Review of Human Factors Research in Nondestructive Examination

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Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
BAM	Bundesanstalt für Materialforschung und -prüfung (German Federal Institute for Materials Research and Testing)
CFR	Code of Federal Regulations
COD	Crack Opening Displacement
CVI	Close Visual Inspection
DPI	Dye Penetrant Inspection
DSM	Dissimilar Metal Welds
EPRI	Electric Power Research Institute
FMEA	Failure Modes Effects Analysis
HF	Human Factors
IGSCC	Intergranular Stress Corrosion Cracking
ISI	In-Service Inspection
LPT	Liquid Penetrant Testing
MPI	Magnetic Particle Inspection
NDE	Nondestructive Examination (also referred to as NDT or NDI)
NDI	Nondestructive Inspection (also NDE)
NDT	Nondestructive Testing (also NDE)
NRC	Nuclear Regulatory Commission
OE	Operating Experience
PANI	Programme for the Assessment of NDE in Industry
PDI	Performance Demonstration Institute
PISC	Programme for the Inspection of Steel Components
POD	Probability of Detection
RES	Office of Nuclear Regulatory Research
ROC	Relative Operating Characteristic
SATO	Speed/Accuracy Trade-Off
SKI	Swedish Nuclear Power Inspectorate
TOMES	Task, Operator, Machine, Environment, and Social model
UK	United Kingdom
US	United States
UT	Ultrasonic Testing
VT	Visual Testing

1. Introduction

1.1. Background

The U.S. Nuclear Regulatory Commission (NRC) and the nuclear industry have been working for decades to optimize 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. To date, in order to have reasonable confidence in the reliability of nondestructive examination (NDE), the industry and the NRC have focused on performance demonstrations and rigorous qualification processes 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 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. In each case, the equipment and procedures, while not always optimal, were physically capable of obtaining discernable signals from the flaws. A variety of human factors challenges present in these inspections set the stage for the failures. Further, an inherent weakness of performance demonstration tests is that the testing is not conducted under field-like conditions; rather, it is conducted under somewhat ideal conditions in a laboratory-like environment. Thus, robust techniques and qualifications are necessary, but may not be sufficient, to accomplish reliable NDE in the field.

Research is currently being conducted by the NRC Office of Regulatory Research (RES) to identify human factors issues associated with NDE. Specifically, the research is focused on manual conventional and manual phased array ultrasonic testing (UT). This report documents the first stage of the research program by providing an up-to-date review of the state of human factors research in NDE. This review will assist the NRC in assessing and identifying human factors issues in NDE and in planning future research.

1.2. Overview of NDE

Nondestructive examination is a means of testing a specimen or component without damaging or destroying it. NDE plays a vital role in ensuring the safety of nuclear power plant operations. It is used to obtain information about 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). Some of the NDE methods used during in-service inspection (ISI) of nuclear power plant components include ultrasonic, eddy current, radiographic, liquid penetrant, magnetic particle, and visual testing (J. C. Spanner, Badalamente, Rankin, & Triggs, 1986).

NDE is considered a special process regulated by the NRC under the Code of Federal Regulations 10 CFR 50 Appendix B, which requires that:

> “Measures shall be established to assure that special processes, including welding, heat treating, and nondestructive testing, are controlled and accomplished by qualified personnel using qualified procedures in accordance with applicable codes, standards, specifications, criteria, and other special requirements.”

The application of effective 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. These human factors issues must be considered in order to have reasonable assurance that the licensee is meeting the “special requirements” referred to in Appendix B.

1.3. Human Factors Considerations in NDE Research

Although human factors issues were identified early on in NDE reliability research, most research programs did not give much attention to including human factors investigations in their research designs (Singh, 2000). For instance, Herr and Marsh (1978) recount three NDE studies using different methods (magnetic particle, ultrasonic, and liquid penetrant) that demonstrated considerable differences between qualified inspectors in their abilities to find defects. A U.S. Air Force sponsored study of NDE reliability in the 1970’s, “Have Cracks Will Travel,” noted variance in results among individual inspectors that could not be explained by skill level, education, training, or age (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.

As part of a discussion of human factors during the 5th European-American Workshop on Reliability of NDE, NDE reliability researchers expressed significant interest in the topic of human factors (Bertovic et al., 2014). Researchers identified the need to raise awareness of human factors considerations to ensure that utilities are aware of how human factors can affect inspection reliability and communicate the importance of considering human factors to NDE vendors.

1.4. Human Factors Elements

Multiple theoretical models have been used to describe the various human factors that can influence NDE performance. For example, Singh (2000) classified human factors relevant to NDE as falling within three categories: physical environment, organizational climate, and mental state. Drury (2001) used the TOMES model to describe human factors issues in inspection. TOMES stands for Task, Operator, Machine, Environment, and Social. Müller, Bertovic, et al. (2014) discuss the reliability of NDE in terms of the Modular Reliability Model, which was conceptualized during a series of European-American workshops on NDE reliability from 1997 through 2014. The Modular Reliability Model frames the reliability of an NDE system in terms of its intrinsic capability, application factors, and human factors. Revisions to the model during subsequent workshops included the addition of organizational context as an overarching influence on all three parts of the model (Müller, Bertovic, Gaal, et al., 2013).

We developed a human factors categorization scheme for this review based on Neville Moray’s sociotechnical systems model (2000). The sociotechnical systems approach has been used extensively in human factors research, and endorsed by multiple researchers included in this review (Bertovic, 2015; Enkvist et al., 1999; Müller, Bertovic, Gaal, et al., 2013; Norros, 1998). 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 into five elements of human factors considerations in NDE: task characteristics, individual differences, team or group characteristics, the physical environment, and organizational factors.

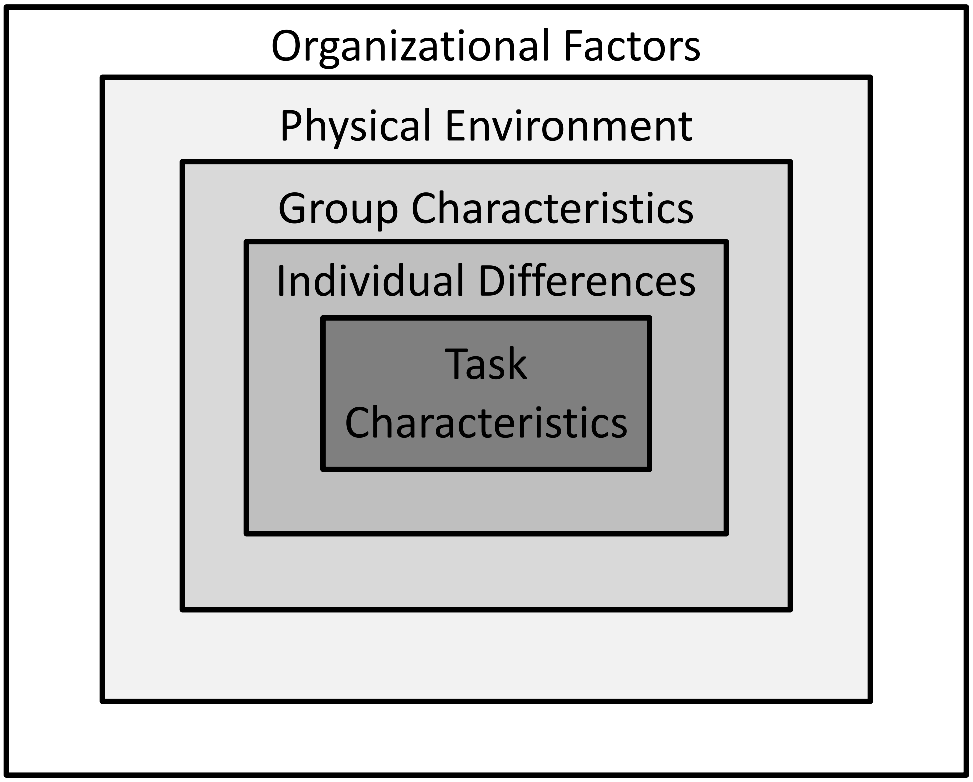

Figure 1. Sociotechnical systems model for categorizing human factors considerations in NDE

1.5. Literature Review Process

We began our review by performing a search for references related to human factors and NDE. We used multiple keywords (e.g., human factors, human reliability, human performance, ergonomics, training, nondestructive testing, nondestructive evaluation, ultrasonic testing, nondestructive inspections) and searched multiple databases for relevant references (e.g., PsycINFO, Google Scholar, EPRI reports, Science.gov, International Nuclear Information System, National Transportation Information System, Human Factors and Ergonomics Society database, Science Direct, BAM, NDE.net). After developing an initial list of relevant articles, we also reviewed the reference sections of those articles to identify additional references that did not turn up in the initial database search. Our comprehensive search resulted in a total of 200 potential references. We reviewed the contents of all 200 references and determined that 91 contained potentially relevant information for the human factors and NDE literature review. We then categorized each reference based on the industry addressed, type of paper, and applicability to various human factors elements of interest.

Overall, 50 of the 91 relevant references were specific to the nuclear industry, 14 references were related to aviation or aerospace, and 1 reference came from the offshore oil industry. Twenty six of the references were not specific to a single industry and were labeled “generic” for the purposes of this review.

Forty of the references reviewed were empirical papers—they involved research studies where quantitative data was collected and analyzed to test hypotheses. Another 7 references were categorized as theoretical papers—they presented hypotheses but did not include a specific test of those hypotheses. A large portion of the references (39 references) were informational papers—they included discussion of human factors elements, but did not explicitly include a theoretical framework or empirical testing. Informational papers included book chapters, reviews of other research, and other generic discussions of human factors in the context of NDE. Five references were classified as experiential—they generally included opinions or recommendations related to human factors issues in NDE based on industry experience.

Many of the identified references discussed various human factors elements spanning multiple elements of the sociotechnical systems model. Task characteristics were discussed in 62 references, such as scanning speed, type of equipment, procedure quality, and use of automation. Individual difference factors, such as motivation, years of experience, skill, and fatigue, were discussed in 63 references. Ten references discussed group interactions when NDE technicians work in teams. Thirty six references considered interactions between the NDE technician and physical environment characteristics (e.g., heat, noise, radiation). Organizational factors that may influence NDE performance were discussed in 53 references. For example, organizational culture, management oversight, and work processes.

The following chapters of this report present a compilation of the current state of knowledge about human factors influences on NDE reliability. The chapters are organized based on the sociotechnical systems model presented in Section 1.4: task characteristics, individual differences, group characteristics, physical environment, and organizational factors. Appendix A: Annotated Bibliography contains an annotated bibliography with additional information about the references identified through this review.

2. Task Factors

For our purposes, task factors relate to the tools (e.g., equipment) and process (i.e., task execution) that inspectors use to conduct an NDE inspection. Our review identified empirical studies along with experiential, informational, and theoretical papers that discussed task factors as influencing the performance of NDE. There was a significant amount of overlap in the factors identified. We sorted the task factors into the following categories: pre-job preparation, inspector resources (e.g., equipment, procedures), and process factors. In addition, we also captured recommendations for mitigating the effect of task factors on NDE performance.

2.1. Pre-job Preparation

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. The Electric Power Research Institute (EPRI, 2009) makes a strong argument for the importance of pre-job preparation. They focused specifically on ultrasonic testing (UT) dissimilar metal weld (DMW) inspections, but the overall message can be generalized across the NDE domain. They state:

> The importance of planning for DMW examinations cannot be overstated. The examination requirements are highly complex and require several technical evaluations before an examination can be implemented. These preparation tasks and associated evaluations require various levels of expertise and information. The utility and vendor need to work together to develop a plan, refine and communicate the details of the plan to their organizations, and implement the DMW examinations.

The United Kingdom Health and Safety Executive conducted a research effort known as the Programme for the Assessment of NDE in Industry (PANI). The objective of the third study in this effort, PANI III, was to identify solutions to enhance performance and minimize inspector variation in manual UT. As part of this effort, a workshop was conducted where inspectors reported their belief that both information and preparation are key to a good inspection. NDE companies reported that lack of pre-job information provided by the client was a major risk to achieving a good inspection (McGrath, 2008). Lack of information can result in issues such as wrong personnel and/or equipment being sent to the inspection site. Results from the inspector workshop stressed the importance of having necessary information and documents before the inspection, which resulted in a recommendation to provide a work package that includes applicable procedures, risk assessments, standards, acceptance criteria, access and cleaning requirements, drawings and photos, and equipment inventory. An EPRI (1988) report also noted the importance of having necessary information during the pre-inspection phase. Specifically, it noted that eddy-current NDE requires the inspector to integrate pre-job information such as the history and characteristics of the component to provide context for signal recognition and interpretation during the inspection.

In addition to lack of pre-inspection information, NDE companies cited poor on-site preparation such as surface finish and component access as risks to quality inspections (McGrath, 2008). Regarding surface finish, a study was conducted by Cumblidge (2007) that looked at the interplay of lighting, surface condition and crack opening displacement (COD) in visual NDE. EPRI guidelines specify that surfaces must be clean, however, visual tests performed are often performed on "as-welded" surfaces. The surface conditions evaluated were as-received, polished, and with scratches perpendicular and parallel to the cracks. Cumblidge (2007) suggested that removing the loose layer of deposits from the surface may be beneficial for crack detection, however, removing the adherent layer may expose a very reflective surface which may make visual testing (VT) difficult under certain conditions (e.g. when using a spotlight). Overall, the study found that surface finish is not the primary factor driving whether a crack is detected, however, it is still an important variable that must be considered. For example, the authors concluded that current cameras being used in the field can be expected to reliably detect cracks of at least .004 inches provided surface conditions are not too unfavorable, lighting is adequate, and scan speeds are appropriately slow. In addition, the use of diffuse lighting can help to decrease the impact of degraded surface finish (scratches, machining mark). Thus, surface finish must be evaluated and prepared whether by altering the surface itself, providing appropriate lighting or adjusting scan speeds.

Multiple reports have identified work space preparation, such as restricted/unstable work space and poor access to components, as a factor that may affect inspection quality (Drury, 2001; Drury, Prabhu, & Gramopadhye, 1990; Health and Safety Executive, 2000; McGrath, 2008). McGrath (2008) noted that unstable platforms or restricted space can make scanning precisely and consistently difficult and can also cause discomfort possibly resulting in loss of concentration. Based on the PANI III results, the Health and Safety Executive (2000) recommended ensuring inspectors have stable platforms on which to work and sufficient access to the component. Ensuring access may include efforts such as providing ladders, removing insulation, or ensuring no other on-going work is blocking access to the component. The problem of limited access is not unique to the nuclear domain. Drury et al. (1990) conducted a task analysis on both the NDE and visual inspection of aircraft. They broke the task into 5 discrete steps: Initiate, Access, Search, Decision, Action. For each step in the process, the authors' proposed strategies for improvement by either changing the system or changing the inspector. The authors recommended changes to the system including better support stands and location for NDI equipment along with a better area location system. According to Drury (2001), access issues can be mitigated using strategies such as customized access stands and easily maneuverable hangers for components. These mitigation efforts can all be done prior to initiation of the inspection.

The nuclear NDE industry has taken note of these pre-job preparation issues and published a report in 2009 to provide guidance to nuclear power plant owners and NDE vendors/personnel for planning and conducting NDE on dissimilar metal welds (EPRI, 2009). The authors recommended pre-outage preparation activities that include:

- Utility shall prepare a detailed bid that specifies the exam scope and the necessary qualifications, training, and experience of personnel.
- Utility should prepare, maintain and execute a surface condition assessment and improvement process for DMWs.
- Utility should ensure that vendor personnel have received procedure training that addresses the examination scope, the specific NDE procedures, equipment, and software that are to be used.
- Utility personnel should have a thorough understanding of the examination procedures, both for preparation for the DMW examinations and for oversight during the examination process.
- Utility should ensure that vendors have available all of the proper, qualified equipment for the examination scope.
- During the pre-job briefing, utility should discuss the verification of surface condition and encourage prompt reporting of any examination limitations or concerns held by the examiner

after the examination. The utility should work with the vendor to address the concerns in a timely manner and support the vendor fully when the vendor requires rescans of a component.

- Vendor should prepare ultrasonic examination procedures using the Performance Demonstration Institute (PDI) generic procedures as a template. Ensure that the procedures are clear, concise, and specific. Train personnel on procedure compliance, and ensure that the procedures are readily at hand during preparation for and execution of the examinations.
- Vendor should ensure that the content of annual ASME Section XI, Appendix VII training addresses potential error points as indicated by industry operating experience (OE).
- Vendor should perform a detailed readiness review in advance of the outage. Utility involvement in this review is highly recommended.
- Consider industry OE in evaluating examination data. Detailed guidance is available for evaluation of encoded data. The prompt determination of the acceptable quality of the data and ordering rescans, as needed, is of particular importance.
- The utility and the vendor should begin to collaborate as early as possible.
- The utility and vendor should maintain a clear mutual understanding of the work scope and of potential scope expansions. Ensure that all qualified equipment, procedures, and personnel necessary to complete the work scope will be available onsite.

2.2. Inspector Resources

Inspector resources include the tools or materials available to the inspector to do their job. These resources include equipment (primary and supplemental) and procedures. Their availability and quality can impact NDE performance greatly.

Historically, oversight of equipment and procedures for NDE has been limited, thus, the quality of the resources could vary widely. Until 1989, ultrasonic equipment was required to meet the ASME requirements for vertical display response, attenuator linearity and instrument calibration capability, but other critical performance characteristics were not addressed. Regarding procedures, it was thought that reliable UT could be ensured through detailed rules. The ultrasonic “examination rules” were prescriptive and had not been evaluated via actual inspections (e.g. examination angles). After a series of missed flaws in the field and results from various research studies, Appendices VII and VIII to ASME Code Section XI were developed for personnel, equipment and procedure qualification. The code requires that combinations of personnel, procedures, and equipment (NDE systems) show objective evidence of acceptable performance through performance demonstration tests (Doctor, Cumblidge, Taylor, & Anderson, 2013). Although performance demonstration has had a clear positive impact on UT reliability (Doctor, 2008), there is still room for improvement. In addition, other NDE techniques do not have ASME performance demonstration requirements. Most techniques require a minimum amount of experience. In some cases, such as eddy-current inspections of steam generators, there are far stricter performance demonstration requirements imposed by the licensees, however, these requirements are not standardized across the industry.

2.2.1. Equipment

Each type of NDE technique (e.g., UT, eddy-current, liquid penetrant testing (LPT)) requires special equipment. For example, a typical UT inspection system consists of several pieces of equipment, such as the pulser/receiver, transducer, and display devices (i.e., scope). The availability, capability, and design of the equipment all have the potential to impact the NDE inspection.

In the NDE community, issues with equipment design have been widely acknowledged (Christner, Long, & Rummel, 1988; Cumblidge, 2007; EPRI, 1988; Enkvist et al., 1999; Herr & Marsh, 1978; Lewis, Sproat, Dodd, & Hamilton, 1978; Wheeler, Rankin, Spanner, Badalamente, & Taylor, 1986). As early as 1978, Herr and Marsh recognized that often there is no standardization of equipment between or even within a manufacturer. One research effort sought to have human factors (HF) specialists evaluate the conformance of UT equipment to HF design principles (Wheeler et al., 1986). The evaluation found that none of the UT equipment conformed 100% to HF design principles. The following design issues were identified: controls are too small and too closely spaced for manipulation with gloved hands; controls are not guarded against accidental actuation; control scales are small and difficult to read; some screen designs fail to minimize reflected glare; screen brightness, contrast, and focus are fixed and cannot be adjusted in the in-service inspection (ISI) environment; and screen size is too small to allow good signal/noise discrimination. In addition, critical incident interviews with inspectors revealed that most inspectors have used a variety of equipment but have a preference for brand and model. Specifically, they preferred equipment with a calibrated time base and, most important, a clear sharp display. Thus, the quality of NDE equipment design is often lacking and design is important to the inspectors who have to use it.

Our review identified only a few efforts that empirically tested NDE equipment design. One such effort by Cumblidge (2007) empirically tested how lighting techniques, camera resolution, scanning speed, camera movement, magnification, and crack size influence the effectiveness of remote visual NDE. The results indicated that the inspection equipment played an important role in that camera resolution and pixel count impacted inspection quality. The results suggested that stationary or very slow moving cameras help in detecting small cracks and a greater pixel count allows for a higher contrast between the crack and the metal surface. Also, having pan/tilt/zoom capabilities resulted in inspectors having less false calls and more confidence in their calls than with a fixed focal length camera.

Another empirical effort was funded by the Air Force Logistics Command program with the objective of determining the existing capability of NDE inspectors under various conditions (Lewis et al., 1978). Approximately 300 Air Force technicians performed ultrasonic, eddy current, liquid penetrant and radiographic nondestructive inspections on aircraft structural samples. Four major test variables were included: 1) field or depot location; 2) NDE method; 3) proficiency of inspectors; and 4) type of structure with accompanying flaw sizes. In addition, other factors were recorded: 5) NDI equipment condition; 6) environment; and 7) position of structure. Overall, it was found that there were wide variations in performance across inspectors and no significant differences were observed between different manufacturer's equipment. However, the authors posed the question, "why is a flaw missed if the process is capable of detection?" They hypothesized that one explanation may be that the inspector is not appropriately alerted when a flaw is present, thus implying the presence of equipment design deficiencies. They suggest that any "improved" equipment should demonstrate its flaw detection reliability under realistic conditions.

Although empirical studies examining the impact of equipment design on performance are sparse, qualitative assessments, operational experience data and feedback from subject matter experts (e.g. inspectors) is extensively reported in the literature (Christner et al., 1988; EPRI, 1988; Enkvist et al., 1999). These equipment design issues span various work domains and NDE methods. Christner et al. (1988) discussed critical flaws that have been found in space shuttles and other space hardware and the impact of sub-par equipment. They surveyed the various NDE practices and capabilities in this domain. For LPT, testing results showed equipment issues encountered during the program included quality and type of developer used, defective and missing wash nozzles, low intensity black lights, inadequate ventilation for developer application, and inability to adequately darken the inspection area. The authors noted that if the equipment does not provide adequate flaw discrimination, the inspection quality becomes dependent on the inspector's ability to compensate for the equipment.

