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Field Operators' Visual Inspection Practices in the Operating Finnish Nuclear Power Plants

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ABSTRACT

In nuclear power plants (NPPs), the integrity of the plant is assured, among other safety measures, by regularly conducted field operator (FO) visual inspection rounds. No previous research has focused on the NPP FOs' visual inspection practices. The objective of this study is to systematically document how visual inspection is conducted and how expertise is developed, as well as to compare the practices of the different NPPs. Five FOs representing all operating NPPs in Finland participated in semi-structured interviews. All FOs reported visual inspection as their most important work task. During the inspection rounds, the FOs examine the integrity of equipment and appropriateness of the facilities using all senses except taste. For the most part, all FOs perform the visual inspection rounds similarly. However, some differences were found, which, at large, seem to be explained by the tools used during the round and the composition of the premises.

Keywords: Visual inspection, Field operator, Work practices, Nuclear power plant

INTRODUCTION

Despite all technical advancements, the human operator continues to play an essential role in ensuring nuclear safety. One vital safety measure for operational reliability and continuous functionality of the plant and its equipment is regularly conducted field operator (FO) visual inspection rounds.

Research has explored visual inspection in conjunction with various inspection methods across multiple fields, such as aviation, infrastructure, renewable energy, manufacturing, construction, and nuclear industry. No studies have focused on nuclear power plant (NPP) FOs' daily visual inspection practices. Here, we investigate the FOs' visual inspection practices in all operating Finnish NPPs. The goal is to document how visual inspection is conducted and how the related expertise is developed. Furthermore, we compare and evaluate the practices between the different plants.

VISUAL INSPECTION IN SCIENTIFIC LITERATURE

Visual Inspection

Visual inspection is one of several non-destructive testing (NDT) techniques utilized across various industries. NDT can be characterized as a collection of examination methods and techniques to gather information about an object or structure without altering its physical state. Visual inspection is the most common, oldest, and usually the first-line NDT method. It is often applied, for instance, in aircraft maintenance, medicine, the food industry, and the nuclear industry (See, 2012). Despite the term 'visual,' the method may also involve using other senses, such as auditory, olfactory, and tactile senses (Charles et al., 2015). The aim is to detect discontinuities, flaws, and defects in products, machinery, or equipment that could affect their integrity and functionality. Depending on the context, visual inspection can be conducted during manufacturing fabrications or as an in-service inspection.

Visual Inspection in NPPs

In NPPs, visual inspection is done as part of the in-service inspection, i.e., the inspection is conducted during the operational period. The aims are 1*) to detect discontinuities and imperfections on the surfaces or components, such as cracks and corrosion*; 2) *to detect evidence of leakage from pressure-retaining components*; and 3) *to determine the general mechanical and structural condition of components and their supports* (Norris, 1999). The most critical objective of visual inspection is to record those flaws that exceed the predetermined reporting threshold and to identify the ones that are significant enough to endanger the plant's safety. These are known as *critical defects* (Bertovic, 2015).

Factors Affecting Visual Inspection

The benefits of a human operator performing visual inspection lie in the operator's ability to use various senses, adapt to unexpected situations, and make decisions (e.g., Vasconcelos, 2019). However, in NPPs, the inspection task is vastly complex in NPPs; inspectors must examine the plant consisting of large components over a long period while relying on their sensory, perceptual, cognitive, and motor skills (Vasconcelos, 2019). Nonetheless, the success of visual inspection is affected by individual factors such as mental and physical abilities and expertise (See et al., 2012), and external factors such as task, group, and organizational characteristics, as well as the characteristics of the physical environment, (Bertovic, 2015; Chen & Huang, 2014; Cumblidge, 2017; Vasconcelos, 2017) and their interaction.

