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Original article

Dose Reduction Factors for High-Exposure Tasks at Korean Pressurized Water Reactors

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ABSTRACT This study was conducted to analyze the characteristics of three high-exposure tasks performed by radiation workers in Korean pressurized water reactors (PWRs) and to identify factors that reduce their exposure during work. Three high-exposure tasks were selected based on a previous study. In this previous study, nozzle dam installation and removal, eddy current testing, and manway opening and closing were determined as high-exposure tasks through normalization (radiation dose per unit time). Based on the analysis of the characteristics of the high-exposure tasks in this study, the high-exposure tasks were steam generator-related tasks performed inside and outside the water chamber. This study analyzed the reduction factors for high-exposure tasks and suggested improvements in terms of time, distance, and shielding. The use of the characteristics of high-exposure tasks and their dose reduction factors enables Korean PWRs to optimize radiation protection for workers who receive relatively high doses.

Key words: Pressurized water reactors, High-exposure tasks, Dose reduction factors, Nuclear power plants

1. Introduction

Currently, 25 nuclear power reactors are in operation in Korea, including 22 pressurized water reactors (PWRs) and three pressurized heavy water reactors (PHWRs). The two new nuclear power reactors under construction are the Saeul Units 3 and 4, which are both PWRs. The nuclear power plants (NPPs) currently in operation in Korea and those to be built in the future are listed in Table 1 [1]. Shinhanul Unit 2 is also a PWR under operational review by a regulatory body.

During the last ten years (2013-2022), the average annual occupational dose in Korean PWRs was 0.37 mSv y^{-1}. Table 2 presents the total number of workers, total radiation dose, and average dose per person in the PWRs during this period [2-11]. As shown in Table 2, the number of workers in the PWRs increased slightly as the number of reactors increased. Although the average individual dose did not exceed the dose limit set by the Korean Nuclear Safety Act (50 mSv y^{-1}), continuous dose reduction efforts are required to maintain optimal radiation protection.

In terms of radiation protection efficiency, it is reasonable to focus on reducing the dose in high-exposure tasks for workers who receive relatively high doses rather than the dose in all tasks [12]. It is also believed that dose reduction in these high-exposure tasks could lower the total dose to the NPP workers. This study focused on reducing high-exposure task doses to reduce the total radiation dose in PWRs. This study presents dose reduction factors for high-exposure tasks to optimize radiation protection.

2. Materials and Methods

Previous studies determined the three high-exposure tasks in Korean PWRs, including nozzle dam installation and removal, eddy current testing (ECT), and manway opening and closing at the steam generator, in the order of high normalized (radiation

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Table 1. Operational and construction status of the Korean nuclear power plants

Name of NPP	Reactor type	Electric power output capability (MWe)	Commercial operation date	Operational Status
Hanbit-1	PWR	950	25.08.1986	Operation
Hanbit-2	PWR	950	10.06.1987	Operation
Hanbit-3	PWR	1,000	31.03.1995	Operation
Hanbit-4	PWR	1,000	01.01.1996	Operation
Hanbit-5	PWR	1,000	21.05.2002	Operation
Hanbit-6	PWR	1,000	24.12.2002	Operation
Hanul-1	PWR	950	10.09.1988	Operation
Hanul-2	PWR	950	30.09.1989	Operation
Hanul-3	PWR	1,000	11.08.1998	Operation
Hanul-4	PWR	1,000	31.12.1999	Operation
Hanul-5	PWR	1,000	29.07.2004	Operation
Hanul-6	PWR	1,000	22.04.2005	Operation
Shin-Hanul-1	PWR	1,400	07.12.2022	Operation
Shin-Hanul-2	PWR	1,400		Commissioning
Kori-2	PWR	650	25.07.1983	Operation
Kori-3	PWR	950	30.09.1985	Operation
Kori-4	PWR	950	29.04.1986	Operation
Shin-Kori-1	PWR	1,000	28.02.2011	Operation
Shin-Kori-2	PWR	1,000	20.07.2012	Operation
Saeul-1	PWR	1,400	20.12.2016	Operation
Saeul-2	PWR	1,400	29.08.2019	Operation
Saeul-3	PWR	1,400		Constructing
Saeul-4	PWR	1,400		Constructing
Wolsong-2	PHWR	700	01.07.1997	Operation
Wolsong-3	PHWR	700	01.07.1998	Operation
Wolsong-4	PHWR	700	01.10.1999	Operation
Shin-Wolsong-1	PWR	1,000	31.07.2012	Operation
Shin-Wolsong-2	PWR	1,000	24.07.2015	Operation
Total	28	28,850		

dose per unit time) calculation values [12]. Annual reports on occupational exposure in Korean NPPs were used to select high-exposure tasks. An analysis of occupational doses confirmed that most radiation exposure to workers occurred during the planned maintenance period. This study also selected nozzle dam work, ECT work, and manway work determined from previous studies as high-exposure tasks to reduce dose reduction.

