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Original article

Analysis of the Procedures for Eddy Current Testing in Steam Generators of Korean Pressurized Water Reactors

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ABSTRACT This study presents a structural analysis of the Eddy Current Testing (ECT) procedure for steam generators used in pressurized water reactors (PWRs). The analysis is based on the official work procedure document employed during actual field operations. ECT is a key nondestructive examination performed during planned outages to assess the integrity of steam generator tubes. This procedure takes place in high-radiation environments, where effective management of processes is crucial. The procedure is organized into three main phases: preparation, inspection, and post-inspection. For each phase, the study identifies and analyzes the objectives, prerequisites, and key checkpoints. Particular attention was given to critical management points outlined in the procedure, such as the criteria for probe replacement and the disposition of defected tubes. This examination highlights the importance of each step beyond a mere summary. The analysis indicates that the ECT process follows a well-defined flow: it begins with initial condition checks and equipment setup, proceeds to signal acquisition and data management, and concludes with decontamination and reporting. Each phase is vital for ensuring the reliability and safety of the inspection. This study demonstrates that even without quantitative dose data, a procedure-based analysis can provide a systematic understanding of tasks performed in high-radiation environments. Additionally, it lays the groundwork for future research that integrates actual dose data with procedural analysis, contributing to more quantitative and evidence-based assessments of radiation protection.

Key words: Eddy Current Testing, Pressurized water reactor, Steam generator, High-radiation task, Radiation protection

1. Introduction

Radiation-related tasks in nuclear power plants are typically performed in high-radiation environments to minimize worker exposure and ensure safety during critical operations. One such task is Eddy Current Testing (ECT), which is essential for verifying the integrity of the U-tubes within the steam generator. The goal of ECT is to detect cracks in the steam generator U-tubes. If any cracks are identified, the U-tube will be blocked to prevent the transfer of radioactive materials from the primary to the secondary system. This nondestructive examination is carried out during scheduled maintenance outages and requires both a high level of accuracy in the inspection results and strict adherence to radiation protection principles. The ECT process takes place inside the steam generator's channel head. Workers access this space through a manway and install the inspection equipment in a confined area characterized by a quarter-spherical geometry, with a radius of approximately 2 meters. They then conduct the eddy current inspection sequentially. The channel head is exposed to a vertical high-dose-rate radiation field due to the accumulation of radioactive corrosion products on the U-tubes. As a result, workers are required to perform tasks in close proximity to the radiation source while maintaining restricted postures for extended periods [1-3]. The limited visibility and confined working environment within the channel head further increase the risks associated with radiation exposure. These risks include high dose rates at close range, prolonged stay times, and limited movement options. Among

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various high-exposure tasks carried out in Korean pressurized water reactors (PWRs), ECT has been identified as the task with the second-highest dose rate per unit time [4-6]. Therefore, a systematic analysis of the ECT procedure, including a detailed workflow and the characteristics of each step, is of both academic and practical importance [7]. This study uses an actual ECT procedure document from a nuclear power plant to identify the structural characteristics and management considerations related to the task, presenting these findings in an organized manner. The results of this study are expected to provide foundational data for future research aimed at enhancing radiation protection and improving work efficiency.

2. Materials and Methods

This study focused on the ECT of steam generators in Korean PWRs. The analysis is based on an official procedure document used in actual field practice, which outlines the step-by-step workflow of ECT tasks performed by workers during scheduled maintenance outages. The document is systematically organized into major, intermediate, and subcategories of tasks, with specific instructions provided for each item. It also includes procedures for equipment installation, inspection execution, as well as equipment dismantling and restoration. This makes it a comprehensive reference for understanding the overall structure and flow of ECT operations.

