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Good Practices in the Maintenance of Operating Nuclear Power Plants

GOOD PRACTICES IN THE MAINTENANCE OF OPERATING NUCLEAR POWER PLANTS

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FOREWORD

Maintenance is a core activity at operating nuclear power plants and is fundamental to ensuring their safe, reliable and cost effective operation throughout their expected lifetime.

This publication was developed with the input of experts from various Member States who shared their knowledge and insights to identify general good practices — rather than specific examples — that maintenance managers and personnel can adopt to address those aspects of maintenance that are critical to high performance in maintenance and to overcome the challenges they face.

These challenges typically include maintaining a highly skilled and committed workforce, optimizing maintenance programmes in a sustained manner, and maintaining effective oversight of suppliers and supplemental personnel.

The critical aspects addressed include the managerial approach to conducting maintenance activities; the contribution of maintenance organizations in selecting and optimizing maintenance; the planning and control of maintenance activities, with a focus on contractor oversight; the management of documentation and personnel skills/qualifications; the use of key performance indicators; and the conduct of benchmarks.

The IAEA wishes to thank all the experts involved and their Member States for their contributions. The IAEA officers responsible for this publication were L. Bourdonneau and H. Varjonen of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Based on chapter 192-06 of International Electrotechnical Commission standard Ref. [1], IAEA Nuclear Energy Series Report No. NP-T-3.8 [2] and the IAEA glossary [3], maintenance can be defined as the organized activity that combine all technical, administrative and managerial actions during the life cycle of structures, systems and components (SSC) intended to retain them in, or restore them to, a state of good operating conditions in which they can perform as required. In this definition, for the purpose of this TECDOC, managerial actions include supervision and oversight of maintenance activities by maintenance managers.

The overarching goal which is typically set to maintenance organizations in operating NPPs is to effectively support safety and operability, thus keeping SSCs in conditions that meet safety requirements and underpin the reliability and availability of the NPP. From experience, maintenance organizations face a series of challenges in serving this goal.

The first challenge is to possess trained, skilled, and fully committed maintenance personnel that mitigate the risk of errors, seek high performance at the preparation and execution of maintenance tasks and deliver event-free execution of maintenance tasks, thus without safety events, rework and outage extensions.

The second challenge for maintenance organizations is to optimize maintenance programmes in a sustained manner, while keeping operational and maintenance costs under control.

As a significant portion of maintenance activities at NPPs are performed during short, planned refuelling and maintenance outages, the third challenge is to maintain full control of quality in maintenance performed by suppliers and supplemental personnel[1] throughout the activity peaks, whereas maintenance organizations are often staffed for on-line maintenance.

1.2. OBJECTIVE

The objective of this TECDOC is to disseminate general good practices — rather than specific examples — to guide maintenance managers and personnel in achieving high efficiency and effectiveness in delivering maintenance of NPPs, thereby addressing the three challenges listed above.

1.3. SCOPE

The scope of this TECDOC covers conduct and execution of maintenance activities. It also covers the roles of maintenance organizations in supporting engineering functions at an NPP, such as equipment reliability and optimization of maintenance programmes.

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[1] In the context of this TECDOC, supplemental personnel refer to all forms of (sub-)contracted external organizations (= contractors) who carry out maintenance-related services, including vendors, equipment manufacturers, and consultants. Those services include preparation and execution of maintenance tasks, diagnostics, and analyses that are usually planned in the work management system of an NPP. Suppliers are contractors who supply equipment (incl. spare parts), tools, instruments, facilities (e.g. test benches), products, consumables, etc. required for maintenance tasks.

This TECDOC formulates good practices in principles (not as specific examples) as identified by experts from various Member States and international organizations who shared their knowledge and insights with the IAEA.

This TECDOC complements other IAEA publications related to:

- Maintenance, testing, surveillance and inspection in NPP, safety guide SSG-74 [4];
- Maintenance optimization programme for NPP, Nuclear Energy Series NP-T-3.8 [2];
- NPP outage optimization strategy, IAEA-TECDOC-1806 [5].

1.4. STRUCTURE

The main body of this TECDOC is divided into eleven (11) sections. The structure adopted for this TECDOC does not follow the three challenges identified in Section 1.1 but, instead, considers the logical order of a plan-do-check-act cycle, and the three ingredients for organizational effectiveness in the nuclear industrial section – effective leadership, management system and nuclear professional – as depicted in Ref. [6].

Section 2 presents the roles and responsibilities to be held by maintenance managers. Section 3 describes the principles for selecting and optimizing maintenance strategies that maintenance managers ought to be familiar with. Section 4 describes key elements and attributes for effective maintenance planning and scheduling. Section 5 describes good practices in preparing high quality maintenance documentation and procedures for executing activities. Section 6 presents effective steps to control work preparation and execution, including control on procured items, and Section 7 discusses how to manage the requisite skills and qualification to support delivery of high quality maintenance at NPP. Section 8 describes guidance on how to effectively oversee contractors, while keeping control and exercising an intelligent customer capability[2].

