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Better Nuclear Plant Maintenance:
Improving Human and Organisational Performance

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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FOREWORD

The CSNI Working Group on Human and Organisational Factors (WGHOF) is tasked to improve the current understanding of human and organisational performance and the way in which this impacts upon nuclear safety. In order to further the understanding of human and organisational performance during maintenance, WGHOF hosted an international workshop in 2005 entitled “Better nuclear plant maintenance: improving human and organisational performance”.

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1. INTRODUCTION

This Technical Opinion Paper (TOP) represents the consensus of specialists in human and organisational factors (HOF) in the NEA member countries on commendable practices and approaches to incorporating a suitable treatment of HOF when managing, assessing, and regulating maintenance programs in nuclear facilities. The TOP is based on the outcomes of a workshop, organised in 2005 by the NEA Committee on Safety of Nuclear Installations (CSNI) on Better Plant Maintenance: Improving Human and Organisational Performance. Modifications made intentionally or unintentionally during maintenance are outside the scope of this TOP, but are addressed in a separate report (CSNI, 2005). The intended audience for this TOP is nuclear safety regulators, nuclear plant operators, design agencies and research institutes.

2. BACKGROUND

Maintenance is done to prevent equipment failures (preventive) or to fix broken equipment (corrective). Periodic testing to ensure equipment will function when required and equipment surveillance are also classified as maintenance. A substantial amount of research and work has been carried out, in a number of industries, to better understand how human and organisational factors can impact maintenance work.

2.1 Human and Organisational Factors in Maintenance – General

Maintenance has been gaining prominence as an area of interest in the overall effort to optimise human-system performance. Several studies have been carried out in various industries to understand the various factors that affect how maintainers perform their work. The emerging picture is that "…human error in maintenance is a pressing problem…" (Dhillon and Liu, 2006). Further evidence is provided by the claim that, across industries, a large proportion of equipment failures occur after maintenance on the same equipment and that a substantial portion of those failures can be traced back to human and organisational factors (Dunn, 2004).

2.2 Human and Organisational Factors in Maintenance – Nuclear Organisations

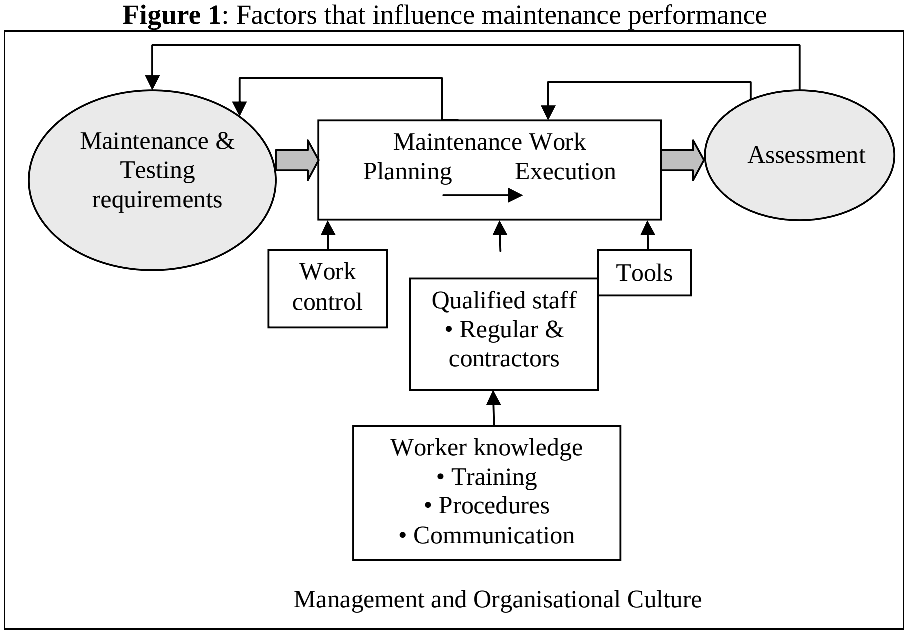
Historically, technical issues and operations have received more attention than maintenance from nuclear design agencies, operators and regulators. However, it is now better understood that errors during maintenance and periodic tests are significant contributors to plant events and that events stemming from maintenance are often rooted in weaknesses in human and organisational performance (Reason and Hobbs, 2003; HSE, 2000). Also, maintenance errors may not always be revealed by post-maintenance tests or may remain undetected for extended periods until the affected system is called upon to function (Svenson and Salo, 2002).