EPRI (1988) conducted a study with the objective of identifying research projects likely to have payoff by improving human performance on critical tasks in NDE, specifically eddy-current and UT, and apply existing HF knowledge to improve NDE performance. The investigation consisted of qualitative analysis of industry procedures, training materials, research reports, interviews with experts, and observations of task performance. Regarding equipment, a variety of design problems were identified, including: equipment set-up and operation are too cumbersome; the system requires excessive manipulation to complete the job; control actions are not logically organized; and operations rely too heavily on human short-term memory The authors also noted that NDE interfaces are furthered complicated by the fact that signal displays do not directly relate to the physical characteristics of what is being studied, therefore, the signals must be mentally transformed. Enkvist et al. (1999) noted that difficult to use equipment affects performance and that it is probable that non-ergonomically designed equipment may lead to mental and physical fatigue.

Many in the NDE community have called for equipment design guidance and/or standardization of equipment (EPRI, 1988; Herr & Marsh, 1978; J. C. Spanner et al., 1986; Wheeler et al., 1986). J. C. Spanner et al. (1986) noted the lack of standardization may be a greater concern in the nuclear field because inspectors tend to move from employer to employer and plant to plant, and in each case they may be using different equipment. Thus, the authors recommended that human engineering guidelines for UT equipment design should be developed and distributed to UT equipment manufacturers. Work by Pond, Donohoo, and Harris (1998) provided an overview and critical analysis of part three of the Programme for the Inspection of Steel Components (PISC III) study. With regard to equipment, they noted that there has been a lack of design consideration in the NDE field and offered five HF principles they feel are most important to equipment design:

- Design to accommodate capabilities/limitation/expectations of anticipated users
- Design HDI to be easily, accurately, and effectively used and to minimize misuse
- Assure adequacy of the design through the full equipment life-cycle
- Interfaces should be intuitive to minimize the need for special capabilities/training/job aids to overcome inadequate design
- Minimize the likelihood and consequences of system-induced human error

Wheeler et al. (1986) recommended developing guidelines for interface design on inspector equipment in the form of a handbook tailored to the design of computer-based inspection systems. In addition, they called for development and experimental testing of new displays that better integrate multiple pieces of data.

In addition to design-related issues, some research suggests that availability of proper functional equipment (both primary and supplemental) is a problem encountered, at times, by inspectors that impacts the quality of NDE. Christner et al. (1988) observed that, for eddy-current inspections, inspection aids (i.e. supplemental equipment) were not always available to inspectors. They recommended that hole templates, plastic rulers, and teflon tape should be available to aid inspectors in achieving a quality inspection. Murgatroyd and Crutzen (1994) suggested that, if inspectors had proper plotting equipment during the PISC III study, error rates would have been five percent lower as five percent of the flaws reported incorrectly were due to plotting errors. The value of the availability of supplemental equipment was also demonstrated in an empirical study conducted by EPRI (1993). The purpose of the study was to develop and evaluate a strategy-based training course for detecting intergranular stress corrosion cracking (IGSCC) in pipe welds. The strategy was reinforced in various ways, including use of a decision aid. The decision aid was developed, based on expert recommendations, in the form of a checklist to help inspectors overcome limitations in information-processing and decision making skills required for NDE. Specifically, the checklist allowed inspectors to note signal characteristics during UT inspections and provided a means for presenting all signal characteristics simultaneously for decision making after inspection completion. In addition, a matrix was provided for noting possible locations of indications from each UT technique. Participants were allowed to choose whether they used the aids or not; approximately 15% of participants used the full set of decision aids. The percentage of successful exams was about 24% higher when aids were used versus not used. The authors recommend providing aids during practice to increase the likelihood that inspectors will want to use them in other settings (e.g., PDI final exam, ISI, etc.).

Equipment also must be in working order, which may include being charged, having batteries, and/or being properly maintained. Inspectors have voiced concerns regarding equipment batteries being properly maintained (Webster, 1989). Krishnamoorthy, Eng, and Energy (2009) note that part of ensuring the quality of NDE is ensuring regular oversight of NDE equipment maintenance and quality assurance checks.

As mentioned previously, the empirical investigation of NDE equipment is sparse. Pond et al. (1998) noted that we know little about the combined effects of the variables impacting performance. Depending on the combination, the effect may be additive, synergistic or antagonistic. More research is needed is this area.

2.2.2. Procedures

Procedures are another inspector resource typically available in the field. As with equipment, the importance of quality procedures has been recognized for decades. Herr and Marsh (1978) suggested that to reduce large performance variations between inspectors, the effects of human factors on performance must be reduced. They suggested identifying parts that are truly critical or fracture sensitive and then mandating that there must be clear, specific, detailed procedures for each of the critical parts that are proofed by inspectors. This suggestion was partially implemented through ASME codes and risk-informed ISI (RI-ISI) programs that require UT systems be qualified via blind performance demonstration establishing objective evidence of the system’s capabilities. However, large performance variations still exist in the NDE domain and research indicates that procedural issues continue to be a contributor to the variation.

One issue identified in the literature is procedure usage and the resulting impact on performance (Enkvist et al., 1999; Gasset, 2012; McGrath, 2008). In the PANI III effort (McGrath, 2008), it was determined through post-trial review of video that inspectors read the procedure initially but did not fully follow it. It was noted that not all procedure-specified probes were used and were not used in the order specified. The best performing inspectors performed the inspection in a methodical way but would often improvise with their version of the “correct scans” in order to complete the task. The low performers seemed unsure about the procedure and spent considerable time reading and referring to the procedure. Thus, the way in which inspectors use or don’t use procedures is likely impacting performance. However, the authors eluded to the idea that their usage may be a result of procedure design. They reviewed the procedure and identified issues such as it being too long and wordy and not specifying task steps and their order.

Based on their review of the literature, Enkvist et al. (1999) also suggested that procedure usage may be suspect, such that inspectors may be basing their assessments on only a portion of information available and that this is likely what underlies poor inspection performance. They too suggest that this must be mitigated through procedure design. Specifically, the development of accurate and easy-to-follow procedures to optimize and standardize the diagnostic portion of the task. Based on field experience, Gasset (2012) suggested that complacency and peer pressure can be lessened by following written procedures and not relying on memory or group habits. Well-designed procedures may reduce the use of "improvised" procedures that rely on personal experience, memory or preference, thus standardizing the task and reducing performance variation between inspectors.

The importance of procedure design is echoed by many in the NDE domain (Drury, 2001; Drury & Watson, 2002; EPRI, 1988; Health and Safety Executive, 2000; Krishnamoorthy et al., 2009; McGrath & Wheeler, 2009) Drury (2001) described the major functions of the human NDE inspector and then derived a set of factors known to affect inspection quality and reliability, one of which was design of documentation. There have been multiple efforts to identify good practices in design documentation. McGrath and Wheeler (2009) re-analyzed the results of the PANI studies in terms of the role of the written procedure. They concluded that: 1) The inspection procedure is key to a reliable inspection; 2) The inspection procedures should be written to promote systematic application; 3) The procedure needs to be designed to assist the inspector in applying the inspection in the desired way; and 4) Inspectors should be briefed on procedures to ensure terminology is understood and any special conditions are highlighted. They also gave specific recommendations regarding how to produce a good procedure:

- The intention for the procedure should be clearly defined to ensure it meets the needs of the inspector
- The front sheet should clearly designate who the procedure is intended for
- The requirements for performing the inspection should be clearly defined (e.g., the specific steps, the order of the steps)
- The desired use of the procedure should be clear (e.g., using it at the site, etc.)

Drury and Watson (2002) conducted a hierarchical task analysis of visual NDE to identify areas where task demands were ill-matched to the capabilities of human inspectors and, again, document design was targeted as an area for improvement. Several tenets were offered regarding good documents: 1) good documents are both accurate and usable; 2) validation is critical to ensure procedures can be performed as written; 3) human factors guidelines should be used when designing procedures; and 4) standard syntax should be used. The authors hypothesized that documents designed according to proven guidelines will help reduce errors and increase usability. Krishnamoorthy et al. (2009) state that procedures help inspectors and management to ensure that an inspection process is applied consistently, increasing the probability of a quality inspection. They note that procedures should: 1) provide clear instructions for conducting the inspection; 2) provide clear acceptance criteria; 3) only approved procedures should be used by inspectors; and 4) all procedures should be reviewed and approved by authorized and qualified personnel. In sum, procedures should be clear, accurate, follow HF guidelines, use standard syntax, have clear acceptance criteria and should be validated and approved by qualified individuals.

In addition to good design practices, several other considerations were noted in the literature. A report by the Health and Safety Executive (2000) noted that inspection procedures should be designed to optimize the inspection for the defect types of concern. The defect considerations should include geometry, material being examined, thickness, orientation, position, roughness, branching, length and through-wall size, and presence of a surface finish on the component. Also, it is important to ensure the procedures are updated when necessary (Wheeler et al., 1986).

Bertovic (2014) conducted multiple empirical studies focused on procedure improvement for mechanized NDE through user-centered design and application of human factors principles. In the first study, the aim was to evaluate the quality of the current version of a NDE instruction (version 4.0). This was done using eye tracking and think aloud processes. The results were analyzed and changes were made to the procedure including: 1) improving layout and navigation; 2) clear language; 3) stepwise presentation of required actions; 4) highlighting important information (e.g. warnings); and 5) increased consistency in writing style. Study 2 was conducted to determine whether the new instruction (version 5.5) was an improvement over the previous version and to further develop and improve the procedure. The participants rated their satisfaction higher with the improved procedures. Additional improvements also resulted from Study 2 (e.g. improved formatting). The third and fourth studies tested the final version of the procedure (version 6.0) generated based on the results of Study 2. The goal was to determine whether the changes led to better: 1) usability; and 2) understanding of the procedure. Regarding understanding, participants were asked to read either the old version or the new version of the instructions and answer several questions. The results showed no significant performance difference between the two versions of the instruction, however, user satisfaction increased with the new version. Regarding usability, participants were asked a question and then directed to a page where the task was to click on the correct answer as fast as possible. Highlighting and stepwise presentation of tasks and actions (one action per step) supported a more efficient use of the instruction (i.e., shorter time before the information was found). The authors concluded that, in general, NDE procedures can be improved through user-centered design and application of human factors principles.

2.3. Process

Process refers to the actions taken to accomplish a task or, in this case, the way in which inspectors execute an inspection. According to the task analysis conducted by Drury et al. (1990), NDE consists of 5 steps: Initiate, Access, Search, Decision, Action. The information attended to and processed, the scanning technique and speed, the posture one is in and how one interprets signals are all process elements that can impact performance.

Harris (1990) conducted a study examining human information processing techniques employed during manual ultrasonic inspections. Twenty six participants from various domains, including nuclear, were asked to examine sample pipe welds. Tape-recorded commentary from 139 pipe-weld inspections were qualitatively analyzed to identify types of information processing techniques used by inspectors. The authors wanted to answer the question, “What factors are present in a successful inspection that are not present in an unsuccessful inspection?” Nine information processing techniques were identified. The nine techniques were analyzed to determine their relationship to inspection performance. Seven of the nine information techniques were correlated with successful inspections, including having an explicit hypothesis, testing an explicit hypothesis, avoiding reaching early conclusions, using if-then logic, avoiding disregard of evidence, explicit signal discrimination and identification of geometry. The four factors determined to be the strongest predictors of inspection performance were testing an explicit hypothesis, avoid reaching early conclusions, using if-then logic, and avoiding disregard of evidence.

A more comprehensive discussion of attention, information processing, along with other pertinent cognitive factors can be found in Section 3.2.

In addition to information processing techniques, the Harris (1990) study also looked at the information available to process. Seven signal characteristics, including continuity, rise time, peaks or facets, dynamics, reference check, location and amplitude, were analyzed to determine their relationship to performance. None of the seven characteristics was significantly correlated with inspection performance, however, the total number of signal characteristics addressed in the inspection was positively correlated with performance. The authors concluded that the more signal characteristics an inspector addresses using a well-defined information processing strategy, the more likely the inspector will achieve a successful inspection.

A study by Norros and Kettunen (1998) also examined what information and strategies inspectors use to process the information. Ultimately, they wanted to understand the factors that inspectors believe affect inspection reliability and their conceptions about the decision making demands of their work. The authors hypothesized that different conceptions would result in different "habits of action" or the way the inspector takes into account the possibilities and constraints of the task situation and how the inspector uses the available resources. Through conducting interviews with inspectors, the authors identified two different habits of action: 1) interpretative habit of action (focus on personal expertise, and emphasis on the perception-action cycle with diagnostic-interpretative aims); and 2) procedural habit of action (focus on standardized performance and emphasis on carrying out the prescribed task). The inspector group was comprised of those qualified to perform NDE defect detection only and inspectors who were qualified to perform both defect detection and characterization. Those inspectors who carried out both defect detection and characterization emphasized the diagnostic-interpretive skills necessary in both tasks. Only two inspectors out of nine in the defect-detection only group, emphasized the diagnostic-interpretative nature of the detection task. The authors concluded that NDE contains diagnostic/interpretive task demands and, thus, awareness of their existence and significance is assumed to affect the adequacy of the inspection.

Light, Holt, Polk, and Clayton (1994) conducted a study to determine whether altering the way in which inspectors receive information may help in information processing and enhance the quality of NDE. Specifically, they converted an ultrasonic signal to an aural signal such that the inspector would have both visual and auditory input. The results showed that an aural signal improved detection of hidden corrosion on aircraft, delamination/cracking in composite material used in the aerospace industry and IGSCC in stainless steel piping.

In addition to the cognitive aspects of NDE (e.g., information processing, signal interpretation) there is also the physical process to consider (e.g., scanning pattern, probe movement). Within a larger study focused on remote VT, the Cumblidge (2007) study examined the effects of scan speed on the contrast and resolution of the image captured by a camera. They found that slow scanning (6mm/s) caused little distortion in the image while fast scanning (76mm/s) caused great distortion in the image. Specifically, the higher scanning speed reduced the resolution to less than half the acuity of a stationary camera. Drury and Watson (2002) proposed that speed is especially important for "resource limited" tasks or tasks where accuracy goes down when speed goes up (e.g., visual search). However, there is a speed/accuracy trade-off (SATO). The authors proposed that there is a single best point to balance speed and accuracy to meet inspection objectives. At some point, more time spent will not result in greater inspection accuracy. Thus, they recommend finding the most advantageous SATO operating point and keeping that point consistent between inspectors.

Webster (1989) examined manual scanning in UT. Manual scanning requires precise skilled probe movement control. The authors proposed four possible scanning errors: scanning too fast, failure to overlap scans, failure to orient the probe in appropriate direction, failure to maintain adequate probe contact. The author noted that manual scanning can be performed in 2 ways: 1) continuous scanning (traverses forward and backward without stopping); and 2) discontinuous scanning (probe movement progresses one sweep at a time). The author suggested that discontinuous scanning is slower, but the better choice when the probe movement cannot be seen in peripheral vision. Also because the probe is always moving in the same direction in discontinuous scanning, it may reduce the possibility of missing an indication due to complex signal patterns. Continuous scanning can be done with or without visual feedback, however, kinesthetic feedback is critical (cold, protective gloves, etc. can affect this). The choice of scan type should be determined based on the inspector, the component being inspected and situational factors (e.g., component access).

In addition to scan speed, overall “speed” or time-on-task can affect performance. In the Cumblidge (2007) study both outside contractors and in-house staff were asked to perform remote VT. The contractors completed the test in less than 2 hours, while the in-house staff took 4.5 hours. The in-house staff were able to detect all cracks greater than .0008 inches, whereas the contractor staff only found the largest cracks (.004 inches and larger).

Another physical consideration is the posture or stance an inspector takes. This may be dictated by preference or circumstance. Drury and Watson (2002) explained that aviation inspections tasks, similar to nuclear power plants, must be performed wherever the structure dictates, which often necessitates awkward postures. The authors identified three ways posture can affect performance: 1) interference such that the posture required by the structure does not allow for the necessary body movements; 2) drain on resources such that the awkward posture may distract the inspector and degrade performance; and 3) loss of motivation due to discomfort or motivation to complete the task faster to relieve the discomfort, both of which may degrade performance.

2.4. Mitigation Strategies

NDE and, particularly, UT is a highly complex task. EPRI (1988) recommend that the complexity of UT should be reduced. Their suggested approach is to use a task-analysis and HF design principles to redesign the task in collaboration with designers of UT inspection equipment. While this is one possible way to reduce performance variation, there may be other more efficient and less resource-intensive strategies.

One widely touted strategy to improve performance is more frequent and more realistic practice (Health and Safety Executive, 2000; Müller, Holstein, & Bertovic, 2014; Summers, 1984). The Health and Safety Executive (2000) authors theorized that some performance problems (e.g. poor scanning technique, misinterpretation of signals) may result from inspection imposing “technical demands which are beyond those for which the inspector has been trained or qualified.” They suggest having inspectors practice on realistic test pieces prior to the inspection. An evaluation of Air Force nondestructive inspection capability concluded that NDE inspections lacked the precision and reliability necessary to ensure the structural integrity of aircraft (Summers, 1984). During the evaluation, inspector interviews revealed that UT inspections are performed infrequently and, as a result, technicians were not confident using the flaw detection equipment. The most frequent suggestion made by inspectors and their supervisors in a survey for improving NDE capability was more hands-on practice. Another effort by the Air Force was a program to determine the existing capability of detecting flaws under field and depot conditions. Approximately 300 Air Force technicians performed ultrasonic, eddy current, liquid penetrant and radiographic nondestructive inspections on aircraft structural samples. Overall, it was found that there were wide performance variations between inspectors. Whether NDE is a part-time activity or a primary job varied between locations. The authors recommended that NDE activities be centralized, made a full-time occupation, and that a standard certification-recertification program be established by administering practical exams at all bases and depots. Müller, Holstein, et al. (2014) captured insights and conclusions from the 5th European-American Workshop on Reliability of NDE which focused on answering, "What is influencing the performance of NDE and how can we measure and optimize what we want to know with minimum effort?" One group of subject matter experts discussed maintaining inspector vigilance in an environment where finding a flaw is rare. The group made several suggestions regarding this question, including: 1) requalification to refresh inspector knowledge and skills; 2) yearly practice on test components with realistic defects; and 3) engagement with staff in non-outage time (developing procedures, performing open trials).

Bertovic (2015) conducted a series of empirical studies that looked at the efficacy of automation and redundancy as mitigation strategies to reduce performance error. Specifically, the study objectives were to: 1) identify and analyze potential risks in mechanized (i.e., automated) NDE; 2) devise measures against them; 3) critically address the preventive measures (i.e., mitigation strategies) with respect to new potential risks; and 4) suggest ways for the implementation of the preventive measures. Study 1 showed, through use of a failure modes effects analysis (FMEA), that there is a chance for failure in mechanized NDE in data acquisition and evaluation. Technical, organizational and human factors were all identified as potential causes of errors. However, the FMEA also produced potential preventive measures including procedure improvement, human redundancy, and increased use of automation. Study 2 explored the use of human redundancy as an error prevention technique. The objective of this study was to identify problems related to human redundancy when applied to the evaluation of NDE data. The author specifically hypothesized that social loafing would result from having redundant inspectors and that knowledge of partner's skill level would moderate this effect. The hypotheses were not confirmed. However, these social loafing effects have been found elsewhere, and Bertovic notes that the limitations of the study may have affected the results. Thus, human redundancy is a potentially useful error prevention technique, however, the way in which it is implemented should be carefully considered as it may influence the success of the technique. The author suggested several ways to optimize the technique, including: ensuring complete independence between inspectors (not knowing who the other is, or that the redundancy is applied), increasing identifiability of each inspector, and finding ways to motivate inspectors to do a quality inspection. Study 3 explored the use of automation as an error prevention technique. The author hypothesized that trust in software can lead to unconditional reliance on the software (i.e., automation bias). Trust was manipulated by telling the participants that the software is "almost always correct" or "not always correct." Automation bias/reliance was defined by agreement with the errors of the software. No significant differences were found. However, the author cites multiple previous studies that have demonstrated the existence of automation bias and attribute the current results to limitations of the study. The author cautions that it is important to be aware of automation bias and work to counteract it (e.g., via training, increasing individual accountability, etc.).

3. Individual Differences

Though the advent of automation has mechanized some aspects, the NDE process still depends highly on the inspector. The quality of the inspection is primarily dependent on the personnel who perform these important tests (Krishnamoorthy et al., 2009). Variation in NDE performance by individual inspectors is evident across many domains (e.g., nuclear, aviation, aerospace) (Bertovic, 2014; Drury, 2001; Enkvist, Edland, & Svenson, 2000; Gasset, 2012; McGrath, 2008; Swets, Dawes, & Monahan, 2000; Taylor, Spanner, Heasler, Doctor, & Deffenbaugh, 1989). In isolation from other types of variables, it is often the individual difference variables that drive this variation between inspectors' performance (J. C. Spanner et al., 1986).

There has been theoretical, experimental and survey-based research on the impact of individual differences on NDE performance, of which and in comparison to the other elements of the sociotechnical systems model discussed in this report, a fair amount is empirical in nature (Bertovic, 2014). This chapter summarizes the many different individual factors found to be relevant to the performance of NDE.

In an attempt to capture the broad scope of individual difference factors impacting nondestructive examination, the framework for the present chapter is based on a combination of two major conceptualizations found in the literature. The characterization of individual behavior by Moray (2000) includes decision making, perception, attention, thought, memory, motor skills, and anthropometrics. Bertovic, Gaal, Müller, and Fahlbruch (2011) developed a human factors model specifically for UT NDE in the nuclear domain in which a set of inter-personal predispositions and a set of external factors (discussed elsewhere in report) influence the quality of NDE performance. The internal individual predispositions include: cognitive processes (e.g., decision making, information processing), visual perception, stress resistance, social feedback, knowledge and skills (experience/expertise). The framework for the present chapter presents a combination of the models presented by Bertovic et al. (2011) and Moray (2000) in an attempt to capture the myriad, sometimes overlapping, complexities surrounding the impact of individual differences on NDE performance.