Section 9 presents good practices in selecting and using key performance indicators (KPI) for measuring maintenance effectiveness and identifies most currently used KPIs. Section 10 addresses the benefits of benchmarking to improve performance.

Section 11 captures the most significant good practices identified throughout this TECDOC.

These sections address the three challenges identified in Section 1.1 as follows:

- Sections 6 and 7: Event-free execution of maintenance tasks by highly skilled and committed maintenance personnel;
- Sections 2 and 3: Delivery of optimized and cost effective maintenance programmes;
- Section 8: Oversight of suppliers and supplemental personnel.

2. CONDUCT OF MAINTENANCE

Conduct of maintenance refers to the manner in which the maintenance organization and maintenance activities are managed and directed by maintenance managers. This section presents exemplary roles and responsibilities to be held by maintenance managers in the

[2] As defined in paragraph 4.4, paragraph 5.83, and footnote 12 of IAEA safety standards series No. GS-G-3.5 [7].

conduct of maintenance, and how the deployment of leader-in-the-field (LiF) programmes [8] and effective teamwork support a vision of excellence.

2.1. MAINTENANCE MANAGERS' RESPONSIBILITIES

Maintenance managers play a significant role in conducting maintenance activities in a controlled manner so that excellence can be achieved. Like any other senior managers in the nuclear sector industry – see references [6] and [9], their main responsibilities are to:

- Establish a vision of excellence that materializes their leadership for safety, where priority is given to nuclear safety, leadership team behaviours are safety-focused, and a strong nuclear safety culture is nurtured and maintained;
- Create the corresponding environment and conditions for personnel to support their vision of excellence, while developing a robust maintenance management system and setting achievable but ambitious goals;
- Drive the organization and correct gaps so that the desired performance is delivered on a short-term and a long-term (sustainability of performance);
- Recruit, develop and retain talented and engaged thinking managers, supervisors and workers that exhibit pride in their professions and work[3];
- Shape and manage interface with other stakeholders within the organization and external to the organization.

Ultimately, maintenance managers are accountable for the effectiveness of the maintenance organization in achieving the desired performance.

To reach out to maintenance managers and workers, including in the contractor organizations, senior maintenance managers define the corresponding policies, fundamentals, and attributes of excellence in the maintenance organizations that materialize their leadership for safety and pinpoint the additional expectations set to the workers and the managers as nuclear industry professionals, not only as maintenance professionals. An example of maintenance fundamentals is given in Ref. [11], whereas WANO guideline Ref. [12] and INPO guideline Ref. [13] provide a definition and attributes of the "essential knowledge, skills, behaviours and practices maintenance personnel need to apply to conduct their work properly" [13].

Maintenance managers make sure that an effective management system for the maintenance organization is established, managed, and continuously improved to support the maintenance policies, strategies and programmes.

The scope of the management system for a maintenance organization covers all structures, systems[4], components (incl. workshops, tools, spare parts) that require maintenance.

Attention is paid to the clarity of the process procedures and the responsibilities across the maintenance organization. Typical roles within the maintenance organization are set out in WANO Ref. [12].

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[3] The concept of pride in one's profession and work is developed in chapter 2.3 of IAEA Ref. [10], alongside suggested actions to maintain this pride at the highest level.

[4] Experience has showed that maintenance of digital and computerized equipment bears specific risks. Good practices are to keep multiple backups of software versions; to consider software parameter setting as a (temporarily) design modification, and to proceduralize maintenance arrangements in specific quality management system documents.

The processes of an effective management system for a maintenance organization include:

- The core processes for the preparation and execution of maintenance[5] with special attention paid to:
  - The preparation, execution and closure of work when errors, including latent errors, could lead to safety events, reactor and turbine trips;
  - The control and oversight of contractors;
- The processes for the conduct of maintenance that describe how maintenance policies, strategies, and programmes are managed and delivered – these processes include the management of operating experience [14], the corrective action programme [15], the conduct of performance reviews and benchmarks, etc.[6];
- The core processes for defining and optimizing maintenance that are assigned to the technical support function in Ref. [7], such as “develop maintenance programmes”, “monitoring age-related degradation mechanisms”[7], “planning of refurbishments”, “replaces equipment and parts”;
- The processes for topical programmes inherent to maintenance that benefit from a programmatic approach. Examples of those processes include:
  - Foreign material exclusion (FME) management[8];
  - Leak management[9];
  - Conduct of rigging, lifting and material handling [22];
  - Conduct of diagnosis and non-intrusive inspections[10];
  - Management of materials (for welding and manufacturing activities at workshops), consumables (incl. lubricants), tools (incl. measuring and test equipment) and spare parts;
  - Electrical safety, etc.[11]

European Standard EN 17007 [26], even though it is not specific to the nuclear industry, provides detailed guidance on how to structure a comprehensive management system for maintenance organizations, while describing typical management/realization/support processes (level 1), sub-processes (level 2) and activities (level 3), their interfaces, the products and considerations for defining indicators.