Further, the following common trends across the nuclear industry have triggered the need to examine human and organisational factors during maintenance:

- Economic pressures have led to reductions in staffing, changes in organisational structures, new shift schedules, and more maintenance work being done by external contractors (CSNI, 2004).
- Nuclear organisations worldwide are facing retirements of experienced staff including maintenance specialists.
- Ageing plants and equipment increase the volume of maintenance activities.
- Life extension projects and new designs are an opportunity to improve the human-system interface used to maintain plant equipment.

Figure 1 presents a framework of factors that influence maintenance performance, including the definition of maintenance and testing requirements, planning and execution of maintenance, and subsequent assessment. The remainder of this TOP discusses the current human and organisational issues in maintenance in nuclear facilities, and is organised according to this framework.

Figure 1: Factors that influence maintenance performance



3. DEFINING MAINTENANCE AND TESTING REQUIREMENTS

Maintenance and testing requirements define the results to be achieved and drive the planning and subsequent execution of maintenance activities. Inputs used to derive the maintenance requirements are numerous and may include the following:

- Technical and safe operating requirements including manufacturer requirements, dictate a large portion of maintenance jobs and their frequency.
- Assessments of plant reliability and risk, including the probabilistic risk assessment (PRA), are used to align maintenance and test requirements with risk. Further work is required to improve the incorporation of human errors during maintenance into HRAs and to validate human error probabilities with plant data.
- Regulatory requirements, as well as international standards, continue to evolve with operating experience and may influence maintenance requirements.
- Ageing equipment may increase planned or corrective maintenance requirements. In addition, as equipment ages, it may be difficult to find like-for-like replacement parts. When upgrading obsolete equipment the different behaviour of new replacement parts from a users' perspective must be considered.
- Market or other commercial forces may pressure nuclear facilities to reduce preventive maintenance requirements if the requirements are perceived as increasing costs.
- Plans for life extension or decommissioning may lead to delaying maintenance tasks or equipment replacements.

- An ageing workforce creates special challenges in terms of knowledge retention and transfer for the organisation; this may in turn lead to additional requirements for proceduralisation and training for a variety of tasks.

- The assessment of maintenance activities is also an input to the maintenance and testing requirements. The outcome of maintenance assessment activities will provide information for future planning and execution of maintenance work.

4. PLANNING AND EXECUTING MAINTENANCE AND TESTING

In this section, the overall activities for planning, and executing maintenance are described. The main human and organisational factors considerations that may affect these activities are discussed.

4.1 Maintenance Planning

Effective planning of maintenance tasks is critical for error prevention. Those who plan work must be familiar with the plant and the work being done. One way to ensure that work planning is coordinated with others, is to locate work planners at the plant. A clear definition of maintenance and testing requirements, along with realistic estimates of the time to complete these tasks, will assist nuclear facilities in ensuring:

- Compliance with technical specifications.
- Sufficient planning and coordination of maintenance activities.
- Adequacy of human resources (number and competence).
- Post-maintenance testing that verifies readiness to operate.

The cooperation between the operations and the maintenance department during maintenance planning is also important and should include direct exchanges, at the appropriate level, between those departments. For example, the operations department may provide information to the planners to ensure that equipment unavailability is minimised.

Maintenance planning tools may be included in the work management system to assist with work scheduling and to reduce the likelihood of errors. For example, daily meetings help to avoid conflicting jobs and to ensure that any schedule changes are communicated to the appropriate individuals. If using contractors or sub-contractors, they must be included in pre-meetings or daily meetings to ensure all conflicting jobs are considered. Walk-downs of complex or infrequently performed tasks improve the quality of maintenance procedures and time estimates for task completion. Critical task analysis helps to identify error-likely tasks, so appropriate error-reduction strategies, such as independent verification or improved pre-job briefings, can be implemented.

Outages are recognised as times of high workload for maintenance with greater risks due to time pressure, fatigue, and the added burden on supervisors. Outage planning must take these factors into consideration. If workers perceive time pressure, they may take shortcuts to complete work faster. Time pressure may be due to a perceived need to get the plant ready for start-up as quickly as possible. Although management may state the need for tasks to be carried out safely, management's actions also shape the perceptions of the workforce. To reduce time pressures, realistic schedules must be drafted which allow adequate time to complete the maintenance tasks safely while minimising the potential for errors.