In the initial stage of this study, the tasks outlined in the procedure were categorized into three main phases: preparation, inspection, and post-inspection. This classification allowed for a systematic organization based on the objectives and characteristics of each task, providing a framework for more detailed analysis. The preparation phase includes tasks such as checking initial conditions, verifying the readiness of the inspection site, and inspecting equipment and components. The inspection phase consists of steps like verifying tube positions during signal acquisition, confirming the tubes that have been inspected, determining when to replace probes, and managing discarded probes. Finally, the post-inspection phase involves activities such as decontaminating inspection equipment and preparing work logs. By categorizing the tasks in this way, the continuity of the entire workflow and the specific role of each phase could be clearly delineated.

In the second stage of the analysis, each task was examined according to the instructions outlined in the procedure. The objectives, necessary prerequisites, and working conditions for each task were summarized. For instance, the step “checking nozzle dam installation” is noted as a simple inspection action in the procedure. However, in this study, it was interpreted as a task aimed at preventing the spread of radioactive materials into the coolant system. Similarly, “checking the dryness of the primary side of the tubes” was understood as a condition essential for ensuring the reliability of inspections. This analysis clarified the significance of each step and the associated procedural control points. Notably, aspects of the work environment—such as the confined space of the channel head, restricted working postures, and the complexity of handling equipment—were addressed [2,3]. Although these elements were not explicitly mentioned in the procedural text, they were considered by comprehensively analyzing worker actions and spatial constraints. This approach emphasized the functional characteristics of each phase rather than simply providing a procedural summary.

In the third stage, we analyzed the sequence and interconnections within the procedure to identify the workflow between tasks. While the procedure lists the tasks individually, this study reorganized them into tables and narrative descriptions to clarify the structural connections between the stages. This approach enabled us to identify workflow continuity and key management points effectively.

The methodological significance of this study lies in its ability to systematically analyze tasks based on procedures, even without quantitative dose data. While many previous studies have concentrated on measuring radiation doses and establishing reduction measures, this study aims to understand the procedure itself in a structured way. This approach lays the groundwork for future research that could integrate radiation dose data with the results of procedural analysis, enabling more quantitative evaluations of radiation protection and discussions on potential procedural improvements.

3. Analysis of the ECT Procedure

This study analyzes the overall workflow based on the actual ECT procedure document used in PWR steam generator maintenance. The procedure document outlines all the detailed steps performed by field workers. We reorganized these steps into a three-phase structure: preparation, inspection, and post-inspection. For each phase, we summarized the objectives of the main tasks and their prerequisites, and we analyzed the connections between stages using tables and narrative descriptions. Additionally, by discussing the management points and procedural

characteristics identified through our analysis, we aim to present the structural features of the ECT task more clearly.

3.1. Preparation Phase

The preparation phase consists of procedures that are carried out before workers enter the steam generator. The goal of this phase is to establish a safe inspection environment and ensure operational safety. According to the procedure document, this phase covers Scenarios 1-19 and includes tasks such as initial condition checks, verification of the readiness of the inspection site, inspections of equipment and components, preparation and evaluation of mock training, assignment of crew members for equipment installation, transportation of equipment, installation of protective sheets and air purging devices, and the setup of signal acquisition and probe-related equipment. As detailed in Table 1, each task is summarized by its purpose and prerequisites. In most cases, the prerequisites depend on the completion of the immediately preceding step.

The initial condition check (Scenario 1) is a crucial step in ensuring the safety of the inspection environment. The procedure mandates that workers perform four essential checks before proceeding: first, they must verify that vinyl shielding is in place to prevent the spread of radioactive contaminants from the channel head; second, they need to confirm that the manway is open for access; third, they should check that the nozzle dam is properly installed to isolate the coolant system; and fourth, they must inspect the primary side of the tubes for dryness. These checks are prerequisites for conducting subsequent inspection steps safely and reliably.

In the equipment and component inspection step (Scenario 3), not only is the functionality of inspection devices verified, but a systematic check of essential components is also required. This includes examining signal acquisition systems, probes, probe driving and positioning devices, calibration standard tubes, data recording media, and communication and monitoring systems. Additionally, verification items such as the availability of certificates for critical consumables and the validity of calibration certificates are reviewed to ensure the reliability of the inspection process.

