Holistic Risk Assessment and Risk Prevention Approach to the Mechanized NDT and the Inspection Procedure

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Abstract. The difficulty to deal with human factors in non-destructive testing (NDT) stems from their diversity and complexity – no single human or organizational factor is responsible for the entire fluctuations in the NDT performance. The typical approach to decrease the variability in the inspection results had been found in replacing manual NDT with mechanized methods. However, even though some human errors can be avoided by automating the process, there are new risks that can arise from its application and need to be further investigated. To address this problem, a combination of theoretical and practical approaches should be applied, where the source of error is not seen only in the inspector, but also in his interaction with social and technical systems, as well as the organization.

An analysis of potential risks in the use of mechanized inspections methods for spent fuel canisters has shown potential for human error in acquisition, as well as in the evaluation of the gathered results. Assessed causes of those errors lay in the inspector, but also in the organization and in shortcomings of the inspection procedure. The aim of the analysis was to provide with preventive measures and optimization recommendations. Those include further automation of the process, application of human redundancy, improvements of the inspection procedure, hardware and software improvements etc. Before improvements can be made, there is a need to understand the resulting processes and the influence of their interaction on the inspection results. The results have shown that when working with an automated system, one must avoid over relying on its proper functioning and form appropriate trust towards automation. Furthermore, human redundancy should be applied only in cases where the redundant inspectors are completely unaware of each other, in order to avoid the effects of social loafing and shirking.

The inspection procedure is one of the most important tools in the application of NDT. On an example of ultrasonic data evaluation, the results will show an improvement of an NDT instruction as a result of consideration of the effectiveness, efficiency and user satisfaction.

1. Introduction

According to the Modular reliability model, developed during the first and the second European-American Workshops [1]–[3], and further developed by Müller et al. [4], reliability of non-destructive testing (NDT) depends on the intrinsic capability (IC) of the NDT system, the application parameters (AP) and the human factors (HF), whereas the whole system of influences is embedded into a larger organizational context. Human factors are considered to be the most variable from all the influences, as well as the least controllable. The main reason for this is that the nature of human factors influences is mostly still unknown to the NDT community.

The difficulty to deal with human factors in NDT originates mostly from their diversity and complexity – no single human or organizational factor is responsible for the entire fluctuations in the NDT performance [5]. Over the years there have been numerous attempts to investigate various human and organizational factors influencing the reliability of NDT and NDT working practices with the goal of finding ways to control them. Some of the research topics include working conditions, training, decision making, personality, abilities etc. (e.g. [5]–[10], etc.). The main problem lies in the fact that much of the gained knowledge is not reaching the end users, i.e. the nuclear power plants or the inspection companies, and the old practices are continued being used. Moreover, there is still a large gap in knowledge that remains to be filled.

The variety of human factors affecting the inspection results will continue to puzzle both researchers, as well as NDT practitioners. The suggested means of gaining more knowledge and changing faulty practices lies in a multidisciplinary holistic approach, i.e. building a bridge between engineering and social sciences in a joint pursuit for knowledge and optimization means, as well as searching for the underlying mechanisms of errors and risks.

In this paper, the attention will be given to, in the opinion of the authors, two major misconceptions about human factors in NDT. First, the origin of human error will be addressed, supported by the knowledge from the field of human factors. Second, potential problems related to mechanized testing will be raised and discussed. Finally, the quality of the current NDT procedures will be addressed by presenting an ongoing study on the usability of the NDT instruction.

2. Main Misconceptions about Human Factors in NDT

Human factors have been mostly neglected in the assessment of the reliability of NDT systems. Typically, they are considered as a so-called “black box”, containing a number of influences stemming from the inspector conducting the inspection, which are variable and unknown. Moreover, those influences are considered to be negative, being that they lead to a higher measurement uncertainty. With this kind of an approach, it is hard not to adopt a negative attitude towards the inspector at the end line, as well as towards human factors, in general. However, it is important to note that human factors do not equal human error, and that human error could originate not only from the inspector, but from deeper within the organization, as will be argued in the following subsection.

The engineering way to deal with human variability is to engineer new methods, that somewhat take the human link out of the equation. This new solution, frequently addressed to as the “solution for the human factors ‘problem’”, is seen in replacing manual with mechanized testing methods.

Even though NDT is a new application field in the research of human factors, there is a lot to be learned from other applications of this discipline, such as the aviation, military, medical care etc, as well as from the discipline of psychology, in general.