To determine the dose reduction factors for high-exposure tasks in Korean PWRs, this study investigated the working environment of high-exposure tasks and analyzed various literature and papers related to radiation exposure reduction in NPPs [13,14]. In particular, this study focuses on the initial conditions and work elements of high-exposure tasks and analyzes the likelihood of reducing exposure in terms of time, distance, and shielding, which are the three elements of external exposure protection. This study also analyzed the problems repeatedly mentioned in the work, the problems common to the three high-exposure tasks, and the cases of dose reduction through literature and paper reviews. The results of this analysis were closely related to the increase and decrease in the radiation exposure of workers. For example, while performing radiation work, NPP workers are constrained by their work movements

Table 2. Occupational doses in Korean pressurized water reactors over 10 years (2013-2022)

Year	Number of workers	Number of reactors	Collective dose (man-mSv)	Average individual dose (mSv)
2013	18,136	19	10,160	0.56
2014	17,155	19	6,825	0.4
2015	19,214	21	7,135	0.37
2016	19,153	21	9,273	0.48
2017	18,633	21	5,877	0.32
2018	21,299	21	7,436	0.35
2019	21,472	22	5,865	0.27
2020	20,601	22	7,431	0.36
2021	22,019	23	7,578	0.34
2022	21,786	23	5,571	0.26
AVG	19,947	21.2	7,315	0.37

when the workspace is narrow. This constraint on movement causes delays in the work process. The problem with a small workspace is that it delays work time, which increases the exposure time of the worker and finally causes a higher radiation dose. Using the analysis results, this study aimed to suggest dose reduction factors for high-exposure tasks.

3. Results and Discussion

3.1. Nozzle dam installation and removal

3.1.1. Characteristics of radiation work

Steam generator nozzle dam work has the highest occupational exposure in Korean PWRs [12]. This nozzle dam work is performed on steam generators, the main equipment in primary PWR systems. When inspecting and maintaining a steam generator, a dam is installed at the nozzle of the steam generator to prevent the input and output of coolant from entering the primary system, and the installed dam is removed after maintenance work [15]. Steam generator nozzle dam work consists of preparation, hydrostatic testing, nozzle dam installation, and removal. The sequence and scope of the nozzle dam are summarized in Table 3 [13]. The nozzle dam was operated inside a steam generator water chamber. The steam-generator water chamber has a very high radiation field from top to bottom, owing to the influence of radionuclides deposited in the U-tubes. The interior of the water chamber has a radius of two meters and a quarter-sphere shape, a space where the operator cannot stand completely [16,17].

Because the nozzle dam has to pass through a manway (steam generator water chamber entrance) with a diameter of 0.4 meters, the nozzle dam is divided into three segments on both sides and a center segment and is transported inside the water chamber. Inside the water chamber, the nozzle dam is bolted to the nozzle ring and welded to the steam generator nozzle inlet using a torque wrench. Once the nozzle dam is installed, a diaphragm is installed on top. The diaphragm prevents water from leaking into the gaps between the three segments of the nozzle dam [15]. In other words, the nozzle dam is installed to block the input and output of the coolant in the primary system for work inside the water chamber, and the task of removing the installed dam is removed after maintenance. The inside of the steam generator water chamber is a narrow space and a high-radiation exposure area, where workers are exposed to a large amount of radiation in a short time.

