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HUMAN RELIABILITY IN NON-DESTRUCTIVE INSPECTIONS OF NUCLEAR POWER PLANT COMPONENTS: MODELING AND ANALYSIS

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ABSTRACT

Non-destructive inspection (NDI) is one of the key elements in ensuring quality of engineering systems and their safe use. NDI is a very complex task, during which the inspectors have to rely on their sensory, perceptual, cognitive, and motor skills. It requires high vigilance once it is often carried out on large components, over a long period of time, and in hostile environments and restriction of workplace. A successful NDI requires careful planning, choice of appropriate NDI methods and inspection procedures, as well as qualified and trained inspection personnel. A failure of NDI to detect critical defects in safety-related components of nuclear power plants, for instance, may lead to catastrophic consequences for workers, public and environment. Therefore, ensuring that NDI methods are reliable and capable of detecting all critical defects is of utmost importance. Despite increased use of automation in NDI, human inspectors, and thus human factors, still play an important role in NDI reliability. Human reliability is the probability of humans conducting specific tasks with satisfactory performance. Many techniques are suitable for modeling and analyzing human reliability in NDI of nuclear power plant components. Among these can be highlighted Failure Modes and Effects Analysis (FMEA) and THERP (Technique for Human Error Rate Prediction). The application of these techniques is illustrated in an example of qualitative and quantitative studies to improve typical NDI of pipe segments of a core cooling system of a nuclear power plant, through acting on human factors issues.

1. INTRODUCTION

Safety, reliability and availability are fundamental issues in design, construction and operation of nuclear facilities, as Nuclear Power Plants (NPPs). Non-Destructive Inspection (NDI) is one of the key elements for ensuring quality of engineering systems and their safe use. NDI systems are characterized by real-time examination, which forces inadequate postures, leading to incidence of Work-Related Musculoskeletal Disorders (WRMSDs) among inspectors, and reducing the level of inspection quality. Moreover, there are many potential failures in data acquisition and evaluation, as well as significant variations in the individual performances, which could not be overcome by physical or engineering methods. At an early stage, the problem of varying performance in NDI has been typically approached by improving the equipment used and by changing the procedures. However, very few resources have been invested in research about the influence of human factors in NDI performance. In order to a NDI be reliable, the whole system, as well as its parts, needs to be reliable (equipment, procedures and inspectors). The largest source of performance variation can be found in the inspectors. After all, the inspectors are responsible for interpreting the signals provided by the equipment [1].

Many definitions of human factors can be found in the literature. According to the Health and Safety Executive HSE [2], "*Human factors refer to environmental, organizational and job factors, and human and individual characteristics, which influence behavior at work in a way which can affect health and safety*". Oriented to NDI, human factors can be understood as the inspector training and experience, as well as the conditions under which he must operate which influence on the ability of the NDI system to achieve its intended purpose. Generally, human factors refer to all of those things that need to be controlled to obtain reliable human performance, i.e. human qualification, standards, technology (equipment design), organization, and environment (e. g., regulator and facility). Human errors, on the other hand, are considered to be a result of unreliable human performance and occur due to an inadequate interaction between the human and systems (hardware and software) [3].

Human Reliability Assessment (HRA) involves systematic prediction of potential human errors when interacting with a system. Once such errors are identified, actions should be taken to eliminate or reduce their occurrence in order to maximize safety and performance. HRA generally encompasses the identification of error types and assessment of likelihood of occurrence, their consequences and recovery opportunities. Quantitative HRA involves the estimation of human error probabilities, while qualitative assessments typically consist of identification of the human Performance-Shaping Factors (PSFs) and cognitive processes. PSFs typically include everything that influences human performance, such as workload, stress, sociological issues, psychological issues and illness. Quantitative HRA is usually considered within Probabilistic Risk Assessment (PRA) of NPPs [4].