From that perspective, we see two major misconceptions about human factors in NDT, which we would like to address in this paper:

1. The source of failure/variability is seen in the inspector at the „sharp end“
2. Replacing manual testing with mechanized methods will reduce human error.

We will argue that a) the source of failure lies not only in the inspector, but has to be looked for, as well, in the team, technology, organization and the extra-organizational environment and that b) changing inspector‘s task from doing into supervising the automation can lead to new sources of errors, which need to be further considered.

1.1. Misconception 1: Source of failure is seen in the inspector at the "sharp end"

Human factors are frequently seen as a synonym for human error. However, it is important to distinguish those two terms. Human factors, as defined by the UK's Health and Safety Executive [11], refer to environmental, organizational and job factors, as well as human and individual characteristics, which have an influence on the behaviour at work in a way which can affect health and safety. Generally, human factors are concerned with all of those things that need to be controlled, in order to obtain reliable human performance, i.e. human, team, technology, organization and environment [12].

In contrast, in NDT, human factors are seen as the mental and physical make of the individual, together with his training, experience and the conditions, under which the inspection is conducted, which have an influence on the ability of the NDT system to achieve its intended purpose [3]. By comparing these two definitions, it becomes clear that the view on human factors in NDT is rather narrow, neglecting the broader scope of influences, such as the organization, the task, the team and the larger intra-organizational environment..

Human error, on the other side, refers to human action, which inadvertently failed to achieve its intended outcome. They are considered to be a result of an inadequate interaction between the human and the situation [13]. In his book titled "Human Error", James Reason [14] defines human error as:

> "*all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency"* (Reason, 1990, p. 9).

Human errors are typically divided into slips, lapses and mistakes. Whereas slips and lapses are failures in an execution of an action (e.g. a slip of the tongue or a failure in memory), a mistake is a result of a failure in planning of an action, can remain undetected for a longer time and, therefore, is far more dangerous [14]. Commonly mistaken for a human error is the term "violation". Violations are defined as a deliberate deviation from a rule or procedure [11] and often arise from the social context, which imposes rules, procedures, norms etc. [14]. Both human errors and violations are termed unsafe acts. In other words, there are two ways people can go wrong – by failing to do something they should have (errors of omission) or by doing something they should not have done (errors of commission) [15].

There are two distinct approaches to human error. The now called "traditional" or the "person approach" and the "modern" or the "system approach". [14], [16]–[18].

According to the traditional, person approach, the source of human error is seen only in the person committing the error. A typical misconception is that errors could have been avoided had someone paid more attention or made more effort. The problem was attempted to be tackled with by implementing more procedures and developing the technology. However, adding more procedures does not necessarily mean that the error will not re-occur, nor does adding more technology reduce the potential for human error - it rather changes and relocates it. As Dekker concludes, "*focusing on individual failures does not take away the underlying problem*" [18; p. 6]. This approach was criticized for neglecting the underlying mechanisms that lead to an error, e.g. environment, organization etc., and, therefore, abandoned in the human error research.

The assumption of the systems approach is that humans are fallible and errors are to be expected, even in the best organizations. Human error is seen as a consequence of a problem hidden deeper within the system. This approach concentrates on the conditions under which people work and tries to build defences to avert errors or mitigate their effects [14], [17]. Countermeasures are based on the assumption that although *"we cannot change the human condition, we can change the conditions under which humans work"* [17, p. 769].

Following the trends in human error and human factors research, and applying them to NDT, we might conclude that, in order to understand which factors cause variability between the inspectors and lead to errors, we need to look at the broader picture. Very frequently, the inspector is "blamed" for the error he/she committed, without it being considered that the error source might not lie in the one committing the error, but rather in the system deeper within. The obvious reason for this is that the inspector's error, whether it is a human error or a violation (i.e. unsafe acts), has an immediate adverse effects and, through that, a direct impact on the safety of the system. These kinds of errors are known as "active failures" and they happen at the "sharp end", usually in human-system interaction. The conditions leading to an error, called latent conditions (e.g. poor design, gaps in supervision, undetected manufacturing defects or maintenance failures, unworkable procedures, clumsy automation, shortcomings in training, less than adequate tools and equipment), can be present for years, before being combined with local circumstances and active failures to penetrate the system's many layers of defences [16].