3.1. Personality Factors

Personality is a factor most often thought of when considering individual differences and their potential effect on behavior. Though some variation in definition exists in the literature, an individual's personality is said to consist of a series of traits that remain largely consistent through a person's lifetime once he/she reaches adulthood. Personality has been both theoretically considered and empirically tested in relation to NDE performance (Behravesh, Karimi, & Ford, 1989; Bell, Munley, Rowley, McGrath, & Bainbridge, 2012; McGrath, 2008).

Within the personality research community, there is a general agreement that there are five major components of personality most commonly known as the Big Five personality factors: 1) Openness to Experience; 2) Conscientiousness; 3) Extraversion; 4) Agreeableness; and 5) Neuroticism (John & Srivastava, 1999). There are empirical findings relating some of these components of personality to NDE inspectors and inspection performance (Behravesh et al., 1989; Bell et al., 2012; McGrath, 2008).

3.1.1. Conscientiousness

Inspectors rating high in Conscientiousness have been found to perform better than those rating low (Behravesh et al., 1989). Conscientiousness is related to one's sense of duty, a propensity for order, or achievement. Several empirical studies have determined various sub-components of personality (related to Conscientiousness) to be related to inspection performance. Two relatively recent studies found that lower scores on Original Thinking and higher scores on Cautiousness and Responsibility resulted in better inspection performance on experimental test pieces (Behravesh et al., 1989; McGrath, 2008).

3.1.2. Extraversion

As NDE inspection performance is considered to be a vigilance task, it is relevant to consider personality factors known to affect vigilance task performance. For example, individual differences in introversion and extraversion have been found to be related to the performance of vigilance tasks (Davies & Parasuraman, 1982). Extraverts tend to get distracted in performance of inspection tasks (Morris & Gale, 1974; J. C. Spanner et al., 1986), while introverts are known to perform better at vigilance tasks (Davies & Parasuraman, 1982). UT NDE inspectors scored significantly lower than the average worker on ascendancy and sociability (Bell et al., 2012). As sociability is a facet of extraversion, these empirical findings support previous findings regarding the relationship between extraversion and inspection task performance. Namely, that inspectors tend to be more introverted, and introverts may be more suited to the characteristics of the NDE task than individuals who are extraverted.

3.1.3. Inspection Procedure Usage

As discussed in Section 2.2.2, it has been empirically determined that individual differences exist in the way inspectors use the inspection procedure, which can affect performance. It should be noted the extent to which someone holds a preference for adherence to the procedure is considered to be a personality factor (McGrath, 2008). Norros (1998) drew insights from using qualitative methods (i.e., interviews and observations) of inspectors regarding procedure adherence. The author identified that inspectors take one of two different subjective approaches to the task. One approach is more skill-based in which personal expertise and interpretive skill is viewed as central to successful inspection process. The other approach is more rule-based in which inspectors perceive that the use of procedures and adhering to standards are key component to successful inspection. Norros and Kettunen (1998) also found that a preference for routine was associated with high theoretical knowledge and long practical experience while a preference for adherence to the procedure was associated with long experience, but less theoretical background. It is the preference of the individual as to which approach they use, but this has an impact on the inspection itself and therefore, should be acknowledged.

3.2. Cognitive Factors

3.2.1. Memory and Perception

Memory and perception play a significant role in the performance of NDE inspection activities, especially in the case of manual inspection (Enkvist et al., 1999). Types and shapes of cracks must be remembered from training or previous experience and then compared to the results of the actual test. This is all accomplished through the perception of information and its subsequent processing.

An important aspect of the NDE process is the interpretation and analysis of the information regarding the potential discontinuities, or cracks. The recording and storage of the information is crucial. For mechanized NDE techniques, the data is encoded (i.e., recorded) and can be analyzed later. For manual inspections, however, data is collected and analyzed in real time. Thus, inspector memory plays a large role in the effectiveness of NDE, especially manually conducted inspections.

There are a great number of different variables involved in the inspection process (e.g., NDE process knowledge, scanning and transducer technique, signal detection and interpretation including accept/reject criteria, component history) Over the course of an inspection, this number can often exceed the limitations of human working memory processing which is known to be approximately seven items (Miller, 1956). There are several ways that the NDE process is managed to overcome these known constraints of human memory (e.g., use of methods that limit the number of variables for simultaneous attention; preemptive organization and integration of inspection data; computer aids); however, acknowledging this very basic human limitation is important to understanding the individual difference factors influencing the performance of NDE (EPRI, 1988).

An inspector looks for familiar patterns in the material and compares them to previously seen patterns from either previous experience or training using a combination of both long term and working memory processes (Enkvist et al., 1999). Another type of long term memory important to the NDE inspection process is called procedural memory. Procedural memory is the memory resource used when remembering how to perform a specific task. The "skillful performance of perceptual-motor tasks" (Tulving, 1993) such as manual NDE depends heavily on an individual's procedural memory (Enkvist et al., 1999).

3.2.2. Attention

The process of NDE requires individual inspector's attentional resources. Resource theory, as described by Wickens (1980), conceptualizes human attentional resources as limited in their overall capacity; resources are depleted as they are used for task completion. Enkvist, Edland, and Svenson (2001) explain the performance of NDE in terms of arousal. Attention is determined by arousal level and arousal level also determines resources associated with attention that are available for use in the performance of a particular task. Both resource capacity and arousal vary from person to person. Different individuals have different thresholds at which point they become aroused and the limits to resource capacity are thusly influenced. For example, one person might thrive under a great amount of stress (higher threshold) because they respond with full attention to the task, while another person's threshold for stress may be lower resulting in poorer performance due to reaching capacity limits of attention.

On the other side of this arousal spectrum is boredom. Boredom is the total lack of arousal (or attention) and this can have a negative impact on performance. Additionally, particularly relevant to the performance of NDE, it is observed that the inspector's attention may be divided (i.e., split attention) between the technology used to perform the inspection (e.g., transducer) and the display used to project the results in real-time (Enkvist et al., 1999). This aspect of NDE performance is important to consider given that performance decrements have been observed for dual-tasks requiring split attention when cognitive processing limits are exceeded (Wickens, 1980).

3.2.3. Stress and Workload

According to the Bertovic et al. (2011) model, the technology, the organizational working conditions, and the physical working conditions all combine to influence the mental workload and stress experienced by an individual performing a task. High workload experienced by individual inspectors has been empirically found to increase variability of and negatively affect precision of inspection performance (Bertovic, Gaal, Müller, & Fahlbruch, 2009; Bertovic et al., 2011).

Stress can impact individual performance indirectly via its effect on some of the cognitive processes needed for good NDE performance. For example, stress can impair working memory, which can ultimately impair an individual's ability to learn from experience, an important aspect of NDE training and performance (Keinan & Friedland, 1984). Although various factors may combine to increase stress, individuals vary in both stress resistance and personal tolerance. Studies show that high levels of stress resistance (how people handle stress), and personal tolerance of environmental conditions have been found to foster inspection precision and is associated with better performance overall (Behravesh et al., 1989; Bertovic et al., 2011; Wheeler et al., 1986). Due to the particulars of the task and environment, persons capable of tolerating high stress and able to manage stress effectively might be ideal candidate inspectors.

Mental workload and perceived time pressure have also been proposed as factors affecting NDE performance (Bertovic et al., 2009). Bertovic and colleagues performed an empirical test of the effects of time pressure on performance with 10 manual ultrasonic inspectors who were asked to identify flaws on mock-up test pieces under three conditions: no time pressure (8.5 hours per inspection area), middle time pressure (6 hours per inspection area), and high time pressure (4.5 hours per inspection area). In addition, the participating inspectors completed questionnaires designed to measure mental workload and perceived time pressure (i.e., NASA Task Load Index). The results suggested that the different experimental conditions, which varied the actual time allowed to perform the inspection, did not have a significant effect on inspection quality. However, inspectors' perceived time pressure and mental workload did have a significant effect on inspection quality. Inspectors who perceived more time pressure and more mental workload, regardless of the experimental condition, did not perform as well as inspectors who perceived less time pressure and mental workload.

3.2.4. Spatial Ability and Mechanical Comprehension

Given that the NDE process is largely spatial in nature, it is plausible that those who are particularly capable in spatial abilities would perform inspections better than those without good capabilities. In fact, spatial ability is one of the psychological abilities that is often theoretically tied with high performance of NDE in the literature (Enkvist et al., 1999). However, thus far, there is no empirical evidence of this relationship. EPRI (1990) conducted a study involving 16 inspectors and came up with little evidence of the impact of spatial ability on NDE performance. More studies with larger sample sizes would be necessary to determine whether statistically significant differences exist.

Several empirical studies have found that inspectors with better ability in mechanical comprehension and numerical estimation had better performance scores than those with lesser abilities in these areas (Bell et al., 2012; McGrath, 2008). Spatial ability is sometimes associated with an ability to mentally rotate objects (Kozhevnikov & Hegarty, 2001); it is possible that this particular skill is not utilized in NDE, but rather the mechanical comprehension of how the material itself is organized along with an understanding of the material history of the component is more specifically at play. More empirical study of these phenomena in the NDE context would be necessary to draw more specific conclusions.

3.2.5. Attitude and Motivation

Inspector attitude and motivation have been empirically found to impact NDE performance (Enkvist et al., 2001; Herr & Marsh, 1978; Krishnamoorthy et al., 2009; Norros, 1998; Norros & Kettunen, 1998;

Shull, 2002).The Swedish Nuclear Power Inspectorate (SKI) conducted several studies on inspector performance in NDE (Enkvist et al., 2000, 2001). They have shown that trust in own performance, motivation, and feedback are determinants of performance quality. Likewise, Norros (1998) purported that inspector attitude toward their work can have a large influence on NDE reliability and inspection performance.

In addition to showing the link between attitude/motivation and NDE performance, research has also been conducted regarding the factors that drive or can change an inspector's attitude and/or motivation. In an early assessment of factors, Herr and Marsh (1978) found that the accept/reject criteria must be reasonable to the inspector. If criteria are perceived as unreasonable, motivation suffers. Additionally, they found that the inspector must be provided feedback on their inspection performance and feel that their decision matters. If they reject a component (i.e., determine a defect exists), they must not be left with the impression that their decision will be dismissed. This can have a very detrimental effect on inspector attitude and motivation and ultimately future NDE performance (Herr & Marsh, 1978). Krishnamoorthy et al. (2009) stressed the importance of motivating NDE inspectors through recognition of effort and reward for successful inspection performance. Farley (2004) asserts that quality NDE cannot be achieved even with good codes and standards if the personnel who implement them are not properly motivated. Some practices such as long shift hours, no paid leave, and the use of temporary personnel are not conducive to developing and maintaining motivated employees. Farley (2004) suggests that implementing a 'code of practice' with research-based guidelines for appropriate employment conditions may be beneficial to supporting NDE personnel motivation.

Although the tactical suggestions to motivate employees captured above are primarily organizational in nature (e.g., performance feedback, working conditions; see Section 6), they are discussed here as they pertain to how the larger sociotechnical system interacts to impact performance.

3.2.6. Fatigue

NDE inspection requires long hours of visual search on what can generally be considered a vigilance task. The general literature on fatigue finds that it is related to poorer performance on vigilance tasks (Warm, Matthews, & Finomore Jr., 2008). Murgatroyd et al. (1994) empirically demonstrated that tiredness and demotivation resulting from working long shifts have a large negative effect on human reliability. Also, the effects of fatigue on performance can sometimes be seen tangentially. For example, fatigue can diminish abilities in visual acuity necessary to perform successful inspections (Shull, 2002).

Cognitive fatigue in particular has been a concern for the performance of NDE and as such has inspired NDE-specific fatigue research in the aviation and aerospace (Gasset, 2012) industries. Drury, Green, and Lin (2006) validated a simulation experiment completed previously with industrially-experienced members of the general public using experienced aviation industry inspectors and found almost no correlation between sleep and task (fluorescent penetrant inspection) performance. They did, however, find that short breaks every 20 minutes proved effective to improve performance and subjective reports of fatigue, workload, and sleepiness for daytime inspection. These effects were not found, however, for the inspections conducted at night (Drury et al., 2006).

Overall, to date, the direct effects of fatigue on NDE performance have not been empirically demonstrated. Krishnamoorthy et al. (2009) suggests that fatigue can be managed by proactive planning and execution by management.

3.2.7. Information Processing

NDE is considered an information processing task in which numerous types of information must be perceived, assessed, interpreted, and weighed (EPRI, 1990). The information processing necessary to perform NDE involves both signal detection and decision making (Ali, Balint, Temple, & Leevers, 2012; Bertovic et al., 2014; Harris, 1990; Rummel, 1984). Specifically, the task involves monitoring for signals to detect a defect, application of knowledge about the component and inspection technique and, ultimately, the integration of all the information available in order to reach a final conclusion as to the presence or extent of a discontinuity (EPRI, 1988). The cognitive processes underlying a person's ability to perform these functions include perception, attention, thought, memory, and decision making (Moray, 2000).

NDE performance variation has also been attributed to differences in the information that inspectors consider to be most important when evaluating whether a defect is present or not (Bertovic, 2014; Enkvist et al., 1999) or, in other words, their decision criteria. Signal detection theory has been used as a way of understanding inspectors' decision criteria. Depending on the true state of the component (i.e., crack or no crack) and the inspector's assessment of it (i.e., crack or no crack), there are four possible performance outcomes: hit, miss, false call, or correct rejection (see Figure 2 for an illustration of this relationship). A number of studies use Probability of Detection (POD) to characterize NDE detection performance (Aldrin, Medina, Allwine, Qadeer Ahmed, & Fisher, 2006; Ali et al., 2012; Drury, 2001; Lilley, 2006; Wall, 2009). POD is related to the decision criteria (i.e., what is considered a 'signal'). If an inspector's criteria threshold is low, then probability of detection will be biased towards avoidance of missed defects (i.e., cracks are called more readily; (Ali et al., 2012)), but a greater likelihood for false positives. Rummel (1984) suggested that a shift in decision criteria can be attributed to a lack of confidence by the inspector (Rummel, 1984). Murgatroyd et al. (1994) demonstrated that the probability of a false alarm is impacted by the decision criteria along with individual preference.

Ideally, decision criteria would be consistent across inspectors. To mitigate individual differences in decision criteria, it has been recommended that decision criteria be both well-defined and recognized by inspectors. Well defined accept/reject criteria reduces the number of decisions to be made; and reduced number of decisions results in improved inspection accuracy (Herr & Marsh, 1978). As a note, decision criteria can also be influenced by managerial practices, which is discussed in Section 6.2.

		TRUE STATE OF THE WORLD	
		Crack	***No Crack***
INSPECTOR'S ASSESSMENT	***Crack***	**Hit**	**False Call**
	No Crack	**Miss**	**Correct Rejection**

Figure 2. Possible outcomes of inspector's assessment depending on true state of the world, according to signal detection theory [Adapted from Enkvist et al. (1999)]

3.3. Physical Factors

There are various physical characteristics and abilities belonging to an individual inspector that can shape NDE performance. The following section discusses these influences.

3.3.1. Visual

Successful NDE requires the inspector to search for and detect irregularities through visually scanning material. The inspector's ability to see such imperfections is therefore critical to the success of the task. Individual differences in the visual capacity of the inspector thus impacts NDE inspection success.

Visual search is characterized to be one of the most error-prone critical functions associated with NDE (Drury, 2001). The visual process of detecting a defect begins with initial detection in the peripheral region with subsequent confirmation of the finding within the fovial fixation (Luk & Chan, 2007). In other words, visually speaking, content in the periphery is examined and brought into the central view for further processing. As NDE often involves a large field of view, the inspector's ability to process peripheral information is just as important as what is directly in front (i.e., fovial view). Luk and Chan (2007) recommended that inspector's field of view in terms of area and shape is an important factor contributing to NDE performance. The 'visual lobe,' which is the area including both the fovial and peripheral views, is highly dependent on the individual inspector's peripheral visual acuity (Drury & Watson, 2002). (Luk & Chan, 2007) recommended a tool that measures individual's visual field and predicts visual search ability to be potentially useful in inspector selection for NDE.

Missed defects are attributable to failures in visual search (Drury & Forsman, 1996). In aircraft NDE, eye movement studies demonstrate large variability between inspectors' search style. For instance, some inspectors used a random pattern of search versus others using more systematic, predictable patterns (Drury & Watson, 2002). In the offshore oil and gas industry, Leach and Morris (1998) found that individual differences in both visual search ability and the ability to detect embedded figures predicted performance of close visual inspection (CVI) and magnetic particle inspection (MPI).

As crack width has shown to be a meaningful predictor for probability of (defect) detection (POD) (Drury, 2001; Drury & Watson, 2002), individual visual acuity is an important individual difference affecting NDE performance (Beard & Ahumada Jr., 2003). Much of the work in visual acuity and NDE performance has been done by the aviation industry. Indeed, empirical findings in the aviation domain demonstrate that performance on the Embedded Figures Test and Peripheral Visual Acuity correlate with inspection performance (Drury, Spencer, & Schurman, 1997; Spencer, 1996).

In an effort to develop empirically based visual standards for the aviation maintenance industry, the use of computational models of human vision have been used to empirically predict detection in complex visual fields by simulating differing levels of visual acuity (Beard & Ahumada Jr., 2003). Luk and Chan (2007) recommend using minimum perceptible acuity as a measure of visual acuity suitable for NDE. They also find that while age is not found to be an influencing factor on NDE performance overall, visual acuity does decrease with age, which presumably could negatively affect NDE performance. To date, however, there is no empirical evidence supporting any direct link between inspectors' age and NDE performance.

Depending on the type of testing, individual color vision and sensitivity to contrast may impact NDE performance. Luk and Chan (2007) recommended that inspector color vision be considered at minimum for the specific colors used in the particular inspection technique used. It is generally acknowledged that this can be difficult to measure and implement. Individual ability to distinguish between lighter and darker spatial areas (i.e., contrast sensitivity) is particularly important in the performance of some NDE techniques (e.g., dye penetrant inspection (DPI), and MPI) (Luk & Chan, 2007). Likewise to visual acuity, contrast sensitivity is also known to decrease with age.

3.3.2. Anatomical

Individual differences in physical strength and manual skills also depend on the specific technique being utilized. For many manual inspection techniques, good eye-hand coordination (Wall, 2009) and manual dexterity (Shull, 2002) have been found to result in better inspection performance.

For MPI testing, there is a lifting component to the task and inspector's physical ability should therefore be considered. In DPI, removal of excess penetrant is the most delicate part of the procedure. The careful and precise removal of the penetrant dye from the non-defect areas while leaving the dye on the defect so it can be revealed is critical to a successful inspection (Luk & Chan, 2007, 2008).

3.4. Intelligence, Gender, and Age Factors

Classic studies of individual differences generally focus on differences in intelligence, gender, and age. However, empirical studies in NDE have not found these variables to be directly related to NDE performance (EPRI, Davies & Tune, 1970; 1999; J. C. Spanner et al., 1986). However, differences in age have been found to influence certain abilities, such as visual acuity, which has been found to influence NDE performance. See Section 3.3.1 on visual acuity for further discussion.

3.5. Experience/Expertise Factors

Successful NDE inspection relies on highly skilled and experienced inspectors (Enkvist et al., 1999, 2000; Krishnamoorthy et al., 2009). An inspector's performance depends on his or her "knowledge, skills, and abilities" (Pond et al., 1998). Behravesh et al. (1989) purports that "experience is paramount for successful inspections."

Taylor and colleagues conducted a mini-round robin study to quantify how well NDE inspectors were able to detect and size IGSCC (Taylor et al., 1989; Wheeler et al., 1986). Part of the testing included a human factors study to identify factors that can affect inspector performance, such as training and experience. It is acknowledged in the literature that general knowledge of NDE methods and theory as well as learning of geometric properties supports good NDE performance (Behravesh et al., 1989; EPRI, 1988; Krishnamoorthy et al., 2009).

In addition to general knowledge of NDE methods and theory, Krishnamoorthy et al. (2009) stressed the importance of inspector skill and knowledge specific to the various NDE techniques. Furthermore, McGrath (2008) found that inspectors demonstrated a good understanding of the basic principles of ultrasonic testing that are frequently used. Those principles that are important but used less often were not understood as well. Principles of NDE should be reviewed and tested frequently to ensure inspectors have recent experience with relevant techniques including those that are used more infrequently.

Rummel (1984) suggests that experience and expert skill development can help to adjust the POD curve to minimize human error. This approach includes training and knowledge of decision criteria as an important factor in reducing systematic errors that occur between inspectors. Similarly, in work performed for the Federal Aviation Administration, Drury et al. (1997) found that training and experience influenced the decision criteria more than by the procedures used. J. C. Spanner, Sr. (1988) used a ROC analysis method to systematically study NDE performance, and concluded that training, experience, and psychological pressures were individual factors that influenced the reliability of NDE.

Psychological pressures may influence NDE, however, more experienced inspectors may overcome some of these pressures with experience and time. For example, in a Swedish study, fear of radiation has been found to be a factor affecting NDE performance (Dahlgren & Skånberg, 1993). Wheeler et al. (1986) found that as inspectors gained more experience, they exhibited less fear of radiation.

There are some contradictory results regarding experience in the NDE literature. In relation to these, (Enkvist et al., 1999) cautioned against relying solely on inspector experience to ensure NDE reliability due to the tendency of very experienced inspectors to sometimes disagree with and stray from procedure guidelines (Enkvist, 2003; Enkvist et al., 2001; J. C. Spanner & Harris, 1999; Wheeler et al., 1986).