This work presents a review of sources of variability in inspection performance, models of human performance in NDI, and the main existing literature on human factors applied to NDI. The available approaches for HRA are explored, considering their strengths and weaknesses for NDI applications. An illustrative example, encompassing qualitative and quantitative studies to improve typical NDI of pipe segments of a core cooling system of a NPP, through acting on human factors issues, is also presented.

2. HUMAN FACTORS IN NDI

2.1. Nondestructive Inspections (NDI)

Human performance plays an important role in all inspection systems, from simple visual inspections to technically sophisticated ones. The types of human actions required in performing a typical NDI are briefly described below [5]:

- **Define inspection strategy.** To be effective, an inspection must be based on existing information about location, geometric profile, maintenance and inspection reports, and facility risks, in order to define inspection strategy.

- **Select inspection technique**. The selection of most effective inspection technique for defect detection involves considerations on geometry and materials properties, as well as detailed procedures to be carefully followed.
- **Prepare equipment and procedures.** The preparing involves calibration, setup and testing of inspection equipment, establishing of team coordination, and following written and trained procedures.
- **Acquire data.** Acquiring data needs explicitly written and trained procedures, i.e., specific steps must be prescribed and followed invariably. Sometimes this is not possible due to the task complexity and the number of variables and conditions that must be addressed in NDI.
- **Analyze data.** Interpreting defects data and discriminating them from other signals depend on many equipment sets, inspector skill and training, and accurate procedures.
- **Record data and report inspections.** Especially in manual data recording and inspection reporting, relevant parameters, such as defect indications and locations, are collected and analyzed at the same time, increasing error possibilities. Automatic data recording and analyses do not need proceed simultaneous with data collection, reducing human errors.

Inadequate performance on the above-mentioned diagnosis and actions can result in missed of falsely reported defects. NDI in nuclear industry is a very complex task, during which the inspectors have to rely on their sensory, perceptual, cognitive, and motor skills. It requires high vigilance, once it is often carried out on large components, over a long period of time, and in hostile environments, usually including radiation, noise, vibration, high temperatures and humidity, poor lighting, and restriction of workplace. The use of protective equipment due to high radiation doses is one of the factors that may significantly degrade NDI performance. A successful NDI requires careful planning, choice of appropriate NDI methods and inspection procedures, as well as qualified and trained inspection personnel [6].

2.2. NDI in Nuclear Power Plants

Safety and effectiveness of NPP operations depend on the performance of many different types of inspections, as In-service Inspections (ISI). The information obtained from these tasks provides the basis, for instance, for detecting and assessing flaws in steam generators, pipes, pipe welds, valves, pumps and other critical plant components. A failure of NDI on detecting critical defects in safety-related components of NPPs, for instance, may lead to catastrophic consequences for workers, public and environment. Therefore, ensuring that NDI methods are capable of detecting all critical defects, i.e. that they are reliable, is of utmost importance. Nuclear industry has been one of the precursors in human factors research, in order to construct and operate safely and reliably facilities [7].

Considering the potential safety implications, the specific conditions encountered in the nuclear industry can make NDI especially demanding. The main reasons why it is important to investigate human factors in this type of application are [5]:

:

- The effects of an unreliable inspection can be catastrophic, e.g. leakage of highly radioactive nuclear waste into the environment.
- The components to be inspected have complex geometries, and consist of materials and welds often difficult to access and inspect.

- Inspections are carried out under unfriendly working conditions, e.g. radiation, wearing of the protective equipment, humidity, surrounding noise, heat originating from the material being inspected and the surroundings, time pressure caused by hostile environment and economic stress, and poor accessibility to the inspection location.

A conceptual model of possible influences on the manual NDI performance in NPPs is show in Fig. 1 [6].