Any organization with high hazard potential, such as a nuclear power plant, has a system of defences installed, in order to prevent errors from happening. These so-called "defences in depth" contain holes (such as in a Swiss cheese), mostly arising from bad decisions by the managers, designers, regulators etc.; and these holes are in constant movement. A rare alignment of the set of holes in the successive defence layers will allow hazards to go through the defences, as illustrated by Reason (see **Figure 1**).

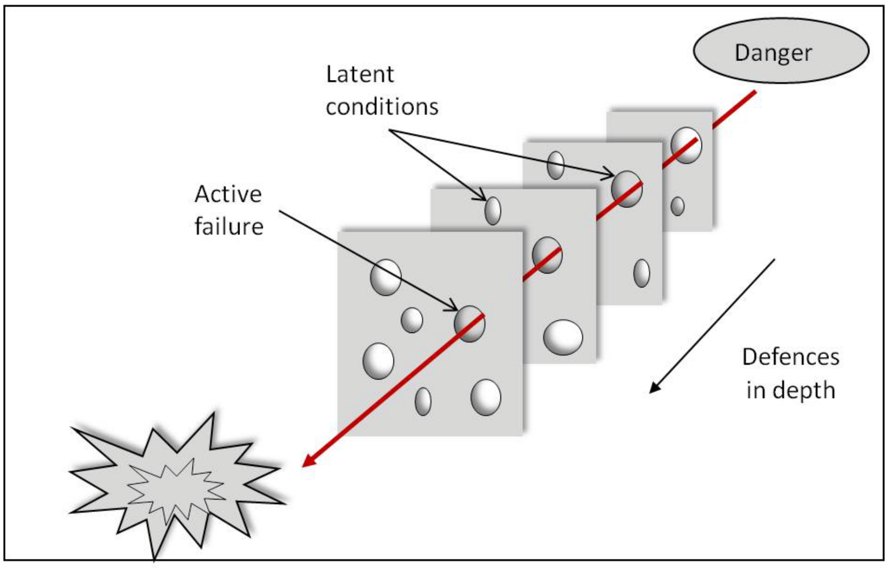

Figure 1 Accident trajectory ([16], p.12)

Following this rationale, it becomes clear that focusing only on the individual operator or on the man-machine interaction, as the main sources of errors does not suffice if we want to design a safe system. Therefore, we suggest that in the consideration of human factors in NDT a holistic approach should be adopted. According to this approach, not only the human element should be investigated, but rather the interactions between five relevant system components (systemic view on safety) - the technical sub-system and the parts of the social subsystem: individual, team/work group (e.g. redundant inspectors, or the interaction between the inspector and the supervisor), organization (the NDT service provider or the vendor), and extra-organizational environment (regulatory bodies, standards and norms, etc.)(see **Figure 2**).

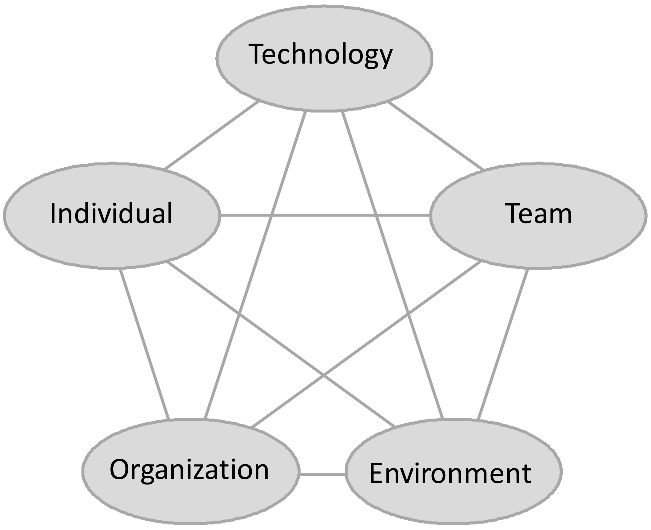

Figure 2 Systemic view on safety ([13], p.9)

1.2. Misconception 2: replacing manual with mechanized testing will reduce human error

Generally speaking, the goal of automation is to reduce workload and provide with higher reliability and safety [19]. This has led to increased automation of systems, especially in organizations with high reliability demands. Modern systems are nowadays more or less complex man-machine systems, in which common goals are achieved by people in interaction with systems [19]. NDT is also following this trend, by developing mechanized, semi- or fully-automated systems to keep up with the high reliability demands.