Good Practices in Visual Inspection

Human factors research has yielded a considerable amount of information in response to shortcomings in visual inspection reliability. Research has highlighted different search strategies, including systematic search techniques and positioning optimization, to minimize errors (Hrymak & Codd, 2021; Hrymak & de Vries, 2020; Takamido et al., 2022). Additionally, implementing thoughtfully created job aids (anything that assists the inspector in the inspection, e.g., lists, check sheets, and pictures) is recommended to foster systematic search strategies (Charles et al., 2015). Particularly, less experienced inspectors can have difficulties identifying deviations or their criticality. Improving teamwork can reduce such uncertainty by allowing feedback exchange and the sharing of expertise (Cumblidge et al., 2017). Similarly, constructing clear accept and reject criteria has been shown to support decision-making (Cumblidge, 2017). Other factors improving inspection reliability found in the previous research include allowing sufficient time to perform the task (Drury & Watson, 2002), minimizing interruptions (Cumblidge, 2017), job rotation, and support from management (See, 2012).

METHODS

To gain a holistic understanding of FO visual inspection practices, we conducted a semi-structured interview study, including all five operating NPPs in Finland.

Participants

Five FOs, all male (mean age 39 years; min 33, max 45 years), participated in the interviews. Their work experience as an NPP FO varied between seven and 15 years (mean 11 years). All interviewees provided written informed consent.

Interviews

The interview questions were tailored under the six main topics: *background questions*; *the basic features of inspection work*; *success and challenges in inspection work*; *training; guidance and development*; *a brief look at the past*; and a final question concerning *what a good inspection worker is like*. Each main topic had several sub-questions, and the interviewer could ask more detailed questions if necessary. The same interviewer interviewed all the participants. One additional researcher always participated in the interviews for notetaking and asking further questions if needed. The interviews were also recorded to resolve discrepancies or omissions in the notes. One interview lasted approximately 1.5 hours and was conducted using Microsoft Teams (version 1.6.00.28557).

Analysis

The data from the interview transcripts was collated and summarized to a table covering the key topics of the current paper: *composition of premises*; *FO training*; *main tasks of the FO*; *types of inspection rounds*; *senses and how they are used*; *devices used*; and *round sharing and collaboration*. Thus, only the part of the interview that dealt with inspection practices was included in this study. Each researcher cross-checked the generated table to ensure all relevant information from the transcripts was correctly included. Once the table was verified, the data were reorganized in three groups (see Table 1) based on the described similarities and differences in the plant characteristics.

RESULTS

The Composition of the Premises

Inspection of the composition of premises and how FOs characterized the plants resulted in three groups: Group 1 (G1), comprising two plants; Group

2 (G2), comprising two plants; and Group 3 (G3), comprising one plant. Thus, the preliminary analysis of the plant characteristics is the key factor according to which all responses are collated. Despite some differences between the plant characteristics (see Table 1), all FOs reported that the plants were noisy.

Table 1. The composition of premises by group.

Group	Number of Plants	Plant Characteristics
G1	2	Facilities are spacious and easy to inspect.
G2	2	The facilities are mazy, with confined spaces and lots of stairs. Some places have high temperatures. Visibility is good in general.
G3	1	The facility is roomy and adequately lit. There are no confined places, and the access to inspected items is good.

Training

The FOs in all groups reported similar training structures. During the first months, the FOs participate in theoretical classroom training under the NPP's training curriculum. This is followed by practical training; new FOs begin to do rounds under the supervision of an experienced FO. One FO mentioned that the duration of supervised training depends on how fast the understanding of the plant and the tasks develop—the enthusiasm and motivation of the experienced FO influence this. Finally, the shift supervisor decides when the new FO is ready to carry out the rounds independently. The final practical test is conducted and evaluated by the manager. In general, it was said that the training takes a minimum of one year. However, as commented by one FO in G1, three to four years of inspection experience is practically required before one can consider him/herself as fully professional. This is due to the fact that some equipment is inspected rather rarely, and it takes time to gain experience with them. FOs in G1 and G3 receive training to operate in both the turbine and reactor areas, while those in G2 work exclusively in either one of those.