To address staffing shortages during outages, nuclear facilities in some countries increase the hours that staff work during outages, thus leading to potential degradations in human performance due to fatigue. Since more work is going on and more work for supervisors to oversee, some stations step people up from workers to supervisors during outages, with little training for these new responsibilities. Poorer quality supervision, especially of contract staff, may contribute to errors. Due to the volume of maintenance work conducted during outages, error-reduction strategies must be incorporated into the work planning process.

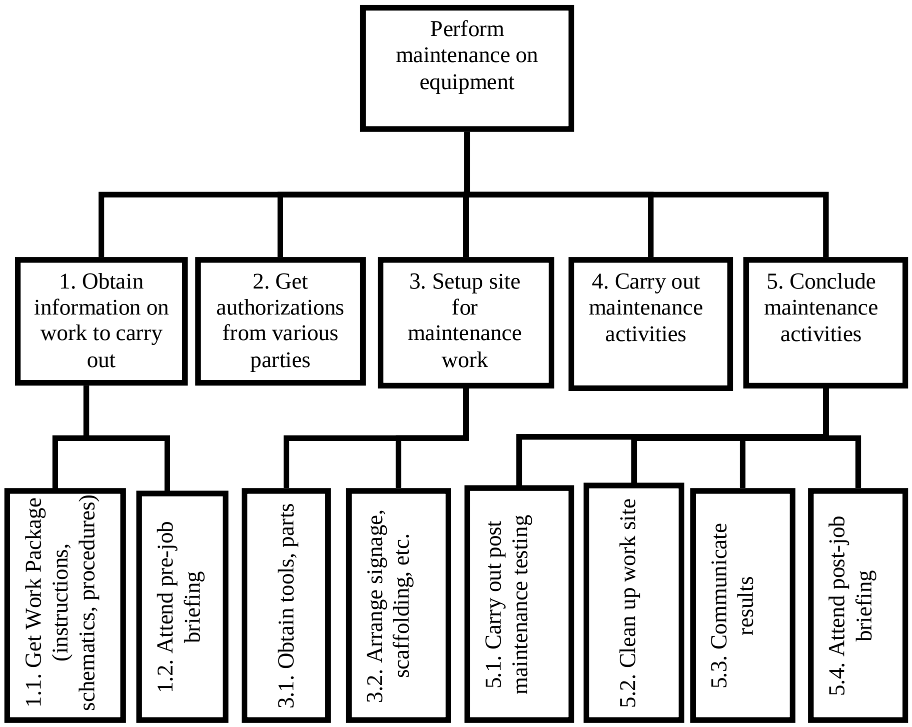
4.2 Maintenance Execution

The figure next page provides a generic hierarchical task analysis (HTA) for preventive maintenance; corrective maintenance is similar except for the need to add a diagnosis task at an earlier stage.

Obtain Information on Work to Carry Out

After maintenance planning is complete, the worker(s) scheduled to do the work must obtain the information required to carry out the job. This information may take the form of work packages that include instructions, schematics and procedures. It is also good practice to carry out pre-job briefings before maintenance jobs to discuss critical steps and potential hazards. Written pre-job briefings can be used when work is complex, unfamiliar or the risk of injury or error is high.

Figure 2: HTA for Maintenance



4.2.1 Get Authorisations from Various Parties

At this step, the worker(s) must secure permission from various groups (e.g., operations) to carry out the required work. When getting authorisations from various parties, accuracy and completeness of communication is paramount. Communication problems between staff and supervisors, between maintenance and operations, or between contractors and plant staff can lead to events if there are misunderstandings about job requirements. Some communication problems can be avoided by strategies such as the following:

- Training staff about ways to reduce the risk of misunderstandings when communicating verbally (e.g. three-way communications, phonetic alphabet).

- Setting limits on verbal instructions, so it is clear when instructions must be written.

- Documenting expectations and training staff about information to include in pre-job briefings, such as critical steps and expected system behaviour.

4.2.2 Setup Site for Maintenance Work

Setting up the site for maintenance entails obtaining and organising tools and parts, arranging to have radiological signage if necessary, and obtaining appropriate scaffolding or ladders, as needed. Some of this work (e.g., building temporary scaffolding) may already have been done earlier. A good site setup helps to enable workers to control the work and to reduce the likelihood of errors.

