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Human and Organisational Factors in Maintenance of NPPs

Giustino Manna

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Contact information
Address: Westerduinweg 3, P.O. Box 2, 1755 ZG, Petten, The Netherlands
E-mail: giustino.manna@jrc.nl
Tel.: 0031-(0)224-56 5416
Fax: 0031-(0)224-56 5637

http://ie.jrc.ec.europa.eu/
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1. Introduction

The objective of the maintenance activity, in a nuclear power plant (NPP) is to maintain the operational reliability and the economic value of the nuclear installation so that the power production can continue as long as planned. The maintenance work in nuclear power plants is varied by its nature. It requires traditional craftsman skills as well as analytical understanding about the different failure mechanisms, the operating principles of the power plant and e.g. condition monitoring techniques.
The maintenance personnel seem to carry a strong craftsman identity. Attending to the machinery, for example when conducting fault repairs, is a crucial source of job motivation. The motivating aspect of the fault repairs partly stems from the fact that they are directly (and visibly) related to the overall goal of the organization; maintaining the operability of the plant.

Maintenance has often been considered as mostly manual labor, which requires little or no mental work. This reflects also to maintenance being sometimes at the bottom of the hierarchy in terms of respect, influence and authority at the NPPs
Although NPP maintenance work, and maintenance in general, suffers from a "dirty hands" image, the nature and significance of maintenance work should be better acknowledged in both research and practice [1]. In fact, in many aspects maintenance work is similar to so called knowledge work.

Maintenance work in a nuclear power plant (NPP) aims at controlling hazards related to nuclear safety and guaranteeing the availability of equipment critical to production as well as safety. A significant part of nuclear plant events is attributable to failures that take place during maintenance and periodic testing.

Human and organisational factors are frequently identified as making a major contribution to these events [2]. Despite this recognition, licensee and regulatory oversight in the human and organisational area has tended to focus sometimes more on operational matters than maintenance.

2. Objective of the report

Starting from the trends registered in the nuclear sector, in particular the aging of the workforce and the lost of knowledge, the report identifies the human and organisational factors appearing in maintenance activities. Suggestions for improving the human and organisational performances are also given.

3. Trends affecting maintenance in the nuclear sector

3.1 Lost of knowledge

The nuclear power sector has recognized since time the importance of the preservation of nuclear knowledge in the coming years. Nuclear knowledge is threatened by two trends: the first concerning the choice of the new generations, the second concerning the workforce in the nuclear power sector. The decrease in the number of students choosing nuclear science and engineering is a phenomenon observed since years; as a consequence, several universities have phased out the related training programs, whilst R&D activities in the nuclear sector have been decreased too.

In the nuclear sector, the nuclear licensees world-wide are facing the ageing and the retirement within a few years of a significant part of their workforce, which makes for them very challenging to preserve the knowledge and the expertise related to the design, the operation and the maintenance of the nuclear power plants.

The knowledge of employees is conventionally distinguished in two types: the explicit and the tacit knowledge. The first type, is the knowledge that can be verbalized, documented and codified (e.g. in the form of verbal instructions and training, training materials, procedures, reports). The second type, is the one accumulated during the work history, created during the many work situations the employee has been facing and the tasks she has been carrying out. This knowledge derives from practical know-how and manifests itself in action. It is considered non-quantifiable and often it is unnoticed.

In reality, explicit and tacit knowledge are not exclusive. In fact, they can be considered as the extremes of a continuum; furthermore, the distinction between the two is not static, considering that part of the tacit knowledge is converted in explicit knowledge (e.g by drafting new procedures), and part of the explicit knowledge is continuously transformed in tacit knowledge (e.g. by an employee or a team who implements a specific procedure) [3].

A consequence of the lost of knowledge, as well as of the purpose of reducing staff costs, is the tendency to use the maintenance staff for performing a wider range of activities which would require more staff. For this purpose, many nuclear power plants are implementing programs of skill-broadening in maintenance, which provide the maintenance with additional skills. This practice has also the advantage to providing staff with new development opportunities. However, there is a risk of affecting the standard competences. Additional training of the less used competences is recommended, as well as the increase of supervision.

3.2 Outsourcing of the maintenance services

In the nuclear sector the increased recurrence to contractors for performing maintenance activities has been registered in the last fifteen years. Contractors can be small, locally-based companies or maintenance teams which provide outage servicing to many different NPPs, and which may work across different countries. When work is contracted out, the licensee must ensure adequate oversight of contractors by maintaining a suitable level of control and supervision and by maintaining an *intelligent customer* capability. In particular, the nuclear licensee, who is the responsible for safety, must ensure that the contractors work within the licensee's work processes and rules. Several events have shown that this has not always been achieved, so increased oversight may be required.

