Research by the U.S. Nuclear Regulatory Commission on the Effects of Human Factors on Ultrasonic Examinations

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Abstract. Recently, several operational experiences have involved failures of the nondestructive examination (NDE) process in both manual and mechanized ultrasonic (UT) examinations. To date, in order to have reasonable confidence in the reliability of NDE, industry and the NRC have focused on rigorous performance demonstration qualification processes for NDE equipment, procedures and personnel. While these measures help to ensure that the equipment, procedures and personnel are capable of reliably detecting flaws in a formal testing environment, notable failures have occurred during application in the field. Currently, research is being conducted by the Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES) to identify human factors issues associated with NDE. Specifically, the research is focused on manual conventional UT. Thus far in our work, we completed a review of human factors literature related to NDE. We are currently conducting research that estimates the probability of detection for procedures and personnel based on qualification examination pass rates and directly compares performance demonstration exams with field exams in order to understand the differences in areas such as task execution (e.g. actions the examiner takes), working conditions, environmental considerations, practice/training, information availability, and staffing considerations. This paper will capture the insights from our efforts thus far.

1. Introduction

Nondestructive examination (NDE) plays a vital role in ensuring the safety of nuclear power plant operations. It is used to detect flaws and deficiencies in steam generators, pipes, pipe welds, valves, pumps, and other critical components in a nuclear power plant (Electric Power Research Institute, 1988). The U.S. Nuclear Regulatory Commission (NRC) and the nuclear industry have devoted considerable attention to optimizing the inspection process for nuclear power plant components. These efforts have taken place during times of emerging materials degradation mechanisms and significant changes in inspection technology. As a result, there has been significant progress in improving NDE reliability over the past two decades through the development of rigorous qualification processes, including performance demonstrations for NDE equipment, procedures and personnel, via the requirements of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI Appendix VIII. Although performance demonstration helps to ensure that equipment, procedures and personnel are capable of reliably detecting flaws in a formal testing environment, notable

failures have occurred during application in the field. In each case, the equipment and procedures, while not always optimal, were physically capable of obtaining discernable signals from the flaws.

These recent events suggest that robust techniques and qualifications are necessary, but may not be sufficient, to accomplish reliable NDE in the field. The effective application of NDE can be dependent on the personnel performing the examination, the design of the task, along with the environmental and organizational conditions within which personnel carry out the task. Further, there is recognition that the performance demonstration environment is very different from working conditions in the field. An inherent feature of performance demonstration tests is that the testing is conducted under somewhat ideal conditions in a laboratory-like environment. Thus, human factors must be considered in order to have reasonable assurance of the reliability of NDE equipment, procedures, and personnel in the field.

2. Research Plan

The NRC Office of Regulatory Research (RES) is currently conducting research to systematically identify human factors issues associated with NDE. Specifically, the research is focused on manual conventional UT. The goals of our research are to:

- Systematically evaluate the human factors that can affect UT inspectors.
- Determine the key differences between UT NDE performed in a performance demonstration qualification environment vs. field inspections.
- Determine the highest priority human factors that may be impacting UT NDE performance in the field.

In order to attain these goals, our research approach consists of three phases: 1) Topic characterization, 2) Task analysis and 3) Prioritization.

2.1 Research Phase 1: Topic Characterization

Our objective for the first phase of research, topic characterization, was to develop a high-level understanding of the NDE domain and associated research relevant to human factors in NDE. We gathered information about NDE through: 1) site visits to the Electric Power Research Institute (EPRI) performance demonstration facility, nuclear power plants, and NDE vendor companies; 2) review of relevant codes, standards and regulations; 3) review of operating experience; and 4) review of relevant NDE research studies. One of our primary activities during this phase was to perform a literature review to characterize the current state of human factors research specific to NDE. The framework for the literature review and key findings are discussed below.

2.1.1 Review of Human Factors in NDE Research

Although human factors issues were often mentioned in NDE reliability research, most research programs did not give much attention to including human factors investigations in their research designs (Singh, 2000). Numerous reviews have concluded that variations in NDE reliability cannot be attributed to a single "human factor," but instead it is likely that many factors interact with each other in a sociotechnical system to collectively impact NDE performance (Carter & McGrath, 2013; Enkvist, Edland, & Svenson, 1999; Norros, 1998). Further, Bertovic et al. (2014) note that characterizations of human factors in NDE tend to be narrowly focused on the mental and physical conditions of the individual, and give less attention to the broader scope of task, team, environmental, and organizational conditions that influence human performance. Bertovic et al. (2014) argue that adopting a systems

approach to human error is more effective at understanding the underlying mechanisms that lead to errors (e.g., task, organizational, environmental) rather than simply blaming the NDE inspector for making an error.

