellos 2 power plant, it was confirmed that the zinc injection operation did not affect the oxide film thickness of the fuel clad pipe.

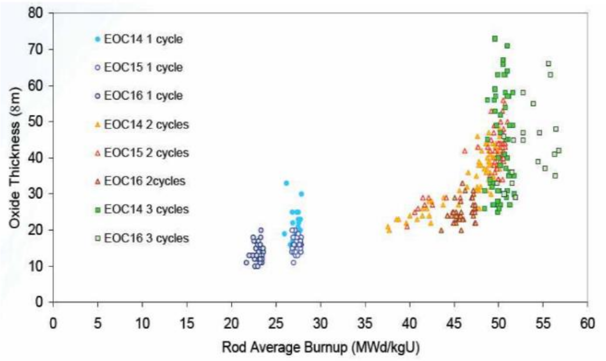

Fig. 2-2 Vandellos Unit 2, the thickness of the oxide film after zinc injection for cycles 15 and 16 vs. Combustion

Even in Korea, through the evaluation of the thickness of the ZIRLO^{TM} cladding pipe, which was performed after the first application of zinc injection for the 17th cycle of the Hanul Unit 1, it was confirmed that zinc injection did not signification affect the corrosion of the cladding pipe (Figure 2-3).

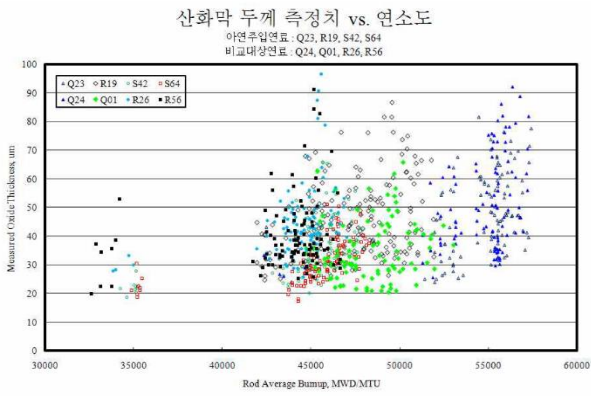

Fig. 2-3 Oxide film measured after zinc injection for the 17th cycle of Hanul Unit 1

In the end, based on the domestic and overseas application experience, there is no abnormality in the soundness of the nuclear fuel cladding tube caused by the implementation of zinc injection operation even in the case of the Hanbit 3 power plant.

Even if zinc is injected into the primary system, the neutron properties of the core are not affected. Zinc is a weak neutron absorbing material with a thermal neutron absorption cross section of about 1 barn. Since the maximum concentration of zinc is kept below 20 ppb, the water density present in the RCS is very low and the absorption cross-sectional area is also small, so the effect on the reactivity of the core is negligible. Therefore, zinc injection does not affect the reactivity of the core, and does not affect the boron concentration, neutron flux, in-furnace reactivity coefficient, dynamic characteristic factor, control rod value, core power distribution, and core peak factor.

Figure 3-3 shows the comparison of the corrosion rate test results of the primary materials in the case of zinc injection and no zinc injection. From this figure, it can be seen that the corrosion rate of the material is reduced by more than 3 times in the case where zinc is injected compared to the case where it is not. In addition, it was confirmed that there was a positive effect of delaying the onset of stress corrosion cracking of Ally 600 material by looking at the results in the laboratory or the zinc injection operation in power plants.