Guidance for the isolation and tagging processes should be established to ensure personnel protection, equipment protection, and status control of all components within the requested boundary. A training program for the tagging and isolation processes should be established and all staff involved should be trained and regularly retrained. Out of service systems and components should be identified by appropriate signs and tags, both in the plant and in the control room. If it is impossible to de-energise all equipment or equipment components within an isolation boundary, the supervisors should ensure that the job supervisor and work group fully understand what equipment is energised and where it is located. Working clearances and actions to mitigate inadvertent contact or interaction should be discussed before maintenance work begins. Proper device identification is also critical when the potential for working on the wrong equipment exists for maintenance staff.

4.2.3 Carry Out Maintenance Activities

This is the point at which the actual maintenance work is carried out.

When conducting maintenance, it is important to recognise that preventive and corrective maintenance pose different risks for human error. For instance, preventive maintenance is usually well planned with procedures written to address failures and clear identification of hazards. In contrast to preventive maintenance, corrective maintenance procedures may be lower quality and less time may be available to plan corrective maintenance due to production and schedule pressures. The frequency of unexpected breakdowns requiring corrective maintenance can be reduced through the assessment process, inspection program, and preventive maintenance program. When corrective maintenance is required, a clearly defined approval process and pre-approved procedures reduce the probability of errors.

Procedures and work instructions are required to guide work in maintenance. Procedures must be technically accurate and written using usability-centred guidelines (Wieringa, Moore and Barnes, 1998). The usability of procedures should be tested through verification and validation activities. Procedure validation should include a walk-down of steps in the plant to ensure the sequence of steps matches the layout of plant equipment. Critical steps or actions during maintenance that will trigger an event, or introduce a latent error condition, need to be identified in procedures, so appropriate defences can be provided (e.g. independent verification). A recent trend is including pictures of station equipment in procedures, work orders and pre-job briefings and this may help to clarify tasks to be performed. An issue with procedures is that there is currently no clear guidance on how to best balance completeness and conciseness of procedures. The trend appears to be to add information to procedures as issues are identified, thus potentially reducing their overall usability.

While a culture of procedural compliance must be developed and nurtured in maintenance departments, procedural compliance must be balanced with a questioning attitude. Workers must have knowledge about the plant systems they are working on and how their work impacts upon other plant systems, so as to avoid error prone situations. In addition, clear management expectations must be communicated to staff so workers know what to do in the event that a procedure cannot be followed as written.

Older nuclear facilities were not designed for ease of maintenance. As a result, maintainers may be faced with accessibility problems, sub-optimal work environments, and high physical demands. Some maintenance tasks are performed in areas with high radiation or noise levels, so maintainers must wear personal protective equipment (PPE). PPE, such as plastic suits, increases the physical and perceptual demands of work, makes it difficult to follow procedures step-by-step, and is a barrier to verbal communication. Wireless head sets can be used for verbal communication in high noise environments or in radiation areas when plastic suits are worn. Maintainers may be at a greater risk of conventional hazards, such as falls. A poorly designed human-system interface for maintenance work increases difficulty when performing tasks, which may increase time to complete tasks, errors, and costs.

In existing plants, some back-fitting can be done to reduce the risk of errors during maintenance. For example, equipment labelling and lighting can be improved. Platforms can be added to improve accessibility of equipment. Ergonomically designed tools can be procured. As equipment is replaced, ease of maintenance should be improved. Also, good housekeeping can be enforced, which encourages the workers to keep their work area tidy and reduces the potential for errors and confusion. Further, once a satisfactory level of housekeeping and tidiness is achieved, it can be used as an indicator to identify emerging problems (e.g., morale, degree of supervisory oversight).

Since maintenance work may extend over several shifts, it is important that maintenance staff know what information needs to be communicated to the next shift. For example, any scope changes, deviations from the work plan and the extent of work completed must be communicated. A process is needed for accurately transferring information between maintainers at shift turnover.

4.2.4 Conclude the Maintenance Activities

At the conclusion of maintenance activities, the equipment and work area must be returned to a suitable state. Post-maintenance testing must be performed to ensure that the system or component works as planned; it is important, however, that post-maintenance testing is not a substitute for adequate work planning and execution. Post-maintenance test plans must allow time for errors to become apparent. For example, equipment must be allowed to run for adequate time to reach required pressures or temperatures.