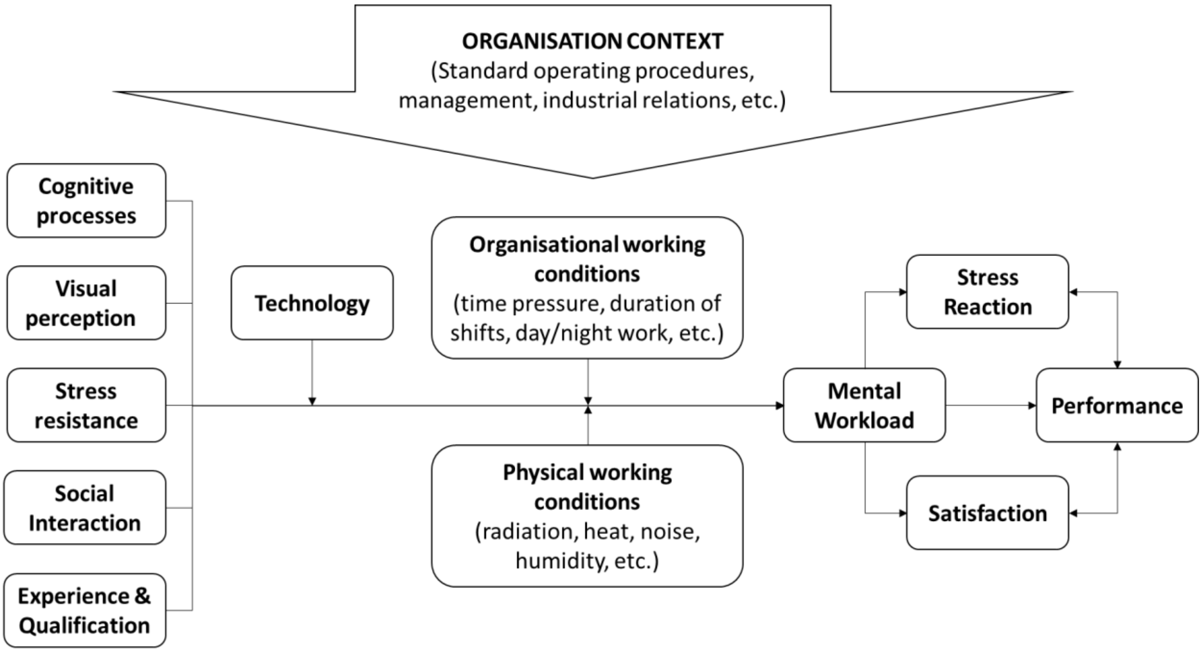

Figure 1: Model of NDI performance in nuclear power plants [6].

According to this conceptual framework, NDI performance is influenced by a set of internal individual predispositions (cognitive, perceptual, social, personality, knowledge, and skills), and by a set of external influences (organizational and physical working environment) and by technology. Working environment and equipment also influence human performance. For example, difficult working conditions, e.g. high radiation, heat, and time pressure, could give rise to mental workload and the arousal, resulting in a decreased inspection performance. Under optimal conditions, on the other hand, mental workload would remain constant and could give rise to work satisfaction, and positively affects the inspection performance. The organizational context, including management practices, standard operating procedures, and industrial relations, is also important for human performance [6].

As NDI is a complex task, no single Performance-Shaping Factor is responsible for the performance of inspections. The attitudes of the inspectors significantly influence the inspections, such as trust in their own performance and motivation, as well as optimal working conditions and feedback. There is also a correlation of ability and personality with the NDI performance, as well as a positive influence of debriefing, understanding of geometry of area to be inspected, application of procedures in a systematic way, and of good preparation [1].

2.3. Performance-Shaping Factors applied to NDI in NPP

Task complexity and the working conditions, typical in the context of NPP, can shape human performance in unwanted ways. The so-called Performance-Shaping Factors (PSFs) can be internal or external to the person. The internal PSFs include all those characteristics of the person that influence his performance, e.g. skills, motivation, and the expectations. The external include the work environment, as equipment, facilities and procedures. The work environment, which places high demands on the operator and does not match the inspector capabilities and limitations, can cause psychological and physiological stressors, considered as one of the most influential PSFs. A good match between the internal and the external PSFs will lead to a more reliable and optimal performance. On the contrary, a mismatch will lead to disruptive stress and suboptimal performance [4].