The Main Tasks of an FO

All FOs considered performing the inspection rounds as their most important work task. During the inspection rounds, the FOs examine the integrity of equipment and the appropriateness of the facilities. They record readings, make notes about the equipment, and observe that everything functions as planned. The FOs in all groups reported being responsible for periodic testing as well as process separations and reconnections, e.g., for maintenance. Furthermore, they conduct several rarely occurring tasks, such as filling and emptying systems and checking alarms. Only the G1 FOs participate in some maintenance tasks.

Types of Inspection Rounds

FOs work in two shifts: a 12-hour day shift and a 12-hour night shift. In each group, there are two rounds during the day shift. Also, two rounds are performed during the night shift in G1 and G2. In G3, FOs do the round once during the night shift. The first round is always scheduled at the beginning of the shift. Typically, those places visited in the first round of the shift are not visited in the second round by the same FO. Equipment requiring more profound monitoring, such as the reactor coolant pump, is inspected more often than other equipment. The rounds are organized so that the entire facility is inspected within 24 hours. The FOs can decide the order of the inspection route themselves. In addition to the regular rounds, all groups perform additional checks when needed. For instance, when there is a pump leakage, the area is followed more frequently during the shift.

The G1 FOs conduct the first round of the day shift with a tablet (duration: 1–2 hours) and the afternoon round, the so-called "free round," without it. During the second round of the day shift, they inspect that equipment that has been separated from and reconnected to the process for, e.g., maintenance activities, are operating as intended (duration: ~30-45 minutes). Both rounds during the night shift are inspected using the tablet. The rounds are divided into a restricted area and a controlled area. The FOs in the same shift alternate visits between the two areas. During a shift, one FO inspects the restricted area and the other FO the controlled area, and vice versa the next time the inspection round is performed. The FOs also mentioned that one more exhaustive round is scheduled for each week on Saturday (duration: 2-2.5 hours), and one even more exhaustive round is conducted on the first Saturday of each month (monthly round; duration: 3–4 hours). The day rounds are often interrupted by tasks related to maintenance. However, there are no interruptions during the night and weekend rounds.

The G2 FOs record the readings using a paper checklist during the first round of the day shift. Both plants of the group have two turbines and one reactor. Regarding, for instance, the turbines, during the first round of a shift, one FO inspects one turbine, and the other FO inspects the other. They switch turns in subsequent rounds to improve the reliability of the inspection, but this was also mentioned to decrease monotony. The round is performed as one entity. However, the round can be interrupted by the need to perform process separations or reconnections. The round lasts a minimum of one hour. If the round includes checking external facilities, such as the water supply facility, then the round is extended by half an hour. Tidiness is essential; hence, leaks or any inappropriateness of the facility (e.g., unclosed fire doors or misplaced items) are often handled by the FOs, extending the round's duration.

The G3 FOs reported that the round, including the supervised and turbine area, as well as the yard, lasts about three hours. However, there is slight variation; the afternoon round of the day shift is not as extensive as the first round, lasting approximately two hours. Moreover, as in G1, one more exhaustive round is scheduled each Saturday, and one more exhaustive round is conducted on the first Saturday of each month. Lastly, it was reported that an FO is not to be disturbed during the rounds; there are no interruptions, nor does one need to rush during the inspection.

Senses and How They Are Used

In all groups, vision, hearing, touching, and smelling are used to detect faults. In general, vision was reported to be the most critical sense for visual inspection. By looking, the FOs get information about the integrity of the surfaces, perceive the meter readings, and evaluate the appropriateness of the facilities. However, hearing was often reported to be as important as vision. With increasing expertise, FOs can collect information by actively listening for indications of faults within the equipment. Background noise, together with the use of earmuffs, was reported to make differentiating between normal and non-normal sounds challenging. The sense of smell was also considered crucial for detecting certain faults. One FO even stated that experienced FOs can detect low oil levels in equipment by smelling. The tactile sense is important for detecting unusual vibrations and deviant temperatures or moisture in both spaces and equipment.