3.1.2. Dose reduction

Based on the radiological characteristics of steam generator nozzle dam work, including a literature review, this study investigated the causes of increased radiation exposure in this task and found dose reduction factors in terms of time, distance, and shielding, which are the three elements of external exposure protection. The main causes of radiation exposure in steam generator nozzle dam work can be categorized as nozzle dams, workplaces, and worker skills. First, because of the weight of the nozzle dam, the work time is delayed. When installing and removing the nozzle dam, the working hours can be increased, or the job can be performed again, depending on the skill of the worker, especially in the process of tightening the bolts [18]. Regarding the workplace, most nozzle dam work is conducted inside a steam generator water chamber, a high-radiation exposure location. Furthermore, the space inside

Table 3. Nozzle dam work scope

Sequence	Scope
Preparation	(1) Preparation for hydrostatic testing - Prepare training drums, water supply, pressurization devices, and calibrated gauges for measuring water pressure - Learn how to use the torque wrench (2) Preparation for installing and removing nozzle dam - Maintain proper ventilation and lighting inside a steam generator water chamber - Keep coolant level below nozzle ring - Safety injection tank isolation to prevent sudden water level fluctuations - Control the temperature inside the water chamber (make sure that it is low enough) and minimize the dose through preliminary training
Hydrostatic testing	(1) Nozzle dam installation: installing and connecting the nozzle dam and hydrostatic test equipment at the test site - Check nozzle dam side and center plates for damage, cracks, etc. - Check cracks around bolt holes, hinges, hinge pins, and split rings for damage - Inspect the diaphragm and all bolts - Clean both sides of the nozzle dam and diaphragm - Connecting the hydrostatic tester and nozzle dam (2) Perform a hydrostatic test - Check the normal operation of a hydrostatic tester and lock the upper exhaust valve - Adjust the pressure by opening the water supply valve - Hold at hydrostatic test pressure for at least 10 minutes and inspect for leaks (3) Nozzle dam removal: remove the nozzle dam from the test site and pack it for water chamber installation
Installing and removing nozzle dam	(1) Nozzle dam installation - Perform a liquid intrusion test - Check nozzle dam side and center plates for damage, cracks, etc. - Check cracks around bolt holes, hinges, hinge pins, and split rings for damage - Inspect the diaphragm and all bolts, and check that the drain line is clear and the drain valve is open - Nozzle dam bolting and installation (2) Inspection - Check water level and seal leaks - Frequently check that the nozzle dam is not leaking (3) Nozzle dam removal - Unbolt and remove (remove hot tubes first, then cold tubes) - Remove the nozzle dam and check for contamination in the water chamber (4) Storage - Decontaminate all parts of the nozzle dam - Keep all parts in a storage box

the water chamber is very narrow, limiting the movement of workers and increasing psychological pressure. Finally, there is a decrease in work proficiency owing to unexpected personnel changes in nozzle dam workers and very rare tasks (twice per year) [14]. Table 4 presents the causes of increased radiation exposure during nozzle dam operation and dose reduction factors [13,14,15,16].

This study suggests dose reduction factors in terms of time, distance, and shielding and analyzes the effects of these improvements. In terms of time, five dose reduction factors were suggested to reduce exposure to nozzle dam work. First, owing to the heavy weight of the nozzle dam, weight reduction of the nozzle dam was identified as the dose reduction factor. The weight reduction of the nozzle dam can reduce the travel time required to move the nozzle dam from the outside to the inside of the water chamber, which, in turn, reduces worker exposure. Second, improvements in mock-up training are necessary to increase worker proficiency. The improvement of mock-up training shortens the work time by conducting intensive training to improve poor work behavior (e.g., delay in entering the steam generator, inaccurate bolting of the steam generator) that was sluggish while performing the work rather than perfunctory training. Third, continuous mock-up training can help maintain proficiency and work skills. This prevents NPP workers from

Table 4. Causes of increasing radiation exposure in nozzle dam work and dose reduction factors

Classification	Causes and factors
Causes of increasing radiation exposure	• Nozzle dam overweight (25 kg) • Reworking the bolt on the nozzle dam • Insufficient space to enter the steam generator water chamber • Narrow space inside the steam generator water chamber • High spatial dose rates inside the steam generator water chamber • Psychological pressure due to narrow spaces and high dose rates in the workplace • Unexpected replacement of skilled workers when performing nozzle dam work • Very rare tasks, less proficiency
Dose reduction factors	• Weight reduction of the nozzle dam • Reinforce mock-up training (focusing on poor performance) • Manage the labor pool of nozzle dam skilled workers • Organize nozzle dam work (create groups, assign jobs to individuals) • Perform consistent mock-up training • Bolting from outside the water chamber with a remote-controlled robot • Wear appropriate protective clothing when working inside a water chamber • Install a shield around the steam generator
Effects	• Reduced nozzle dam transportation time • Reduced work time by improving poor performance • Immediate response to nozzle dam work • Simplify personal roles to relieve psychological pressure and reinforce personal expertise • Increase proficiency and maintain work proficiency through repetitive training • Reduced time in and out of the steam generator water chamber • Reduced occupation dose • Reduced dose during worker shift