The organization of equipment installation crews (Scenario 7) involves more than just assigning personnel. The procedure specifies that each installation crew should be divided into at least two teams, taking into account factors such as time spent in high-radiation areas. This measure aims to reduce the cumulative radiation exposure of individual workers while maintaining efficiency and safety during equipment installation.

The installation of protective sheets around the steam generator (Scenario 9) is also of significant importance. As the area surrounding the steam generator is a high-radiation zone, the procedure requires the installation of vinyl sheets to prevent the spread of contamination [8]. This measure serves as a radiation protection strategy that not only protects the workspace but also minimizes unnecessary exposure to radioactive materials for workers.

The installation of an air purging device (Scenario 10) is designed to dry the interiors of the tubes and ensure proper ventilation. According to the procedure, the air purging device dries the primary side of the tubes to facilitate smooth probe insertion and removes internal dust to prevent contamination. It is also specified that the operation of the air purification system must be frequently confirmed through the main control room or supervising department. If the purging device is used while the purification system is not functioning, radioactive contaminants may spread within the containment vessel. Consequently, as the purging device becomes heavily contaminated after use, careful storage and management within a controlled area are essential.

The preparation phase is not just a series of preliminary checks; it is a crucial process that guarantees both inspection quality and radiation safety through detailed checklists and verification items. Although each step may seem independent, they are interconnected and collectively form essential prerequisites for conducting the inspection.

3.2. Inspection Phase

The inspection phase is the central part of the ECT process, where the integrity of the tubes is assessed. According to the procedure document, this phase includes Scenarios 20-25, beginning with the confirmation of tube locations during signal acquisition and concluding with corrective actions for any defective tubes. This phase consists of six key steps: confirming tube locations during signal acquisition, verifying inspected tubes, determining whether probe replacement is necessary, disposing of used probes, managing data, and implementing corrective actions for defective tubes. As outlined in Table 2, each step is summarized with its purpose and prerequisites. In most cases, the prerequisites are based on the completion of the previous step.

Tube location confirmation (Scenario 20) is crucial for ensuring accurate signal interpretation by clearly identifying the coordinates of the tubes during inspection. The verification of

Table 1. Preparation Phase Tasks

No.	Sub-task	Objective	Precondition
1	Initial Condition Check	Verify that safety and environmental conditions are satisfied before inspection begins	Prior to task initiation
2	Verification of Inspection Area Segregation	Secure a data management system by separating the signal acquisition room and the evaluation room	Completion of initial condition check
3	Equipment and Component Check	Confirm the proper condition of major inspection equipment and components	After area segregation verification
4	Pre-training Instruction	Enhance worker proficiency and ensure safety	Completion of equipment check
5	ZR-100 Robot Installation Mock Training	Familiarize with the installation process of the robot system and identify potential issues in advance	After pre-training instruction
6	Evaluation of Mock Training Results	Review outcomes of mock training and verify procedural adequacy	Completion of mock training
7	Crew Formation for Equipment Installation	Assign workforce and roles for installation tasks	After the training result evaluation
8	Equipment Transport In & Out	Transfer major equipment to the work location and remove unnecessary items	Completion of crew formation
9	Installation of Protective Cover around Steam Generator	Reduce radiation exposure and prevent the spread of contamination	Completion of equipment transport
10	Installation of Air Extractor	Remove residual gases and secure ventilation in the water chamber	Completion of protective cover installation
11	Installation of Signal Acquisition Device	Install the eddy current signal recording device	Completion of air extract
12	Installation of Probe Positioning Device	Install the device to control probe positioning	Completion of the signal device
13	Installation of Probe Driving Device (4D)	Install device for forward & backward probe movement (4D)	Completion of positioning device installation
14	Installation of Probe Driving Device (10D)	Install device for forward & backward probe movement (10D)	Completion of 4D device installation
15	Installation of Remote Cable between Containment and Signal Acquisition Room	Establish a remote data transmission line	Completion of driving device installation
16	Installation of Equipment and Controllers	Install control devices and confirm the interface	Completion of cable installation
17	Installation of Signal Acquisition Room Devices	Set up the evaluation room equipment and confirm the signal linkage	Completion of controller installation
18	Assembly of Fixture, Push-Puller, and Controllers	Combine equipment and verify operational performance	Completion of signal acquisition room setup
19	Installation of Probe	Prepare the probe prior to inspection execution	Completion of assembly