Sometimes, how the actual maintenance work is carried out deviates from the work plan because the situation in the field is different than expected; deviations from the work plan must be done within the confines of an approved process. It is also useful to feedback those deviations, and how they were dealt with, to those responsible for planning the work so that this knowledge can be incorporated into future plans. Post-job debriefings are a useful mechanism for identifying deficiencies and strengths in the work planning process and for improving planning of future jobs.

If post-maintenance testing is done by operations, the maintenance workers should be involved or should have a process for turning work over to operations that ensures they are aware of any deviations from the work plan so the actual changes are tested.

5. ASSESSMENT

Assessment of maintenance performance relies on tools such as self-assessments, independent assessments, peer-reviews, and field observations. Regulatory inspections provide an external review of a nuclear facility's safety management system. Reporting and investigating events arising from maintenance is important for improving safety. Maintenance workers must be encouraged to report near misses and minor events, since they provide valuable learning opportunities and identify emerging trends in performance. Root cause investigators must identify root causes of events by probing human and organisational contributors.

Performance indicators can be useful tools for monitoring performance. Actions are underway in various countries to develop performance indicators that are valid, reliable, and sensitive to changes in human and organisational aspects of maintenance performance. Care must be taken to combine performance indicators with other information rather than being driven by performance indicators alone (CNRA, 2005). Some indicators being monitored by nuclear plant operators and regulators include:

- Backlog of maintenance work, plant modifications, or maintenance procedure updates;
- Equipment failure rates and unavailability of safety equipment;
- Maintenance rework;
- Work hours/workload during outage periods;
- Supervisory presence in the field;
- Late planning of tasks for outages; adding tasks after the freeze date.
- Maintenance work schedule challenges during regular operation and outages.

Developing and prioritising corrective actions requires integration of performance information from a variety of sources. A challenge with monitoring plant performance is data overload. Integrating findings from different performance measurement tools can provide useful information about the adequacy of human and organisational components of a maintenance program. Knowledge gained from assessment tools should be transferred throughout the organisation to create a culture of continuous learning for all employees. This information also provides valuable feedback to maintenance and testing requirements and the planning and execution of maintenance work (see Figure 1). Through assessments, the station's leadership can gain a better understanding of the strengths and weaknesses of actual work practices and behaviours in maintenance activities.

6. OTHER FACTORS THAT INFLUENCE MAINTENANCE PERFORMANCE

The following are additional human and organisational factors issues that affect the planning and execution of maintenance activities.

6.1 Management and Organisational Culture

The background in Figure 1 represents the management and organisational culture of the workplace and of the maintenance organisation. The culture is pervasive and can influence the success of the maintenance program. Differences can exist between the culture in operations versus maintenance or the culture of contractors versus plant staff. Maintenance work may be seen as lower status or of lower safety significance than operations and as a result may receive lower quality training, procedures and supervision. Differences in perceived risk and organisational support may negatively influence the safety culture in maintenance departments. In recognition of the special needs of maintenance departments, the IAEA produced a report that describes good practices to strengthen the safety culture in maintenance (2005). There is an ongoing need for licensees and regulators to promote awareness of the importance of maintenance and its contribution to plant safety.

6.2 Availability of Sufficient Qualified Staff

Nuclear licensees and regulators world-wide are facing retirements of experienced staff. The transfer of tacit knowledge from experienced workers to a younger generation must be planned and managed. Experienced maintainers require adequate time and incentives to serve as role models and mentors to younger staff members (Kuronen and Rintala, 2005).

6.3 Increasing Use of Contract Staff

Contractors are increasingly used to perform maintenance activities, either to replace retiring staff or during outages or life extension projects. The nuclear licensee retains the ultimate responsibility for safety whether work is done by contractors or permanent staff. Licensees must ensure that its contractors work within the organisation's work processes and rules. Any efforts to improve human performance must include contract staff, so that contractors adopt similar work practices as nuclear facility staff.

6.4 Training

Training for maintainers should be based on a systematic and proven approach comprising a needs analysis that informs the training program design, development, delivery, and evaluation. Many nuclear facilities have initiatives underway to train maintenance staff about factors that influence human performance. Some plants train workers to use Event Free Tools, such as peer checking, three-way communications, independent verification, pre-job/post-job debriefs, and walk downs of isolations to verify correct device configuration. Some stations have mock-up work areas where tasks and error prevention tools are practiced in a hazard free work environment.