The concept of PSF is used for estimating the Human Error Probabilities (HEPs) of tasks within PRAs of NPPs, in order to calculate if the risks are acceptable. The understanding of the nature of human errors resulted, among others, in identification of many PSFs. The analysis of these PSFs aids the assessment of human error rates and the development of relevant methods of reducing the incidence of human errors. Table 1 shows some examples of types of PSF that influences the performance of diagnosis and actions of typical NDI in NPPs [1].

Table 1: Examples of Performance-Shaping Factors applied to NDI in NPPs [1].

Type of PSF	Examples of PSF in NDI
Available Time	NDI in NPP is usually performed in radioactive areas, with time pressure caused by heat, radiation, poor accessibility, and economic stress. Moreover, protective clothes difficult and delay the accomplishment of the tasks.
Stress and Stressors	Stress includes mental stress, excessive workload, time pressure, and physical stress (such as that imposed by hostile environment).
Complexity	Although the principles of NDI techniques are generally simple, the NDI task is complicated by a relatively large number of variables that must be addressed during preparation, conduction, and interpretation of inspections (locations, areas, geometry, techniques, frequencies, risks, etc.).
Experience and Training	Task performance tends to deteriorate if feedback is lacking or inadequate. Complete, accurate, and timely information on task performance is one of the best ways to improve and sustain human performance of NDI through training improvements.
Procedures	NDI procedures usually offer many opportunities for human errors. Many inspections are in general, similar, but different in significant details. The best way of avoiding inspection errors is to provide understandable and action-oriented instructions.
Ergonomics and Human-Machine Interaction	The use of ergonomics principles, as usability and accessibility, in the inspection planning and design of equipment and workplace, is a good way of avoiding WRMSDs and improving NDI performance.
Fitness for Duty	Fitness for NDI tasks include knowledge and understanding of NDI theory, skill, personality, attitudes (e.g., preference for the routine), mental workload, attention, motivation, self-confidence and tenacity.
Work Processes	Manual NDI are typically too complex to produce reliable results, because many variables must be addressed in order to prepare and conduct inspections. Manual NDI should only be performed where accessibility limitations preclude automatic ones.

A simple approach to HEP estimation is based upon the assignment of tasks to one of two types, diagnosis or action. Examples of action tasks include operating equipment, conducting calibration or testing, and any activity of following procedures. Diagnosis tasks consist of cognitively engaging planning and prioritizing activities, determining appropriate courses of actions, and using knowledge and experience to understand existing conditions. For diagnosis tasks, people tend to exhibit a nominal human error rate equal to 0.01, excluding any adjustment for PSFs (multipliers, according to Table 2) or human dependencies within a chain of events. For tasks that are more action oriented, the nominal human error rate is equal to about 0.001 [4, 8].

Table 2: Multipliers for Performance-Shaping Factors [8].