losing work skills because of the long period between planned maintenance. Fourth, an experienced worker may perform the nozzle dam task and be unable to work because of an unexpected accident (such as overexposure and bruises). Managing the labor pool of nozzle dam-skilled workers in advance for such cases can reduce the radiation exposure of workers by ensuring that replacement workers can be utilized immediately in the case of an emergency and that work time is not delayed.

A dose reduction factor was identified in terms of distance. When installing and removing nozzle dams, workers enter the water chamber and are directly exposed to radiation from the radiation source. To improve this, there is a way for workers to perform work outside the water chamber instead of inside. For example, a remote-controlled robot can tighten bolts outside a water chamber. In terms of shielding, it is possible to have workers wear protective clothing. However, the inside of the steam generator water chamber is narrow, and wearing thick protective clothing may adversely affect work; therefore, appropriate protective clothing should be considered. Shielding can be installed outside the steam generator water chamber to reduce the exposure of workers waiting around the steam generator to work shifts.

3.2. Eddy current testing

3.2.1. Characteristics of radiation work

ECT is the second-highest radiation exposure task in Korean PWRs [12]. ECT involves inspecting facilities such as steam generator tubes and in-reactor neutron flux detectors using nondestructive methods [19]. The ECT is performed using a remote control. The ECT equipment consists of a probe insertor and withdrawer, a probe, a probe guide tube, and data collection equipment. In addition, ECT is performed by inserting the probe into the steam generator heating tube and then collecting and analyzing the signal of the eddy current remaining in the steam generator heating tube through the alternating current of the frequency set on the probe to inspect the defect.

ECT consists of the preparation, installation, connection of the test equipment, removal, and decontamination. The sequence and scope of ECT are summarized in Table 5 [13]. ECT is performed both inside and outside the steam generator water chamber. The ECT performed inside the water chamber is conducted in a very high radiation field, similar to nozzle dam work, and in a small space where the worker’s movement is restricted. The ECT performed outside the water chamber includes signal

Table 5. ECT scope

Sequence	Scope
Preparation	(1) Preliminary training of workers installing and removing equipment inside the steam generator water chamber - Quickly and accurately install and remove equipment with repeatable runs (2) Set up tents, air vents, and dividers around the steam generator - Prevent unnecessary access (3) Preventing the spread of contamination when importing and exporting testing equipment - Utilize plastic packaging
Installing and wiring inspection equipment	(1) Inspection equipment and components - Adjust probe position and inspect probe driving equipment - Check calibration standard trials - Check the heating tube number reader (2) Installing and wiring inspection equipment - Install the heating tube number reader (install it such that the holes in the reader and heating tube match) - Install probe driving equipment - Set up a probe protection net - Installing probe positioning equipment - Wire, cable, and test equipment - Install the calibration standard tester (3) Collecting and recording signals - Adjust the position of the stimulator - Probe driver operations
Withdrawal and decontamination of testing equipment	(1) Withdrawal and decontamination of testing equipment - Remove debris from inspection equipment - Check inspection equipment - Decontamination - Equipment shutdown and data management

acquisition and data processing. Signal acquisition and data processing also involve the exposure of workers because of their proximity to the water chamber. The work performed inside the water chamber involves the installation and removal of ECT equipment, which results in high exposure for the workers. However, tasks other than the installation and removal of the ECT equipment are performed outside the water chamber. Although it can be concluded that the work performed around the water chamber is likely to result in a lower dose to the worker than the work performed inside the water chamber, the steam generator manway (water chamber entrance) must be kept open until the ECT equipment is withdrawn, so that the worker may continue to receive a high dose outside the water chamber.