4. Group Characteristics

Compared to other types of human factors, NDE researchers have paid scant attention to the effects of group characteristics on NDE performance. Most studies focus 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. For instance, one inspector may be responsible for scanning the component while the other inspector documents the results. Inspectors may share scanning responsibilities. Inspectors may also use a team scanning approach, where one inspector scans the component while the other inspector observes the signal on the display screen (Wheeler et al., 1986). The choice among different team arrangements can be influenced by a variety of factors, such as inspector qualifications, accessibility of a component, team dynamics, and organizational norms.

Some studies have proposed group characteristics as having a positive influence on NDE performance. Wheeler et al. (1986) found that NDE inspectors considered feedback from fellow inspectors to be their best aid in inspections. Inspectors who work in teams may benefit from the ability to solicit and receive feedback from their teammate, particularly in situations where the inspector is uncertain of his or her initial assessment. Enkvist et al. (1999) also discussed the social influence of peers. Feedback from a peer may influence an inspector's decision making about the presence or absence of a defect by confirming or disputing the original inspector's assessment. Performing inspections in teams may also facilitate the sharing of experience and common practices among inspectors. Norros and Kettunen (1998) suggested teamwork as a means reducing differences among inspectors' habits of action (i.e., how they approach the inspection task).

Teams have also be suggested to increase inspection efficiency. In a study by Spencer and Schurman (1995), teams of two inspectors worked 20 percent faster than single inspectors. However, the team approach did not result in a significant difference in terms of POD. Enkvist et al. (1999) noted that because the teams in the Spencer and Schurman study included two inspectors working on the same component, the man-hours per component was higher than for the single inspector. This may be of particular concern in the nuclear industry because the radiation dose per person would also be higher for the team as compared to the single inspector. However, it is possible that the team of two would benefit from having an immediate second opinion on possible defects, resulting in more correctly identified defects and fewer double-checks for more difficult assessments.

Group characteristics have also been hypothesized to have detrimental effects on NDE performance. Bertovic (2015) investigated this possibility in sequentially redundant teams (one person inspects a component followed by a second inspector that serves as a quality control check). Specifically, it was hypothesized that individuals led to believe they are working in a team, such that another inspector will do the same task after him, will "loaf" (i.e., give less effort) in comparison to those who believe they are working alone. Bertovic also hypothesized that the second inspector will loaf more if they believe that the inspector that precedes them is highly experienced than if they have no information about the preceding inspector. The hypotheses were not confirmed. However, these social loafing effects have been found elsewhere, and Bertovic notes that the limitations of the study may have affected the results.

Other group interactions, such as between inspectors or inspections teams, may be critical to successful NDE as well. Wheeler et al. (1986) suggested that social influences of other technicians may influence a technician's decision criteria, either by confirming his or her perception of an indication or creating doubts. In addition, working well with others was viewed as a potential influence on performance. Seven of 12 inspectors interviewed indicated that having to work around the schedules of others made it difficult to do a good job. Drury (2001) also discussed group interactions as a social factor that can affect performance, particularly in terms of handing off work during a shift change or other disruption. Errors are more likely to occur when handing ownership of a job from one inspector to another. Drury (2001) noted that, "Inspectors hand off work whenever a shift changes or an interruption occurs. The handover procedures have been implicated in incident and accident reports so that good practices need to be followed whenever ownership of a job changes." Thus, good peer interaction is critical throughout the NDE process.

5. Physical Environment

The physical environment can present many challenges to inspectors when performing NDE. 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 (Behravesh et al., 1989; Bertovic, 2015; EPRI, 2009; Müller, Bertovic, Gaal, et al., 2013; Müller, Bertovic, et al., 2014; Pitkänen, Bertovic, Müller, Pavlovic, & Salonen, 2009; J. C. Spanner, Sr., 1988), 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 is another characteristic of the environment that 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 (Dickens & Bray, 1994; McGrath, 2008; Schroeder, Dunavant, & Godwin, 1988; Singh, 2000; J. C. Spanner, Sr., 1988).

The majority of the NDE references discussing elements of the physical environment are informational, citing general observations and conclusions regarding the effects of physical environmental characteristics in industrial domains. Only a few empirical studies have been performed to investigate the effects of physical working conditions on NDE performance, and the results of those studies have been mixed. For example, Murgatroyd et al. (1994) found that suboptimal working conditions (e.g., temperature, noise) did not have a significant effect on UT performance. However, Pond et al. (1998) argued that the experimental conditions represented in the Murgatroyd et al. (1994) study were not difficult enough, nor were they representative of actual conditions in the field. Environmental factors are some of the most readily apparent differences between performing NDE in the field as compared to training and testing settings. Rather than performing empirical research specific to the NDE domain, many researchers have instead sought to take lessons learned from more general research and operational experience to understand and improve NDE.

5.1. Temperature, Radiation, and Humidity

Temperature, radiation, and humidity are commonly acknowledged as factors that can negatively impact the reliability of human performance across various industrial settings (Müller, Bertovic, Kanzler, et al., 2013; Müller, Bertovic, et al., 2014; J. C. Spanner, Sr., 1988). Concerns about environmental conditions in the workplace (e.g., high heat, humidity, radiation) were characterized by inspectors as having detrimental effects on their performance (Taylor et al., 1989; Wheeler et al., 1986). Wheeler et al. (1986) noted that some inspectors have a fear of radiation and are negatively affected by the time pressure associated with time limits due to radiation. Triggs, Spanner, Badalamente, and Rankin (1986) reference a study by (Ramsey, 1983), which showed that heat stress can disrupt information processing performance. Inspectors interviewed during a round robin assessment of UT performance considered "tolerance of environmental conditions" vital to successful NDE (Singh, 2000). Bertovic (2015) noted that the work environment coupled with the equipment an inspector uses can have an effect on performance. For instance, difficult working conditions (e.g., high radiation, heat, and time pressure) could increase the mental workload of inspectors, resulting in decreased inspection quality. McGrath (2008) believed that reducing the impact of temperature and humidity as much as possible would improve the working environment. J. C. Spanner et al. (1986) suggested that research is needed to determine how studies performed in laboratory conditions generalize to a hot, long, humid, heavy, and awkward real-world inspection task. Schroeder et al. (1988) indicated that NDE inspectors and their supervisors should be made aware of the possible effects of environmental characteristics on human performance to mitigate those effects. Another mitigation strategy may be to reduce time exposure to unfavorable environments, such as by utilizing rest breaks (J. C. Spanner et al., 1986).

5.2. Noise

Noise in the environment has also been identified as an influencing factor that can affect the reliability and quality of NDE (Bertovic, 2015; Krishnamoorthy et al., 2009; McGrath, 2008; Müller, Bertovic, Kanzler, et al., 2013; Müller, Bertovic, et al., 2014; Pond et al., 1998; Schroeder et al., 1988). Krishnamoorthy et al. (2009) noted that noise along with other factors can produce undue stress during field testing, potentially producing unsatisfactory results. Noise can disrupt attention, causing inspectors to focus on things outside of the primary NDE task (Enkvist et al., 2001). Loud noises in the work environment can also interfere with communication (Wheeler et al., 1986). Schroeder et al. (1988) explored these concerns, possible solutions, and generated recommendations for NDE inspectors when performing their tasks. For example, it has been proposed that having a quieter work space could potentially improve inspector performance (Herr & Marsh, 1978).

5.3. Restricted Work Space

Another physical element identified by researchers that could impact inspectors' NDE performance is restricted work space (McGrath, 2008). The dimensions of the work space may require inspectors to arrange themselves in uncomfortable positions for extended periods of time, limit their ability to see or access the material being inspected, or affect their ability to see the equipment they are using to perform the inspection. It has been suggested that inspectors performing in awkward and cramped positions have an increased rate of fatigue and decreased endurance and sensory factors while performing tasks (Singh, 2000; J. C. Spanner et al., 1986; J. C. Spanner, Sr., 1988). Regular rest breaks have been suggested as a means of mitigating the potential negative effects of uncomfortable positions due to restricted work space (J. C. Spanner et al., 1986). As discussed in Section 2.1, pre-job preparation for restricted work spaces can also mitigate negative effects.

5.4. Lighting

Lighting was identified as an environmental factor that can challenge inspector performance in multiple papers (Bertovic, 2015; Cumblidge, 2007; Dickens, 1992; Dickens & Bray, 1994; Drury, 2001; Drury & Watson, 2002; Krishnamoorthy et al., 2009; Luk & Chan, 2008; McGrath, 2008; J. C. Spanner, Sr., 1988; Triggs et al., 1986). An empirical study by Cumblidge (2007) examined variables influencing the effectiveness of remote visual testing, and stated that poor lighting can make it difficult for inspectors to distinguish cracks from scratches when performing visual examinations. In particular, lighting styles can affect an inspector's ability to detect cracks. The study noted that common practice in remote visual testing is to use one or two spotlights to illuminate the area under inspection. However, when spotlights are misaligned relative to the crack orientation, the spotlights can effectively hide larger cracks. The style and placement of the lighting can result in a missed crack, require more time and resources to re-inspect the material, and lead to a lack of confidence in the inspection results.

Similar across most domains that perform NDE, poor lighting or luminous light can impose stress on individuals. Luk and Chan (2008) stated that glare and reflections from lighting can produce discomfort, which may increase levels of stress and fatigue and result in decreased performance. A unique perspective from Triggs et al. (1986) noted that light can influence an inspector's decision making skills while performing inspections. Vision relies heavily on the quality of light. If lighting is obscure, the literature suggests that it can influence an inspector's ability to interpret and make decisions about data that may be unclear in the field. Overall, lighting is a major factor that can affect the speed at which the task is performed and the reliability of the inspection results. As discussed in Section 2.1, lighting issues can be mitigated during pre-job preparation.

5.5. Personal Protective Equipment in Hazardous Environments

As a consequence of the environment within which NDE is performed, personal protective equipment is often required, particularly due to the presence of radiation in nuclear power settings. Various difficulties resulting from required personal protective equipment were discussed in the literature in terms of their potential effect on inspector performance. J. C. Spanner et al. (1986) and Taylor et al. (1989) both shared perspectives on the challenges that protective equipment (e.g., gloves, masks, and air packs) can impose on NDE performance. Masks, in particular, can interfere with an inspector's visual ability. Researchers note that fog produced in masks can limit an inspector's vision, making it difficult to read equipment display screens (Wheeler et al., 1986). Masks can also create difficulties with communication between inspectors in the field. Prolonged periods of wearing personal protective equipment in hazardous environments can also increase fatigue and lead to heat exhaustion. Interviews with inspectors as part of a mini round robin study suggested that the combination of fatigue due to long work hours and physical fatigue from wearing full protective gear negatively influenced their ability to detect defects (Wheeler et al., 1986). Inspectors also indicated that the protective clothing and gloves make it harder to move around in the field.

5.6. Combined Influence of Environmental Factors and Task Characteristics

An insight of note in the research literature was that degradations in the physical environment may have a greater impact on performance when combined with other performance influencing factors, such as task difficulty and cognitive workload (Dickens, 1992; Dickens & Bray, 1994; Enkvist et al., 2001). Research conducted by Dickens and colleagues suggested that if tasks are known to be simple, physical elements in the environment will not play a significant role as influencers (Dickens, 1992; Dickens & Bray, 1994). If the task is difficult, then physical elements will likely have more of an influence on the inspector. Inspectors may experience cognitive overload when performing difficult tasks in challenging physical environments because of the combined drain on attentional resources, which may then introduce vulnerabilities resulting in degraded performance. Enkvist et al. (2001) investigated fatigue, time pressure, and noise as possible performance shaping factors that affect individual's performance. The study exposed participants to a combination of stress factors associated with bad working conditions and stressful environment (i.e., noise and time pressure). The authors describe noise and time pressure as being additional cognitive loads that can influence task performance. Over the course of two days, inspectors worked under two conditions: 1) the non-stress condition with low time pressure and noise; and 2) the stressful condition with higher levels of time pressure and noise. Contrary to the authors' hypotheses, average inspector performance was higher under the stressful condition. The results suggested that moderate amounts of time pressure and noise can have a positive influence on inspector performance for familiar tasks. Given the tasks in the experimental study were familiar to the inspectors, Enkvist et al. (2001) hypothesized that short distractions in some tasks may not lead to any negative consequences, but inspection performance may be negatively impacted for more complex tasks. Regarding future research efforts, Pond et al. (1998) suggested that rather than further investigating environmental factors that inspectors have little control over, more attention should be given to develop strategies to mitigate the performance challenges imposed by the environment.

6. Organizational Factors

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. Bertovic noted that past studies have been predominantly theoretical rather than empirical tests of organizational factors. There was also a significant lack of information that establishes causal, or even correlational, relationships between organizational influences and NDE performance. 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. In addition, many studies presented recommendations directed at organizational strategies for improving NDE reliability.

6.1. Organizational Culture

Organizational culture is a broad concept that encompasses many of the organizational factors commonly referenced in human factors research. Schein (1990) describes organizational culture as, "a set of shared basic assumptions learned by a group to cope with its problems of external adaptation and internal integration that has worked well enough to be considered as valid" (p. 111). Safety culture is a related term, often used in the nuclear power industry and other high reliability industries, that refers to the extent to which an organization's culture prioritizes safety over competing goals. Specifically, the NRC defines safety culture as, "the core values and behaviors resulting from a collective commitment by leaders and individuals to emphasize safety over competing goals to ensure protection of people and the environment" (Nuclear Regulatory Commission, 2011).

Discussions with inspectors and NDE organizations as part of the UK Health and Safety Executive's PANI III study revealed that they believe organizational culture can play a major role in inspection reliability (McGrath, 2008). Drury (2001) describes inspection as being part of a sociotechnical system, such that the relationship between the inspector and others will influence inspection performance. For example, the standards, attitudes, and practices of supervisors and managers may influence inspectors' perceptions of the relative value of performance (Behravesh et al., 1989). The organization's support for the inspector can also enhance an inspector's intrinsic motivation to do good work, which can increase inspection reliability (Enkvist et al., 1999). The characteristics of an organization's culture can affect all aspects of the NDE process: how the work is planned by the utility and NDE vendor; how the work is managed and supervised; and how the work is carried out by NDE inspectors.

6.1.1. Organizational Pressures

The extent to which an organization's culture prioritizes safety over competing organizational pressures provides cues to workers regarding how they should perform their work tasks. Insights from the PANI III project suggested that inspectors are aware of, and potentially influenced by, organizational pressures associated with the potential time and cost delays of finding a defect (McGrath, 2008). These same pressures may subvert not just the inspection process, but also the reporting process. Shull (2002) noted that it is particularly important that inspectors can freely report findings without the pressure to produce specific results.

Dickens (1992) also mentioned the potential for economic pressures to affect performance. During inspections, finding a defect means that the part will likely be taken out of service for repair, which costs the company money. On the other hand, there are fewer immediate consequences when no defects are found. As a result, inspectors may become more lenient in what they determine to be a defect because the risk of a false call is perceived to have more immediate negative consequences than the risk of a miss.

6.1.2. Work Planning and Coordination

When the culture of the organization regards NDE inspections as simply a contractual or regulatory obligation, then it is more likely that inspection planning and coordination will suffer. For instance, there are more likely to be problems with lack of information, inadequate preparation, poor access, and unreasonable time pressures (Carter & McGrath, 2013). McGrath (2008) observed that, “NDE is often characterized as an activity that manufacturers and plant owners only do because they have to, and therefore NDE is seen as a burden on the resources of the company. This often means that NDE suffers from lack of funding and client support.” On the other hand, an organizational culture that regards NDE as a valuable process to help the organization avoid failures is more likely to prioritize planning and coordination of the NDE process.

Organization of the inspection effort, in terms of work planning and coordination, is critical to an inspector’s capability to perform the NDE. The work process specifies how the organization carries out preparation for the inspection, acquisition and analysis of the data, management the data, and use of the results (EPRI, 1988). Singh (2000) argued that without clearly defined work processes and decision criteria, NDE inspectors are set up for failure. A report prepared by EPRI notes that, “Inspectors consistently report that, when conducting inspections in the plant, they cannot attend to all the variables or apply all the procedures in the manner they have been taught. They say they do not have time to perform the task as completely as prescribed in training. Some consider that the task, as taught, might actually be too idealistic to be implemented under the time pressure and environmental conditions that exist in the plant” (EPRI, 1988, pp. 4-21).

Proactive interactions between the NDE vendor and utility customer were viewed as important to ensure the inspectors have all the information they need to perform the inspection and thereby minimize distractions and interruptions during the inspection (McGrath, 2008). As part of the PANI III study, NDE vendor companies indicated that lack of information from the client was a major risk to achieving a quality inspection (McGrath, 2008). Vendor companies tended to attribute the lack of information as arising from a lack of knowledge of NDE by the client organization. See Section 2.1 for additional discussion of pre-job preparation activities.

Holstein, Bertovic, Kanzler, and Müller (2013) discussed a model of the organizational factors that influence NDE performance in terms of the business process, information process, and delivery process. They focus on the relationship between the customer (utility) and service provider (NDE vendor) as a primary driver of NDE reliability. In the Holstein et al. (2013) model, the business process refers to the agreement or contract between the customer and service provider. The information process refers to the information that must be exchanged between the customer and service provider before the NDE service begins (e.g., schedule, history of the component, work environment, procedures, reporting requirements). Finally, the delivery process refers to the actual performance of the NDE service from when the NDE inspectors are on site to the final reporting of the inspection results. Although this model has not been tested, Holstein et al. note that it may be helpful for visualizing the organizational factors that influence NDE reliability.

6.1.3. Organizational Working Conditions

Organizational working conditions can be visible artifacts of an organization's culture that influence inspectors' perceptions of the relative importance of the NDE task. Multiple researchers have noted that working conditions that are controlled and implemented by the organization can affect inspection performance (Bertovic et al., 2009; Drury, 2001; Farley, 2004; McGrath, 2008; Wheeler et al., 1986). Although some environmental conditions of the inspection task cannot be controlled, the NDE vendor and utility customer typically exercise some control over such things as work scheduling and the provision of adequate facilities at the work site (e.g., meeting rooms, changing rooms, and cafeteria facilities). Bailey (1989) suggested that the work environment is a reflection of the organizational structure and tends to indicate what level of performance is acceptable. Dickens (1992) further stated that when management feels that a task is high priority workers will be well provided for, whereas low priority tasks will be apparent in the quality of the work environment. When workers perceive that a task is low priority from cues based on the organizational working conditions, performance will decline accordingly.

Work hours and work scheduling is one of the most common working conditions identified as potentially impacting NDE performance. Because inspection is a cognitively demanding task that requires constant vigilance, the effects of long work hours and disruptions to circadian rhythm, such as when working night shifts, can contribute to fatigue and decrease the attentional resources that are devoted to the NDE task (Bertovic et al., 2009; Drury, 2001). Interviews with NDE inspectors suggested that they perceive fatigue to be a contributing factor in NDE performance when a wrong call is made. Inspectors generally grouped fatigue-related errors into those resulting from more acute fatigue (e.g., working a long shift in full protective gear), and more long-term fatigue from working continuously over multiple weeks without a day off. Acute fatigue was more often associated with single mistakes, whereas long-term fatigue was associated with inspector's general attitude and disposition (Wheeler et al., 1986). See Section 3.2.6 for discussion of fatigue as an individual difference factor.

The availability and quality of facilities at the work site can also influence NDE performance because it provides cues to inspectors regarding the extent to which an organization values their contributions. Although adequate facilities may not necessarily improve inspection performance, it can reduce an inspector's intrinsic motivation because they perceive a lack of organizational support. McGrath (2008) noted, "Factors which motivate are often different to factors that de-motivate personnel. Whilst good housekeeping in mess facilities may not inspire inspectors to greater performance, poor housekeeping will definitely de-motivate them."

Farley (2004, 2008) noted that there is a need for a code of practice on working conditions for NDE personnel. There are many organizational factors that are not conducive to high quality inspection, yet often exist in NDE operations, likely because of commercial pressures and the portability of NDE personnel. For example, in some cases NDE is performed by temporary, contract personnel who do not necessarily have the full technical and managerial support that employees of the utility possess. NDE inspector wages may be by the hour with few, if any, of the benefits often associated with full-time, salaried positions. In addition, extended shifts over long periods without days off can be common, particularly given that the majority of NDE work is performed during time-constrained outages. These employment conditions and working arrangements are managed by the NDE organization and the utility, and can have a strong impact on the motivation and commitment of NDE personnel.

6.2. Management Oversight and Supervision

The most common organizational factor that researchers have identified as influencing NDE inspector performance is management oversight and supervision. Wheeler et al. (1986) discussed the influence of management and supervision on inspection reliability in terms of the level of supervision, supervisor trust in their inspectors, and the way an organization supports (or frustrates) the inspector's activities.

Research by Norros and Kettunen in Finnish nuclear power operations strongly suggested there is a close connection between inspection management and the reliability of NDE (Kettunen, 1997; Norros, 1998; Norros & Kettunen, 1998). In particular, interviews with NDE inspectors suggested that the NDE foreman plays a critical role in NDE reliability (Norros, 1998). The foreman was considered to be a significant contributor to the preparation of work, coordinating activities, and monitoring radiation exposure. Enkvist et al. (1999) also discuss the role of the foreman to provide social support to inspectors and a back-up or sounding board for checking difficult assessments.

Spanner et al. (1986) classified management instructions and attitudes as a subset of "training variables" that influence NDE performance, because management attitudes regarding the cost and consequences of misses and false calls can be considered a sort of "instructional set" provided to the inspector. Management can significantly influence inspector's decision criteria (see Section 3.2.7) in terms of willingness to make false calls versus missing defects. A supervisor's reaction to false calls and missed defects can relay a set of implied costs and values to the inspector. When asked about expectations for having work re-checked, seven out of 12 inspectors expected to have their work checked if they reported a suspicious indication, but only one out of 12 expected their work to be checked if they did not report any indications (Wheeler et al., 1986). This suggests that inspectors perceived their management to be more concerned with false calls than missed defects. Expectations regarding what work would be re-checked seemed to be dependent on the potential cost of follow-on work. All inspectors interviewed agreed that their supervisors stressed the importance of finding any flaws that may exist, but 9 of 12 also agreed that those same supervisors stressed the importance of being certain that a flaw exists. Further, inspectors perceived the utility as placing more value on avoiding false calls. See Section 3.2.7 for further discussion of individual decision criteria.