When the maintenance organization at a specific NPP is only responsible for a subset of the processes listed above – for example only the execution of maintenance, senior managers make sure that the integration of all maintenance-related processes is achieved at the plant level.

Experience shows that the processes for managing operating experience, investigating events, and establishing efficient corrective actions under the corrective action programme (CAP) are crucial to the effectiveness of the maintenance management system. To ensure these processes work effectively, it is good practice, at a minimum, to review and assess input as follows:

- Internal and external reports on technical and organizational issues;

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[5] as detailed in paragraph 5.6(1)(b) of IAEA Safety Standards Series No. GS-G-3.5 [7]

[6] Other elements of supporting and management processes are listed in paragraph 5.6(2) of IAEA Safety Standards Series No. GS-G-3.5 [7]

[7] See also chapter 4.2 of Ref. [16]

[8] See, for example. IAEA Ref. [17], EPRI Ref. [18], WANO references [19] and [20].

[9] See, for example, EPRI guidance for establishing an effective leak management programme [21].

[10] Using inspection techniques such as acoustic emission, tracer gas leak detection and infrared thermography. See for example EPRI Ref. [23] for conducting infrared thermography, Ref. [24] for acoustic emission, and Ref. [25] for methods for locating condenser water in-leakage.

[11] See also chapter 8 of Ref. [4] for further examples. Processes that could also benefit from a programmatic approach include management of cyber security requirements, preservation of equipment qualification (incl. qualification for accident conditions), preservation of design configuration (incl. prevention from uncontrolled modifications during maintenance), post-maintenance testing of equipment.

- Post-job debriefs (PJD) from maintenance activities including written notes and completion remarks from the workers;
- Rework evaluation;
- Post-outage critique report or project critique reports identifying lessons learned and stakeholders concerns;
- Self-assessment reports of maintenance processes and teams.

Extensive knowledge of internal/external events, lessons learned from those events, and best international practices enables managers to provide context when setting objectives, sponsoring improvement plans, reinforcing standards/expectations, and coaching maintenance personnel.

Overall performance can be effectively managed using representative KPIs (see Section 9), where, specifically, continuous improvement tools such as kaizen[12], lean management, six sigma or any other model/combination of models developed for optimizing output, can be used for improving cost effectiveness.

2.2. LEADER-IN-THE-FIELD PROGRAMMES

As maintenance is mostly delivered in the field either by plant staff or supplemental personnel, senior managers, maintenance managers and technical leaders at all levels verify that maintenance activities are conducted as expected, and that the intended leadership for safety has materialized, while carrying out systematic walkdowns (see Requirement 9 of SSR-2/2 [28]) and implementing a comprehensive LiF programme. Guidance for developing and implementing an effective LiF programme is presented in WANO guideline Ref. [8].

Time in the field spent by managers (senior managers, second line managers and first line managers), supervisors and technical leaders is commensurate with the risks borne by the activities and the opportunities for coaching the workers. More than the time itself, the value and 'quality' of that time are critical to an effective LiF programme.

Quality observations are delivered when the managers, supervisors and technical leaders:

- Actively engage with the workers;
- Have a low threshold for coaching workers and supervisor behaviours with specific, constructive, and balanced feedback if deviations or undesired effects are observed, and provide positive feedback for good behaviours and practices (see also Section 7);
- Reinforce the defined standards of excellence and the fundamentals, especially when it is found that they had not been effectively communicated or understood;
- Make sure that benefits and actions from the LiF programme are actually implemented;
- Evaluate the effectiveness of the strategies, processes and programmes that have been defined to achieve the vision and the intended leadership for safety, including detecting organizational weaknesses and identifying areas for improvement.

The situations observed are representative of the full scope of work carried out under the responsibility of the maintenance organizations. Those situations include tasks done by plant and supplemental personnel, online and in outage work, supervised tasks and tasks not

[12] See appendix VIII of Ref. [27] for an example of application in a maintenance organization at an NPP.

supervised, nuclear safety-related work and production-related work, tasks sanctioned by performance indicators or not, etc. Maintenance managers do not only observe workers but also supervisors and technical leaders coaching workers (‘coach the coach’ situations). Observation of activities bearing high risks may be seen as a disturbance (as such, as a potential for errors) and are to be considered carefully. Findings – positive and negative – from observations and discussions with attendees are recorded in databases, systematically categorized using a structured coding system, and are ultimately fed in into the performance reviews and evaluation sessions so that actions and suggestions for improvement are raised.