In general, the role of supervisors at the plant level becomes more important with the loss of experienced workers. In addition to technical skills, supervisors must be competent in dealing with people. It is important to introduce specific incentives, in such a way to motivate staff to move to more administrative tasks. In addition, training programs are required to assist supervisors in developing their leadership and management skills.

Contracting out and moving to skill-broadening are examples of organisational changes that are used to optimise the use of plant staff resources. Nevertheless, if inadequately conceived or implemented, they also have the potential to negatively impact on station performance. Organisational change processes are necessary to ensure that the safety significance of organisational changes are recognised and addressed.

4 Human errors registered in maintenance activities

Recent statistics carried out in the USA (INPO) [4] show that 40% of the failures at US NPPs are related to human factors: among them, 30% are related to engineering deficiencies and 30% to work performance during maintenance.

An other interesting conclusion is that most of the significant events in the latter category have been triggered by the supplemental workers. Therefore the human in general and the contractor performance in particular become a crucial issue where many utilities are investing large effort for their reduction.

Also supplier reliability is an issue: in many cases equipment were delivered with wrong or different specifications.

It was noted by many participants to the above mentioned International Events that human errors and their minimization still lacks good models, including contractor performance, training effectiveness, work control, etc.

In particular, the direct errors on equipment are classified as follows [5] :

Error of Omission (missing human actions):

- Restoration errors of operability after work, such as omission of the realignment of process or instrument valves, disconnectors, breakers, fuses, limit settings or blockings. Omission of refilling of fluid or gas into lines, tanks or draining at the end of work,
- Disconnected cables or electronic components not reconnected, during work. Omission to install packing or adjusting device. Settings, adjustments, preventive maintenance or inspections omitted.
- Foreign objects or impurities left behind inside the object of the work. Examples are dirt, garbage, metal shives, tools, scaffolds or covering material.

Errors of Commission (wrong human actions):

<u>Wrong order or direction</u>

- Wrong order, such as cables or instrument pipelines crosswise connected,
- Wrong direction, such as reversed or twisted installation of valve or another sub-component. Wrong positioning of valve.

<u>Wrong selection</u>

- Wrong place or object, such as cabling fixed on wrong connection, setting of wrong tripping conditions, or draining of wrong pipeline. Item installed on wrong equipment place.
- Wrong or mixed spare parts, parts, materials, tools, fluids or chemicals selected for work. Spare part, equipment or material or function deviates from design.

Wrong settings/adjustments/calibrations
- Wrong settings of trip limits, limit switches, reference, indication or time delay values, or of adjusting devices. Deficient alignment of shaft, stem/spindle or pipe. Wrong setting of pipe support or packing.

Other maintenance quality problems
- Too little force, e.g. loose connections of bolts, nuts, cables, terminals or sensors,
- Too much force, e.g. excessive tightening or greasing,
- Damaging other equipment e.g. cabling, cable trays or small diameter piping by falling material or slugging/contacting. Can be due to carelessness and narrow spaces for work or transport.
- Other carelessness: e.g. worn tools, falling material, deficient weld, solder joint or insulation. Unclear trips initiated during testing, installation or maintenance. Wrong subtitling or recording. Wrong timing.

5 An important issue: the bending of rules

Procedures and work instructions are required to guide work not only in operations but also in maintenance, and a culture of procedural compliance must be developed and nurtured in maintenance departments.
In safety critical organizations, rules and procedures have the purpose to make the activities carried out by the employees more reliable. This view is based on the assumption that humans are prone to making mistakes. The purpose of rules and procedures is, then, to control these ‘human’ characteristics, erecting safety barriers to the troublesome variability of human performance [6]. Moreover, Dien [7] suggests that the rule designers often consider procedures as tools for controlling the worker, not as tools for allowing the worker to better control her work.

Procedures must be technically accurate and written using human behaviour principles. The usability of procedures should be tested through verification by human factors experts, and validation activities, including walk-downs of the procedures in the plant. However, an appropriate balance must be maintained between procedural compliance and preserving a questioning attitude among plant staff.