Behravesh et al. (1989) conducted a study designed to elicit descriptions of NDE performance of varying quality (i.e., typical, superior, and unusually poor performance). A sample of 100 episodes were collected from 20 subjects. Behravesh et al. (1989) found that context-related attributes were more salient than the worker-related attributes in distinguishing between typical, superior, and poor performance. The context-related attributes included the quality of pre-planning, the organization's efficiency (bureaucracy), managerial and supervisory cooperation and support, and attitudes, values and philosophy. Overall, the findings suggested that supervisory and managerial practices are major contributors to performance quality. As a result of the study's findings, Behravesh et al. (1989) recommended targeting management and training practices as a way to improve NDE performance. In particular, management practices should cultivate workers' autonomy and provide positive feedback so that workers can perform in a supportive and learning environment.

6.2.1. Performance Feedback

One particular aspect of management oversight that has been identified as having an influence on NDE reliability is performance feedback. Inspectors interviewed as part of a mini round-robin study indicated that they rarely received feedback on inspections in the field. Inspectors further stated that knowledge of how they were doing was particularly important to them, and that the lack of feedback on performance from a utility gives the impression that the utility does not take the NDE inspectors' efforts seriously. In addition, feedback about the presence or absence of defects can be useful operating experience for NDE inspectors, and help inspectors adjust their expectations about the relative frequency of defects in the field (Wheeler et al., 1986). Expectation of base rate plays a role in how an individual sets decision criteria and overall decision making for signal detection and vigilance tasks. Feedback from management can also influence performance in terms of external time pressures or decision making pressures. For instance, if managers regularly contradict an inspector's decisions, then it is likely that the inspector will adjust their decision criteria for reporting defects based on management expectations (Drury, 2001; J. C. Spanner et al., 1986).

Enkvist and colleagues discussed the role of feedback in influencing inspector performance. For instance, the psychological principle of discounting future consequences can influence inspector's decision making (Enkvist et al., 1999, 2000). Negative consequences that are more distant in time tend to be weighed as less important than more immediate negative consequences. Therefore, if an NDE inspector makes an erroneous decision about a component, it can result in either immediate negative feedback when making a false call, or more distant negative feedback if a call is missed. The type of feedback inspectors receive from management can influence inspectors' decision criteria to prefer misses to false calls. Often this may not be a conscious decision, but stems from a person's desire to please others (i.e., management).

Behravesh et al. (1989) indicated that many of the differences in performance in training or laboratory conditions versus field conditions may be attributable to organizational factors like feedback. Moreover, behaviors that are rewarded in the context of training may be responded to negatively in the field. In training situations, inspectors are often given frequent and immediate feedback that rewards the correct detection of defects. On the other hand, feedback is not always possible or timely when inspecting in the field. In situations where informational or supportive feedback is not available, workers may develop negative beliefs about their capabilities and opportunities for exercising those capabilities (Behravesh et al., 1989). This can lead to deteriorations in performance over time. If workers' believe that they will receive a negative response from management if they detect a possible defect, then they may tend to be more conservative in identifying potential defects to decrease the possibility of making a false call, but also increasing the likelihood of missed calls.

6.3. Training Strategies

Another factor that can affect inspection reliability is how inspectors are trained. Individuals are more easily able to recognize stimuli that are previously known to them; this is known as pattern recognition (Tulving, 1993). Pattern recognition is a key component to the NDE process. The act of recognition is facilitated by prior experience with the stimuli or similar stimuli. The quality and fidelity of training is therefore very important to an inspector's ability to more quickly recognize and process similar patterns and has the potential to greatly influence NDE inspection performance. Drury and Watson (2002) discuss a number of studies related to the inspection of aviation equipment (Drury & Gramopadhye, 1992; Gramopadhye & Drury, 1997; Kleiner & Drury, 1993) that suggest that a Progressive Part strategy to teach knowledge and skill, which includes use of numerous job aids and simulations, can be much more effective at training inspectors than on-the-job experience. In fact, two novices who completed 2-day training using this approach were able to perform more reliably on the task of inspecting jet engine roller bearings than inspectors with 15 years of experience. The authors concluded that, "between knowledge instruction (from classroom or computer-based training) and on-the-job training (OJT) should come carefully developed simulations that allow control over which defects are present, where and when they are presented, and the form and frequency of feedback.

A review of NDE research by Spanner et al. (1986) suggested that “hands on” training with immediate feedback is most likely to improve performance. The review also suggested that using a broad range of training samples, providing feedback regarding the results, and using cueing (i.e., prompting that a particular form of signal is about to occur) during training can enhance performance.

6.4. Recommendations for Addressing Organizational Factors

Pond et al. (1998) argued that there is a critical need to explore organizational influences on NDE performance in future research, even in preference to other more frequently-studied variables like heat and noise. Investments in research on organizational factors may lead to improvements that can have a greater or more immediate impact on NDE performance than research on other variables that cannot be fully altered or removed from the NDE task. Singh (2000) echoed this suggestion, arguing that whereas individual difference variables like mental state are relatively uncontrollable, organizational factors are somewhat controllable. Consequently, organizational factors may be better targets for interventions to improve performance.

Herr and Marsh (1978) provided two organizational recommendations for reducing the effects of human factors on NDE reliability: specialized training and consideration of inspector attitude and motivation. Although much attention has been given to NDE training and qualification since 1978, there has been much less attention devoted to inspector attitude and motivation as a means of improving NDE reliability. A report by EPRI (1988) argued that there is ample information about creating a motivational working environment for inspection performance. The problem, then, is not due to lack of research, but due to implementing that knowledge within the constraints of a nuclear power utility. Pond et al. (1998) discussed motivation to perform as a variable that is often different in laboratory conditions versus field conditions. For example, inspectors who are more motivated by internal sources (i.e., intrinsic motivation) may require a different type of managerial approach than inspectors who tend to be externally motivated (e.g., motivated by monetary or other external rewards). Intrinsic motivation may be stimulated through challenging tasks that provide a feeling of accomplishment, whereas extrinsic motivation may be influenced through incentive systems.

In their evaluation of human factors research in ultrasonic inspection, Pond et al. (1998) noted that it is particularly challenging to conduct laboratory studies that adequately represent all of the contextual conditions present in the field. Further, the most difficult to reproduce may be social or organizational factors. Karimi (1988) suggested that contextual factors (e.g., supervisory and management practices) are major determinants of performance, and called for training which, “resembles the field as much as possible in terms of physical conditions as well as the social influences.”

A major finding of the PANI project was that additional work is needed to identify the level of organizational support needed by NDE inspectors to perform reliable inspections (McGrath, 2008). As a result of the PANI program, the UK Health and Safety Executive issued a number of recommendations relevant to human factors that can affect NDE performance. The majority of the recommendations are aimed at the organizational level (Health and Safety Executive, 2000).

- Inspectors should be given appropriate training and qualification
- Inspectors should be given practice on real test pieces prior to inspection

- Purchasers should consider additional job-specific qualifications in addition to ones available through central certification schemes
- Inspections should be subject to supervision and audit
- Independent repetition of the inspection should be considered
- Good access conditions should be provided
- Use of semi-automated inspections should be considered
- A reasonable time should be allocated for the inspection and should include regular breaks
- Environment should be as benign as possible

The Health and Safety Executive (2000) also emphasized the importance of the contractual arrangement between the NDE vendor and utility customer. The contract should define the responsibilities of each party and specify the requirement for a quality control system.

- Contractual responsibilities should be made clear when inspection contracts are placed
- NDE companies should have a quality system for controlling the implementation of NDE
- Qualification of the entire inspection (Procedures, equipment, and inspectors) should be considered when very high assurance is needed or if the inspection is a novel one

A 2009 report by EPRI (also discussed in Section 2.1) provided extensive discussion of the role of the utility and the role of the vendor in ensuring reliable NDE performance (EPRI, 2009). The guidelines emphasize the need for good collaboration between the utility and the examination vendor to ensure adequate preparation for a successful inspection.

7. Summary

The primary objective of our work is to identify human factors issues associated with NDE. Specifically, issues associated with manual conventional and manual phased array ultrasonic testing (UT). The literature review captured in this report reflects the first step in achieving that objective.

As described in the introduction section, we developed a human factors categorization scheme for this review based on Neville Moray's sociotechnical systems model (2000). 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 into five elements of human factors considerations in NDE: task characteristics, individual differences, team or group characteristics, the physical environment, and organizational factors. Based upon our literature review, we are able to further inform and expand the model for all categories except "Group Characteristics," as research in this area was sparse. See Figure 3.

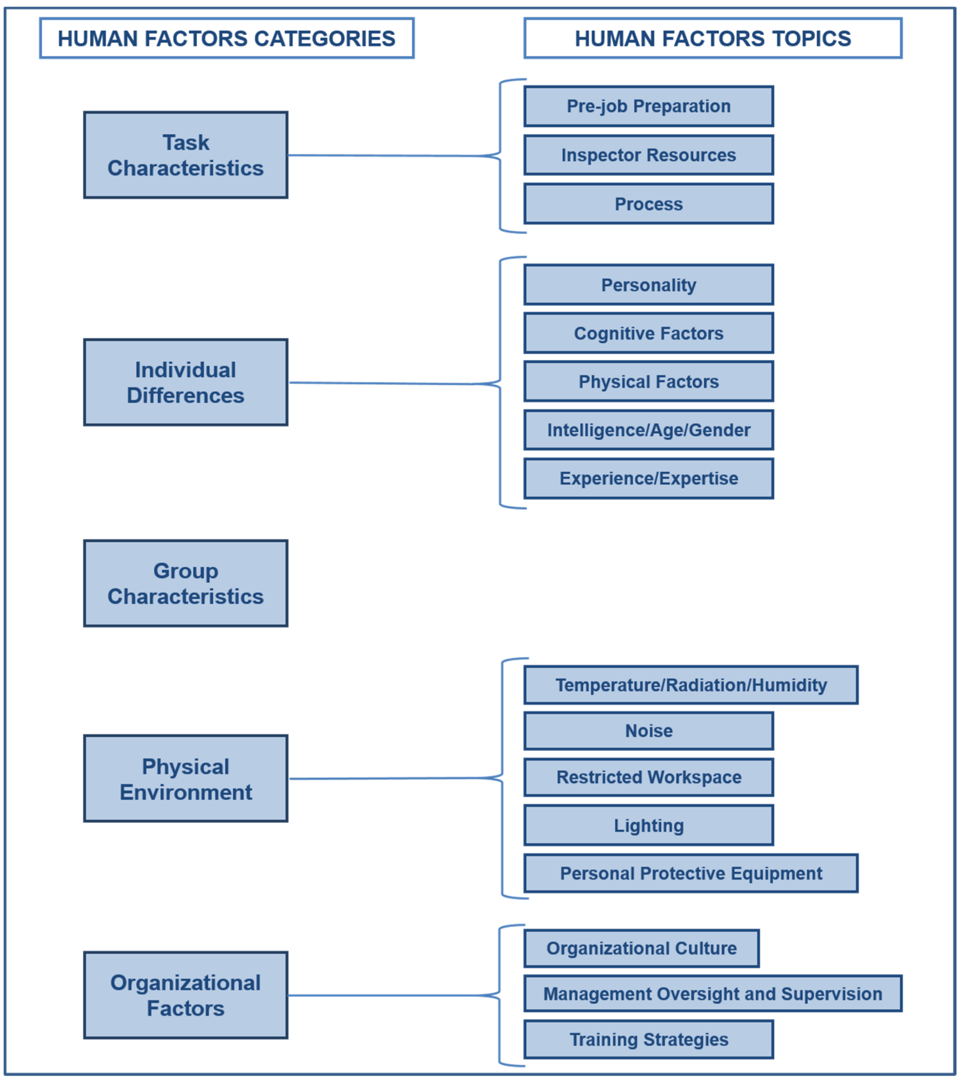

Figure 3. Expanded model of human factors topics in NDE

We will look to validate and further expand this model through review of operating experience, observations of NDE in the field and at PDI, and through input from SMEs (e.g. interviews, focus groups, discussions). Once the model is completed, we will seek expert input to prioritize the human factors issues identified. The information gathered in this project will serve as input to the development of a long-term strategy and plan for addressing human performance in NDE.

8. References

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Appendix A: Annotated Bibliography

The following is a list of references related to human factors in nondestructive examination. Each reference is annotated with a summary describing findings and insights relevant to the human factors review.

Aldrin, J. C., Medina, E. A., Allwine, D. A., Qadeer Ahmed, M., & Fisher, J. (2006). Probabilistic risk assessment: Impact of human factors on nondestructive evaluation and sensor degradation on structural health monitoring.

This paper looks at the utility of using traditional NDE versus structural health monitoring. Specifically, it investigates critical issues concerning human factors in NDE and sensor degradation in SHM. It analyzes each method via a cost-benefit analysis with probabilistic risk assessment. Quantitative probabilistic risk assessments and cost evaluations are presented concerning the effects of variations in POD associated with human factors. This study leverages previous HF research to adjust POD parameters. For example, false call rate has been attributed to lack of recent experience and training with the procedure and degraded concentration. The authors examine how false call rate impacts the probability of failure and total life cycle costs. The authors created another probabilistic model for SHM sensor degradation. The study concluded that a hybrid approach is encouraged on a case-by-case basis.

Domain: Aviation
Paper Type: Theoretical
HF Elements: Organizational factors; Individual differences; Task characteristics

Ali, A.-H., Balint, D., Temple, A., & Leevers, P. (2012). The reliability of defect sentencing in manual ultrasonic inspection. *NDT & E International, 51*(0), 101-110. doi: http://dx.doi.org/10.1016/j.ndteint.2012.04.003

This paper discusses the probability of successfully detecting critical defects. A framework is introduced for analyzing the reliability of identifying critical defects. The authors used a general model for NDE inspection techniques to predict the probability of missing critical defects or misclassifying harmless defects. A framework was created for the analysis of the reliability of defect decision making and two examples were presented to test the model. The two examples were a 20dB drop technique and the second example illustrates how physical access limitations may affect the likelihood of failing to detect an unacceptable defect in a v-butt weld. The authors state that calibration of equipment, Inspection procedures, shift patterns , failure of inspectors to seek clarification, and use of proper probes were the areas of concern that were deemed to be the most relevant.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Individual differences; Task characteristics

Behravesh, M. M., Karimi, S. S., & Ford, M. E. (1989). Human factors affecting the performance of inspection personnel in nuclear power plants.

This paper explores human factors using two different theoretical approaches to conceptualize effective performance. The "top-down" approach defines effective performance as a product of a skillful, motivated person interacting with a responsive environment. The "bottom-up" approach defines effective performance by people's conception of a competent worker or productive work episode. The authors applied the "top-down" approach through a literature review, and concluded that differences between performance in training and performance in the field may be primarily due to contextual and motivational factors. For example, a skillful NDE technician who passes qualification examinations may do poorly in the field context because he/she may not be able to endure the environmental conditions of the plant, or because he/she may be functioning under a different set of values, standards, or directives than those learned in the training context. Also, technicians who are intrinsically motivated to do good work may demonstrate more consistently effective performance that those who are extrinsically motivated. The authors then conducted two studies to apply the "bottom-up" approach. The first study consisted of semi-structured interviews with 37 subjects representing a cross-section of the NDE industry. The interviews suggested that the attributes of a highly competent worker include conscientiousness, stress tolerance, knowledge, and self-efficacy. In the second study the authors gathered a sample of 100 descriptions of typical, superior, and poor performance from 20 participants. The results suggested that the quality of performance was associated with 4 worker-related attributes (organized pre-planning; experience and knowledge; professional performance; self-evaluative thoughts and feelings) and 4 context-related attributes (organized pre-planning; efficient; cooperative and supportive; attitudes, values, and philosophies).

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Individual differences

Bell, A., Munley, G., Rowley, K., McGrath, B., & Bainbridge, H. (2012). Personality traits and cognitive abilities associated with manual ultrasonic operator performance. In J. Wilson, A. Mills, T. Clarke, J. Rajan, & N. Dadashi (Eds.), *Rail human factors around the world.* Leiden, The Netherlands: CRC Press.

This paper describes the individual differences that may account for variability found across inspectors while performing manual ultrasonic inspections. This is the third stage of research conducted in the Programme for the Assessment of NDT, which suggested that overall differences in NDT performance were due to inspectors' individual differences. The second stage of the research involved systematic changes to the inspection process by improving procedures and training. There were 40 inspectors that participated in the third stage of this process by completing six timed ability tests, a personality inventory and performed a manual ultrasonic examination of a test piece. The authors analysed the data for correlations between the perfomance and the personality and ability tests. The results provided insight with regard to cautiousness, years of manual UT experience, original thinking and mechanical comprehension, and training of inspectors. The ultrasonic ability test scores revealed that inspectors performed significantly higher than the average worker on Numerical Estimation and Mechanical Comprehension test, and performed significantly lower than the average on Spatial Checking; Fault Finding; and Diagrammatic Thinking. Also ultrasonic inspectors scored significantly higher than the average on Responsibility and Cautiousness, but scored lower on Ascendancy and Sociability.

Domain: Generic
Paper Type: Empirical
HF Elements: Organizational factors; Individual differences

Bertovic, M. (2013). *Holistic risk assessment*. Paper presented at the 5th European-American Workshop on Reliability of NDE.

This paper proposes that NDE must be viewed in a holistic way. It must be approached from both an engineering and psychological stance. The paper discusses that a common misconception is that errors result from unreliability of the inspector, while it is often an issue hidden deep in the system (e.g. organization, task, team) causing the problem. The study also addresses the approach of replacing the human with automated NDE. Replacing manual with mechanized NDE can lead to a decrease in errors. However, one has to be aware that with every new application, new errors and error sources can arise, which have to be systematically investigated and controlled. Finally, the paper addresses the role of the written procedure. The inspection procedure is an important tool in NDE and should be developed using human factors principles. A number of shortcomings were identified in a procedure written according to requirements and by qualified NDE personnel.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Group characteristics; Task characteristics

Bertovic, M. (2014). User-centered approach to the development of NDT instructions. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company.

The authors conducted 4 studies focused on mechanized NDE. The goal was to identify factors that can cause errors and determine how to prevent them. The factors were identified via a Failure Mode Effects Analysis. One factor identified was shortcomings in instructions and procedures. The authors chose procedure improvement as the area of focus for the 3 subsequent studies. In the first of these studies, the aim was to evaluate the quality of the current NDE instruction. This was done using eye tracking and think aloud processes. The results were analyzed and areas for improvement were identified (e.g. presentation of information, consistent terminology). Changes were made to the procedure and Study 2 was conducted to determine whether the new instruction was an improvement over the previous version. The third study tested a new version of instructions that were changed based on the results of study 2. The goal of study 3 was to determine whether the changes led to a more efficient and effective use of the instructions. The authors found that some of the changes increased efficiency and effectiveness. They concluded that NDE instructions and procedures can be improved through user-centered design and human factors principles, but validation of a new procedure requires both reading through the procedure and actively carrying it out.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Task characteristics

Bertovic, M. (2015). *Human factors in non-destructive testing (NDT): Risks and challenges of mechanised NDT.* (Doctor of Philosophy), Technical University of Berlin, Berlin, Germany.

This paper argues that reliability of NDE is affected by human factors, but that HF has received the least amount of attention in the reliability assessments. The paper's stated objectives were "to (1) identify and analyze potential risks in mechanized NDE, (2) devise measures against them, (3) critically address the preventive measures with respect to new potential risks, and (4) suggest ways for the implementation of the preventive measures." The paper presents a comprehensive review of the HF work that has been done to date in nuclear NDE. It also goes on to assess the current state of the art and identify challenges and knowledge gaps. Three empirical studies are also presented in this dissertation. The first study was aimed at identifying risks associated with mechanized NDE through a Failure Mode Effects Analysis, Studies 2 and 3 looked at the application of human redundancy in the evaluation of NDE data; Study 3: Use of automated aids in the evaluation of NDE data.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Group characteristics; Individual differences; Task characteristics

Bertovic, M., Calmon, P., Carter, L., Fischer, J., Forsyth, D., Holstein, R., . . . Selby, G. (2014). Summary of the open space technology discussions. *Materials Testing, 56*(7-8), 602-606. doi: http://dx.doi.org/10.3139/120.110604

This paper summarizes discussions that occurred during the 5th European American Workshop on Reliability of Non-destructive Evaluation using the "Open Space Technology" approach. This approach allows participants to identify topics of interest during the course of the workshop to allow the selection of topics based on participant's interests and ideas that emerge throughout the course of the workshop. Human factors was one of the topics identified and included in the open space discussions. The authors observed that there was a lot of interest in the influence of human factors on the reliability of NDE. However, there seemed to be a gap in communication between the utilities and NDE service providers, and therefore, human factors does not always receive appropriate attention in the field. Other topics included discussion of how to maintain vigilance in the field and how to raise awareness of human factors and associated research needs.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Bertovic, M., Fahlbruch, B., & Müller, C. (2013). Human factors perspective on the reliability of NDT in nuclear applications. *Materials Testing, 55*(4), 243-253.

This article presents a series of 4 studies that explore various HF elements and their effects on NDE performance. The elements include time pressure, mental workload, automation, and human redundancy (teams). The results showed that time pressure and mental workload decrease UT performance. Influences of social loafing and automation bias were also shown to affect performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Group characteristics; Individual differences; Task characteristics

Bertovic, M., Fahlbruch, B., Müller, C., Pitkänen, J., Ronneteg, U., Gaal, M., . . . Schombach, D. (2012). *Human factors approach to the acquisition and evaluation of NDT data*. Paper presented at the 18th World Conference on Nondestructive Testing, Durban, South Africa.