Table 2. Inspection Phase Tasks

No.	Sub-task	Objective	Precondition
20	Verification of Tube Location during Signal Acquisition	Confirm tube location to ensure signal accuracy	Completion of the preparation phase
21	Verification of Inspected Tubes	Check tubes that have already been inspected	After tube location verification
22	Probe Replacement Decision	Determine whether probe performance has degraded	During inspection
23	Disposal of Used Probes	Safely handle and dispose of replaced probes	After probe replacement
24	Data Management	Organize and store inspection data	After inspection and processing
25	Action for Defective Tubes	Carry out follow-up actions for defective tubes	After data management

Table 3. Post-inspection Phase Tasks

No.	Sub-task	Objective	Precondition
26	Decontamination of Inspection Equipment	Clean and decontaminate used inspection equipment to prevent contamination spread	Completion of the inspection phase
27	Preparation of Work Log	Record progress details for future verification and management	Completion of equipment decontamination
28	Preparation of Field Summary Report	Summarize and organize on-site inspection results	Completion of work log
29	Preparation of Final Report	Compile and analyze overall inspection results for official documentation	Completion of the field summary report

inspected tubes (Scenario 21) prevents omissions and duplicates by rechecking tubes that have already been tested.

Probe replacement judgment (Scenario 22) is a critical step that determines the reliability of the inspection. This procedure outlines specific criteria for replacing probes, including damage to the probe head that makes insertion difficult, any shaft damage that causes withdrawal problems, signal noise due to probe wear, and wobbling or signal distortion that prevents proper calibration. Additionally, replacement may be carried out based on the operator's experience and judgment regarding the necessity of the action. These criteria are essential for maintaining inspection quality and data reliability, minimizing unnecessary re-inspections, and controlling radiation exposure.

Used probe disposal (Scenario 23) involves the safe collection and handling of replaced probes to prevent the spread of contamination. In the data management step (Scenario 24), the collected inspection data are organized and archived, serving as the foundation for subsequent analysis and the preparation of the final report.

Finally, corrective actions for defective tubes (Scenario 25) are determined based on the inspection results. According to the procedure, if the size of the defect exceeds the criteria outlined in each plant's final safety analysis report or relevant standards, the affected tube is subject to corrective actions, such as plugging. Moreover, tubes suspected of degradation due to corrosion or erosion must undergo re-inspection to ensure accuracy and safety.

The process of attaching the probe, which is a sensor inserted into a tube to generate and measure eddy current signals, involves several additional tasks. A full-tube inspection using a bobbin coil, a basic probe designed for rapid screening of all tubes, improves efficiency. However, when abnormal signals are detected, a precise re-inspection with the RPC probe (Rotating Pancake Coil), a high-resolution probe utilizing a rotating pancake coil, is necessary [9,10]. Re-inspection with the RPC probe is crucial for ensuring inspection accuracy, but it also extends inspection time and increases the duration workers spend on-site. This can lead to higher radiation exposure, making effective management of the process essential [5].

The inspection phase builds upon the preparation phase and focuses on signal acquisition and data management, which are critical for the quality and reliability of the inspection. Key management elements during this phase include probe replacement and disposal, corrective actions for defective tubes, and re-inspections of RPCs. These processes are essential for ensur-

ing accurate results and serve as a link between the conditions established in the preparation phase and the actual inspection outcomes. Consequently, this phase is a crucial determinant of the overall success or failure of the ECT process.