Several case studies have shown that most maintenance workers think that it is not possible for them to observe rules and procedures to the letter; they also think that it is not even possible to make rules that could be followed to the letter, and that the appliance of the rules depends on the situation [8]. These beliefs are rooted in the view that part of the professionalism of the maintenance technicians is to know how to interpret, apply and neglect the procedures so that the work can be carried out [1, 9].
Such attitude is in general perceived as potentially harmful for the safety and effectiveness of maintenance. However, it is worth to note that also the strong tendency to standardize and proceduralize the work may be experienced as reducing

the meaningfulness of the work, and as threat for job motivation and for the professional identity of many maintenance workers who see themselves as skilled craftsmen [7,1].

Oedewald & Reiman [9] have studied the phenomenon of rule violation. They noted that employees are more willing to bend the rules if the consequences are interpreted as being probabilistic, whilst they will carefully follow the rules carefully if they believe that the failure to comply with the rules or the violation will have inevitable deterministic consequences. Also for this reason it is recommended that the employees using the rules, in particular the field workers, participate in their creation so as to gain ownership of the instructions and the awareness of the consequences of non-compliance.

In reality, it is difficult to ascertain if the effects of a violation are deterministic or probabilistic and under what conditions. Moreover, many rules include precautionary measures; in this way, the non-compliance should not lead to deterministic consequences unless redundant defences have been made inactive.

Also good rules are sometimes broken, and not only by risk takers and sensation seekers. More important than to try to completely prevent violations and rule bending is to seek to understand the organisational causes that promote or force to act against the rules. For example, organizational culture and the structural elements of the work can be such that working strictly according to rules would in practice be impossible, as believed by many maintenance workers. The cultural dimension is evident in those cases where rule bending and violations is silently and implicitly accepted by the management, until the occurrence of a serious event.

6 Elements affecting human and organisational performances

6.1 Motivation

Most of the maintenance workers interviewed have been proud of their job. They have seen maintenance work as very important for the plant safety. The maintenance work produced a feeling of meaningfulness, especially when there were technical problems to solve.

The motivating aspect of the problems and fault situations is a paradox in the sense that one of the goals of maintenance is to avoid problems and keep the technology running reliably. This conception of maintenance work is not optimal in terms of fulfilling the maintenance task, where preventive maintenance, condition monitoring and analysis of the maintenance history of the equipment are important for keeping the production safe and reliable in the long run. As stated in IAEA [10], “constant repairs tend to create a firefighter mentality among the workers, which is further bolstered by both the feeling of satisfaction after the repairs are successfully completed and ‘rewards’ or praise following a job well done. These feelings contrast starkly with the otherwise mundane and systematic approach of preventive maintenance” [11].

The fact that a large proportion of the work is routine preventive maintenance is a challenge for the safety and reliability of the maintenance. Routine work decreases motivation [12] and can lead to lower quality or increased slips and lapses due to inattention. Too much routine can be avoided by organizational practices e.g. by the division of the tasks and job rotation. More attention should be paid to offering learning opportunities and challenging jobs to all the workers. For example, modification projects and rare disturbance situations could be exploited better. In addition to their motivation enhancing effect the early acquiescence with the new equipment, for example, contributes to anticipating maintenance needs, including preventive and corrective maintenance [13].

6.2 Sense of responsibility

The importance of a sense of personal responsibility for effective maintenance, and of a feeling of personal ownership for an equipment or an area of plant, is suggested by several studies [1,14]. Still, the meaning and content of personal responsibility in nuclear power plant domain have remained vague both in research and practice [9].

The conditions necessary for obtaining the sense of personal responsibility in a complex sociotechnical system such as a NPP are seldom perfectly clear for the personnel or the management. In NPPs, the achievement of a sense of personal responsibility is complicated by strict rules, procedures, and a tendency to emphasize shared responsibility and collective action instead of individual initiative.

There are different views about the opportunity to localise or spread responsibility in a NPP. For example, Schulman [15] argues that a localized responsibility can be dangerous in NPPs, because actions taken too soon, without a broad awareness of what is going on, can jeopardize other parts of the system. At the contrary, other scholars (e.g. [16]) think that the risk of having a diffusion of responsibility is a non clear identification of responsibility.

From one side, the sense of responsibility enhances the motivation; from the other, the fact that a task is very important and safety relevant, brings the management to design and supervise the work with the purpose of ensuring performances without errors; this prescriptive attitude of management can be perceived as reducing or removing the individual choice and, consequently, destroy the feeling of responsibility and the motivation.

The prescriptive attitude of management, on the other hand, is rooted in the awareness both of management and maintenance staff of the impossibility of translating in procedures all the aspects of the maintenance work; the limitations and sometimes the inadequacy of the procedures to cope with the reality are well known to the maintenance personnel [1,7], who, in general, considers that the knowledge on how to interpret, apply or neglect the procedures, in such a way that work can be carried out thoroughly and efficiently, is an important part of their professionalism [6, 8].