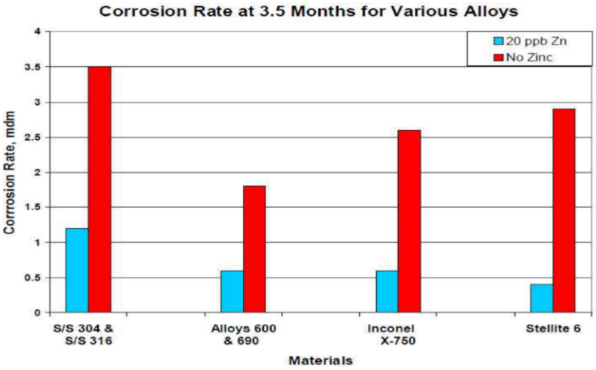

Fig. 3-3 Effect of zinc on general corrosion rate

As a temporary increase in corrosion products is expected due to zinc injection, it was also evaluated whether the capacity of the current purification demineralizer could be acceptable. Even assuming that the zinc concentration of up to 20 ppb is kept constant for one cycle at Hanbit Power Plant 3 and all injection zinc is removed from the purifying ionizer, the amount of ion exchange resin required is calculated as 2.5 ft^3. Since the resin capacity of the CVCS purification ion exchanger at Hanbit Power Plant 3 is 32.0 ft^3, the CVCS purification resin tower has sufficient ion exchange capacity even after one cycle of zinc injection operation, even assuming that the cation resin and anion resin in the mixed phase resin are charged 1:1 at a simple volume ration. even after one cycle of zinc injection operation, the CVCS purification resin tower can continue to maintain sufficient ion exchange capacity. That is, even if the zinc injection operation is performed at the third Hanbit Power Plant, purification operation is still possible with only one purification exchanger without resin replacement, and thus the zinc injection operation does not have an additional effect on the amount of waste resin generated.

Looking at the example of Hanul Unit 1 on the amount of filter replacement during zinc injection, it was confirmed that the zinc injection operation did not significantly affect the increase of the filter replacement amount(Table 3-1)

아연주입 전/후	운전 주기	교체이력		
		정상운전 중	O/H 시	소계
아연주입 전	15	1	1	2
아연주입 전	16	5	1	6
아연주입 후	17	4	-	4
아연주입 후	18	5	3	8
아연주입 후	19	2	3	5

Table 3-1. Hanul Unit 1 Purification Filter Replacement History by Cycle Before and After Zinc Injection

2.2. Effect on radiation operation

The evaluation of the effect on the radioactivity operation of the power plant was carried out by dividing into the effect on the operation of the purified ion exchanger, the effect on the operation technical guideline, and the effect on the radiation verification of equipment and instruments.

2.2.1. Impact on the operation of purified ion exchanger

The chemical and volume control system of Hanbit 3rd Power Plant is equipped with two purifying ion exchangers and one lithium removing ion exchanger. Purified ion exchanger provides the main means to remove cation and anion nuclear fission products and radioactive corrosion products (crude), and lithium removal ion exchanger can adjust the lithium concentration of the reactor coolant at a constant level, thereby reducing the reactor coolant pH from 6.9 to 7.4. To minimize the generation of radioactive materials.

The radiation source term for the shielding design of Hanbit 3rd Power Plant is calculated based on the assumption of the nuclear fuel cladding damage rate of 0.25% and the operation of the full power of the reactor and no deaeration equipment. The proportion of radioactive corrosion products to the total radioactivity of nuclear fission products and radioactive corrosion products for shielding design is about 0.02% (excluding H-3 and N-16) (refer to Table 12.2-5, FSAR of Hanbit Power Plant 3). , As in the case of Hanul Unit 1, Co-58 is about 4 times from 1.0E-3 μCi/cc to 4.2E-3 μCi/cc, and Co-60 is from 7.4E-6 μCi/cc to 8.42E-5 μCi/cc. Even when considering an increase of about 11 times, nickel is increased to 4.5 ppb. The increase in the specific radioactivity concentration of Co-58 and Co-60 does not exceed 0.1%. That is, the effect of zinc injection operation on the shielding design of the purifying ion exchanger is negligible.

2.2.2. Impact on operating technical specification

Paragraph 3.4.15 of the operating technical specification for Hanbit Power Plant 3 restricts the following with respect to the specific radioactivity of reactor coolant.

○ Iodine (I-131) equivalent dose ≤ 3.7×104 Bq/g
○ Total specific radioactivity ≤ 3.7×106/Ē Bq/g
(Ē: average decay energy)

In other words, there is no limiting value for the radioactivity level for individual nuclides in the operational technical guidelines related to the radioactivity level of the reactor coolant, and the effect of radioactive corrosion products is not separately considered when setting the limiting condition variable.

The operating technical guidelines for Hanbit 3rd Power Plant require that if the equivalent dose of iodine (I-131) exceeds the limit, the monitoring of the radiation level is strengthened, and the I-131 equivalent dose is checked at a certain time and restored within the limit. The zinc injection operation does not negatively affect the occurrence of new defects in the fuel or the lapse of previously generated defects. In addition, if the I-131 equivalent dose increases due to the zinc injection operation, the operator can perform an operation to reduce the I-131 equivalent dose of the reactor coolant, such as increasing the CVCS purification flow.