To support effective coaching and on-the-job training of workers, a good practice is to establish ‘what excellence looks like’ sheets that describe the fundamental steps and elements of activities such as non-complex lifting, management of foreign material, procedure use and adherence, fire and radiation safety at the workplace, work area standards, equipment conditions’ assessment[13], conducting a pre-job brief, etc. While observing and coaching more complex activities that require the implementation of craft skills, training materials, detailed aids and topical leaflets can be used. These can show correct vs incorrect practice in areas such as tightening pattern of bolted connections, locking tabs and cable gland for seismic qualified equipment, cable connections, assembly of rotating machines, troubleshooting of valve positioners, conduct of diagnosis and inspections, etc.

In addition, for managers, supervisors, and technical leaders doing observations, methodological aids and leaflets that remind them how to coach and correct workers in areas such as knowledge retention, interpersonal interaction, use of human error reduction tools, and risk awareness (incl. ability to stop work when unsure and to define mitigating actions) can be developed and made available. A good practice is that experts in those areas witness and advise the maintenance managers, supervisors and technical leaders when they perform their observations, and ultimately evaluate the organizational effectiveness to prevent errors (see also Section 7.2). At senior manager and director level, a good practice is to pay attention to the quality of risk assessments, the proficiency of managers and supervisors, and the organization’s ability to learn effectively while performing observations.

2.3. TEAMWORK

Managers establish an organization and foster a culture that ensure diverse, complementary, multi-disciplinary maintenance teams (such as fix-it-now, on-line, outage) that are specialized but work together – see attribute 1 of nuclear safety culture trait ‘Leadership accountability’ in Ref. [30]. Maintenance managers secure support not only from other departments such as operations, work management and engineering departments but also from external organizations (and vice versa) by building in an effective stakeholders’ management for all related processes.

Regarding engineering and technical support functions, maintenance managers make sure that the maintenance organizations are involved at the early stages of the design modification process, to support smooth handover of new installations and technologies to them, and work as one team at the plant level to optimize maintenance – for example using the model of process blocks 3 and 6 of the equipment reliability process set out in WANO guideline 2018-02 [31].

[13] See Ref. [29] for an example of field guide developed by EPRI for assessing the condition of coatings.

Maintenance managers make sure that the maintenance organizations benefit from field operator walk downs done during shifts to observe devices and facilities. Observations and visual inspections done by operators capture devices failures, functional errors, and abnormal behaviour, such as abnormal temperature, noise, vibration, smell, leakages etc., that can be reported into the maintenance system as a deficiency report. All observed abnormal conditions are communicated properly to maintenance personnel for them to initiate corrective actions from the observation reports as needed within the plant work management process.

Both in maintenance organizations and in other departments the concept of equipment 'owner' can help to better follow up the current condition of an SSC. Creating ownership and thus partnership across the organization helps to keep striving for excellence in maintenance of equipment, especially for those systems and equipment where multiple stakeholders are involved. This can also support an effective suggestion management system, where ideas and feedback from staff and supplemental personnel are collected, assessed, and, when sanctioned, captured in actions in the plant's CAP.

3. MAINTENANCE STRATEGIES

A maintenance strategy refers to the approach and the corresponding actions defined to achieve the performance objectives that are typically set to maintenance organizations: high availability of plant and SSCs commensurate to their significance to safety and production in a cost effective way. A maintenance strategy for a specific item of equipment is formed by three elements: the selected maintenance type[14] (e.g. preventive maintenance), the decision to outsource maintenance or not, and the resources allocated for performing the maintenance (How many workers? Their level of knowledge and skills? What budget? etc.).

This section presents the principles for selecting maintenance strategies, discusses the effects of regulations on the strategies, and outlines methods to further optimizing maintenance strategies maintenance managers ought to be familiar with to actively contribute to optimizing maintenance strategies.

3.1. PRINCIPLES FOR SELECTING STRATEGIES

The high level principles for selecting a suitable maintenance strategy are set out in chapter 6.7.1 of Ref. [33]. By experience, the prerequisite for owner-operator organizations to select a maintenance strategy is a deep knowledge and understanding of the maintenance management principles, and the specific maintenance requirements for safety related/non-safety related SSCs over their lifetime.

When selecting a suitable maintenance strategy, key areas to be considered include:

- Applicable regulations (see Section 3.2);
- Plant conditions required for maintenance activities (i.e. online versus outage);

[14] The historical maintenance types are repair after failure (corrective maintenance), systematic and periodic maintenance (preventive maintenance (PM) at predetermined intervals of time), and targeted maintenance before failure (condition-based and predictive maintenance as a form of PM). These different maintenance types are further outlined in chapter 1.1 and 3 of Ref. [2], and chapter 2.3 of EPRI report Ref. [32] (publicly available). Chapter 3.1.3 of Ref. [32] briefly describes the relationship between maintenance effectiveness and equipment reliability, as a reminder that maintenance does affect equipment reliability.