7 Approaches to enhance human performance in maintenance

7.1 Planning of maintenance

First of all, the utility is expected to have a maintenance strategy to define and justify the maintenance programme, eliminating tasks that are not required. This approach is likely to reduce the occurrence of human errors. The error prevention requires an effective planning of maintenance. Error prevention strategies differ between preventive and corrective maintenance, because preventive maintenance is more affected by slips and lapses while corrective maintenance is prone to knowledge-based errors and production-related pressures [2,8].

The planning of maintenance tasks must be realistic in order to reduce the risk of workers perceiving time pressures.
Outages are usually moments of high workload with greater risks of time pressure, due to the perceived need to get the plant ready for start-up as soon as possible. The time pressure influences the task performance. Moreover, during the performance of maintenance tasks, the workforce may perceive that what is required by management is not consistent with management statements on the need to give paramount importance to safety. Successful planning and execution of plant maintenance requires strong communication between workers and supervisors, between maintainers and operators, and between contractors and plant staff.

With the purpose of ensuring the effective planning, and good work scheduling, appropriate maintenance planning tools may be introduced in the work management systems. Such tools include: e.g. critical task analysis, pre-meetings to avoid conflicting jobs and priorities, walk-downs of complex or infrequently performed tasks.

7.2 Organisational learning

Post-job debriefings are a useful tool for identifying deficiencies and strengths in the work planning process and for learning lessons. There are many other ways for improving maintenance performance by promoting learning paths in the organization.

For example, the reports on near misses and minor events provide valuable learning opportunities. For this reasons, maintenance workers must be encouraged to report. The root-cause analyses offer other opportunities for organizational learning, in particular if the experts carrying out root cause analysis carefully examine the human and organizational contributors to maintenance events. Other sources are audits, self-assessments and maintenance logs.

7.3 Knowledge management and training in maintenance

Training is one of the instruments for creating an awareness of hazards as well as sufficient skills for carrying out the work in a safe manner. An ongoing change of workforce generation calls for tools to analyze the existing know-how of the personnel in order to create effective training programs. Maintenance work in nuclear power plants is not routine-like activity which could be carried out just by following the procedures. It requires different types of skills and knowledge. Practical craftsman skills, overall understanding of the functioning of and couplings between the systems as well as technical knowledge about the materials and equipments are needed in maintenance work [1,17,18]. Thus, in addition to the tacit knowledge about maintenance practices and specific tasks, understanding of the theoretical basis of technical phenomena and work processes are essential contents of the know-how of the personnel.

Long tenures, experience, and adequate training are often considered a proof of high competence in the nuclear area. However, long tenure and experience as such does not guarantee competence. Long tenure can also lead to routinisation. Experience is then no longer a benefit, but can actually be a source of errors when the work and its outcomes are not actively reflected upon. Routine tasks are a major source of incidents. Furthermore, new technology, new job contents and working practices, and new safety and efficiency demands placed on maintenance set new requirements, which means that some of the old habits and out-dated conceptions have to be unlearned.

There are a number of error management techniques in maintenance, including training, work planning, job cards, licence-to-work systems, licensing and certification, audits, procedures, disciplinary procedures, human resource management, and Total Quality Management. They note that these techniques have not been effective in preventing a steady rise in maintenance-related errors during the past decade. They comment of the techniques that "their limitations include being piecemeal rather than principled, reactive rather than proactive, and fashion-driven rather than theory-driven".

Human error prevention tool is a general term for the various techniques and approaches aiming to improve human performance by facilitating the prevention, discovery and recovery from human error. Human error prevention tools include the following [8]:

- Peer checking
- Three way communication
- Pre and post job briefing
- STAR (Stop, Think, Act, Review, Communicate)
- take two (minutes to think before acting)

Human error prevention and human performance enhancement tools can provide a good way of facilitating the noticing of human factors in maintenance. However, the tools are only as good as their users, designers and implementers. The tools cannot compensate for a lack of understanding on technical issues or hazards, nor can they compensate for inadequate organizational processes or human resource management in terms

7.4 To create conditions for working safely

The maintenance work is changing in nature. Information technology is utilized in a larger extent and new maintenance strategies and methods are continuously introduced. However, the innovations have faced resistance from the field workers. Sometimes the management has considered this to indicate that the maintenance personnel are not motivated and committed to the organization. In reality most of the maintenance personnel are very committed to the work and the safety and functioning of the plant is important to them. New methods and tools should be introduced in a manner that allows the personnel to see the functional relevance and the safety relevance of the innovations. Further, new tools and working practices create new competence requirements. It takes time and practice to acquire sufficient confidence to be able to take care of the new tasks or to utilize the new methods effectively. More training resources and time for learning new methods and practices should be offered.