The specific radioactivity values of Co-58, Co-60, and Zn-65, which are expected to increase due to zinc injection operation, are far less than the total specific radioactivity limit value of the operating technical guideline as shown in Table 3-2 (at Hanbit

Power Plant 3). Since the recently measured values of Ē are 2.11 (Unit 5) and 1.85 (Unit 6), the total specific radiation limit value is 1.8×106～2.0×106 Bq/g), and the total specific radiation limit value in the current operating technical guideline is the actual power plant in operation. It is a value with sufficient margin compared to the total specific radioactivity measurement value of. Therefore, the radioactivity value of radioactive corrosion products in the coolant due to the zinc injection operation of the third Hanbit power plant has no effect on the limiting condition of the total specific radioactivity level of the reactor coolant.

핵 종	농도, Bq/g*
Co-58	1.43E+03
Co-60	1.64E+02
Zn-65	1.58E+02

* Value set by multiplying the existing FSAR specific radiation value by a correction factor of 10 according to ANSI/ANS-18.1-1999

Table 3-2. Steady-state reactor coolant specific activity at 100% output

2.2.3. Effect on radiation verification of equipment and instruments

The radiation dose for environmental verification of equipment and instruments is determined based on the expected radiation source term during normal operation, the shielding design standard radiation source term, and the coolant loss accident (LOCA) radiation source term, depending on the type of accident requiring the operation of the equipment and instruments.

The normal operating radiation source term shown in Table 11.1-6 of the FSAR of Hanbit Power Plant 3 is determined entirely by the specific activity value of the fission product (the total specific activity of the fission product is the total specific activity of the radioactive corrosion product (Crud)). 850 times equivalent). In particular, the proportion of the total specific radioactivity of the fission product is significantly higher than the total specific activity value of the radioactive corrosion products (see Table 3-2) after zinc injection operation (about 160 times). the zinc injection operation has no significant effect on the cumulative radiation dose of equipment and instruments considering the design life.(refer to Figure 3-3)

The specific radioactivity of nuclear fission products in the shielding design criterion is calculated assuming a nuclear fuel damage rate of 0.25%.In the case of Hanbit 3rd power plant, the total non-radiation concentration including N-16 and H-3 is 1.13×107 Bq/g (Hanbit Table 12.2-5) of the FSAR of the third power plant. Existing shielding because the increase in specific activity of nuclear fission products expected from the zinc injection operation of Hanbit Power Plant 3 (refer to Table 3-2) is negligible compared to the total specific activity of nuclear fission products in the radiation source section based on the shielding design. There is no significant effect on the design standard radiation source term.

The LOCA radiation source term of the radiation dose evaluation for the verification of radiation resistance of devices and instruments was calculated based on the radioactivity of the core fission product. A very conservative assumption is applied that the light is released into the environment. Compared to the radioactivity of such fission products, the increase in radioactivity of radioactive corrosion products of the coolant expected by zinc injection operation at Hanbit 3rd power plant is negligibly small.

2.3 Effects on the primary system water chemistry

As the effect on the primary system water chemistry caused by zinc injection, evaluation of the effect on the dissolved oxygen concentration in the reactor coolant during normal operation, the effect on the hydrogen concentration after an accident, and the effect on the performance and pH of the emergency core cooling system recirculation collection tank. In addition, water quality inspection items and inspection cycles during zinc injection operation were also described.

2.3.1. Effect on dissolved oxygen concentration

The zinc injection device will be installed at the rear end of the volume control tank of the chemical and volume control system. The zinc injection tank of the zinc injection device designed as an atmospheric pressure tank receives demineralized water from the pure water supply system, dissolves zinc acetate, and stores the dissolved zinc acetate until it is supplied to the reactor coolant system.