Tools Used During the Round

The G1 FOs have a tablet on which the readings are recorded. The tablet also shows a brief five-day history of recorded values and the trends of the past 30 days. The tablet can also be used for taking pictures and recording video and sound. The tablet includes threshold values, allowing inspectors to identify and assess whether equipment values approach or surpass predetermined limits. In addition, round devices include a pen and paper, keys, a DECT phone, a badge, a multi-purpose tool to tighten door handles, and radiation meters (when the FOs go to the restricted area). Lastly, some FOs report sometimes having a circuit diagram in the round to understand the piping better.

The G2 FOs reported using a paper checklist. The checklist is round-specific for the first round of the day shift, and both rounds of the night shift. The checklist also has free space for additional information if needed. Furthermore, they have a walkie-talkie or a DECT phone, a flashlight, radiation meters (in the restricted area), and a spanner on the round.

The G3 FOs have a tablet on the round. The tablet has a checklist for marking the items that have been inspected. The tablet also provides the order (defined by the FOs themselves) in which the premises are inspected and has free space for writing additional information. The tablet also includes threshold values and provides information on what needs to be inspected for each equipment. Tool cabinets exist in the restricted area, and they also reported having radiation meters on the round when needed.

Round Sharing and Collaboration

Each plant has at least two FOs working in the same shift. Primarily, all FOs conduct the inspection rounds individually, i.e., one FO at a time. The G1 and G2 FOs reported that when there is a fault in plant equipment, the second FO often joins to inspect it. When there are any anomalies, the information is always delivered to the main control room (MCR) operators. All

FOs reported discussing all matters with the MCR operators during and after the round as well as among the colleague(s) in the shift.

The G1 FOs reported that during the rounds, FOs are sometimes in contact with the MCR operators and the other FO in shift via walkie-talkie and vice versa. If there are concerns or issues with the plant equipment, the FOs may request maintenance for inspection or ask them for advice. The FOs deliver the daily round report primarily to the auxiliary panel operator. The report is then evaluated and approved by the shift supervisor. Cleanliness issues are separately reported to the cleansing department. In addition, the FOs between the units of the same plant sometimes collaborate; the FOs from one unit may call the FOs on the other and ask for support.

The G2 FOs reported that the FOs consistently work alongside the same colleague during their shifts, fostering collaborative practices. For instance, one FO reported occasionally cleaning the seawater filter with his colleague. The FOs that were interviewed stated that the turbine operator in the MCR is the closest operator for the FOs inspecting the secondary circuit. Thus, any change in equipment values is reported to the turbine operator. Additionally, the FOs may call the maintenance to take the required actions. Once a month, FOs inspecting the secondary circuit conduct the round with a turbine operator. Supposedly, the same applies to the FO inspecting the primary circuit – the closest MCR operator is the reactor operator. Lastly, the FOs collaborate with the cleaning personnel concerning the cleaning matters.

In G3, the FOs may conduct the round with another FO if the other FO is not busy with other tasks. If the two FOs conduct the inspection together, they follow each other without spreading out to the plant. The MCR operators are informed about any deviations in equipment or values during the round. If any work is left for the FOs in the following shift, that is written in the control room diary by the MCR operators. The shift supervisor approves the notes before the shift ends. The shift supervisor was reported to be the FOs' closest superior.

DISCUSSION

The current study examined the FO visual inspection practices in all five operating NPPs in Finland. All FOs considered the visual inspection rounds as their most important work task. In addition to inspecting the components and plant's structure, utilizing all senses except taste, the FOs also inspect the appropriateness of the premises. This can include inspecting that the fire doors are closed, the facility is clean, and there are no misplaced items. The most significant differences were found in the composition of the premises and the tools they used.

In some groups, the FOs used a tablet to guide the inspection, and some used a paper checklist. The FOs have determined the sequence in which the premises are listed on the tablet, guiding the inspection order accordingly. Two main differences were noticed between the two tools. First, compared to the paper checklist, the tablet can provide a history and short-term trends of the process values. This can benefit the FOs by improving their understanding of the functioning of the equipment relevant to the inspection work and by increasing their interest in the work. The tablet allows FOs to track trends, enabling FOs to identify consistent value changes and, thus, provides insights about evolving potential issues. Moreover, the tablet includes threshold values, allowing inspectors to assess equipment values more efficiently, which supports decision-making. Second, using the tablet, one can take photos and record a video and sound. This facilitates delivering accurate information about the equipment state to the MCR operators. From the tablet and paper checklist, one can structure the inspection round by following the order in which the items are listed. Hence, both methods can guide the task and support performance if they are carefully designed (Charles et al., 2015).