We used Neville Moray's sociotechnical systems model (2000) as a basis for organizing our human factors literature review. Moray's model uses a systems approach to understand how technical, behavioral, environmental, and organizational factors interact to affect human performance. We adapted this model to include five categories (see Figure 1): task characteristics, individual differences, team or group characteristics, the physical environment, and organizational factors.

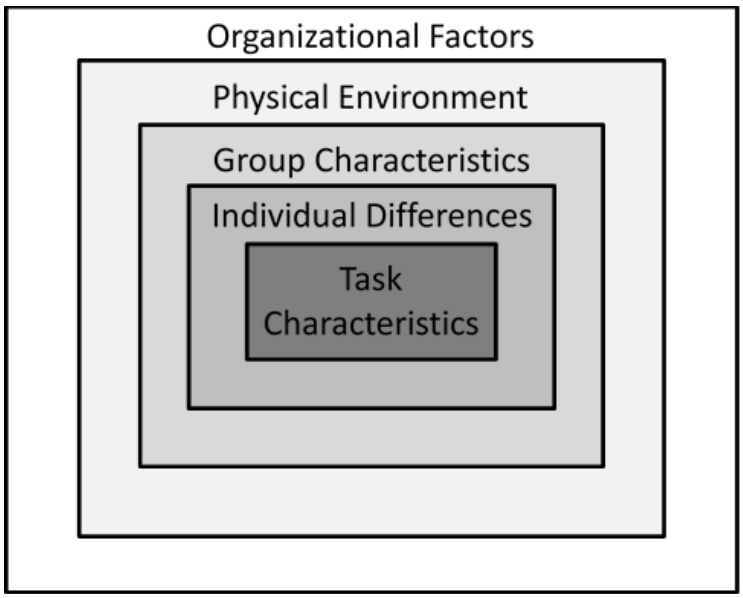

Figure 1. Sociotechnical systems model adapted from Moray (2000) for categorizing human factors considerations in NDE.

Task factors relate to the tools (e.g., equipment) and process (i.e., task execution) that inspectors use to conduct an NDE inspection. Pre-job preparation was a task factor frequently discussed in the research literature. Pre-job preparation includes activities that can be carried out or materials that can be provided before component inspection that enhance the inspector's ability to perform a quality NDE. While these activities/materials are not part of the examination, they have the potential to significantly impact the quality and accuracy of the examination. Equipment design issues were also widely acknowledges in the literature, with multiple calls for design guidance or standardization of UT equipment. Multiple attributes related to the scanning process, such as scanning speed, technical, and an inspector's posture while scanning were also discussed as influencing NDE reliability.

Individual differences refer to differences between personnel who perform NDE, and can include such things as personality, motivation, memory, spatial ability, physical ability, and visual acuity. One key finding related to individual differences was that NDE inspectors with greater mechanical comprehension demonstrated better performance than inspectors who scored lower on a test of mechanical comprehension (Bell et al., 2012; McGrath, 2008). Inspector attitude and motivation has also been empirically linked to NDE performance (Enkvist et al., 2001; Herr & Marsh, 1978; Krishnamoorthy et al., 2009; Norros, 1998; Norros & Kettunen, 1998; Shull, 2002). An inspector's trust in their own performance, motivation, and feedback are all potential determinants of performance quality.

Compared to other types of human factors, there was very little research about the effects of group characteristics on NDE performance. Most studies focused solely on the inspection reliability of a single inspector working in isolation. However, operating experience suggests

that NDE inspectors frequently work in pairs when inspecting a component. Coordination between inspectors can vary greatly depending on how the inspection task is performed.

Various elements of the physical environment have been discussed in the NDE literature in terms of their influence on the quality and reliability of an inspector's performance. One unique characteristic of the physical environment in nuclear power operations is the presence of radiation, which also means that inspectors are often required to wear extra personal protective clothing and equipment. Other physical characteristics that are common across many industrial settings and can negatively influence performance include extreme temperatures, noise, and vibrations. Lighting in particular can have a direct influence on an inspector's ability to perform their task. Due to the nature of the NDE task in a nuclear power plant—typically inspecting pipes and welds—the NDE task may also be performed in restricted work spaces.

Although our review identified many references that mention organization factors, there was a significant lack of empirical research on organizational factors in relation to NDE performance. A recent literature review by Bertovic (2015) identified only a handful of NDE studies that explicitly considered organizational factors. Nevertheless, organizational factors were often theorized as having a significant influence on NDE reliability. The types of organizational factors mentioned were most often related to the culture of the organization, management oversight and supervision, and training strategies.

Based on these results from our phase 1 research, we further informed the sociotechnical systems model to identify specific factors that influence NDE performance (termed performance influencing factors) within each of the five human factor categories (see Figure 2).