Assuming that the zinc injection tank of Hanbit 3rd Power Plant is in contact with air and saturated with dissolved oxygen (8 ppm O2 at room temperature), and conservatively, assuming that both zinc injection pumps are operated at the maximum flow rate (i.e. 0.5 gal/hr), 15 mg of dissolved oxygen per hour is introduced into the reactor coolant by zinc injection. That is, considering that the mass of the reactor coolant of Hanbit 3rd Power Plant is 1.97E+05 kg (FSAR Table 11.1-1), the dissolved oxygen concentration per hour increases by 0.08 ppb. However, in the primary system, the concentration of dissolved hydrogen in the reactor coolant is maintained in the range of 25 to 50 cc/kg by pressurizing hydrogen in the gas phase of the volume control tank of the chemical and volume control system as a means to suppress the increase in the concentration of dissolved oxygen. . In this case, since the dissolved oxygen introduced into the primary system is effectively removed by reaction with dissolved hydrogen, it is estimated that there is no effect of increasing the dissolved oxygen concentration substantially due to the zinc injection operation (the dissolved oxygen increased by zinc injection is removed. The dissolved hydrogen consumed for this is 0.0001 cc/kg per hour, so there is little effect on the dissolved hydrogen consumption.)

2.3.2. Effects on Post-Accident Hydrogen

Metallic zinc can react with acid to produce hydrogen, but if the concentration of hydrogen gas in the atmosphere of the nuclear reactor increases excessively, the risk of explosion of the nuclear reactor building increases, so strict management of the amount of metallic zinc in the nuclear reactor building is required.

To Zinc by injection of zinc in the reactor coolant does not produce hydrogen by reacting with acid because it exists in the form of +2 in aqueous solution or primary system oxide, not in the form of neutral zinc atoms (metals). In other words, zinc injection does not affect the generation or accumulation of hydrogen gas after an accident in the nuclear reactor building.

2.3.3. Effect on the performance of the emergency core cooling system recirculation collection tank

The reactor building recirculation collection tank is a facility installed at the bottom of the reactor building to use as a water source for long-term safety injection and sprinkling in the event of a loss of coolant. It obstructs the flow of flow, which can degrade the performance of the emergency core cooling system and the reactor building watering system.

Conservatively, assuming that the zinc concentration of the reactor coolant at Hanbit 3rd Power Plant is 20 ppb, the zinc concentration when the zinc released from the reactor coolant system in the event of a coolant loss accident flows into the recycling collection tank is calculated as 3.11 × 10 -8 M. This value is about 3,200 times smaller than the metal salt concentration of 10-4 M, which was found to cause significant head loss in the recirculation collection tank filter according to the results of LANL (Los Alamos National Laboratories) experiments conducted with the sponsorship of the US Atomic Energy Regulatory Commission. In the case of the 3rd power plant, the possibility of deterioration of the recirculation collection tank performance due to zinc injection is evaluated to be very low. Table 3-3 shows the calculation results of zinc concentration in the recycling collection tank according to the zinc concentration in the reactor coolant system.

냉각재상실사고 전 냉각재 아연농도 (ppb)	냉각재상실사고 발생 후 재순환집수조 아연농도 (M)
5	7.77×10^{-9}
10	1.55×10^{-8}
20	3.11×10^{-8}
40	6.22×10^{-8}
50	7.77×10^{-8}
100	1.55×10^{-7}

Table 3-3. Calculation result of zinc concentration in recycling collection tank according to zinc concentration in reactor coolant

In particular, since the reactor coolant and the boric acid water of the reloading tank are mixed in the recirculation collection tank in the event of a coolant loss accident, it is expected to show a lower value than the zinc concentration during output operation. As the solubility of zinc increases, the possibility of precipitation of zinc is low, so it is very unlikely that the performance of the recycling collection tank is degraded by zinc injection.

2.3.4. Effect on pH of Emergency Core Cooling System Recirculation Collector

The boric acid water and tri-sodium phosphate (TSP) flowing into the recirculation collection tank after the loss of coolant are the main factors affecting the pH of the recirculation collection tank. maintain. Even if the zinc concentration in the recirculation collection tank is conservatively set to 40 ppb, assuming that the zinc that has flowed into the oxide layer, including the zinc injected into the reactor coolant during normal operation, is also re-dissolved as a coolant, Hanbit after the loss of coolant accident The zinc concentration in the recirculation collection tank of the third power plant is calculated as 6.22 × 10 -8 M. At this time, since the molar concentrations of boric acid and sodium triphosphate are more than 106 times greater than the molar concentration of zinc, the effect of zinc ions on the pH in the recirculation collection tank is negligible, and thus there is no effect on the ability to remove fission products of the containment building watering system.