3.2.2. Dose reduction

Based on the radiological characteristics of ECT and a literature review, this study investigated the causes of increased radiation exposure and provided dose reduction factors from the perspective of external exposure protection. The main causes of increased radiation exposure in ECT workers can be categorized as ECT equipment and worker skills. First, differences in ECT equipment (new and old) exist among the NPPs. This difference in equipment leads to differences in the time required to install and remove ECT equipment and the signal acquisition time for inspection methods [19]. There is also the problem of borrowing and using ECT equipment. As ECT equipment is borrowed and used in several NPPs, there is insufficient time to maintain the equipment in advance, leading to increased failures and delays in work time. Second, regarding the skill level of workers, mistakes in the installation of ECT equipment can increase their exposure. These mistakes require the reinstallation of ECT equipment (increasing work time) and additional workers (increasing exposure). In addition, assistant workers in ECT are primarily subcontractor employees. Their ability to repair equipment and cope with abnormal situations is relatively low compared to that of professional workers. It has been shown that the doses from assistant workers are very high [13]. Table 6 presents the causes of increased radiation exposure during ECT and identifies dose reduction factors [13,19].

This study suggests dose reduction factors for ECT in terms of external exposure protection and analyzes the effects of this improvement. In terms of time, three dose reduction factors have

Table 6. Causes of increasing radiation exposure in ECT and dose reduction factors

Classification	Causes and factors
Causes of increasing radiation exposure	• ECT assistant worker's inability to repair equipment and handle abnormalities • Frequent breakdowns due to borrowed ECT equipment and lack of proactive maintenance • Increase dose by simultaneously installing a nozzle cover during pre-work prior to ECT • Manway access multiple times due to probe changes, inspections, etc. • Increased work time due to differences in ECT equipment (new and old)
Dose reduction factors	• Conduct training for ECT assistant workers on equipment utilization and abnormal situation handling • Require sufficient pre-maintenance of ECT equipment • Have a spare set of ECT equipment • Decommission old ECT equipment and acquire new ECT equipment • Wear lead vests for workers approaching the manway when replacing and inspecting probes • Install shields in work areas around the water chamber during signal acquisition and data processing
Effects	• Increased worker skills and ability to handle abnormal situations due to increased worker pool of ECT experts • Reduce rework due to ECT equipment failure • Reduce working hours with immediate response from ECT equipment • Reduce ECT equipment failure rates and work hours • Reduce the dose for workers approaching the water chamber

been suggested for ECT. First, because the equipment repair and abnormal situation-handling abilities of ECT assistant workers are relatively insufficient compared to those of professional workers, additional equipment training and abnormal situation-handling training of assistant workers were identified as dose-reduction factors. Additional education and training for ECT assistant workers can improve their overall proficiency and provide opportunities to train additional skilled workers, thereby increasing the labor pool. Second, to solve the problem of borrowing and using ECT equipment (not being able to maintain them in advance), it is necessary to prepare a spare set of ECT equipment for each NPP. Having a spare set of ECT equipment can reduce the failure rate of ECT equipment during operation through the integrity of the equipment and sufficient pre-maintenance. In the event of equipment failure, spare equipment can be utilized to prevent delays in work time. Finally, to solve the problems caused by differences in ECT equipment (old and new), it is necessary to acquire new equipment for each NPP. Acquiring new ECT equipment can reduce the failure rate of the ECT equipment, and because the performance of the new equipment is better than that of the old equipment, it reduces work time.

In terms of shielding, two dose reduction factors were identified. Currently, NPP workers performing ECT approach the manway when replacing and inspecting probes and stay in the work area around the water chamber when collecting and processing signals. Thus, wearing lead vests can be a dose-reduction factor to lower their radiation exposure for ECT workers who approach the manway during probe replacement and inspection. In addition, workers who remain and work around the water chamber can install temporary shields in the work area to continuously reduce the dose received.

3.3. Manway opening and closing

3.3.1. Characteristics of radiation work

Manway work is the third-highest exposure task among Korean PWRs [12]. Manway work involves opening and closing the manway to enter and exit the steam generator water chamber during steam generator nozzle dam installation, steam generator tube plugging, steam generator ECT, and checking the condition of the manway cover disk and bolt [13]. The opening and closing of the manway are performed manually by the operator using a torque wrench and torque multiplier [20].