3.3. Post-inspection Phase

The post-inspection phase occurs after the completion of the ECT process. This phase involves decontaminating the equipment used during the inspection and systematically documenting the results. According to the procedure document, this phase corresponds to Scenarios 26-29 and comprises four main tasks: decontamination of equipment, preparation of work logs, preparation of a field summary report, and preparation of the final report. Each task is briefly summarized in Table 3, outlining its objectives and prerequisites, and all steps are organized sequentially.

Equipment decontamination (Scenario 26) involves cleaning and decontaminating used inspection equipment to prevent the spread of radioactive contamination. This process goes beyond just handling the equipment; it ensures the safety of future workers and allows for the potential reuse of the equipment. Next, the preparation of the work log (Scenario 27) is essential for documenting the inspection process and key events. This log serves as reference material for verification and management later on.

The preparation of the field summary report (Scenario 28) is another critical step, as it consolidates and summarizes the inspection results. The procedure document outlines in detail the items that must be included in this report. It typically contains the inspection name, inspection period, responsible and supporting departments, inspection and evaluation methods, performance and results, recommendations for corrective actions for defective tubes, and additional remarks. These items not only form a comprehensive report but also serve as official records of the inspection, laying the groundwork for future management systems.

Finally, the preparation of the final report (Scenario 29) takes the findings from the field summary report to compile and analyze the overall inspection results. This final report serves as the official record for the plant. Specifically, the evaluation and corrective actions for defective tubes are linked to the final safety analysis report, providing key data for future safety assessments.

The post-inspection phase, although seemingly straightforward, is crucial for ensuring radiation protection and effective work management. Inadequate decontamination can lead to increased radiation levels in the workplace or a heightened risk of contamination spreading. Similarly, if the preparation of reports is lacking, the traceability and reliability of the inspection results may suffer. Thus, the post-inspection phase is crucial as it serves as the final step, ensuring not only the implementation of physical measures but also maintaining radiation safety and transparency in documentation.

4. Conclusion

This study examined the ECT process utilized in Korean PWRs. It provided a step-by-step analysis based on the actual procedure document. A systematic review of the workflow outlined in the procedure revealed that the entire process can be divided into three phases: the preparation phase (Scenarios 1-19), the inspection phase (Scenarios 20-25), and the post-inspection phase (Scenarios 26-29). This classification helped clarify the functional roles of each phase and their interconnections.

The preparation phase includes detailed procedures such as initial condition checks, inspections of equipment and components, crew organization, and the installation of protective covers and air extractors. These steps lay the groundwork for ensuring inspection readiness and radiation safety. During the inspection phase, tasks such as signal acquisition, tube verification, probe replacement and disposal, data management, and defect tube handling are conducted. The procedure document clearly outlines the criteria for probe replacement and the actions required for addressing defective tubes. The post-inspection phase involves equipment decontamination, the preparation of work logs and reports, and the official documentation of inspection results. Each of these procedural steps is essential not only for executing the workflow effectively but also for ensuring inspection reliability, safety, and the establishment of a comprehensive management system.

The significance of this study lies in its demonstration that, even without quantitative dose data, the structure and meaning of tasks can be systematically analyzed using the procedure document. While previous research has primarily focused on measuring doses and identifying reduction strategies, this study establishes a structural framework for the procedure, allowing for the derivation of operational meanings and management points. This framework provides a foundation for future studies that combine actual dose data with procedural analysis, enabling more quantitative and empirical evaluations of radiation

protection. However, since this study relied on documented procedures, it has limitations in capturing exceptional situations or worker-specific behaviors that may arise in real field conditions. Therefore, future research should integrate procedural analysis with actual dose data, worker movement patterns, and spatial constraints to facilitate more concrete evaluations of radiation protection and improvements in procedures.

In conclusion, this study has conducted a structural analysis of the ECT procedure, laying the groundwork for understanding the characteristics of high-radiation tasks in nuclear power plants and ensuring radiation safety. This analysis is anticipated to serve as a foundation for future research aimed at improving procedures, with the goal of enhancing both work efficiency and safety.

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