4) Safety analysis

Since the zinc solution injected into the coolant does not contain boron at all, if the zinc solution of this non-boric acid water is injected into the chemical and volume control system (CVCS), it may affect the dilution flow rate applied to the boron dilution accident analysis, and safety injection occurs. It may affect the boron concentration in the primary system according to the safety injection flow rate. In addition, since zinc injected as a coolant affects the radiation source term of the primary system, it can also affect the evaluation of alienated doses for each accident. Excluding this, the transient safety analysis evaluation assumes that the boron concentration in the coolant does not change after the accident, so there is no effect of zinc injection.

2.4.1. Boron dilution accident

The dilution flow rate applied in the most conservative case in the boron dilution accident analysis by operation mode in Chapter 15.4.6 of the Hanbit 3rd Power Plant Final Safety Analysis Report (FSAR) is 180 gpm. Meanwhile, the zinc injection device will be connected to the pipe between the volume control tank of the chemical and volume control system and the charge pump suction pipe. Therefore, when a boron dilution accident occurs, the dilution flow rate applied to the accident analysis increases by the zinc injection flow rate. However, the maximum zinc injection flow rate considering the failure of the zinc injection device is 0.0084 gpm (0.5 gph; assuming that both zinc injection pumps are operated at the same time), compared with the dilution flow rate of 180 gpm used in the current FSAR boron dilution analysis. Since it is a very small amount, the effect is insignificant and there is no effect on the analysis results described in the current FSAR.

In addition, the pure water supply to the zinc injection tank is a method in which the operator connects the pure water supply pipe to the zinc injection tank and fills it manually (using the Quick Connector).When the desired amount of pure water is supplied to the zinc injection tank, the pure water supply pipe is injected with zinc. Since it is separated from the tank, additional pure water supply is essentially blocked. Therefore, there is no need for separate measures to block the dilution water source.

2.4.2. Accidents in which safety injection occurs

When safe injection occurs, the boron concentration in the reactor coolant decreases as much as the amount of non-boric acid water injected according to the zinc injection. However, when safety injection occurs, a very large flow rate safety injection is made according to the pressure of the reactor coolant system, and the initial boron concentration in the injected water is also very high. In addition, since the pressure in the reactor coolant system gradually decreases after the accident, the flow rate of safe injection is continuously increased. Therefore, when comparing the non-boric acid water injection flow rate (0.0084 gpm) and the safety injection flow rate according to zinc injection, the amount is very small, so the impact on accidents in which safety injection occurs is insignificant. The result is valid.

2.4.3. Large coolant loss accident and main steam engine breakage

The most important design criterion accidents from the viewpoint of mass and energy emission for the analysis of pressure and temperature in the containment building of a nuclear power plant are the large-sized coolant loss accident and the main steam engine failure. It was examined whether the zinc injection operation at Hanbit Power Plant 3 had an effect on the reactor building mass and energy emission amount and the reactor building design pressure and temperature suggested in the existing FSAR. In general, factors that affect the mass and energy release of a nuclear reactor building include energy sources (core output, decay heat, initial storage energy, metal storage energy, etc.), fuel cladding pipe heat transfer coefficient, steam generator heat transfer pipe heat conduction coefficient, and heat transfer coefficient. Factors that can be affected by zinc injection include fuel cladding pipe heat transfer coefficient, steam generator heat transfer pipe heat conduction coefficient, and heat transfer coefficient. However, these heat transfer characteristics are not affected by the very small amount of zinc injection, and conservative initial conditions and assumptions were used when analyzing the mass and energy emission of the existing Hanbit 3rd power plant FSAR. The impact is evaluated to be sufficiently included in the conservatism previously reflected in the Hanbit Power Plant.

In the case of a main steam engine break, the mass and energy of the secondary side of the steam generator are released, so it is irrelevant to the zinc injection operation of the primary system, and the heat transfer characteristics between the primary system and the primary and secondary systems, such as the effect of the loss of coolant, are affected. As there is no change, there is no effect on energy release. Therefore, the zinc injection operation of the primary system has no effect on the mass and energy emission analysis of the main steam engine breakage accident.