This paper provides as overview of human factors elements that influence the reliability of NDT in nuclear energy production. First, the authors present a theoretical model of potential human factors elements that influence non-destructive testing (NDT) performance. Second, the authors describe a process for evaluating human factors issues in NDT using an adaptation of the Failure Modes and Effects Analysis (FMEA) method. Third, the authors demonstrate how eye-tracking technology can be used to optimize existing NDT practices and procedures. The paper also includes summaries of a number of experimental studies, such as an examination of the influence of time pressure on performance, the effects of social loafing on team NDT performance, and automation bias in human-computer interactions while evaluating NDT data.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Group characteristics; Individual differences; Task characteristics

Bertovic, M., Gaal, M., Müller, C., & Fahlbruch, B. (2013). *Investigating human factors in manual ultrasonic testing: Testing the human factor model*. Paper presented at the 4th European-American workshop on reliability of NDE, Berlin, Germany. http://www.ndt.net/article/reliability2009/Inhalt/th4a3.pdf

The authors present a model of human factors influences on ultrasonic inspection performance using a socio-technical systems approach. They tested parts of the model with an experimental study where 10 experienced inspectors were asked to perform manual ultrasonic inspection on a reactor pressure vessel replica under three experimental conditions intended to model low, middle, and high time pressure. Additionally, mental workload, stress resistance, stress reaction, organizational context and experience of the inspectors were also measured. Performance was measured in terms of the scattering of the results, where larger scattering corresponded to lower measurement precision. Perceived time pressure (i.e. temporal demand) and mental workload significantly influenced the quality of the inspection. The inspectors performed better when they perceived temporal demand and mental workload to be low, and more experienced inspectors performed better than less experienced inspectors. Contrary to expectation, perceived time pressure (temporal demand) was more indicative of performance than the actual experimental condition of low, middle, or high time pressure.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Individual differences; Task characteristics

Bertovic, M., Müller, C., Ewert, U., Fahlbruch, B., Pitkänen, J., & Ronneteg, U. (2012). *Consideration of human factors in the application of human redundancy and automation of the defect*

detection process. Paper presented at the 9th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, Seattle, WA, USA.**

This abstract discusses ways to consider human factors in the application of nondestructive testing methods. It expresses that understanding the identified risks and implementing the right preventative measures is necessary to ensure errors will not reoccur. The authors discuss approaches for identifying potential errors made by humans, determining their causes, empirically testing hypotheses, and optimizing parts of the NDT system and procedures. The authors also communicate that some measures used to prevent human, technical, or organizational errors, such as human redundancy or automation, can lead to new error sources and new risks.

Domain: Generic
Paper Type: Informational
HF Elements: Individual differences; Task characteristics

Bertovic, M., Müller, C., Fahlbruch, B., Pitkänen, J., & Ronneteg, U. (2010). *Human factors approach to the reliability of NDT in nuclear waste management in Sweden and Finland*. Paper presented at the Proceedings of the 8th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components.

This paper explains how a Failure Modes and Effects Analysis (FMEA) technique can be used to identify possible human failures when evaluating NDE methods. The authors evaluated four different NDE methods. Each method was broken down using the FMEA technique and was analyzed in steps. The results identified potential human errors, the causes of errors, and consequences of those errors. The results allowed experts to prepare a risk priority ranking table of the FMEA results for all the NDE methods that were analyzed. This method highlighted causes of errors due to procedure quality, software limitations, individual differences, and technology.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Individual differences; Task characteristics

Brown, S. J. (1985). *Residual-life assessment, nondestructive examination, and nuclear heat exchanger materials: Proceedings of the 1985 pressure vessels and piping conference*. New York, NY: American Society of Mechanical Engineers.

This author proposes that most variation in NDE performance is not due to the human operator, but rather, it is the NDE process parameters variation outside of the characteristic boundary conditions. The author identifies 5 controlling factors that influence NDE reliability: 1) Physics of flaw; 2) Applicability of the NDE method; 3) Inspection materials; 4) Inspection equipment; and 5) Human factors. Human factors are listed last because unless all other factors are operating correctly, the human "doesn't have a chance."

Domain: Generic
Paper Type: Theoretical
HF Elements: Task characteristics

Carter, L., & McGrath, B. (2013). ***We know how to improve inspection reliability - why don't we do it?*** **Paper presented at the 5th European-American workshop on reliability of NDE Proceedings, Germany.**

This paper summarizes the results of the PANI projects, which sought to quantify the performance of manual UT for inspectors outside the nuclear industry. The authors primarily discuss the impact that the client organization, the NDE organization, and individual inspector have on reliability of inspections. The results showed that many organizational and task elements need to be improved (e.g. culture, work process, adequate documentation, available time). There is also a brief mention of physical environment impact on reliability.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Task characteristics

Christner, B. K., Long, D. L., & Rummel, W. D. (1988). NDE detectability of fatigue-type cracks in high-strength alloys: NDI reliability assessments.

This article discusses the critical flaw sizes that have been found in space shuttles and other space hardware. The authors objective was to survey NDE practices and capabilities and to generate quantitative NDE flaw detection data. Contractors were sent to evaluate the inspection procedures using test specimens containing fatigue cracks of various sizes. Procedures for liquid penetrant, eddy current, and ultrasonic NDE were tested. The inspectors that tested the procedures were selected from the current skill certification list at each facility. Each inspector was observed for techniques, habits and tendencies which may have affected performance. A total of 85 inspection sequences were completed that presented a total of 20,994 fatigue cracks to 53 different inspectors. The data shows that the minimum size crack that could be reliably detected was estimated and used to update previous flaw detectability assumptions. The manual and automated scan eddy current inspection procedures demonstrated a similar flaw detection capability. The automated procedure provided more consistency in the signal amplitude that detected flaw length. The manual inspections were slightly less consistent by missing more larger flaws, but the inspectors were able to detect more of the smaller flaws than the automatic inspection. The penetrant inspections determined the effects of different materials and material combinations on flaw detection capability. The penetrant results showed that the effectiveness of the inspection process and the form of developer used, affected the results much more than the sensitivity level of the penetrant. The authors note that the selected inspectors, the tasks performed, and procedures used influenced inspection performance.

Domain: Aviation
Paper Type: Informational
HF Elements: Organizational factors; Individual differences; Task characteristics

Cumblidge, S. E. (2007). An assessment of remote visual methods to detect cracking in reactor components.

This article summarizes a study that examined the variables influencing the effectiveness of remote visual NDE. The variables of interest were lighting techniques, camera resolution, scanning speed/camera movement and magnification, and the crack size. The variable that had the largest effect on detection reliability was crack opening displacement, such that cracks over .004 inches are easier to detect. The results showed that the most important factor affecting quality of inspection for cracks in the .0008-.004 inch range was scanning speed such that high speeds severely limited crack detection. The second most important factor was lighting. High resolution and a greater pixel count were also found to impact inspection quality.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Physical environment; Task characteristics

Dennis, M. (2009). Improving NDE reliability through performance demonstration and attention to human factors.

This presentation describes 30 years of changes in NDE qualification requirements, including widespread adoption of performance demonstration programs. It highlights lessons learn from operating experience, particularly that NDE reliability depends on proper implementation of procedures in the field. The presentation also outlines a guidance document produced by EPRI in 2009 that provides advice for utilities on preparing for efficient and reliable NDE.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Task characteristics

Dickens, J. R. (1992). Human factors in nondestructive testing. In D. E. Bray & D. Mcbride (Eds.), *Nondestructive testing techniques* (pp. 747-752). New York, NY: John Wiley and Sons, Inc.

The authors argue in this paper that individual differences, namely boredom and vigilance, along with environmental variables (e.g. presence of others, illumination) all can have a significant impact on human performance during NDE. In addition, the authors briefly mention that organizational structure may plays a role in determining the physical environment that the NDE personnel face. They provide anecdotes from two aviation events that support their argument. They conclude by saying that NDE reliability will improve when boredom, vigilance, and environmental influences are taken into account.

Domain: Aviation
Paper Type: Theoretical
HF Elements: Organizational factors; Physical environment; Individual differences

Dickens, J. R., & Bray, D. E. (1994). Human performance considerations in nondestructive testing. *Materials evaluation, 52*(9), 1033-1041.

This paper provides an overview of the types of human factors that can affect the reliability of nondestructive testing. The authors discuss factors intrinsic to the NDE inspector, such as knowledge, skill, and motivation, and factors extrinsic to the inspector, such as supervision, environment, equipment, and procedures. The authors describe the tradeoffs between Type I and Type II errors, and the role of the engineer as an indirect contributor to inspection reliability. For example, engineering decisions about selecting an inspection process and what to include in the inspection procedure can influence the extent to which an NDE inspector will be capable of detecting a crack when one exists.

Domain: Generic
Paper Type: Informational
HF Elements: Physical environment; Individual differences; Task characteristics

Doctor, S. R., Becker, F. L., Heasler, P. G., & Selby, G. P. (1983). *Effectiveness of US inservice inspection technologies: A round robin test*. Paper presented at the Proceedings of a Specialist Meeting on Defect Detection and Sizing.

This paper summarizes the results of testing to determine the probability of detecting cracks in different types of pipe welds using manual ultrasonic testing (UT). The results suggest that there is substantial variability in the effectiveness of UT, depending on the type of weld, the equipment used, and the quality of the procedures. However, even when equipment and procedures were identical, there was still significant variability in detection probability between different teams of NDE examiners. The authors recommend that crack detection reliability should be qualified via demonstration testing.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Task characteristics

Doctor, S. R., Becker, F. L., & Selby, G. P. (1982). Effectiveness and reliability of US inservice inspection techniques: Pacific Northwest Lab., Richland, WA (USA).

This article discusses a round robin test to measure the effectiveness and reliability of in-service inspection (ISI) procedures of light water reactor systems. The round robin test involved six inspection teams. The first objective was to determine the reliability and effectiveness of in-service inspection procedures and the second objective was to define the source and magnitude of inspection uncertainties. The teams performed the detection scan and the results were recorded. The authors then manually examined the data to identify errors. The conclusions drawn from the round robin data were: 1) Large differences in performance between teams, all meeting the ASME Code, were observed; 2) The care and accuracy of plotting the axial position of indications appears to be an indicator of performance effectiveness; 3) Access to the flaws had no statistical significance for the clad ferritic pipe; 4) Little difference was noted between the laboratory and difficult conditions as applied in the test; 5) Performance improvements resulting from the "improved procedure" were modest, except for the clad ferritic case where improvement was significant; and 6) Inspection of clad ferritic pipes can be highly effective, given inspection sensitivity.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Group characteristics; Individual differences

Doctor, S. R., Cumblidge, S. E., Taylor, T. T., & Anderson, M. T. (2013). Technical basis supporting ASME Code, Section XI, Appendix VIII: Performance demonstration for ultrasonic examination (pp. 129).

This report presents the technical rationale for the requirements specified in ASME Code, Section XI, Appendix VIII. It describes the evolution of in-service inspection qualification requirements in the United States, and summarizes how procedure, personnel, and equipment qualification demonstrations contribute to ensuring the effectiveness of non-destructive examinations.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Task characteristics

Drury, C. G. (2001). Human factors in aircraft inspection.

This report describes models of the major functions of the human inspector and applies these within a framework of inspection reliability. The author used the models to define good practices necessary to continuously improve inspection performance. The report also covers the modeling and improvement of aviation inspection performance and treating human factors as an explicit aspect of inspection capability. The report communicates that in the aviation industry, reliability of the inspection system must be known in order to schedule safe inspection intervals. This paper has sections discussing NDI techniques, its reliability and the probability of detection (POD), and the relative operating characteristic (ROC) in the aviation domain. The author states that decision making, inter-inspector variably, time availability for task completion, training, environmental interventions, and social interventions (i.e., management and peer interactions and working hours) were factors that could affect inspection performance.

Domain: Aviation
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Drury, C. G. (2002). Good practices in visual inspection.

The focus of this report is good human factors practices for visual NDE. A hierarchical task analysis was used to break down the task of visual NDE and find points at which the demands of the task were ill-matched to the capabilities of human inspectors. Several areas were specifically discussed at length, including: 1) Time limits on continuous inspection performance; 2) The visual environment; 3) Posture and visual inspection performance; 4) The effect of speed of working on inspection accuracy; 5) Training and selection of inspectors; and 6) Documentation design for error reduction. Good practices were derived from several sources: 1) Reference information on aircraft visual inspection; 2) Extensive literature on factors affecting visual inspection outside of the aviation industry; 3) Observation and task analysis of aircraft inspection tasks covering a wide range of different activities.

Domain: Aviation
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Drury, C. G., Green, B. D., Chen, J., & Henry, E. L. (2006). Sleep, sleepiness, fatigue, and vigilance in a day and night inspection task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 50*(1), 66-70. doi: 10.1177/154193120605000115

This paper presents an experimental study of the effects of fatigue factors on performance and stress in a fluorescent penetrant inspection task. The experiment included 80 participants from the local community from different industrial occupations. The authors used a between-subjects design to test shift, time on task, task duration, rest breaks, and lighting. The results did not demonstrate a significant relationship between any of the fatigue-related variables and performance. There was a small decrease in probability of false alarms as time on task increased. Day shift participants who took breaks had a faster inspection speed than their counterparts without breaks, whereas night-shift participants with breaks were slower than their counterparts without breaks. Breaks were associated with increased speed for day shift participants, but decreased speed for night shift participants. Lighting also appeared to improve speed when it matched the outside lighting; brighter light for day-shift and dimmer for night-shift. Overall, the data demonstrated a good fit to standard probability of detection curves, showing increased probability of detection as crack length and crack contrast increased.

Domain: Aviation
Paper Type: Empirical
HF Elements: Physical environment; Individual differences

Drury, C. G., & Prabhu, P. (1994). Human factors in test and inspection. In G. Salvendy & W. Karwowski (Eds.), *Design of work and development of personnel in advanced manufacturing* (pp. 355-401). New York: John Wiley & Sons.

This chapter discusses the human elements of performing a generic test or inspection. It describes the tasks involved in carrying out an inspection, and the types of errors that can happen at various stages. Human behavior is discussed in terms of knowledge-, rule-, and skill-based across five basic tasks in testing and inspection: setup, present, search, decision, and response. The chapter also reviews human machine interactions in automated inspection activities, and briefly discusses the importance of organizational design for effective inspection.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Task characteristics

Drury, C. G., Prabhu, P., & Gramopadhye, A. (1990). *Task analysis of aircraft inspection activities: Methods and findings*. Paper presented at the Human Factors and Ergonomics Society Annual Meeting.
This paper presents a task analysis of inspection activities in commercial aviation. The authors present a task description, followed by an analysis of human and system errors that may occur at each stage of the task, and finally recommendations for improving aircraft inspection. The recommendations for improving inspection focus on strategies for changing the system to fit the inspector, and changing the inspector to fit the system.

Domain: Aviation
Paper Type: Empirical

HF Elements: Task characteristics

Electric Power Research Institute. (1988). Human performance in NDE inspections and functional test.

This report examines factors that influence human performance in different types of non-destructive testing (e.g., eddy current, ultrasonic, in-service inspection, and functional testing), and provides recommendations for improving human performance. The investigation consisted of qualitative analysis of industry procedures and instructions, training materials, research reports, interviews with experts, and first-hand observations of task performance. The recommendations focus on improving the preparation of written instructions, developing guidance for operator-control interface design, performing analyses of eddy current and ultrasonic performance data, assessing eddy current signal interpretation strategies and developing more effective display designs, reducing the complexity and defining optimal strategies for manual ultrasonic inspection, and assessing human factors issues in automated data scanning and recording for ultrasonic inspections.

Domain: Nuclear
Paper Type: Experiential
HF Elements: Organizational factors; Individual differences; Task characteristics

Electric Power Research Institute. (1990). Cognitive correlates of UT inspection performance.

This paper focuses on assessing the relationship between cognitive strategies and UT performance. The authors identified a list of cognitive elements likely to be important to UT performance by reviewing previous research on cognitive processes and by reviewing actual processes used to complete UT. The study found that using a combination of certain cognitive elements and specific signal characteristics in UT inspection improved performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Individual differences

Electric Power Research Institute. (1992). Effect of decision making on UT exam performance.

This report discusses human information processing and the decision making that is required in an ultrasonic examination. A previous EPRI study (NP-6675) identified elements that were considered important to human information processing and decision making and found that these elements correlated with examination success and accurate flaw detection. The objective of this report was to transform the results of previous research findings and expert recommendations into a practical decision making strategy for ultrasonic examinations and evaluate the impact of using this strategy on examination performance. A decision aid was developed to overcome some of the examiners' limitations in information processing and decision making. The aid was in the form of a checklist that provided a means of noting signal characteristics and providing feedback on performance during training. The results were compared with and without the aid and recommendations were made by a panel of experts. The study findings indicated that steps taken to improve examiner decision making can significantly improve ultrasonic detection performance. The use of the decision aid increased ultrasonic defect detection performance by 25%. EPRI's recommended next steps were to develop and evaluate more complete implementation of strategy-based ultrasonic examinations.

Domain: Nuclear
Paper Type: Informational
HF Elements: Individual differences

Electric Power Research Institute. (1993). Strategy based training for NDE.

The purpose of this study was to develop and evaluate a strategy-based training course for detecting IGSCC in pipe welds. The IGSCC training was provided within the framework of a specific fault detection strategy, and this strategy was reinforced through use of performance aids, progressive part-task training, and providing feedback at each stage of the strategy development. After implementation of the strategy-based training, inspector qualification rates increased from an average of 34.4% to 54.9%, and inspectors rated the effectiveness of the training higher than in previous years.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Task characteristics

Electric Power Research Institute. (1999). Swedish human factors study of NDE.

This report documents the cooperative efforts between Sweden's SKI organization and EPRI. Specifically, it discusses results obtained by incorporating an EPRI developed testing program, Dynamic Inspection Aptitude Test (DIAT) into the Swedish human factors program. DIAT is software program designed to predict the success of NDE personnel in successfully passing a performance demonstration by dynamically measuring the combination of five aptitudes: general cognitive ability, abstract reasoning, spatial visualization, pattern recognition, and stress tolerance. The study found that age, experience and DIAT score did not consistently predict the performance of the candidates.

Domain: Nuclear
Paper Type: Theoretical
HF Elements: Individual differences

Enkvist, J., Edland, A., & Svenson, O. (1999). Human factors aspects of non-destructive testing in the nuclear power context.

This report is a review of human factors literature relevant to NDE. The authors' purpose was to determine what has been done and what still needs to be done to improve performance in NDE. An overview of NDE and the associated problems are provided. In addition, the authors highlight research results and discuss their conclusions based on the research. Regarding conclusions, the authors specifically address the role the organization plays, the working conditions and the qualification of inspectors. Suggestions for future research include research with proper experimental design in the areas of psychosocial environment, the effect of non-ergonomically designed equipment, the impact of organizational characteristics on inspection performance, and the implications of using different personnel selection strategies.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Group characteristics; Individual differences; Task characteristics

Enkvist, J., Edland, A., & Svenson, O. (2000). Operator performance in non-destructive testing: A study of operator performance in a performance test: Swedish Nuclear Power Inspectorate, Stockholm (Sweden).

This was an empirical study focused on three factors that may impact inspector UT performance including: 1) The importance of following a procedure; 2) The role of experience; and 3) the utility of personnel selection tests. Sixteen inspectors participated in this study and all were certified to perform manual UT. Participants were asked to perform detection and characterization on test pieces. The inspectors also completed several ability tests and questionnaires that assessed their strategy and state of mind. It was found that the ability tests did not predict performance. Instead, motivation and attitude were important predictors of performance. Decision strategy and time spent on task also impacted performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Individual differences

Enkvist, J., Edland, A., & Svenson, O. (2001). Effects of time pressure and noise on non-destructive testing. Stockholm, Sweden: Swedish Nuclear Power Inspectorate.

This report presents an experimental study examining the effects of stress (time pressure and noise) on manual ultrasonic testing performance. The study included 21 qualified inspectors performing manual ultrasonic testing on six test pieces with manufactured flaws. The authors hypothesized that stress would have a negative impact on performance, but found that when inspectors were in the high stress condition of the experiment they actually performed better than in the low stress condition. The authors concluded that performance is affected by arousal, and the stress condition in the experiment actually produced optimal levels of arousal, thereby improving performance. It was also observed that the group of inspectors who received the stress condition first performed better than the other group of inspectors in both the high and low stress conditions. The authors suggest that this effect may be due to inspectors developing more efficient performance patterns during the high stress condition on the first day, and those patterns helped performance on the second day.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Physical environment; Individual differences

Farley, J. M. (2004). Best practice in the application of NDT - an update.

This paper provides an overview of international developments in standards, certifications, and qualifications to achieve and assure quality in NDE. For instance, the paper discusses the evolution of training and qualification standards in the U.S. and Europe. The author notes that while human factors clearly influence the reliability of NDE, it may be the weakest link in the NDE quality chain because there is not a well-developed infrastructure for assuring quality of human factors in NDE. The author focuses on motivation as an important human factor in NDE, and suggests the need for a "code-of-practice" on employment conditions for NDE staff. In addition, management and planning is discussed as an important but not always recognized component of assuring NDE quality.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Individual differences

Farley, J. M. (2008). EFNDT guidelines on the overall NDT quality system in Europe.

This paper presents a pictorial representation of the "NDT quality chain" (i.e., elements that contribute to the quality of NDT inspection), with the foundational pieces being procedure, personnel, equipment, and human factors. It goes on to identify infrastructure elements such as standards, best practices, training guidelines, and qualification programs in place to support quality NDT. The authors giver ecommendations regarding infrastructure elements that should be used and when they should be used to achieve high quality NDT.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors

Federal Aviation Administration. (2005). Correlates of individual differences in nondestructive inspection performance.