Through that development, the NDT community sees a way to cover big surfaces, reach areas with limited access, decrease the exposure of people to radioactivity, etc., but also to decrease the variability in the inspection results, by taking the control from the "unreliable" inspector and handing it over to a "reliable" automation. Be that as it may, automation will lead to a reduction of errors occurring during manual inspections. However, mechanized and semi-automated NDT methods still involve human operators at almost all stages of the inspection process, from setting up the equipment and the software, over measurement, up to the data evaluation process. Automation does not replace humans, but rather changes what they do, often in ways unintended and unanticipated by the designers [20]. Hence, replacing manual with mechanized testing will reduce human errors occurring during manual inspections, however, changing the inspector's task from conducting the entire task manually into controlling of the equipment, could lead to new sources of errors.

Supporting this theory is a study conducted by Bertovic et.al. [21], in which errors arising from the application of mechanized NDT were investigated for the first time. Potential errors during the acquisition and evaluation of data acquired with mechanized NDT methods, i.e. ultrasonic phased array (UT PA), radiography (RT), eddy current (ET) and visual testing with a remote camera (VT) were investigated within a scope of two NDT reliability projects, concerning the application of NDT for the inspection of the canister, to be used for the final disposal of spent nuclear fuel in Sweden and Finland. During a series of customized Failure Modes and Effects Analyses (FMEA) workshops, a number of potential failures, their causes and consequences were identified and analyzed, with the goal of producing a number of measures to be used to prevent those errors from occurring. The outcome of the FMEAs was a clear statement towards the argument, that failures can and will happen, even during mechanized NDT. The causes of discussed risks were assigned to the inspectors, but also to the organization and the shortcomings in the inspection procedure. The proposed countermeasures include further automation of the process, application of human redundancy, improvements of the inspection procedure, hardware and software improvements etc. These preventive measures were further investigated in a series of experimental studies [21].

In a paper titled "Humans and Automation: Use, Misuse, Disuse, Abuse", Parasuraman and Riley [20] addressed different issues occurring when humans interact with automation. Problems with the use of automation become especially evident when automation doesn't function as expected, makes errors or fails. The people are then expected to "jump in" and take over [19]. The major safety problem is found in misuse, i.e. the overreliance on the correct functioning of automation. The study, conducted by Bertovic et al. [21], raised the question of automation bias, i.e. uncritical reliance on a correct functioning of a an automated aid [22], in this case - software for the evaluation of eddy current data. In NDT, missing defects due to overreliance on the correct functioning of automated defect-detecting and -analyzing software is a potential safety issue. In this study, 70 NDT trainees were asked to control the data already analyzed by the software. Missing defects, sizing errors and false alarms were implemented into the report sheets by the experimenting team and it was investigated whether the participants will detect those errors or rather rely on the software. The results of the study show that the participants agreed with almost half of the implemented errors, i.e. 56% of the missing values, 25% of the sizing errors and 53% of the false alarms [21], [23]. This result raises concern that if automated software does make errors in detection and sizing of defects, not all of them will be detected by the data evaluators, probably due to high trust in the automated system.

Forming of appropriate trust in automation, as well as raising individual accountability, lowering the workload and understanding of the factors which lead to overreliance, are suggested ways for the prevention of automation bias [20].

Mechanized NDT is often performed by more than one inspector. Sometimes, different people take part in different phases of the testing, e.g. during preparation, measurement, evaluation; and sometimes two inspectors are assigned to evaluate the same data, in order to prevent errors from single inspectors (human redundancy). A study on the effects of social loafing (investing less effort when working on tasks collectively as compared to working alone [24]) on the application of human redundancy in the evaluation of ultrasonic data showed further potential problems arising during mechanized NDT [21]. In this study, the participants were randomly assigned to one of four experimental conditions – working alone, working as inspector 1 (and told that someone will do the same task afterwards), working as inspector 2 (controlling the data from inspector 1) and working as inspector 2, where inspector 1 is told to be very experienced. The task was to evaluate a set of ultrasonic c-scans – find all indications and characterize them, or control that the results of inspector 1 were correct. The results indicate that teams might not always work better than single individuals, namely due to them being dependent on each other, in terms of either relying on other's experience, or overcompensating for the lack thereof. Redundancy, in technical terms, relies on the fact that two systems are completely independent from each other and this principle should be followed in redundant systems involving humans [25]. However, as stated by Sagan [26], individuals in redundant systems are normally aware of each other. Therefore, when applying human redundancy, the independency requirement needs be taken into consideration.