Manway work consists of the preparation, opening of the manway cover, inspection, and assembly of the manway cover. The sequence and scope of manway's work are summarized in Table 7 [13]. Most manual work is performed outside the water chamber, although some tasks are performed inside the water chamber. The manway-opening task is the beginning of the task and is performed outside the water chamber. The primary purpose of the opening task is to remove the manway cover and the insert-disk. The manway cover weighs approximately 295 kg; therefore, careful handling is necessary. In addition, when the water chamber is opened by removing the insert-disk, the radioactively contaminated cooling water remaining inside the

Table 7. Manway work scope

Sequence	Scope
Preparation	(1) Isolation and line-up must be performed in accordance with the operating procedure manual (2) Check the steam generator primary water seal pressure release, drainage status, and steam generator primary drain valve opening status (3) Identify the status of the equipment to be used (4) When the steam generator's internal pressure is above the atmospheric pressure, do not perform work
Manway cover open	(1) A worker accesses the manway and installs a lift device (2) Remove the manway cover and the insert-disk (3) Attach a temporary cover to prevent foreign objects from entering the water chamber - Numbering and unbolting bolts - Install and secure the manway cover lift equipment - Removal of the manway cover - Insert-disk removal: beware of radioactively contaminated coolant leaks - Remove the manway gasket - Attachment of temporary cover: prevent insertion of foreign substances in the water chamber
Inspect	(1) Check the status of the disassembled manway cover, insert-disk, and various bolts (2) Replace the broken bolt and perform a cleaning (3) Workers enter the water chamber to check for abnormalities and remove foreign objects - Inspection of disassembled parts: inspect and clean bolt threads and bolt holes, check bolt hole insertion - Steam generator water chamber internal inspection: visual inspection, cleaning if debris is present
Manway cover close	(1) Perform the tasks in the reverse order of the manway cover opening task to return to the original state when the task inside the water chamber is completed - Rechecking the water chamber - Cleaning and preparing disassembled parts for assembly - Install the gasket and insert-disk - Assembling and bolting the manway cover - Remove manway lift equipment - Recheck bolting status - Remove debris from the manway cover and bolt - Performance testing: check leaks in a reactor’s hot atmosphere

chamber leaks, increasing the ambient dose. Next, the inspection task is to check the condition of the disassembled manway cover, the insert-disk, and various bolts outside the water chamber and replace the damaged equipment with new ones. Subsequently, the workers enter the water chamber to check for abnormalities and remove foreign objects. The task of removing foreign objects by entering a water chamber causes the most exposure in manway work. Finally, the manway cover is assembled to close the entrance when the work inside the water chamber is completed. The manway cover is assembled outside the water chamber and ends after the final performance test.

3.3.2. Dose reduction

This study analyzed the radiological characteristics of manway work and the causes of increased radiation exposure in manway work through various literature reviews and suggested dose reduction factors in terms of external exposure protection. The main factors that increase the radiation exposure of workers when performing manway work can be categorized as manway cover weight and bolt fixation, manway cover opening, and work inside the water chamber, which is a high-dose area. First, the manway cover is heavy (approximately 295 kg). Those who work on opening the manway must be careful when handling the manway cover, as falling accidents may occur. Furthermore, when opening the manway cover, the bolts may become stuck, causing problems when performing the work. The bolts of the manway cover are manually tightened by the operator using a torque wrench and torque multiplier, and the bolts may become stuck more frequently, depending on the skill level of the operator. Stuck bolts require additional work to cut, which may delay the time to open the manway cover, further increasing the workers’ radiation exposure. Second, when the manway cover is opened, the ambient dose rate increases due to the leakage of contaminated cooling water inside the steam generator water chamber. Currently, workers place a 20-L bucket at the bottom of the manway to prevent leakage. The bucket

Table 8. Causes of increasing radiation exposure in manway work and dose reduction factors