- Typical failure modes[15], degradation mechanisms and in-service inspection regimes of SSCs (mechanical, electrical, nuclear fuel, instrumentation and control components, civil) including failure modes and degradation mechanisms specific to ageing (see chapter 5 of Ref. [34] and footnote[16]);
- Principles for classifying SSC against their significance and criticality to nuclear safety and production (see process block 1 in WANO guideline 2018-02 [31]);
- Original equipment manufacturer (OEM) recommendations;
- Benefits and effectiveness of the typical maintenance types, noting that only ‘perfect’ maintenance (e.g. ‘perfect’ one-to-one replacement) does not affect equipment reliability;
- For safety-related SSC, use of probabilistic safety assessment models for validating maintenance optimization measures and controlling the overall operational risk – see principles in chapter 6.11.2 of Ref. [33] and details in Ref. [32];
- Principles of reliability centred maintenance (RCM), see Section 3.3;
- Internal and external operating experience.

Experience has showed that the deep understanding of the correlation between the adopted maintenance type and the class of SSC is a key factor in successful and effective maintenance organizations. Maintenance managers understand that the priority is to allocate resources and maintain acute attention to equipment which failures could adversely impact safety or operation of the plant production, and not to equipment that can ‘run-to-maintenance’ where ‘normal’ operators walkdowns are sufficient. Awareness of the SSC classes are high throughout maintenance personnel (plant staff and supplemental personnel).

Given the complexity of certain SSC, the number of items of equipment to be maintained, and the limitations of own staff (specifically during outage periods and for complex troubleshooting), owner-operator organizations routinely use external experts and supplemental personnel. Using contractors for maintenance activities is an opportunity for benefiting from contractors’ specialization and expertise in key areas where the qualifications of plant staff may not be cost effective or efficient, specifically for tasks that are performed infrequently. Challenges and key aspects to be considered when outsourcing activities are set out in Section 8.

Once the maintenance strategies and the level for outsourcing are set, the next steps are to define the combination of maintenance tasks that implement the selected strategies, and, then, to plan, subcontract (when outsourced), and schedule the corresponding tasks (see Section 4). All these tasks, alongside the tasks from the topical programmes (see Section 2.1), forms the maintenance programmes. The function of maintenance programmes is to compile all actions to preserve and restore the inherent safety, reliability, and availability of plant SSCs in a single, cross-functional approach with clear rules for the implementation and prioritization.

Maintenance programmes ultimately help managers to define the total workforce and resources required for:

- Developing technical information and documentation;

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[15] Typical failure modes for nuclear and non-nuclear SSC are captured in industry guides such as EPRI, the International Council on Large Electric Systems (https://www.cigre.org/), etc.

[16] The IAEA has published a whole set of documents that contain detailed guidance and recommendations on how to set maintenance strategies and carried out repair and modernization for specific components subjected to ageing mechanisms. Examples of SCC covered include instrumentation and control systems (chapter 3.9 of Ref. [35]), cables [36], buried and underground piping (chapters 5 to 8 of Ref. [37]), concrete structures (chapters 5 to 8 of Ref. [38]).

- Preparing (incl. subcontracting) maintenance tasks (incl. time for walkdowns, set-to-work steps, and work area preparation);
- Executing maintenance tasks (‘wrench time’) as per schedule, with allowances for unplanned maintenance;
- Developing and maintaining work facilities (incl. test benches, storage facilities, machining workshop, welder stands);
- Designing, procuring and managing tools (standard and special tools, portable devices);
- Procuring and managing spare parts, materials and consumables.

Identified maintenance tasks are categorized and assessed to risks, typically using a tiered approach, at least consistent with the classification adopted to manage equipment reliability – see guidance in Ref. [31]. Examples of criteria that define the risk categories include likelihood to trip the reactor or the turbine – concept of single point vulnerability (SPV) in Ref. [39], likelihood of technical specifications breach on errors or prolongation of work, effect or contribution to increasing the core damage frequency, likelihood of rework. This categorization helps to identify risk mitigating actions and prioritize resources on short-term. This is reflected in the work schedule, in the documentation used for the tasks, in the way the pre-job brief (PJB) is implemented, and in the human performance tools selected while preparing and delivering the tasks.

A good practice is to (pre-)select strategies and combination of maintenance tasks at the design or construction phases of NPPs, the latest about 2 years before start of operation. This is done through an iterative process between the design/construction/operating organizations considering equipment’s expected lifetime, equipment’s maintainability, intended maintenance facilities, intended storage capacity, intended infrastructure, intended inventory policy, and supposedly available technical support from manufacturers and suppliers.

During the lifetime of an NPP, the maintenance strategy is assessed and updated frequently (almost continuously) based on operating experience that has been collected by the operating organization and/or supplier and/or from the industrial sector in accordance with their operating experience programme [28], and on an assessment of the wider environment of the NPP.