In all plants, the inspection duration was at least one hour, often extending beyond. All plants were noisy, and some included occasional workplace restrictions, had high temperatures, and were described as mazy. On the other hand, some plants were described as roomy, having sufficient lighting, and some were easy to inspect. Long inspection work in a challenging working environment can result in cognitive overload and fatigue, finally lowering vigilance and posing a threat to inspection quality (Cumblidge et al., 2017; Drury & Watson, 2002). To mitigate the impact of prolonged duration in such tasks, See (2012) suggested that five minutes of rest can restore vigilance. Such breaks do not need to be non-working time; alternating inspection with other tasks every 30 minutes has been shown to suffice (See, 2012).

Another notable difference observed between the groups was related to inspection interruptions. While the FOs in one group reported no interruptions or rush during the inspection, FOs in two groups mentioned that those occasionally occurred due to, for instance, process separations and reconnections. According to Drury and Watson (20002), interruptions can create a possibility of memory failure, and the search may become incomplete, increasing the likelihood of error (Drury & Watson, 2002). When coupled with challenging environmental conditions, external factors such as interruptions and time pressure can add to the complexity of the inspection task.

The effectiveness of the inspection was reported to largely depend on the training, particularly on the tacit knowledge accumulated from the experienced FO. According to the FOs, the proficiency, practices, and the trainer's motivation greatly affect the trainee. FOs reported that approximately after one year of learning, the new FO can perform rounds independently. However, learning to inspect using all senses typically takes years to master, highlighting the complexity of the task. Furthermore, some events are so rare that it takes time for the FO to become familiar with all equipment-related events in the plant. This may put new FOs at risk of missing defects as the required skills are still developing during the first years of inspection. Research indicates that a modular training approach, building progressively on earlier learned modules, enhances learning and defect detection (Progressive part training; Dury & Watson, 2002). However, whether such an approach in combination with learning in practice could aid FOs in their inspection is yet to be studied.

Finally, the interviews uncovered three practices on how FOs may improve inspection reliability. First, all FOs can decide the order in which they conduct the round. This can lead to a sense of autonomy, increasing motivation, a feeling of responsibility, and greater ownership over the FO's work, all attributes of an effective inspector (Behravesh et al., 1989). Second, the FOs develop collaborative practices with their work pair, who are the same in each shift. For instance, one FO reported performing some tasks with another FO in the shift. Also, some FOs alternate inspection areas from shift to shift, each inspecting the other's previously examined area and vice versa. Such practices can support vigilance as these behaviors may reduce the monotony of repetitive work. Third, the FOs engage in continuous discussions with each other, MCR operators, and sometimes with maintenance concerning the observations made in the field. Such collaboration, especially if it includes feedback from colleagues, can benefit inspection reliability, resulting in more correct defect detection (Cumblidge et al., 2017). Lastly, different FOs inspect the same components and structures consecutively throughout the shifts. Inspections performed repetitively by different inspectors are suggested to increase inspection reliability (Tian et al., 2012).

CONCLUSION

Visual inspection in the NPP, conducted frequently and regularly by FOs, is an example of the constant endeavor to ensure safety. Workers conduct it without extensive theoretical training but largely with the skills they develop during their work. This way, they constitute an important barrier against otherwise unnoticeable flaws in the equipment. Using a tablet or a paper checklist, the FO scrutinizes the equipment, identifies the important information, and delivers the message to the MCR. Visual inspection completes the daily safety measures performed by MCR operators who monitor plant processes from a distance through sensors. As visual inspection is performed daily and by several FOs, the possibility of a latent flaw is diminished. Identifying an anomaly that would develop into a critical defect over time saves the plant many resources and ensures the safe operation of an NPP.

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