Type of PSF	PSF Level	Description	Multiplier
Available Time	Inadequate time	Problem not diagnosed in amount of time available.	*HEP* = 1
	Barely adequate time	Only 2/3 the average time required is available.	10
	Nominal time	There is sufficient time to diagnose the problem.	1
	Extra time	Between one to two times greater than the nominal time.	0.1
	Expansive time	Greater than two times the nominal time required.	0.01
Stress and Stressors	Extreme	Performance of most people will deteriorate drastically.	5
	High	A level of stress higher than the nominal level.	2
	Nominal	The level of stress that is conducive to good performance.	1
Complexity	Highly complex	Very difficult to perform.	5
	Moderately complex	Somewhat difficult to perform.	2
	Nominal	Not difficult to perform.	1
	Obvious diagnosis	Diagnosis becomes greatly simplified.	0.1
Experience and Training	Low	Less than six months of experience and/or training.	10
	Nominal	More than six months of experience and/or training.	1
	High	Extensive experience (a demonstrated master).	0.1
Procedures	Not available	Procedure needed for a particular task is not available.	50
	Incomplete	Information needed is not contained in the procedure.	20
	Available, but poor	Difficult to use (formatting, ambiguity, or inconsistency).	5
	Nominal	Procedures are available and enhance performance.	1
	Diagnostic/symptom oriented	Diagnostic procedures assist the operator/crew in correctly diagnosing the event.	0.5
Ergonomics and Human-Machine Interaction	Missing/misleading	Instrument fails to support diagnosis (or is inaccurate).	50
	Poor	Design of the plant negatively affects task performance.	20
	Nominal	Typically expected, but does not enhance performance.	1
	Good	System interfaces are easy to see, use, and understand.	0.5
Fitness for Duty	Unfit	Unable to carry out task (illness or other incapacitation).	*HEP* = 1
	Degrade fitness	The individual is able to carry out the tasks, although performance is negatively affected.	5
	Nominal	The individual is able to carry out tasks.	1
Work Processes	Poor	Performance negatively affected (fatigue, distracted).	2
	Nominal	Work processes do not play important role on performance.	1
	Good	Work process enhance performance (more than expected)	0.8

3. HRA IN NDI - MODELING AND ANALYSIS

Despite increased use of automation in NDI, human factors still play an important role in NDI reliability. Human reliability is the probability of humans conducting specific tasks with satisfactory performance. As HRA involves systematic prediction of potential human errors, once such errors are identified, actions should be taken to eliminate or reduce their occurrence, in order to maximize safety and performance. Many techniques are suitable for modeling and analyzing human reliability in NDI of nuclear power plant components. Among these can be highlighted Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Modes and Effects Analysis (FMEA), THERP (Technique for Human Error Rate Prediction), SPAR-H (Standardized Plant Analysis Risk - Human Reliability Analysis), CREAM (Cognitive Reliability and Error Analysis Method) and ATHEANA (A Technique for Human Error Analysis). Taking into account the strengths and weaknesses of these techniques to perform HRA of NDI of NPP components, FMEA and THERP were selected to be applied in this work [4, 6].

3.1. Identifying human errors in NDI using FMEA

Among strengths of FMEA for analyzing human factors in NDI can be highlighted: identification of human failures, causes, and their consequences, and generation of measures for preventing and mitigating risks; improvements on NDI performance through optimization of design of procedures and processes; and application to analysis of human errors, as well as equipment, hardware, software, and procedures failures. A weakness of this technique is that it analyzes only a single failure mode at a time, not a combination of failure modes [6].

FMEA can be applied in NDI to identify potential failure modes, determine their effect on performing the tasks and operating inspection equipment, identify potential cause(s)/ mechanism(s) of errors, identify the current design controls for prevention and detection of errors, and propose actions for preventing and mitigating the failures or human errors. Different inspection methods of acquisition and evaluation can be compared using FMEA, for instance, gathering expert opinions about potential human errors during NDI tasks. Additionally, the use of this technique can be a starting point for building hypotheses to support the assessment of HEPs by THERP technique [6].

Human errors in typical NDI tasks can occur in each one of the subtasks: define inspection strategy, select inspection technique, prepare equipment and procedures, acquire data, analyze data, record data and report inspections. Applying FMEA, the prioritization of recommended actions for reducing human errors and improving NDI performance can be carried out using the Risk Priority Number (RPN = O x S x D), where “O” is a number that represents the error probability, “S” the severity of the effects, and “D” the detection probability of the error. A scale for these three factors (ranging from 1 to 3) suitable for FMEA analysis of NDI is shown in Table 3 [6].