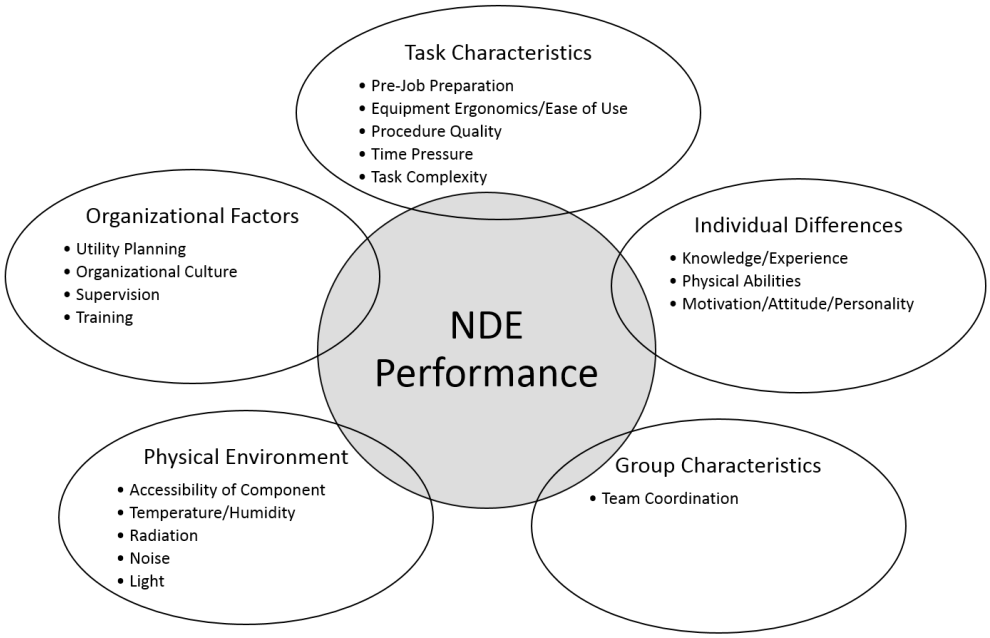

Figure 2. NDE performance influencing factors.

2.2 Research Phase 2: Task Analysis

The outcomes of Phase 1 of the research helped to establish a high-level understanding of the NDE domain and the current state of human factors research in NDE. The objectives of Phase 2 are to develop a deeper understanding of the tasks UT inspectors perform, the environment they work in, and the challenges they face. In addition, we are interested in

identifying the primary differences between UT NDE in a laboratory-like environment (i.e., performance demonstration qualification exam) and a field environment that may affect performance.

The activities in Phase 2 consist of performing a job-task analysis. Job-task analysis is a "mixed method" research approach using a range of information sources, including interviews with subject matter experts, observations, tabletop discussions, procedure analysis, and document reviews. Progress on Phase 2 is ongoing. A preliminary task list and initial insights from field observations are presented below.

2.2.1 Manual UT Functions and Tasks

Based on discussions with subject matter experts and reviews of UT procedures, we developed a list of functions and tasks related to the job of manual UT. A function is defined as a group of activities generally performed together to accomplish an overall goal, whereas tasks are smaller units of behavior that provide information about human-information processing demands, communication requirements, and interactions with people and equipment. After developing an initial task list, we then worked with EPRI to conduct a tabletop analysis with 11 subject matter experts to validate and expand the list. We identified four primary functions for manual UT: plan inspection, prepare for examination, conduct examination, and report results. Each function is distinct based on its overall goal, and where and when it is performed. Specific tasks are listed within each function. Figure 3 presents the list of functions and tasks.