Tools guide the way people think and work. For example, the measures used in condition monitoring define what information the worker will acquire and can utilise in his/her work. There exists also a variety of other tools than technical, for example documents and meetings. In order to utilise these tools effectively attention should be paid to issues such as who needs to participate in different meetings and who have access to e.g. plant information systems. From the accuracy of the information point of view the technicians are usually the ones with the best knowledge of the plant. Usually, however, the reporting and documentation to information systems and in various meetings is conducted by other members (supervisor or engineers) in the organization.

Division of the tasks should support the formation of an overall picture of the different activities in the maintenance organization as well as of the functioning of the plant. It seems that specialization to quite narrow responsibility areas has been typical in NPPs. But, from the organizational effectiveness point of view the "one man areas" may be fragile and inflexible. Due to that reason the organizations have started to emphasize e.g. teamwork and multiple skilled persons.

According to Reiman [8] the experienced maintenance workers stress the importance of concentrating deeply in some technologies, not learning a little about everything. They stress the importance of the tacit knowledge in planning and developing the maintenance activities as well as in diagnosing the faults.

Training needs of the maintenance workers should be checked systematically from time to time. Even the very experienced workers could benefit from basic plant technology training. They can for example diagnose an equipment failure correctly, still not understanding the mechanisms causing it. Or they can carry out an overhaul but they cannot explain the basis of it or remember the correct names of the components. This can be harmful when cooperating with other organizations or when teaching newcomers.

More attention should be paid to offering learning opportunities and challenging jobs to all the workers. For example modification projects and rare disturbance situations could be exploited better. In addition to their motivation enhancing effect for example the early acquiescence with the new equipment contributes to anticipating maintenance needs (preventive and corrective maintenance).

8 The role of the regulatory body

Owing to the growing recognition of the importance of reliable human and organisational performance during maintenance, regulatory bodies are increasingly scrutinizing this area. For example, some countries require a formal treatment of human factors in the safety case for the plant (and modifications) to demonstrate that maintenance tasks are properly understood and supported. Suitable regulatory frameworks should oversee the challenges facing the industry, such as management of ageing plants and workforce, plant life extensions, deregulation, institutional changes, design of new plants and decommissioning. Common concerns identified by regulatory bodies include outsourcing, contractor management, maintenance of competency, communication, and work planning.

Regulators are also able to promote good practices and document regulatory expectations on topics that may be new to the industry, such as the trend towards increasing use of contractors which has increased the focus on maintenance of "intelligent customer capability". Many regulators are working to ensure that their activities are planned using a risk-informed approach. However, there are differences between countries in their views on the extent to which the regulator should engage with the licensee to influence its safety management system [8].

9 Conclusions

Motivated and competent maintenance work force is a key prerequisite of nuclear safety. Maintenance organizations should consider the meaningfulness of work and clarify the significance of the more ordinary tasks to the reliability of plant performance. Maintenance organizations should encourage sense of personal responsibility for the safety of the entire plant and a feeling of professional pride. Further, maintenance organizations should strive to make their contribution to the overall functioning of the plant clearer by pointing out the unique knowledge maintenance acquires of plant condition.

Maintenance organizations should clearly communicate differences in the importance that different rules have for safety and that the organizations regularly monitor the gap between work as officially described and work as actually conducted. Further, the rationale for the different rules and procedures should be thought of and explained to the personnel.

Maintenance organizations and maintenance work is undergoing a lot of changes. Human and organizational factors and the specific organizational culture should be given the attention warranted by their significance.

Training that maintains expertise is needed throughout working life. Both experienced and less experienced employees need to review the fundamentals from time to time.

The maintenance organizations should discuss the ways in which they learn as individuals and as a collective. Learning should strive to challenge the assumptions and conceptions concerning hazards and safety, but also to make improvement to the existing practices. Incidents and errors should be seen as opportunities for learning about the functioning of the organization and about its current vulnerabilities, not as opportunities for blaming individuals.

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Abstract
A significant part of nuclear plant events is attributable to failures that take place during maintenance and periodic testing. Human and organisational factors are frequently identified as making a major contribution to these events.
The trends affecting the nuclear sector and the maintenance organization are described, as well as the most recurrent forms of human errors in maintenance. Consideration is given to the factors affecting human performance and to a possible approach to enhance human performance.

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