Classification	Causes and factors
Causes of increasing radiation exposure	• Manway cover is overweight (approximately 295 kg) • Delayed work time due to stuck manway bolts, resulting in increased radiation dose • Cutting stuck bolts during manway opening delays manway opening time, increasing dose exposure • Increased dose rate around steam generator when manway is open • Increased ambient dose rate due to leakage of radioactively contaminated coolant when the manway is open • Rework cases occurred when removing foreign objects from the water chamber, causing unnecessary radiation exposure
Dose reduction factors	• Manway bolt material improvements • Establish a plan of action for manway bolt stucks • Minimize work time with mock-up training when opening manway • Develop remote or automated machines for opening and closing manway • Fully shield reactor coolant system (RCS) and resistance temperature detector (RTD) lines before performing work • Reduce the ambient dose rate by covering the manway entrance with a temporary shield when not performing work inside the steam generator water chamber
Effects	• Reduced manway bolt sticking rate reduces work time • Quickly remove stuck bolts to reduce work time • Reduce manway access time by using automation • RCS and RTD shielding reduce the dose to workers outside the steam generator water chamber • Reduced dose to workers performing manway closing

containing contaminated coolant also increased the ambient dose rate. Finally, the worker received the highest dose by entering the water chamber during inspection tasks. The worker enters the steam generator water chamber for internal cleaning and inspection. If the cleaning and inspection tasks inside the water chamber are not performed correctly, they may need to be reworked. Reworking increases the number of exposed workers and delays their work time. Table 8 presents the causes of increased radiation exposure during manway work and identifies dose reduction factors.

This study provides dose reduction factors for manway work from the perspective of external exposure protection and analyzes the effects of this improvement. In terms of time, three dose reduction factors were identified for manway work. First, the bolts of the manway cover are subjected to material deformation owing to the high heat of the steam generator and irradiation. The deformation of the bolts causes them to get stuck when the manway cover is opened, which delays the work time. To solve this problem, it is necessary to improve the material of manway bolts. In addition, it is possible to reduce the incidence of bolt sticking by improving the bolt material, thereby shortening the work time. Second, it is necessary to have a manual that can immediately handle manway bolts when they become stuck. In the manway cover opening, bolt sticking is a significant cause of work delays. If one can deal with the stuck bolt immediately through the manual, the effect of shortening the time of the manway cover opening can be obtained. Finally, mock-up training for manway openings can shorten work time. When performing manway opening work, bolt sticking is caused by the deformation of the bolt owing to heat and irradiation from the steam generator. However, the bolt-sticking rate also varies depending on the skill level of the worker (i.e., how to tighten the bolt). Improving workers' skills through mock-up training can reduce the sticking rate of bolts and work time.

A dose reduction factor was identified in terms of distance. The development of remote or automated machinery for manway opening and closing would allow workers to perform tasks away from the manway. In addition, utilizing automated machines can reduce the impact of human factors owing to a lack of proficiency and reduce the number of reworks. In terms of shielding, two dose reduction factors were identified. The first is to fully shield the reactor coolant system (RCS) and resistance temperature detector (RTD) lines before performing the manway work. Shielding of the RCS and RTD lines reduces the radiation dose to workers performing work outside the steam generator water chamber. Second, if there is no work to enter the water chamber during the interim process of steam-generator-related work, utilizing a temporary shield at the entrance of the manway is necessary. The use of a temporary shield can reduce the ambient dose rate during periods when there is no work inside the water chamber.

4. Conclusion

The average annual individual dose at Korean PWRs is 0.37 mSv y^{-1}, which is much lower than the annual effective dose limit (50 mSv y^{-1}) for radiation workers under the Nuclear Safety Act. However, continuous dose reduction is required to maintain optimal radiation protection. From the perspective of efficiency, it is reasonable to focus on reducing the dose in high-exposure tasks for workers who receive relatively high doses rather than reducing the dose in all tasks. In addition, reducing the dose of high-exposure tasks can lower the total dose to workers in Korean PWRs. Therefore, this study focused on dose reduction in high-exposure work for the optimization of radiation protection in Korean PWRs. In addition, the characteristics of the radiation work were analyzed, and dose reduction factors for high-exposure tasks were presented.