This report addresses various topics including: 1) A review of NDI research programs conducted by the Air Force, the nuclear power industry and the FAA; 2) A review of research related to individual difference variables in inspection and vigilance; and 3) The direction of the NDI performance research to be performed under an FAA/AAM contract. In general, most of the literature review captured in this report emphasizes the lack of findings in terms of correlation between individual differences and NDI. However, the authors identify a few studies in which individual differences did show a positive correlation with either inspection or vigilance performance (e.g. introversion, field independence, locus of control). Thus, the authors concluded that at least some of the variance in performance can be accounted for and that using tests covering a wider range of abilities is warranted. They suggest that the most promising approach may be to select tests based on a detailed analysis of task behaviors for a specific task and produce a selection battery more likely to correlate with performance on the intended task.

Domain: Aviation
Paper Type: Informational
HF Elements: Individual differences

Fucsok, F., Müller, C., & Scharmak, M. (2002). *Reliability of routine radiographic film evaluation - an extended ROC study of the human factor*. Paper presented at the 8th European Conference on Non Destructive Testing, Barcelona, June.

This paper reports on one part of a round-robin study conducted in Croatia and Hungary examining probabilities of detecting defects when evaluating X-ray films of welds. The participating inspectors were divided into four groups based on years of experience, and no statistical differences were observed in the receiver operating characteristic (ROC) reliability curves for each of the different groups. However, the authors noted that the group with over 25 years of experience had the lowest number of false indications and lowest scatter (i.e., better performance). In addition, there was still substantial variability observed between inspectors with the same level of experience.

Domain: Generic
Paper Type: Empirical
HF Elements: Individual differences

Gardner, W. E., & Murgatroyd, R. A. (1989). Quantitative evaluation of NDE reliability. United States: Plenum Press.

This paper provides an overview of an NDE reliability program in the U.K. The paper discusses use of a human error analysis method, called SHERPA, to identify opportunities for human error in proceduralized tasks like NDE. The paper also describes a retrospective analysis of data from the PISC II international round robin study, which examined the effects of mis-location errors on defect detection.

Domain: Nuclear
Paper Type: Informational
HF Elements: Individual differences; Task characteristics

Gasset, R. (2012). Human factors in non-destructive testing. *The Shot Peener, 26,* 12-14.

This article briefly discusses the HF elements within the aviation industry that may impact the reliability with which components are processed and inspected. The author is relaying his previous experience as a FAA repairman. He identifies twelve human factors, also called the "Dirty Dozen", that can cause human error. They include: lack of communication, complacency, lack of knowledge, distraction, lack of teamwork, fatigue, lack of resources, pressure, lack of assertiveness, stress, lack of awareness, and norms. The author suggests that the consideration of human factors will often lead to an efficient and effective NDT process.

Domain: Aviation
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Group characteristics; Individual differences; Task characteristics

Harris, D. H. (1990). Effect of human information processing on the ultrasonic detection of intergranular stress-corrosion cracking. *Material Evaluation, 48*(4), 475-480.

This paper describes a study examining human information processing techniques employed during manual ultrasonic inspections. Twenty six participants from various domains, including organizations that provide inspection services and nuclear facilities, were asked to examine sample pipe welds. Tape-recorded commentary from 139 pipe-weld inspections were qualitatively analyzed to identify types of information processing techniques used in the course of the inspection. Nine information processing techniques were identified. The 9 techniques along with 7 signal characteristics were analyzed to determine their relationship to inspection performance. Seven of the 9 information processing factors were correlated with successful inspections. A step-wise regression analysis further revealed that the following factors accounted for 44% of the variability in inspection performance: avoiding early conclusions, testing an explicit hypothesis, using if-then logic, avoiding disregard of evidence, and signal continuity. The number of signal characteristics addressed in the inspection was positively correlated with performance. The authors conclude that human information-processing factors are important to inspection success and that a well-defined information-processing strategy and related training may improve effectiveness of UT inspection performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Individual differences; Task characteristics

Harris, D. H. (1997). *Prediction of inspection performance with a dynamic, computer-based, multi-aptitude test*. Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting. http://pro.sagepub.com/content/41/1/574.abstract

This conference paper explores an approach to predict job performance of NDE inspectors. A computer-based, Dynamic Inspection Aptitude Test (DIAT), was designed to predict job performance. Validity studies of DIAT were conducted in which the task was to detect intergranular stress-corrosion cracking in the piping of nuclear power plants. The aptitudes assessed were general cognitive ability, abstract reasoning, and spatial visualization. The Dynamic Inspection Aptitude Test (DIAT) consisted of 36 items, each administered and automatically scored by a computer. The participants had 36 minutes to complete the 36 items. Results showed the correlation coefficient between the DIAT scores and the ultrasonic NDE performance measures was 0.51. The authors conclude that the Dynamic Inspection Aptitude Test (DIAT) might be valid and useful for the selection of personnel for NDE jobs. The paper also states that the use of DIAT can result in cost savings for training and the cost associated with personnel that would be used for screening and selecting qualified candidates.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Individual differences

Health and Safety Executive. (2000). Part 1: Manual ultrasonic inspection. *Best practice for the procurement and conduct of non-destructive testing*. United Kingdom.

This report discusses best practice guidance for conducting non-destructive testing (NDT) and procurement of NDT services. In particular, the guidance provides recommendations for addressing common difficulties in detecting flaws, such as identifying the defect type, component geometry, component material, surface finish and coatings, and access to the test site. There are also recommendations for inspector performance, such as ensuring inspectors have appropriate training, opportunities to practice on realistic test pieces, benign environmental conditions, and adequate time to complete the inspection. Finally, the report suggests ensuring that the NDT requirements are well defined when procuring NDT services, and the responsibilities of the purchaser and supplier are clearly defined in the contractual arrangements.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Task characteristics

Herr, J. C., & Marsh, G. L. (1978). NDT reliability and human factors. *Materials evaluation, 36*(13), p. 41-46.

The authors summarize the results of three different NDI studies. All three studies indicated large performance variations between inspectors. The authors go on to focus on reducing the effects of human factors on performance. They suggest that selection and training of personnel are a large contributor to an effective NDE program. They state that training programs must incoporate feedback from production inspections to ensure trainees are familiarized with the types of indications typically found. In addition, the authors propose that well-defined accept/reject criteria will also help improve the reliability of NDI. Environmental aspects are mentioned as an area for improvement (light, heat, etc.). They further suggest that common reference standards for equipment set-up and calibration and some standardization of equipment would help eliminate human factors issues. The authors also stress that management must consider NDI an integral and important process. This along with having motivated employees can help NDI reliability.

Domain: Generic
Paper Type: Experiential
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Holstein, R., Bertovic, M., Kanzler, D., & Müller, C. (2013). *NDT reliability in the organizational context of service inspection companies*. Paper presented at the 5th European-American workshop on reliability of NDE, Berlin, Germany.

This paper discusses the organizational factors that are relevant to non-destructive testing, through a review of relevant literature and a qualitative study of material testers in Germany. The authors state that the process of providing an NDT service should take into account inspector selection, information processing, motivation, training, experience, and procedures. Further, these factors should be considered in three stages of the NDT service: the business process, information process, and delivery process.

Domain: Generic
Paper Type: Experiential
HF Elements: Organizational factors

Kauppinen, P. (1988). *Nordic efforts in the field of NDE reliability*. United States: American Society for Metals.

This paper summarizes the results of four reliability studies carried out in Nordic countries. The studies involved various NDE techniques including UT, radiographic, eddy current, liquid penetrant and magnetic particle inspection. The aim of this Scandinavian research program is to improve the reliability of nondestructive testing by identifying and controlling physical and psychological factors. Early results indicated that the practical experience of inspectors, specifically performing at least 2-3 months of UT yearly, is correlated with better performance. General educational background does not seem to be important. The study suggests that certification of inspectors and increasing inspection time improves performance.

Domain: Generic
Paper Type: Empirical
HF Elements: Individual differences

Kettunen, J. (1997). Beliefs concerning the reliability of nuclear power plant in-service inspections: Finnish Centre for Radiation and Nuclear Safety (STUK), Helsinki (Finland).

The aim of this research was to study belief systems held by the officials responsible for the planning and supervision of NDE operations within the Finnish nuclear industry. They were asked to express their opinions on: 1) The reliability of NDE methods; 2) The factors influencing reliability of in-service inspections; and 3) The degree of reliability of the current inspections operations. Another goal was to assess the adequacy of officials' beliefs. Data was collected by interviewing representatives from Finnish power companies, independent inspection organizations, and the Finnish Center for Radiation and Nuclear Safety (STUK). The overall reliability of NDE methods was considered very high among the representatives of power companies and inspection organizations but less so by STUK. There was a strong belief by all groups that the reliability of in-service inspections depends on various human and organizational factors including inspector attitude, an understanding of inspection items, inspection costs, timetables, personnel qualification, and radiation. The current inspection activities in the Finnish NPPs were generally considered to be of high quality.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors

Krebs, W. K. (2003). Human factors aviation maintenance: Program review FY03. Washington, DC: Federal Aviation Administration Office of the Chief Scientist for Human Factors.

This report was a collection of articles regarding work being done in the Human Factors Aviation Maintenance program. One article titled, "A Demographic Profile of Nondestructive Inspection and Testing (NDI/NDT) Personnel: A Preliminary Report," specifically addresses the individual difference in vision capability. The authors conducted a survey among 3 airlines to determine what type of NDT method is used most often and what visual standards are in place. The most frequently performed NDI/NDT procedure is eddy-current inspection, and the least often performed procedure is radiographic inspection in the facilities surveyed to date. Vision testing procedures differed between the three airlines surveyed. Additional research is ongoing to identify the vision requirements associated with the most visually demanding tasks performed by these workers. Once the requirements are properly assessed, appropriate vision standards and screening procedures can be developed.

Domain: Aviation
Paper Type: Empirical
HF Elements: Organizational factors; Individual differences

Krishnamoorthy, K., Eng, P., & Energy, A. (2009). Quality assurance in NDT. *NDT in Canada*.

This article discusses factors that influence quality assurance in NDT and emphasizes the importance of having a Quality Management System. The paper communicates key roles of human factors in the quality and reliability of NDT. The authors state that environmental conditions (e.g. poor lighting), stress and fatigue of personnel, inadequate site conditions, unexpected equipment failures, and noise can all affect the performance of NDT tasks. Some key elements of quality assurance the authors highlight are personnel qualification and certification, training and motivation, facilities and equipment, procedures, codes and standards, calibration standards, work management and maintaining records of work tasks. The authors conclude that the overall quality and effectiveness of NDT depends on the pro-active planning and execution by management. The authors recommend implementing a Quality Management System that focuses on NDT and considers the elements that were discussed in the paper.

Domain: Nuclear
Paper Type: Informational
HF Elements: Physical environment; Individual differences; Task characteristics

Leach, J., & Morris, P. E. (1998). Cognitive factors in the close visual and magnetic particle inspection of welds underwater. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 40*(2), 187-197. doi: 10.1518/001872098779480460

This study examined the accuracy of NDE carried out by commercial underwater divers. They looked at both the technique of close visual inspection and magnetic particle inspection (MPI) via two experiments. In both experiments experienced NDE divers performed inspections and completed a battery of cognitive tests. For visual inspection, the error rate was 47% and performance was correlated with GEFT (Group Embedded Figures Test). In the MPI experiment, 25% of the targets were not detected and again GEFT correlated with performance. Performance on the visual search test (VST) was also correlated with crack size estimation performance.

Domain: Offshore Oil and Gas
Paper Type: Empirical
HF Elements: Individual differences

Lewis, W. H., Sproat, W. H., Dodd, B. D., & Hamilton, J. M. (1978). Reliability of nondestructive inspections: DTIC Document.

This report describes an Airforce Logistics Command program that uses NDI procedures to determine the reliability of Air Force Nondestructive Inspections (NDI). The objective of the program was to determine the existing capability of how NDI inspectors detect flaws under field and depot conditions. Approximately 300 Air Force technicians performed ultrasonic, eddy current, penetrant and radiographic nondestructive inspections (NDI) on the aircraft structural samples. The individual results were recorded in terms of "finds", "misses" and "false calls". The authors state that Air Force NDI needs improvement in several areas in order to meet existing requirements for inspection of Air Force hardware. Those areas include operations and optimization for managing NDI technicians, equipment availability, the techniques and procedures used among technicians, and the variance of performance among individual technicians.

Domain: Aviation
Paper Type: Empirical
HF Elements: Individual differences; Task characteristics

Light, G. M., Holt, A. E., Polk, K. D., & Clayton, W. T. (1994). Simultaneous use of multiple human senses to actively interpret NDE signals for improving the precision of process control and inspection. In E. Usui (Ed.), *Advancement of intelligent production* (pp. 144-149). Amsterdam: Elsevier.

This paper discusses a technology to convert electronic signals generated by NDE equipment into audible information. The authors argue that providing information both visually and aurally can enhance an inspector's ability to detect flaws.

Domain: Generic
Paper Type: Informational
HF Elements: Task characteristics

Lilley, J. (2006). The integration of plant condition assessment with risk management programmes.

This report talks about risk-based inspections and risk-based methods in supporting NDT procedures. In particular, the author applies probability of detection (POD) curves to risk based methods. The author discusses the history of POD curves and how POD curves are developed. The author also states how expert panels are used and the effect of field conditions on POD curves. The author mentions how human factors like lack of concentration, forgetting materials, working long hours, being poorly trained, or misinterpreting data could influence NDT performance.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Individual differences

Lindberg, J. (2009). Nondestructive evaluation: Guideline for conducting ultrasonic examinations of dissimilar metal welds.

This report provides guidance to both vendors and utilities regarding the planning and execution of dissimilar weld exams in such a way as to minimize the occurrence of human errors. Guidance regarding physical environment, organizational environment, training, equipment, and communication is provided. In addition, the report specifies the roles of the utility and the examination vendor and the collaboration between the two. Both needed and good practices are provided to assist utilities and vendors in implementing effective and reliable DMW NDE.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Task characteristics

Luk, B. L., & Chan, A. H. S. (2007). Human factors and ergonomics in dye penetrant and magnetic particles nondestructive inspection methods *Engineering Letters*.

This report focuses on human factors elements which could affect the reliability of dye penetrant inspection (DPI) and magnetic particles inspection (MPI) testing. It discusses each method and reviews related issues of ergonomics, safety, and health. It mentions the human abilities and skills required (e.g. cognitive and perceptual abilities) along with the ergonomics, personal safety, and health problems that inspectors may encounter when performing inspection tasks. The authors concluded that inspectors were not aware of their personal safety and health. Inspectors' posture and use of safety protocols (e.g., using certain chemicals with proper ventilation and personal protective equipment) werer recommended as areas for improvements.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Individual differences

Luk, B. L., & Chan, A. H. S. (2008). Human factors and ergonomics for nondestructive testing. In A. H. S. Chan & S.-I. Ao (Eds.), *Advances in industrial engineering and operations research* (pp. 127-142). United States: Springer.

This book section describes dye penetrant inspection, magnetic particles inspection, ultrasonic inspection, and eddy current inspection and the human factors elements that may affect the reliability of these methods. Inspectors' vision, physical strength , working posture, and the lighting in the environment can affect inspection performance. The authors identify potential risks and hazards of performing these tasks and recommend changes that should be considered. The authors also mention precautions regarding certain chemicals and ventilation issues in the work environment and their potentially hazardous effects on inspectors.

Domain: Nuclear
Paper Type: Informational
HF Elements: Physical environment; Individual differences

McGrath, B. (2008). Programme for the assessment of NDT in industry. Cheshire, United Kingdom: Health and Safety Executive.

The report describes an empirical effort to assess the human factors aspect of manual UT and how they may affect performance. Specifically, the experimental work was performed with the objectives of investigating inspectors' decision making processes and the correlation of ultrasonic performance with inspectors' scores on ability tests and personality scales. Some of the more noteworthy findings from the study are: 1) Better performance was associated with higher scores on the mechanical comprehension test and lower scores on the personality scales measuring original thinking and cautiousness; 2) The inspectors demonstrated a good understanding of the basic principles of UT that are frequently used, but those principles that are important but used less often were not understood as well; and 3) High performers go about their inspection methodically. The authors concluded with recommendations based on the study concerning selection, training, procedures, organizational culture and the inspection process.

Domain: Generic
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

McGrath, B. (2012). *The lessons of PANI for ultrasonic and NDE in general*. Paper presented at the 8th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, Berlin, Germany.

This paper summarizes key results from the Programme for the Assessment of NDE in Industry (PANI), sponsored by the UK's Health and Safety Executive. The purpose of the project was to assess the effectiveness of NDE as applied outside of the nuclear industry. In particular, the PANI 3 report addresses the influence of human factors on NDE performance. The results from PANI 3 suggest that inspector performance on NDE test pieces was related to their performance on a test of mechanical comprehension, and scores on personality measures of original thinking and conscientiousness.

Domain: Generic
Paper Type: Informational
HF Elements: Individual differences

McGrath, B., & Carter, L. (2013). *Improving inspection reliability through operator selection and training*. Paper presented at the 5th European-American workshop on reliability of NDE Proceedings, Germany.

This paper summarizes a series of three projects that investigated the manual ultrasonic testing and inspector performance. Specifically, it focuses on the issues raised by the Programme for the Assessment of NDE in Industry (PANI) projects that relate to inspector training and inspector selection. Variables of interest were the inspectors decision making, self-knowledge and individual characteristics. The authors suggest that inspector awareness of their personality and behaviors can impact ultrasonic task performance. The authors make recommendations for improving inspection reliability focused on training and inspector preparation prior to attending a site inspection.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Individual differences

McGrath, B., & Wheeler, J. (2009). *PANI and the role of the written procedure*.

This study summarized the 3 PANI studies. The authors re-analyzed the results of the PANI study in terms of the role of the written procedure. Throughout the three PANI projects, the written procedure was really only considered as to whether it was able to detect the defects in the test pieces. It was only when the analysis of the PANI 3 results highlighted that the best performing inspectors performed the inspection in a methodical way and that many inspectors did not necessarily follow the procedure, that consideration was given to the format and layout of the procedure. The authors stated four conclusions based on their analysis: 1) The inspection procedure is key to a reliable inspection; 2) The best performing inspectors perform an inspection in a methodical way and so inspection procedures should be written to promote their systematic application; 3) The procedure needs to be designed to assist the inspector in applying the inspection in the desired way. Procedures should be commensurate with the level of training of the inspectors; and 4) Inspectors should be briefed on procedures to ensure terminology is understood and any special conditions are highlighted.

Domain: Generic
Paper Type: Theoretical
HF Elements: Task characteristics

Müller, C., Bertovic, M., Kanzler, D., Dobberphul, T., Heckel, T., Boehm, R., . . . Pitkänen, J. (2013). *Plenary view on the vigor of our NDE reliability models*. Paper presented at the 5th European-American Workshop on Reliability of NDE, Berlin, Germany.
The article discusses the Modular Reliability Model. The Modular Reliability Model's reliability formula states that the total reliability of an NDE system is composed of the intrinsic capability, application factors, and human factors. The authors state the Modular Reliability Model helps to understand and weight different human factors elements. The authors discuss that attention should focus on task demonstration for training and performance, task preparation, procedures and protocols, and supervision. This paper displays how the level of reliability of NDE has an impact on acceptance or rejection of safety critical parts. The authors conclude that human factors should be more deeply investigated to demonstrate ways of optimizing working conditions, training, inspection procedures and preparative actions for the inspectors.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Group characteristics; Individual differences; Task characteristics

Müller, C., Bertovic, M., Kanzler, D., Heckel, T., Rosenthal, M., Holstein, R., . . . Pitkänen, J. (2014). *Assessment of the reliability of NDE: A novel insight on influencing factors on POD and human factors in an organizational context*.
This paper gave an overview of the Modular Reliability Model for Node which takes into account intrinsic capability of the system, application parameters and human factors. They discuss the research progress regarding determining intrinsic capability using a multi-parameter POD. In addition, the authors discuss research progress regarding human factors in NDE. Specifically, they provide a summary of the main conclusions from the human factors studies that have been conducted to date. In addition, the authors point out the deficits in the business process, the information process, and technical delivery process of NDE.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Task characteristics

Müller, C., Bertovic, M., Pavlovic, M., Kanzler, D., Ewert, U., Pitkänen, J., & Ronneteg, U. (2013). Paradigm shift in the holistic evaluation of the reliability of NDE systems. *Materials Testing, 55*(4), 261-269.

This articles provides an overview of new methodologies for evaluating the reliability of NDE systems. Specifically, the article focuses on the modular reliability model. The modular reliability model helps to understand and weight the different influences impacting NDE reliability including intrinsic capability, application parameters, human factors and the organizational environment. The model also helps to determine which factors can be determined by modeling. The authors believe that multi-parameter POD and methods employing modeling-assisted POD or data combination by Bayesian approach appear promising to simultaneously fulfill safety and economic demands.

Domain: Nuclear
Paper Type: Theoretical
HF Elements: Organizational factors; Task characteristics

Müller, C., Holstein, R., & Bertovic, M. (2014). Conclusions of the 5th European American workshop on reliability of NDE. *Materials Testing, 56*(7-8), 599-601. doi: http://dx.doi.org/10.3139/120.110603

The authors summarize the key points from the 5th European-American Workshop on Reliability of NDE. The focus of this workshop was: 1) What is influencing the performance of NDE and how can we measure and optimize what we want to know with minimum effort? 2) What is the delta to the everyday field conditions? and 3) What do we need to overcome? Regarding human factors, discussions focused around the communication gap between utilities and NDE service providers. The customers (i.e. utilities) are not NDE experts which makes it difficult to implement improvements in the field to increase reliability via addressing human factors issues. The discussion also addressed the question "How do we keep inspectors vigilant when they never see a flaw?" Refresher training, yearly practice on realistic defects and engagement with staff in non-outage time (e.g. developing procedures) were some of the suggested solutions. It was also noted that more work needs to be done to investigate the utility of various levels of automated inspection systems. Further knowledge is also needed about the optimal working conditions and organizational environment for information flow.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Task characteristics

Murgatroyd, R. A. (1988). Reliability of application of inspection procedures (pp. 361-368). Nuclear Energy Agency of the OECD (NEA).