Examples of sources of operating experience and elements of the environment to be considered include:

- Internal sources and factors such as:
  - Accumulated knowledge at the NPP of the equipment’s behaviours (incl. ageing, failures, events) and design weaknesses;
  - Change in skills and qualification of the staff;
  - Actual and projected effectiveness and efficiency of the maintenance programmes;
- External sources and factors such as:
  - New corporate’s and regulatory requirements;
  - Obsolescence of components;
  - Contractors’ feedback and operating experience;
  - Actual, mid-term and long-term procurement lead time of spare parts, especially critical spare parts such as for SPVs;
  - Availability and quality of OEM services;
  - Merges/bankruptcy – actual, potential – of suppliers who were used to provide essential services and spare parts to the owner-operator organization;

- Other owner-operator organization’s operating experience, at national or international level;
- Economic conditions (budget), at present, on mid-term and long-term, up to the end of lifetime.

3.2. EFFECTS OF REGULATIONS AND LEGISLATIONS TO MAINTENANCE PROGRAMMES

Governments and regulatory bodies impose requirements that are aimed at protecting workers, the public, and the environment. There are differences in Member States laws, technical regulations and detailed legislations related to the maintenance of NPPs. Examples of differences are as follows:

- Technical regulations may require NPPs to select certain maintenance strategies. Some states’ legislations include prescriptive requirements for preventive maintenance programmes and in-service inspection for safety related SSCs. Other Member States use more performance-based requirements that enables the licensee to choose the best options to achieve set aims and goals.
- The philosophy for oversight can vary between different regulatory bodies. In some states, several regulatory bodies are responsible for different areas of the nuclear activity and/or subcontract third party organizations to enforce regulations. In other states, there is only one regulatory body responsible for all areas of the nuclear activity without the support of third party organizations but technical support organizations instead (see Ref. [40] for roles and responsibilities of technical support organizations).
- Laws can also regulate the use of supplemental personnel versus own personnel or restrict the interaction between the owner organization and the contractor organization’s supplemental personnel. As a consequence, the supervisors of the owner organization cannot freely direct supplemental personnel nor set common work teams.

Prescriptive regulatory requirements[17] generally reduce the scope of activities that can be reviewed to optimization by the owner-operator organizations. In addition, some plant owner-operator organizations adopt a conservative approach when implementing the regulations, creating additional internal requirements reflected in the management system. However, this does not prevent the owner-operator organization from exploring the opportunity for these regulatory requirements to be altered and relieved. It remains always the responsibility of the plant management to ensure maintenance best practices are implemented and opportunities for optimization are explored.

For making a case for changing regulatory maintenance requirements, the maintenance function can take credit from information such as as-found conditions, SSC performance trends, health status/ageing (e.g. actual running hours for rotating equipment, number of valve movements, number of high voltage power switch movements), and operating experience at site, fleet-level and from suppliers.

[17] Including from non-nuclear safety regulations such as regulations related to fire safety or insurance coverage.

3.3. METHODS FOR FURTHER OPTIMIZING MAINTENANCE

Departing from the historical maintenance optimization methods[18], owner-operator organizations have explored other methods to further optimizing maintenance programmes, while combining all types of maintenance for a given SSC (‘proactive maintenance’ – see Section 3.3.1) or refining models to implement RCM (see Section 3.3.2). In both approaches, predictive maintenance – to reduce classical interval-base, periodic maintenance – and advanced condition-based maintenance are deployed at large scale thanks to the use of new technologies such as ‘plug-in’ remote sensors, embedded diagnostic systems, digital twins, artificial intelligence-based applications. Figure 1 shows the effectiveness of the maintenance types, using terminology presented in annex A of Ref. [42].

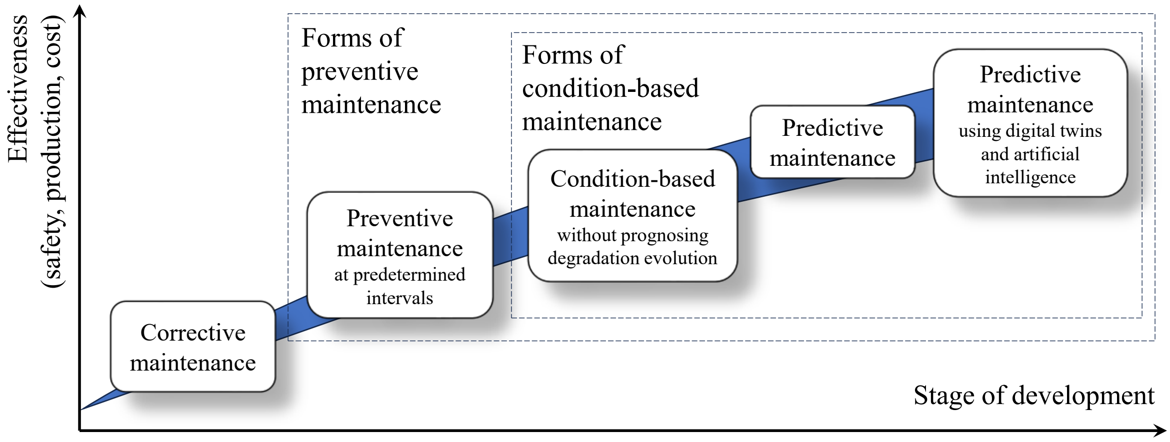

FIG. 1. Conceptual diagram showing the historical development and effectiveness of maintenance types.