2.4.4. Total loss of feedwater loss accident

A total loss of feedwater accident (TLOFW) is an accident with a very low probability of accident because it is assumed that water supply loss accident and auxiliary water supply loss occur at the same time. Moreover, since the auxiliary water supply system is designed in consideration of a single failure, the probability of complete loss of auxiliary water supply, which is a means of removing the core collapse heat in case of an accident, is very low. Therefore, a TLOFW accident is classified as an accident exceeding the design standard. The accident analysis also assumes the initial conditions of normal operation, assumes that all systems and devices that are not affected by the control system, protection system, and TLOFW accident are available, and the optimal evaluation method is used.

Among the main factors in the analysis of the TLOFW accident at Hanbit Power Plant 3, the factors that can be affected by zinc injection are the thermal shear coefficient of the nuclear fuel cladding pipe, the heat conduction coefficient and heat transfer coefficient of the heat transfer pipe of the steam generator, and the specific heat of the primary material. However, since these heat transfer characteristics are not affected by the low-concentration zinc injection operation, the analysis results of the current TLOFW accident are valid.

2.4.5. Evaluation of alienated dose in case of accident

Injecting zinc into the primary system can increase the concentration of Co-58, Co-60 and Zn-65 in the system. However, iodine and inert gas are considered nuclides when evaluating the alienated dose in a design-based accident, and Co-58, Co-60, and Zn-65 nuclides do not affect the evaluation of the alienated dose in a design-based accident. Therefore, even if zinc is injected into the primary system, the results of the evaluation of estranged doses for design-based accidents in the current FSAR Chapter 15 are valid.

3. Conclusions

In the case of applying zinc injection operation to reduce the radiation dose of the primary system at Hanbit 3rd Power Plant, the results of the core and primary system safety evaluation are summarized as follows.

As a result of nuclear fuel integrity evaluation, the thickness of the oxide film of the cladding tube does not increase due to zinc injection, and the injected zinc does not change the performance characteristics of the fuel rod, so the existing replacement core safety evaluation results are valid.

As a result of the evaluation of the nuclear design field, zinc injected in a trace amount of 20 ppb or less does not affect the reactivity of the core, and does not affect the boron concentration, neutron flux, reactivity coefficient in the furnace, dynamic characteristics factor, control rod value, core power distribution, and core peak factor. Therefore, the existing replacement core safety evaluation results are valid.

Zinc injection can increase the risk of AOA occurrence in the short term, but if the concentration and timing of zinc injection are adjusted, the risk of AOA generation can be managed at a level similar to that of a conventional core without zinc injection. Since trace amounts of zinc do not affect the core flow distribution and heat transfer characteristics from the viewpoint of thermal hydraulic power, the existing replacement core safety evaluation results are valid.

As a result of evaluating the effect on the material and main equipment of the primary system of Hanbit Power Plant 3, it is expected that when zinc injection operation is performed, the general corrosion rate of the main material of the primary system is lowered and the stability of the surface oxide film is improved. I can. In addition, there is an effect of delaying the initiation of PWSCC due to zinc injection through various laboratory studies or field application experience. In other words, there is no negative effect on the main devices of the primary system of Hanbit Power Plant 3 and the materials of these devices due to zinc injection.

The evaluation of the radiation source port that is expected to change due to the zinc injection operation of Hanbit Power Plant 3 was conducted, including the results of various analyzes of overseas power plants that are already performing zinc injection operation, design data and related code requirements provided to the FSAR of Hanbit Power Plant 3 As a result of conducting it as a basis, there was no significant effect on the design margin in terms of the overall radiation source term. Based on this result, it was reviewed in terms of the effect on the radioactivity of the power plant and the effect on the radioactive effluent, but it does not affect the results described in the FSAR of Hanbit Power Plan

As the effect on the primary system water chemistry caused by zinc injection, the effect on the dissolved oxygen concentration in the reactor coolant during normal operation, the effect on the hydrogen concentration after the accident, and the effect on the performance and pH of the emergency core cooling system recirculation collection tank were evaluated. As a result of the evaluation, the effect may be negligible or negligible.

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