Table 3: Example of Severity, Occurrence and Detection Scale for FMEA [6].

Category	Assessment		Description
Occurrence (O)	Low	1	The occurrence of errors and deviations is improbable.
	Medium	2	Errors or deviations occur seldom.
	High	3	The probability that errors or deviations will occur is very high.
Severity (S)	Low	1	No observable effects of an error/deviation.
	Medium	2	Effects lead to dissatisfaction, e.g. delays, increasing efforts.
	High	3	Safety-related effects or violations of rules and regulations.
Detection (D)	Low	1	Error will be detected in successive steps.
	Medium	2	Error will be detected by 100 % testing /quality checks.
	High	3	There is no testing/possibility of independent tests.

3.2. Assessing HEPs using THERP

Among strengths of THERP for analyzing human factors in NDI can be highlighted: investigation of the impact of humans on NDI performance; evaluation of human error influences on the system; identification of PSFs; and assessment of HEPs. A weakness of this technique is that THERP requires detailed decomposition and analysis of the tasks into task elements (subtasks). Moreover, THERP is a usual practice in the nuclear industry [9].

Swain and Guttmann define THERP as a method to predict Human Error Probabilities (HEP) and to evaluate the degradation of a man-machine system. This degradation can be caused by human errors alone or in connection with equipment malfunctions, operational procedures and practices, or other system and human characteristics that influence system behavior [4].

THERP analysis encompasses, among others, the following steps: understanding of human error context and how human tasks influence activity or system being assessed; listing and prioritizing human errors, their effects and design controls; estimating error probabilities for each task using database, expert opinion or literature data; estimating the final HEP for the whole activity using a THERP event tree; and proposing recommendations to reduce HEP. FMEA, PSFs and modeling of human dependency can support the THERP analysis [8].

An important issue in quantitative assessment of THERP event trees is the dependency of human errors, in the chain of events (subtasks). There are available many dependency models to account for potential dependencies among multiple tasks or human interactions. In the model proposed by Swain and Guttmann, the dependency level between two tasks or human interactions is broken into five levels, as shown in Table 3: Zero Dependence (ZD), Low Dependence (LD), Moderate Dependence (MD), High Dependence (HD), and Complete Dependence (CD). In Table 3 HEP_n is the HEP for task *n* given Zero Dependence to task *n-1* [4].

Table 4: Dependence model for a Human Error Probability System [4].

Dependency Level	Dependent Probability
ZD - Zero Dependence	HEP_n
LD - Low Dependence	$\frac{1 + 19HEP_n}{20}$
MD - Moderate Dependence	$\frac{1 + 6HEP_n}{7}$
HD - High Dependence	$\frac{1 + HEP_n}{2}$
CD - Complete Dependence	1

4. APPLICATION OF HRA TO A TYPICAL NDI

An illustrative example, encompassing qualitative and quantitative studies to improve a typical NDI of pipe segments of a core cooling system of a NPP, through acting on human factors issues, is presented. The hypothetical context is In-service Inspection using a Non-destructive Testing (NDT), taking as an example the manual ultrasound testing of welds [10]. The human factors are investigated in the six basic steps of NDI (definition of inspection strategy, selection of inspection technique, preparation of equipment and procedures, data acquisition, data analysis, and data recording and inspection reporting). FMEA is used for illustrating a qualitative assessment of the potential failure modes and prioritizing the recommended actions in order to prevent human errors, mitigate their effects, and improve NDI performance. Table 5 shows a simplified worksheet illustrating the use of FMEA for typical NDI in NPPs,

According to preliminary analysis of Table 5, carried out in a general context and without gathering expert opinions about potential human errors during NDI tasks, many recommended actions can be, in principle, be prioritized, taking into account the RPN values. In this context, the following actions should be considered:

- Use of Risk-Based Inspection approach (Risk-Informed In-service Inspection, in the context of NPPs) in order to prioritize locations and higher risks systems, improving inspection strategy [11].
- Organization improvement in order to solve the problem of task complexity, designing the task to fit the human cognitive, physical, and time constraints (training, schedule, human redundancy, accessibility, usability, etc.) [5].
- Increase the automation level of inspections, in order to overcome some human limitations of manual inspections (e. g., in acquiring, analyzing and recording data) [6].
- Crosschecking of inspection results using complementary inspection techniques, reducing defects missed and false calls [6].