Based on previous studies, three types of high-exposure tasks exist in Korean PWRs: nozzle dam installation and removal, ECT, and manway opening and closing. Nozzle dam work is the task with the highest exposure for Korean PWR workers. Most nozzle dam work is performed inside a steam generator water chamber with a high radiation field from top to bottom because of the radionuclides deposited in the U-tubes. The water chamber has a very narrow space for workers and is shaped like a quarter sphere. Because of these characteristics, workers performing nozzle dam work receive large amounts of radiation in a short period of time. Dose reduction factors for nozzle dam work are identified from an external exposure perspective based on the main causes of increased radiation exposure. Based on the results of this study, the dose reduction factors for the nozzle dam work include lightening the nozzle dam, strengthening and continuously performing mock-up training, systematizing the work and managing the workforce pool, and wearing appropriate protective clothing when working inside the water chamber. ECT is the second-highest exposure task for Korean PWR workers. ECT is performed both inside and outside the steam generator water chamber. Workers performing work outside the steam generator water chamber continue to be exposed because the manway remains open while the work is performed in the steam generator. The following dose reduction factors for ECT were suggested from the study: having a spare supply of ECT equipment, sufficient pre-maintenance, obtaining new equipment, training ECT assistant workers in equipment utilization and abnormal situation handling, wearing lead vests for workers approaching the manway, and installing shielding in the work area around the water chamber. The third-highest exposure task for Korean PWR workers is manway work. Manway work is performed at the beginning and end of steam-generator-related work, and the worker performs the opening and closing of the manway cover manually. Some tasks were performed inside a water chamber. To reduce exposure to manway work, this study provides the following dose reduction factors: improvement of the material of manway bolts, establishment of countermeasures in case of sticking, and improvement of removal equipment. In addition, in terms of shielding, the RCS and RTD should be fully shielded before performing manway work, the manway shield should be utilized when closing the manway, and the manway entrance should be blocked using a temporary shield when not performing work inside the steam generator water chamber. This study aims to provide technical and practical proposals for optimizing radiation protection during high-exposure work in Korean PWRs.

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References

1. Korea Hydro & Nuclear Power. Nuclear Power Plant Status. KHNP; Gyeongju, Korea: updated Dec 2023; [cited Dec 2022], Available from: https://npp.khnp.co.kr/index.khnp?menuCd=DOM_000000102002001001.
2. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2013 ([in Korean]).
3. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2014 ([in Korean]).
4. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2015 ([in Korean]).
5. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2016 ([in Korean]).
6. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2017 ([in Korean]).
7. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2018 ([in Korean]).
8. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2019 ([in Korean]).

9. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2020 ([in Korean]).
10. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2021 ([in Korean]).
11. Korea Hydro and Nuclear Power. Annual Report of Occupational Exposure in Nuclear Power Plants, KHNP, Gyeongju, Korea, 2022 ([in Korean]).
12. Song C, Kong TY, Kim S, Son J, Kim H, Kim J, Park J, Kim HG, Kim Y. 2024. High-radiation-exposure work in Korean pressurized water reactors. Nuclear Engineering and Technology, under publication, https://doi.org/10.1016/j.net.2023.12.048.
13. Korea Hydro and Nuclear Power. Development of Occupational Radiation Exposure Reduction Technology at Nuclear Power Plant, KHNP, Gyeongju, Korea, 2005.
14. Korea Electric Power Corporation. Radiation Exposure Analysis Report, KEPCO KPS, Naju, Korea, 2022.
15. Lee DH. 2017. Managerial Factors Influencing Dose Reduction of the Nozzle Dam Installation and Removal Tasks Inside a Steam Generator Water Chamber. *J Ergon Soc Korea*. **36**(5):559-568. https://doi.org/10.5143/JESK.2017.36.5.559.
16. Kim HG, Kong TY, Jeong WT, Kim ST. 2010. An Effects of Radiation Dose Assessment for Radiation Workers and the Member of Public from Main Radionuclides at Nuclear Power Plants. *Journal of Radiation Protection*. **35**(1):12-20.
17. Kim GH and Kong TY. 2010. Selection of the Most Appropriate Two-Dosemeter Algorithm for Estimating Effective Dose Equivalent during Maintenance Periods in Korean Nuclear Power Plants. *Radiation Protection Dosimetry.* **140**(2):171-181. https://doi.org/10.1093/rpd/ncq073.
18. Lee DH. 2018. Performance Evaluation of Experts Predicting the Delay Factors and the Delay Time of the Nozzle Dam Installation and Removal Tasks. *J Ergon Soc Korea.* **37**(2):155-168. https://doi.org/10.5143/JESK.2018.37.2.155.
19. Chae GS. 2004. Review on the Working Hours of the Radiation Work Plan for ECT through In-service Inspection. *J Korea Asso Radiat Prot.* **29**(1):57-63.
20. Oh HC, Na JH, Lee JS, Moon JH. 1999. Methodology to Reduce Occupational Dose in NPP Design. K. Korean Nuclear Society Conference.