From the perspective of owner-operators of NPP, the main lessons learned when selecting maintenance types is that finding the right balance between the different types for a specific SSC is challenging and try-fail cycles are inevitable.

3.3.1. Proactive maintenance

The proactive maintenance concept is an optimization method that combines the different types of maintenance such as:

- Device type-specific maintenance programmes (flowcharts);
- RCM analyses;
- Predictive maintenance from calculation programmes (e.g. for bearing lubrication intervals);
- Fault and root cause analyses;
- Assessment of maintenance tasks, based on history data.

[18] See guidance on how maintenance programmes were historically optimized in Ref. [2] and, for a timescale of when the different methods were developed and detailed, in chapter 1.1 of Ref. [41].

Optimization methods are selected on a case-by-case basis depending on device type and criticality.

Analyses carried out before implementing proactive maintenance consider:

- Information gathered from corrective, preventive, predictive, and a combination of these (preventive and predictive) maintenance – see Fig. 2;
- Work cycle data and work completion notes (incl. condition reports, as found conditions);
- Results and parameters from tests performed by operations and/or maintenance organizations;
- Experience and advice from component and system suppliers;
- Plant evaluations (e.g. WANO peer reviews, IAEA operational safety review team (OSART) missions, reviews by national authorities);
- Metrics and KPIs;
- Lessons learned from industrial working groups, workshops, and seminars held by international organizations such as IAEA, INPO, EPRI, WANO;
- Industry experience such as INPO event reports, WANO significant operating experience reports, lessons from events reported to the International Reporting System[19] for operating experience jointly managed by the IAEA and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, good practices identified at IAEA OSART missions in the area of maintenance (topic #4)[20].

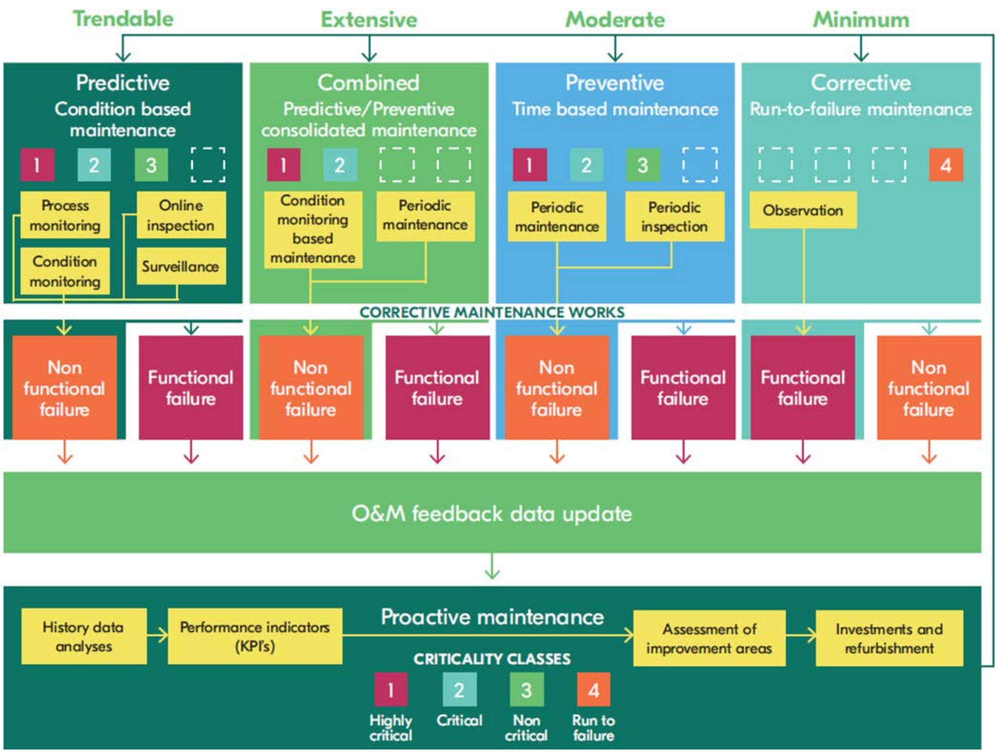

FIG. 2. Proactive maintenance flowchart used at Loviisa NPP (courtesy of Fortum).

[19] Available at: https://www.iaea.org/resources/databases/irsni
[20] Available at: https://www.iaea.org/services/review-missions/operational-safety-review-team-osart/good-practices

Once feedback from operations and maintenance activities is updated, historical data and KPIs are analysed, potential areas for improvement are identified (e.g. optimizing maintenance intervals), and, consequently, investment and refurbishment are implemented.