Table 5: Simplified FMEA Worksheet for typical NDI in NPPs.

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S	Potential Cause(s)/ Mechanism(s) of Failure	O	Typical Current Design Controls	D	RPN
Define inspection strategy	Incorrect choice of location	Defects missed	3	Incorrect procedure	3	Based on information about location, history and frequency	3	27
Select inspection technique	Inappropriate choice of equipment (manual/automatic)	Poor data quality	2	Time and economic stress	1	Training on principles of NDI techniques	2	4
		Radiation exposure of inspectors	3	Hostile environment	3	Use of EPI (protection clothes, dosimetry)	1	9
Prepare equipment and procedures	Incorrect setup/calibration	Defects missed	3	Not considering Human Factors in equipment design	3	Training on specific equipment, procedures and manuals	2	18
		False calls	2			Periodic calibration, testing and maintenance	2	12
Acquire data	Incorrect scanning of location	Poor data quality	2	Inadequate experience and training on acquiring data	2	Verification of data inconsistency	2	8
Analyze data	Incorrect interpretation of data	False recommendations	3	Error-enforcing conditions due to task complexity	3	Relying on inspector skill	2	18
				Inadequate experience and training on analyzing data	2	Periodic training on NDI procedures	2	12
Record data and report inspections	Error on data record	False recommendations	3	Error-enforcing conditions due to hostile environment	3	Relying on inspector skill	2	18
	Error on reporting inspections	Feedback lacking or inadequate	2	Inadequate experience and training on reporting inspection	2	Periodic training on reporting inspections	1	4

This preliminary FMEA is the starting point for building the THERP event tree shown in Fig. 2. This THERP illustrates the estimation of HEP of human subtasks and the inspection reliability, through the analysis of PSFs and human dependencies. Considering the events independent and the nominal HEPs ($P(A) = P(B|a) = P(E|d) = 0.01$, $= P(C|b) = P(D|c) = P(F|c) = 0.001$), according to item 2.3, considering tasks *a*, *b* and *e* as diagnosis oriented and tasks *c*, d and *f* as action oriented, the inspection reliability would be $P(a) \, . \, P(b|a) \, . \, P(c|b) \, . \, P(d|c) \, . \, P(e|d) \, . \, P(f|c) = 0.967$. This is a very optimistic estimate, comparing with results of ultrasound testing that are considered acceptable in analogous conditions (80 percent correct call rate and 20 percent false call rate, according to reference [5]). The main reason for this unconformity is that PSFs and human dependencies were not considered in estimation of HEPs in this application example. Just for illustration, if we consider a PSF multiplier of 25 for $P(A)$, 2 for $P(C|b)$ and 5 for $P(E|d)$, maintaining the nominal values for the other probabilities, the inspection reliability becomes 0.697, that is a more realistic estimate. Even more realistic approaches, taking into account the human dependence model shown in Table 4, can be carried out for specific cases, considering details of geometry, team, techniques, procedures and facilities.