6.5 New Reactor Design

As new reactors are designed, design agencies, licensees and regulatory bodies must place greater emphasis on maintainability issues in the plant's design. Operating experience with existing equipment and plant design data is a useful source of information for improving future designs. Human Factors Specialists involved with new plant designs should review maintenance tasks and work areas in existing plants and identify areas for improvement. Surveying maintainers in existing plants about their concerns with their job design is also a useful input to design requirements in new reactors. Regulatory strategies for licensing new reactor designs also need to address human factors aspects of maintenance.

6.6 Use of New Technologies

New technologies have the potential to facilitate reliable maintenance performance. When trying new technologies, their context of use and the needs of end users must be considered. Special needs of older workers, who tend to be more resistant to electronic technologies than younger workers, must also be considered. New practices, methods, and tools should be introduced in a way that allows maintenance staff to understand the functional and safety relevance of the innovation (Oedewald and Reiman, 2005).

Examples of new technologies in use are as follows:

- In some countries, maintainers use procedures on palm pilots and wearable computers. The usability of the electronic systems must be optimised for them to be successful.

- There is increasing use of simulation and virtual reality in training and planning for maintenance tasks. Virtual reality can be a useful training tool for new hires and for learning about areas that cannot be accessed during normal operations (Nystad, 2005). Virtual reality could also be a useful tool for designing and testing maintainability in new plant designs.

There is the potential for new systems to be more computerised or otherwise more complex than previous generation equipment, thus risking an increase in the difficulty to trouble-shoot and maintain them.

7. CONCLUSIONS

There is a weight of evidence showing that human errors during maintenance and periodic tests are significant contributors to plant events. Nuclear licensees should understand where and why these errors can occur and design maintenance work to minimise the likelihood of errors which have the potential to impact upon nuclear safety. Licensees should therefore acknowledge the need to involve human factors specialists in the assessment and specification of their maintenance activities. Regulators should be prepared to challenge licensees where this contribution is missing.

This TOP presents a framework for considering human and organisational factors that influence reliable maintenance in a systematic way. It can be used to prompt consideration of factors that influence human performance throughout the maintenance process. One of the key steps in securing reliable and effective maintenance is the development of an effective planning process. Critical steps or actions which may directly trigger an event or introduce a latent error condition must be identified so that defences and error prevention strategies can be incorporated into the planning process. The maintenance plan must take account of interactions between the maintenance task and other activities on the plant that affect, or could be impacted by, the work of the maintainers. Effective verbal and written communication is essential to ensure an accurate transfer of information between shifts, individuals and work groups to avoid mis-understandings which may lead to errors. These communication processes should be formalised rather than being left to individuals to determine in order to avoid weaknesses or inconsistencies developing. Arrangements must be put in place to ensure that maintenance personnel understand the task and its nuclear safety implications and that the maintenance activities are subject to suitable control and supervision. This can be of particular importance where contractors are used who may be less familiar with a utility's practices and expectations.

Maintenance procedures must be technically accurate and designed with an understanding of the context in which they will be used in order to provide effective support to the maintainer. A number of procedure-writing guidelines are available and licensees should ensure that suitable guidance is understood and applied by procedure authors. Tools such as pre and post job briefings, three-way communication, peer checking and independent verification are effective measures that can be used to identify and mitigate errors in the execution of maintenance activities. However, they should be used intelligently to focus on those activities that have the potential to impact on nuclear safety such that their effectiveness is not diluted. Outage schedules must include adequate time to complete maintenance tasks safely while minimizing the potential for errors.

Valuable information about maintenance performance can be obtained by integrating data from assessment tools that provide information about error-likely situations and the maintenance history. The licensee should therefore consider, and implement lessons learned from, operating experience gained both from within its organisation and also from wider industry experience.

New nuclear facilities should be designed to support plant maintainability. In other words, plant designers should ensure that issues such as plant access, lighting, heating, tooling, etc are considered before design decisions are finalised. Human factors input should therefore be made not only to the assessment and specification of maintenance activities but also to inform the design of plant and equipment that will be subject to maintenance. In a similar way, where refurbishment work is carried out, a requirement to consider opportunities to improve maintainability should be included as part of the design process.

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