In conclusion, in spite of many advantages of human redundancy (especially in defect detection and sizing, where errors of single individuals could lead to serious consequences), one has to keep in mind, that when applied incorrectly, it can backfire. NDT, as a small community, is at risk from not profiting from human redundancy, if applied incorrectly.

3. How Good is Our Current Inspection Procedure?

One of the most important tools in everyday work of an NDT inspector is the inspection procedure. In general, the inspection procedure refers to a "*written description of all essential parameters and precautions to be applied when non-destructively testing products in accordance with standard(s), code(s) or specification(s)*" [24, p.3]. The inspector is often guided by a precise written description of the steps to be followed during testing, which is known as the NDT instruction [27]. Both the NDT procedure and the NDT instruction are written according to standards, codes and specifications and by certified NDT personnel; and they are meant to be used by trained NDT personnel.

One of the aims of a written procedure is to restrict human action to pathways that are not only efficient and productive, but also safe [16]. The main goal is to ensure reliable results from different inspectors. The literature and the experience have shown that the procedures are not always written in a way that is understood by all users; not used when too complex; and that sometimes the inspectors go over and beyond the procedure when it does not provide with the necessary information. This can further lead to a decreased reliability of the results.

Studies (e.g. [7], [21], [28], [29]) have shown, that NDT procedures and instructions are not always used in a way intended by designers and that they might require optimizing, in terms of content and matters of usability. Following the approach of the Usability Framework, initially developed for the assessment of computer software, usability is defined as an "*extent to which a product can be used by specific users to achieve specified* *goals with effectiveness, efficiency and satisfaction in a specified context of use"* [27; *Definitions*].

The goal of an ongoing study, in cooperation with SKB, was to evaluate their current NDT instruction and generate improvements. In line with the Usability Framework, the aims were to evaluate the instruction in terms of effectiveness (completeness and accuracy of the data evaluation task while using the current NDT instruction), efficiency (the amount of effort (e.g. time) invested in the use of the instruction) and satisfaction (positive attitudes towards the instruction). By observing the NDT data evaluation task, while using the instruction, a number of problems in the initial NDT instruction were identified and, through the discussions with the users, further evaluated. This process led to a creation of a new instruction, with significant improvements in terms of content, supporting visual material, and to a great deal, the format of the instruction. The preliminary results point out that the procedure content is the most important determinant of the evaluation performance, as reported by Bento in his evaluation of events in Swedish nuclear power plants [29]. The changes in the instruction format, mostly suggested by the PANI project [7], have elicited higher satisfaction from well experienced and less experienced users. Those changes include highlighting of relevant information, transferring from narrative into a stepwise information presentation, organization and presentation of information, language, terminology and many more. Which of the changed formatting properties will in fact lead to a more effective (less effort, less time) use of the instruction, is being tested in an ongoing study.

In general, these preliminary results show that there is room for the improvement of the current instructions and procedures. This improvement can be achieved by applying human factors principles [31] and through a user-centred approach, taking into consideration the task and the environment [7], as it was attempted in this study. The reason for this is to ensure that the procedures are not only qualified for the inspection task, but also equally understood by all users and written in a way that supports their use and increases acceptance by the users.

Changing the approach towards procedure writing is not an easy task. Raising the awareness that our current procedures are not perfect and that they indeed need to be improved is the first step.

4. Conclusions

A proper consideration of human factors in NDT requires not only looking into the inspector and assigning the blame for committed errors, but rather a multidisciplinary holistic approach, which focuses on the matter at hand from different perspectives, e.g. the engineering and the psychological, and takes into consideration all the relevant influencing factors, i.e. the individual, the team, the technology, the organization and the environment.

In search for the causes of the variability in the inspection results, one has to look deeper in the system, and not only at the inspector at the "sharp end". Frequently, the causes of errors are hidden in the organization, the task and the interaction between the individual and the situation.

Replacing manual with mechanized NDT can lead to a decrease of 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. As shown by a series of studies, mechanized NDT is not error-free.

The inspection procedure is an important tool in NDT and should be developed using human factors principles. A number of shortcomings were identified in a procedure, written according to requirements and by qualified NDT personnel. The ongoing study is expected to show that, next to the content, the format and procedure usability play a very important role in supporting the procedure use, as well as accurate completion of the NDT task.

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