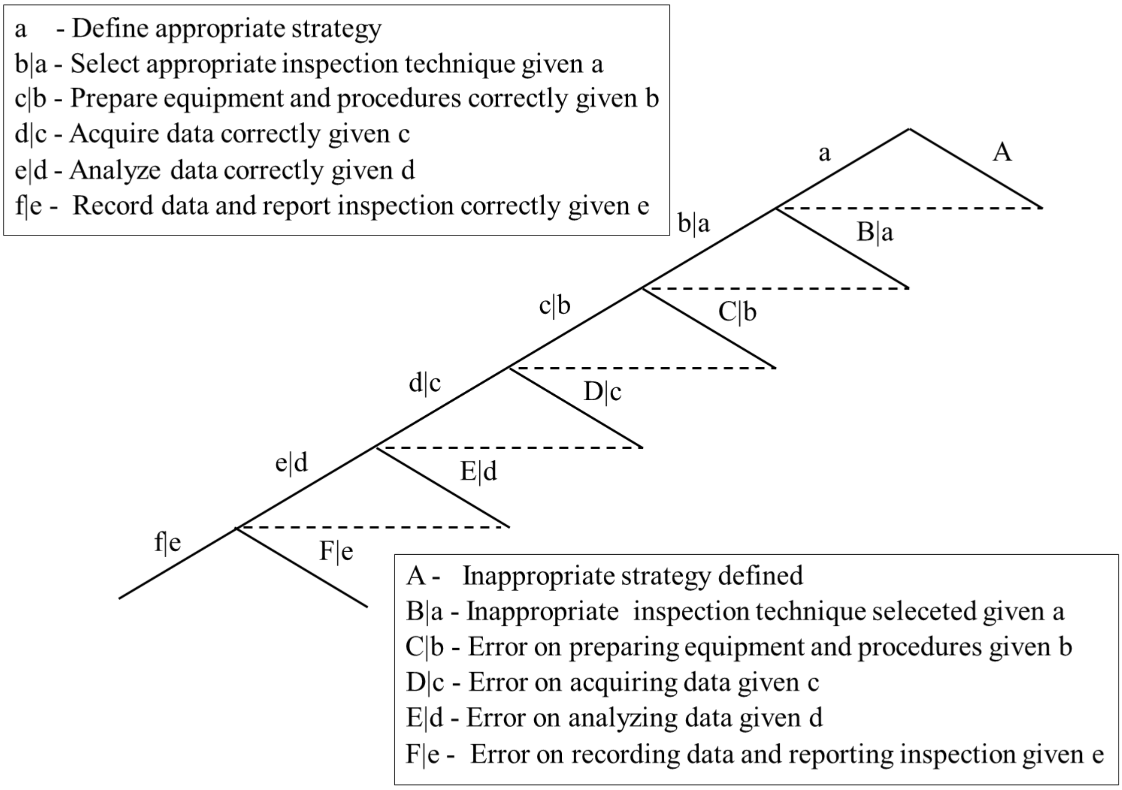

Figure 2: THERP for evaluating the probability of human errors occurring throughout the completion the task of piping inspection.

5. CONCLUSIONS

The importance of human factors in complex tasks, as NDI, especially in the field of nuclear industry, was analyzed. An approach to qualitative and quantitative assessment of human factors in NDI was proposed. Applying FMEA, the prioritization of recommended actions for reducing human errors and improving NDI performance can be carried out through using the RPN (Risk Priority Number). The qualitative analysis of FMEA is the starting point to a quantitative analysis of human error probabilities through THERP technique, supported by analysis of PSFs and modeling of human dependencies.

As illustration, an application example, studying alternatives to improve a typical NDI for pipe segments of a core cooling system of a NPP, through acting on human factors issues, is presented. Among the recommended actions prioritized through FMEA, taking into account the RPN values, can be highlighted: use of Risk-Based Inspection, improving inspection strategy; organization improvements, in order to solve the problem of task complexity of NDI, designing the task to fit the human cognitive, physical, and time constraints (training, schedule, human redundancy, accessibility, usability, etc.); and increasing the automation level of inspections. The results of inspection reliability, taking into account nominal HEPs, were very optimistic estimates, comparing with acceptable values observed experimentally in analogous conditions. More realistic approaches, taking into account PSFs and human dependence model, should be considered in future works.

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