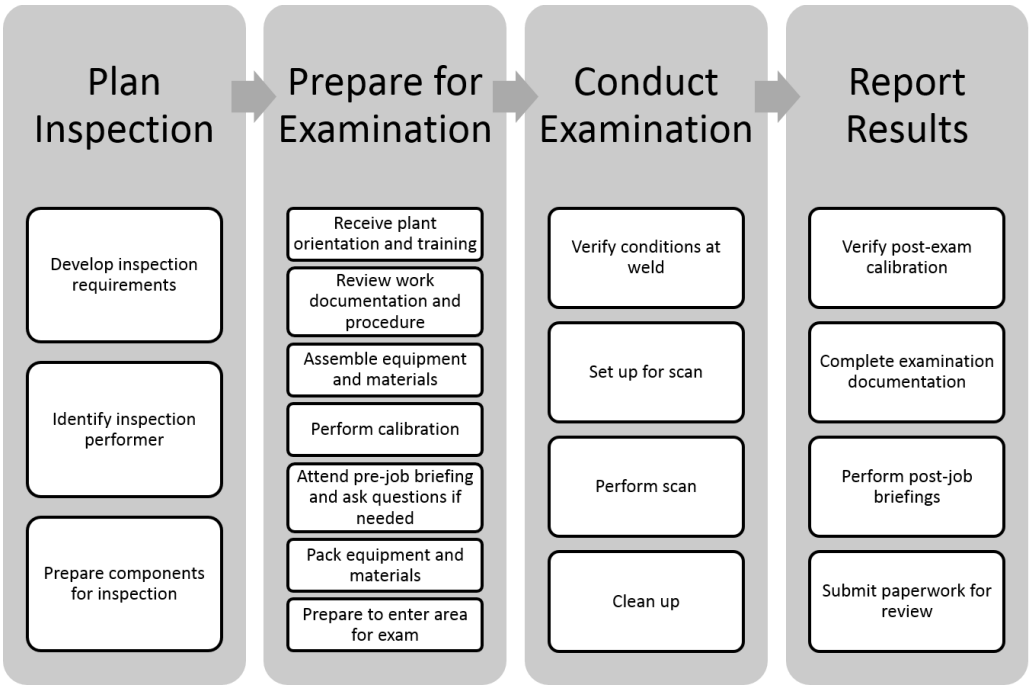

Figure 3. Manual ultrasonic testing functions and tasks.

This list of functions and tasks was used as the basis for developing an interview protocol to collect in-depth information from personnel who perform manual and phased array UT at nuclear power plants. To date, we have interviewed a total of 32 personnel qualified to perform UT from nuclear power utilities and vendor organizations. We conducted ten individual in-person interviews, and two group interviews with 12 Level 2 qualified UT personnel and ten Level 3 qualified UT personnel, respectively. Additional data collection is ongoing.

2.2.2 Observations from the Field

In addition to discussions and interviews with subject matter experts, we have conducted multiple observations of manual UT in nuclear power plants. These observations have provided valuable insight about the context in which manual UT is performed. One initial observation about NDE in nuclear power plants is that working conditions can vary widely. Inspectors may perform UT scans on pipe welds prior to the pipe's installation in the plant (pre-service exam) in a relatively mundane environment, such as a weld shop. On the other end of the spectrum, inspectors may need to ascend multiple ladders in high heat, high radiation environments, wearing multiple layers of protective clothing and equipment, encounter space restrictions, and contort themselves into awkward postures when performing scans on components.

When asked about the tasks that are most difficult to perform, multiple inspectors noted that performing the scan is often the most straightforward task, but coordinating with other personnel to prepare for the exam and actually getting to the correct component can be onerous. We observed numerous examples of the significant coordination required among NDE personnel, scaffold builders to access the component, maintenance personnel to prepare the surface of the weld, radiation protection personnel to allow access to the area, and plant outage coordinators to ensure the inspection can be performed. Once NDE inspectors access the area where the component is located, it can also be difficult to positively identify the correct weld. Nearby tags are often difficult to find or nonexistent, and isometric drawings may show the plant as-designed, rather than as-built.

We also observed different varieties of time pressure faced by NDE inspectors. The NDE inspection team may face time pressure due to the overall plant outage schedule. The coordination needed to prepare and access the components may lead to short windows of time when the scan can be performed. There is also time pressure related to NDE personnel's shift schedules. Although a UT scan may only take 45 minutes to complete in the field, the preparation for that exam may take multiple hours. Given the amount of time invested in preparing for an exam, an NDE inspector is particularly motivated to complete the exam during their shift. If the exam cannot be completed during the shift, then the exam may need to be performed on a different day or by a different inspector on the next shift, and all the preparation tasks (e.g., reviewing work documentation, procedures, calibration, pre-job brief, etc.) must be repeated. There is also task-specific time pressure, often due to radiation exposure limits in the area where the exam is being performed. Inspectors may feel pressure to move quickly to complete an exam because they are only allowed a certain amount of time in the high radiation area before they exceed radiation dose limits, or because they are nearing their yearly radiation dose limits, which may then impact their ability to work in nuclear power plants for the rest of the year.

We are continuing to collect data through interviews and observations for the job-task analysis and anticipate completing phase 2 of the research by the end of 2017.

2.3 Research Phase 3: Prioritization

The final phase of our research will consist of taking our findings and insights from the first two phases and developing a prioritized list of the most critical human factors that can affect UT inspector performance. The prioritization will be based on criteria developed collaboratively with key stakeholders. The list will serve as input to future research efforts.

3. Summary

The primary objective of our work is to identify the human factors that can challenge NDE reliability. Specifically, our work is focused on factors associated with manual conventional

and manual phased array ultrasonic testing (UT). The literature review completed in phase 1 of this research reflects the first step in achieving that objective. The ongoing job-task analysis in phase 2 will provide more in-depth information about the tasks NDE inspectors perform, how human factors can influence those tasks, and differences between how tasks are performed in a laboratory environment versus a field environment. The prioritization in phase 3 will aid in identifying the most critical human factors that can affect performance of NDE. Altogether, the information gathered from this project will serve as input to the development of a long-term strategy and plan for addressing human performance in NDE.