The authors conducted a study using the Systematic Human Error Reduction (SHERPA) methodology. This analysis allows procedures to be examined for potential sources of error and the results suggest mechanisms that can be used for error control or elimination. The process involves a hierarchical task analysis to 1) Identify the tasks necessary to achieve the system objective 2) Identify possible error modes, recovery mechanisms, consequences of unrecovered errors, and 3) Identify psychological mechanisms underlying the error modes and 4) Develop recommendations to minimize the probability of errors and maximize the probability of recovery. This method was applied retroactively to the PISC II round robin exercise to further assess participant performance and other retrospective analyses. In one such case, the results revealed that SHERPA predicted 99% of human errors that were known to have occurred.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Task characteristics

Murgatroyd, R. A., & Crutzen, S. (1994). Human reliability in inspection: Final report on Action 7 in the PISC programme (pp. 104-107). Nuclear Energy Agency of the OECD (NEA).

This paper summarizes the results of Action 7 from the third phase of the Program for the Inspection of Steel Components (PISC III), which sought to evaluate human reliability in non-destructive inspection. A series of experimental studies were performed with 6 experienced inspectors in an environmental laboratory. The inspectors performed NDE tasks in both nominal laboratory conditions and simulated field conditions. The investigators also monitored the inspectors' work attitudes, physical, and mental condition throughout the experiment. The results suggested that flaw detection capabilities varied considerably between inspectors. The investigators inferred that the variability may have been due to differences in technical skills (e.g., scanning skill and maintaining ultrasonic coupling), or due to loss of concentration and vigilance when fatigued. There were also a significant number of errors made during the data plotting and reporting stage. The authors suggest that simulator-based training could be a valuable tool to improve human performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Physical environment; Individual differences; Task characteristics

Norros, L. (1998). *Human and organisational factors in the reliability of non-destructive testing (NDT)*. Paper presented at the Proceedings of the Symposium on Finnish Research Programme on the Structural Integrity of Nuclear Power Plants.

This paper discusses human factors relevant to NDE reliability based on an international literature review, interviews with Finnish NDT experts, and interviews and observations of 15 Finnish NDT inspectors. Research suggests that inspectors possess different flaw detection capacities, and an inspector's capability may vary within a working day. This variability may be based on tight time schedules, fear of radiation and deficient motivation. There also does not seem to be a statistically significant correlation between level of certification and ultrasonic testing capability. Generally, the experts believed that reliability was high overall, but human and organizational factors can impact reliability (e.g., inspectors' attitudes toward their work, understanding of inspection items, costs, time schedules, personnel qualification, and radiation). The inspectors indicated that many of the human factors concerns identified by the experts did not significantly impact their performance (e.g., time schedules, lack of interest from the utility, fear of radiation, or deficient motivation), but that the role of the foreman was extremely important to reliability. The foreman was seen as the primary resource for the inspectors in terms of preparing for the work, coordinating activities, and monitoring radiation exposure. Good communication and coordination between different personnel groups was evaluated as one of the key factors for successful work. Through interviews with the inspectors, the authors characterized two different types of habits in how the inspectors approached their task: one habit focused on personal expertise (i.e., focus on diagnosis and interpretation), whereas the other habit focused on standardized performance (i.e., focus on following prescribed procedures). The authors concluded that no single human or organizational factor is responsible for the NDT performance fluctuations obtained in various reliability studies, and there seems to be a close connection between inspection management and the general reliability of NDT operations.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Norros, L., & Kettunen, J. (1998). Analysis of NDT-inspectors working practices: Radiation and Nuclear Safety Authority, Helsinki (Finland).

This paper focuses on the analysis of the decision making demands of NDT inspectors based upon interview data. The participants were 15 Finnish NDT inspectors completing annual UT inspections during outages at 2 Finnish NPPs. The authors wanted to identify the factors that inspectors believe affect the reliability of inspections and inspectors' conceptions of the decision making demands of their work. They expected that differences in these conceptions would indicate differences in habits of action . Based on the inspectors' conceptions concerning the decision making demands of their work, two different habits of action could be identified: 1) interpretive habit of action; and 2) procedural habit of action. The interpretative habit of action was characterized by an emphasis on personal judgment as a determinant of quality of inspection and on the interpretative demands in carrying out inspections and . The procedural habit of action emphasized standard procedures and reduction of the demands of work to carrying out the prescribed task. Inspectors with both theoretical background and long practical experience belonged to the interpretative group, while those with only long experience preferred the procedural habit of action. The results provide evidence to the belief of the of an earlier study, that the attitudes of the inspectors significantly influence the inspection.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Individual differences

Pitkänen, J., Bertovic, M., Müller, C., Pavlovic, M., & Salonen, T. (2009). *NDT reliability in risk minimization during manufacturing and welding of spent nuclear fuel disposal components - a realistic tool for reliable inspections*. Paper presented at the 4th European-American Workshop on Reliability of NDE.

The authors evaluated various NDT methods (VT,ET,UT and RT) to find potential weak points in quality control during the manufacturing of canister components of spent nuclear fuel. Materials that were tested were oxygen free copper-lid tube, weld, and nodular cast iron inserts. The authors explain that each single NDT-method has its own characteristics and inspection reliability and that using a combination of several methods may give more realiable results. The main issue in NDT inspection is the defect response to the chosen technique. An inspection technique should be determined by which defect types must be found. The NDT reliability can be increased when the whole process of mechanised inspections will be evaluated critically in order to find weak points in inspection. The deficiencies will be improved by a continuous feedback process.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Task characteristics

Pond, D. J., Donohoo, D. T., & Harris, R. V., Jr. (1998). An evaluation of human factors research for ultrasonic inservice inspection: Nuclear Regulatory Commission, Washington, DC (United States). Div. of Engineering Technology; Pacific Northwest Lab., Richland, WA (United States).

This objectives of this report were: 1) to determine if the PISC III or other HF research has provided information which may be applicable for use in upgrading ASME codes and 2) to suggest research that might contribute to code upgrades. The report provided an overview of the PISC III study and then went on to discuss variables affecting UT performance including heat, noise, task duration, fatigue, individual differences, equipment and organizational and social factors. The authors went on to provide a variety of recommendations regarding how to conduct future research and recommendations regarding the current practice of UT.

Domain: Nuclear
Paper Type: Theoretical
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Ronneteg, U. (2014). *Reliability studies, a tool in the NDT development for the canister for the Swedish spent nuclear fuel*. Paper presented at the 11th European Conference on Non-Destructive Testing, Prague, Czech Republic.

This paper focuses on the NDE of spent fuel canisters. For the inspection of canister components, mechanized inspections are applied. The inspection is conducted in two steps: first, the semi-automated data collection, and then the evaluation of collected data. The primary inspections are performed using phased array UT. The authors investigated what human factors must be considered when mechanized inspection techniques are applied. Their investigation included a failure modes and effects analysis (FMEA) and workshops with SMEs. The results showed errors can happen during the entire inspection chain. According to the FMEA, instructions play an important role in the inspection process. The authors focused on the instruction aspect of the process and conducted a study with the following objectives: 1) To evaluate the quality of the current instruction by assessing the performance resulting from the use of the specific instruction; and 2) To generate improvements. The development of NDT instructions was conducted in several iterative stages. The study was performed in two sections, understanding and usability. The results indicated that both the instruction content and the format play an important role in supporting reliable inspections.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Task characteristics

Rummel, W. D. (1984). Human factors considerations in the assessment of nondestructive evaluation (NDE) reliability. *Review of progress in quantitative nondestructive evaluation* (pp. 37-46): Springer.

This paper discusses the influence of human factors on the probability of detection in NDE. Human errors are classified as systematic (consistent offset from ideal performance), errors in precision (consistent but random variations around the norm), or sporadic errors (occasional occurances varying significantly from the norm). The author describes these types of error classifications based on how they would affect the shape of a POD curve. Differences in performance may be due to differences in skill or decision criteria used by the inspectors; or may be due to differences in processing material, equipment, calibration standards, or procedures. The author asserts that the human operator can be very reliable if signal to noise acceptance criteria are established and a high degree of discrimination is attained by the specific NDE method. The human operator is reliable only within the boundary conditions and physical limits of the task to be performed.

Domain: Generic
Paper Type: Informational
HF Elements: Individual differences; Task characteristics

Rummel, W. D. (2004). *Qualification and validation of the performance capability POD for non-destructive inspection procedures*. Paper presented at the 16th World Conference on Nondestructive Testing, Montreal, Canada.

This paper describes practical experiences with development and validation of non-destructive inspection procedures in the aerospace industry. The author notes that both successes and shortfalls in quantifying NDT capability is often attributed to "human factors," but if other methods, materials, equipment, procedure, and process variables are not controlled, then the human operator at the end of the line has little chance to reliably detect flaws using NDT. The author argues for use of a multipoint calibration method to improve reproducibility for manual scanning applications and reducing human factors variance. Multiple point calibration can provide positive feedback and reinforcement of operator skills in reproducing the system response that was established during procedure validation.

Domain: Aerospace
Paper Type: Experiential
HF Elements: Task characteristics

Rummel, W. D., & Rathke, R. A. (1982). *Flaw detection reliability assessment and analysis*. Paper presented at the Army Symposium on Solid Mechanics, Cape Cod, MA. http://www.dtic.mil/docs/citations/ADP000013

This report provides an approach to understanding and modeling NDE inspection processes with respect to overall process reliability. The authors discuss how probabilities are captured and presented when measuring inspection reliability . The authors also mention the outcomes of inspection reliability test. The authors specifically mention that signals and noise affect inspection responses and probability of detection (POD) curves. The authors state that signals and noise are common denominators to inspection process performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Physical environment

Schneider, C., & Bird, C. (2009). *Reliability of manually applied phased array inspection*. Paper presented at the 4th European-American Workshop on Reliability of NDE, Berlin, Germany. http://www.twi-global.com/technical-knowledge/published-papers/reliability-of-manually-applied-phased-array-inspection-june-2009/

This conference paper aims to provide industry with the objective technical information about the current standard of inspection reliability for manually applied phased array inspection. This paper presents a statistical analysis of the results for defect sizing with respect to flaw size, flaw characterization and inspector qualifications. Phased array inspectors from different industries were used to quantify the reliability of defect detection and sizing of manually applied phased array systems for ferritic welds. Six phased array companies and ten phased array inspectors were used for a blind trial. Each were provided and used a generic inspection procedure. Detection of the flaws were recorded and compared among inspectors. A large variation was found in the ability of phased array inspectors to size flaws. There is evidence that this sizing capability is linked with training, experience, size of flaw and whether the flaws are rough or smooth.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Group characteristics; Individual differences; Task characteristics

Schroeder, J. E., Dunavant, D. W., & Godwin, J. G. (1988). Recommendations for improving air force nondestructive inspection technician proficiency.

The goal of this report was to make recommendations for a program to increase Air Force NDI technician proficiency. This was approached by identifying relevant areas of concern that could negatively impact the proficiency of Air Force NDI technicians. The authors addressed this approach in three phases. Phase one identified the areas of concern from reviewing existing literature on Air Force NDI technician proficiency, reviewing the existing industrial NDE technician proficiency literature, reviewing comments from past interviews, observations and site visits. From this information, a list of human performance areas of concern were generated including: training, work environment, policies, procedures, equipment, and inspector motivation. Phase two identified the possible solutions for those identified concerns and Phase three evaluated recommendations for improving Air Force NDI Technician proficiency.

Domain: Aviation
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Shull, P. J. (2002). *Nondestructive evaluation: Theory, techniques, and applications*: Taylor & Francis.

Section 1.6 of this book explains the influence that human factors has on the reliability of NDE. The author states that inspectors impact reliability and they can be affected by personal, environmental, and external factors. Specifically, physical and mental attributes, lighting, cleanliness, and temperature. The authors also discuss the importance of the inspector feeling that he/she can freely report findings without the pressure to produce specific results.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences

Singh, R. (2000). Three decades of NDI reliability assessment. San Antonio, TX: Karta Technologies, Inc.

This paper provides a review of all of the major engineering and research efforts associated with NDE. The report provides overviews of each effort. In addition, information about facility and inspector sampling techniques, specimen configurations, inspection scheduling and execution and data handling and analysis are provided for each effort. The authors also reported on whether human factors were considered in the effort and the overall outcomes of each effort. In addition to identifying and summarizing major efforts, a review of smaller programs/research was also included. The report attempts to identify best practices of those reviewed.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Spanner, J. C. (1988). Human factors impact on NDE reliability. In D. Thompson & D. Chimenti (Eds.), *Review of progress in quantitative nondestructive evaluation* (pp. 1791-1798): Springer US.

This book section explains that NDE research is needed in both laboratory and field conditions to identify, characterize, and quantify human performance factors and the overall effectiveness of NDE. The authors describe a study that identified and characterized human factors aspects of NDE, developed a model for the UT man-machine system, explored methods for measuring performance, and performed a round robin test of effectiveness for IGSCC. The authors concluded that training, experience, procedures, equipment, working environment, and psychological pressures were factors that influenced the reliability of NDE.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Spanner, J. C., Badalamente, R. V., Rankin, W. L., & Triggs, T. J. (1986). Human reliability impact on inservice inspection phase 1 summary report (Vol. 1). United States: Nuclear Regulatory Commission.

This report gives a comprehensive discussion of the UT process and the human factors elements involved in that process. In addition, there is an in-depth discussion about the various techniques for measuring UT reliability and the factors that affect reliability. Specifically, the authors discuss task, procedures, training, individual difference and environmental variables. These 5 groups of variables are then evaluated with respect to their impact on UT performance and recommendations are made regarding improved UT reliability and the follow-on work that is needed.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Summers, R. H. (1984). Nondestructive inspection: Improved capabilities of technicians. Lowry Air Force Base, Colorado: Air Force Human Resource Laborary.

This report covers two research and development efforts regarding NDI in the air force industry. Several surveys concluded that Air Force nondestructive inspection capability lacked the precision and reliability necessary to ensure the structural integrity of aircraft. As a result, two needs were identified: 1)to develop the capability for NDI personnel to practice inspection techniques in field laboratories and, 2) identify particular features of good Air Force-trained inspectors. The author's discuss the process used to specify the characteristics of a trainier (i.e. simulator) that would provide a capability for Air Force 3-level technicians to practice the application of contact-type pulse echo ultrasonic inspection. For the second need,a sample of inspectors were accessed to complete a job performance test. In addition to performance measures. personnel information was also gathered on inspectors in order to determine what, if any, personnel information correlated with performance. The personnel information data failed to identify clear-cut features which correlate with inspection skills.

Domain: Aviation
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Taylor, T. T., Spanner, J. C., Heasler, P. G., Doctor, S. R., & Deffenbaugh, J. D. (1989). An evaluation of human reliability in ultrasonic in-service inspection for intergranular stress-corrosion cracks through round-robin testing. *Materials evaluation, 47*(3), 338-344.

This paper documents the results of a mini-round robin study to quantify how well NDE inspectors were able to detect and size intergranular stress corrosion cracking (IGSCC). Part of the testing included a human factors study to identify factors that can affect inspector performance, such as organizational characteristics, training and experience, equipment design, and the inspection environment. The human factors study included a written questionnaire and one-on-one interviews with the 12 inspectors who participated in the experiment. The investigators determined that a wide variation existed between the "best" and "worst" inspectors. They found that relative operating characteristic (ROC) curves were useful for measuring inspector performance, but could not point to a single performance shaping factor as accounting for variations in performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Triggs, T. J. (1988). *Non-destructive testing in maintenance and the role of the human operator*. Paper presented at the IEEE Fourth Conference on Human Factors and Power Plants, Monterey, CA.

This paper discussed several variables that are likely to influence inspector performance in non-destructive testing, and advocates for the use of relative operating characteristic (ROC) curves for analyzing performance data. The author argues that the ROC curve is preferred over other methods because it captures both false calls and correct detections in plotting performance. The author also reviews research related to human factors in NDE, including inspection time, equipment and procedural factors, trace-recording, data recording and record keeping, training, experience, and inspection strategy considerations. The author concludes by calling for systematic multi-variable evaluations in the NDE field for those factors that are likely to influence inspector performance.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Triggs, T. J., Spanner, J. C., Badalamente, R. V., & Rankin, W. L. (1986). Human reliability impact on inservice inspection. Review and analysis of human performance in nondestructive testing (emphasizing ultrasonics) (Vol. 2). United States: Nuclear Regulatory Commission.

This report is a supplement to NUREG-4436 Volume 1. The authors describe the purpose of the report as two-fold, 1) to develop an acceptable measure of performance for NDE and 2) to review research literature in NDE and related fields in order to develop an understanding of how human performance can be improved through the application of human factors principles. An overview of NDE is presented along with an overview of the measures of performance used in NDE. The authors also discuss, at length, human performance in areas related to NDE (e.g. reading x-rays). Finally, the authors discuss HF issues in NDE and what can be learned from other fields. The authors draw two primary conclusions from this work: 1) the measures of performance currently used for NDE are inadequate and can be misleading and should be replaced with performance measures based on ROC analysis. 2) Several types of variables have the potential to improve NDE technician performance including training, task and procedural variables.

Domain: Generic
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Turnbow, M. (2009). *Reliability of NDE – the criticality of procedures and personnel*. Paper presented at the 4th European-American Workshop on Reliability of NDE, Berlin, Germany.

This paper suggests that independent third party qualification/certification and on-the-job training may not provide the necessary confidence needed for safety critical NDE inspections. The authors cite findings from empirical studies that have suggested only a 50% flaw detection rate. They propose that the use of interactive, self-paced training along with hands-on specialized training may help to improve flaw detection. They state the NDE technicians must be specialists not generalists. The authors propose that performance demonstration testing should be established to test the ability of a specific examination system (i.e. equipment, procedures and personnel) to achieve a desirable level of performance. They go on to describe the specific qualification methodology that is captured in ISO CD 11774.

Domain: Generic
Paper Type: Experiential
HF Elements: Organizational factors

Waites, C., & Worrall, G. M. (1995). *Improving the reliability of on-site NDT inspection*. Paper presented at the Joint OECD/NEA-IAEA Symposium on Human Factors and Organisation in NPP Maintenance Outages: Impact on Safety, Stockholm, Sweden.

This paper highlights research conducted at AEA technologies, including the PISC III program, and broadly identified some factors that can affect the reliability of inspections. The sources of poor reliability identified included: poor inspection technique, mistakes during the evaluation and reporting of results, the length of shift and inspection period, and inherent characteristics of the inspector. The authors suggest a number of methods to improve reliability, such as training, redesigning drawing equipment to minimize errors, reconsidering work schedules, identifying and selecting for the characteristics of reliable inspectors, and using automation (although they note that this can introduce other sources of poor reliability).

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Wall, M. (2009). *Human factors in POD modelling and use of trial data*. Paper presented at the 4th European-American Workshop on Reliability of NDE, Berlin, Germany.

This paper illustrates a number of approaches to use human error probability of detection (POD) data, derived from models, trials, or experiments , to improve NDE reliability. The authors communicate the details of human factors elements that are experienced in site conditions and trial conditions and identify the factors that can reduce reliability. The authors note that fatigue, environment, inspector skill level, repetition, supervision, familiarity, and hand to eye coordination, and interpretation are factors that may influence the reliability of NDE performance.

Domain: Nuclear
Paper Type: Informational
HF Elements: Organizational factors; Physical environment; Individual differences; Task characteristics

Webster, C. (1989). Some individual psychological factors leading to error in ultrasonic testing. *British Journal of Non-destructive testing, 31*, 680-682.

This paper discusses individual variables that may lead to human error, with a particular focus on the motor action of scanning while using a manual probe and evaluating an indication on a display screen. Manual scanning in ultrasonic testing requires precise skilled movement control. Errors can occur from scanning too fast, failure to overlap scans, failure to orient the probe appropriately, or failure to maintain adequate probe contact. The author notes that motor control is often more precise when the inspector received visual feedback, but, because the inspector must also focus on the display screen, they can only use peripheral vision to control their scanning motion. While scanning, the inspector must also observe the display screen, which can be considered a type of vigilance task and therefore something that humans are often poor at performing over long periods of time. When a change in signal is detected, the inspector must then decide whether the signal change indicates the presence of a flaw, and may choose different strategies to determine positioning, interrogation, and sizing of the reflector. At this stage there are again opportunities for error due to failure to maximize the signal, incorrect timebase reading, or erroneous beam angle or index point. Theoretical knowledge, spatial visualization, and decision making are all important for correct evaluation of an indication.

Domain: Generic
Paper Type: Informational
HF Elements: Task characteristics

Wheeler, W. A., Rankin, W. L., Spanner, J. C., Badalamente, R. V., & Taylor, T. T. (1986). Human factors study conducted in conjunction with a mini-round robin assessment of ultrasonic technician performance. Washington, DC: Nuclear Regulatory Commission.

This report details the findings from a human factors study conducted as part of a mini-round robin assessment of NDE technician reliability in detecting intergranual stress corrosion cracking (IGSCC) using manual ultrasonic testing (UT). Twelve UT technicians inspected samples of welded sections of piping that either had or did not have IGSCC. Each technician completed a questionnaire and participated in a critical incident interview to provide information on their experience with UT. In addition, human factors (HF) specialists evaluated the UT equipment used by the technicians for conformance to HF design principles. The investigators concluded that the technicians in this study did not perform better than technicians from a previous study, despite having greater field experience and passing performance demonstration tests. Also, there were not significant differences between level II and level III technicians in their ability to detect IGSCC. The investigators did not find an effect of fatigue on performance, but questioned whether the experimental setting allowed for an adequate test of fatigue. The HF specialists identified design deficiencies in the UT equipment, which may also affect technician performance. Finally, the investigators indicated that relative operating characteristic (ROC) analysis was an effective way to describe and analyze technican performance.

Domain: Nuclear
Paper Type: Empirical
HF Elements: Organizational factors; Physical environment; Group characteristics; Individual differences; Task characteristics