3.3.2. Evolution of reliability centred maintenance

The principles of RCM and a short introduction of the streamlined RCM are presented in chapter 5.1.1 of Ref. [2], and extensively in Ref. [43] alongside with examples of implementation at NPPs. The deployment of RCM is often seen as resource-intensive with questionable return on investment. Experience has showed that improving the understanding of the behaviour of SSC by using science and simulation modelling could increase the return on investment of RCM on long term (typically 5–10 years).

On top of data used to determine maintenance strategies (Section 3.1), technical characteristics of the SSC where RCM is applied are collected and managed in databases. Those knowledge databases encompass:

- Models on how failures occur at the level of microstructures, and the corresponding experiments, considering material and degradation science;
- Structural integrity models for pressure equipment and dynamic digital models for active components (e.g. digital twins) that simulate critical thresholds where maintenance must be done;
- Diagnostic systems that predict the behaviours of the SCC, depending on the duty cycles and actual trends.

When rolling out the PM optimization programme at an NPP, an analysis of all data and technical characteristics is carried out in teams comprising SSC experts (such as component engineers), reliability experts, data scientists, representatives from plant’s departments (incl. maintenance technicians), and facilitators. The decisions to reduce maintenance (or marginally to increase maintenance) can then be made on more solid ground and more likely lead to the desired performance.

4. PLANNING

Well planned and scheduled maintenance activities can significantly reduce the risks of production losses and safety events and improve cost effectiveness.

Usually, maintenance schedules in NPPs are drawn on three terms as follows:

- Short-term, for on-line maintenance between refuelling/maintenance outages and in anticipation of the upcoming refuelling/maintenance outage;
- Mid-term, for on-line maintenance of large components and for routine maintenance carried out in refuelling/maintenance outages;
- Long-term, for complex maintenance of large components.

Short-term schedules are managed under the work management process. Mid-term plans and long-term plans are managed on a higher level but in the end generate activities that also needs to be planned in the work management process in combination with the short-term plan.

4.1. PLANNING AND SCHEDULING OF ACTIVITIES

Maintenance planning is a defined process where maintenance activities are prepared (e.g. work instructions) and identified, ensuring the required resources – incl. supplemental workers and contractors for outsourced activities, spare parts, tools and supporting tasks (e.g. scaffolding) are identified and available. The level of detail and effort required for planning work activities is directly related to several factors such as:

- Complexity and frequency of the task;
- Risks to nuclear safety (e.g. reactor trip, transient, breach of technical specifications, entry into limiting conditions of operation (LCO[21]));
- Risks to industrial, fire, environmental and radiological safety;
- Requirements for specific control steps (e.g. a qualified inspection is required for the activity, high FME-risk zone, etc.);
- Knowledge and skills of workers;
- Availability of technical procedures.

The output from planning supports the development of a credible and executable schedule, therefore the staff assigned to planning and scheduling is preferably:

- Highly experienced staff with solid technical skills across all disciplines (i.e. mechanical, electrical, instrumentation and control, logistics);
- Knowledgeable of SSCs and related technical specifications' requirements (incl. LCO);
- Able to identify potential risks to personnel/plant (i.e. radiological, electrical, seismic, working at height, confined space, hot spots, etc.);
- Knowledgeable of operating experience;
- Familiar with the activities being planned.

The overall intent of scheduling is to ensure the right scope of work is scheduled for the right time in the plant's life cycle, supported by the right resources, maximizing the availability of safety and safety related equipment, and overall reliability of the plant.

In addition to technical specification requirements, tools such as a risk matrix based on the probabilistic safety assessment or guiding procedures minimizing unavailability can help to make informed decisions for scheduling maintenance activities.

4.2. SHORT-TERM SCHEDULE

Short-term schedules cover the period from current day up to the next outage, including the final phase of the outage preparation.

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[21] In this document, LCOs refer to rules that set operational parameter limits and performance levels beyond which safety-related equipment cannot be operated or is deemed unavailable for normal operation as required in the technical specifications for operation. This leads to actions by operators within a set time to prevent a technical specification breach, potentially resulting in a safe shutdown. An LCO entry is the same as the case of "limit for normal operation exceeded (curve no. 2)" in the annex of IAEA safety guide SSG-70 Ref. [44]. Depending on national jurisdiction, LCO entries may or may not be reported to nuclear safety authorities, whereas technical specifications breaches are assumed to be reported. The number of LCO entries per unit varies based on jurisdictional requirements and reactor design, from thousands, through hundreds to less than 10 (as reactor designs with multiple redundant and diverse systems 'can allow' for more LCO entries). Alternative terms to 'LCO entry' and 'LCO' include allowable period of inoperability, allowed outage time, unavailability of safety-related equipment, systems-important-to-safety action level.

Typical maintenance schedules include daily, weekly, monthly, three-month rolling, and cycle schedules.

The activities in the short-term schedule are optimized and coordinated considering duration of tasks, resources, required competences, and risks on a detailed level, especially when capacities from different teams in the maintenance organizations are required, when restrictions and conditions related to time, physical space, radiation protection, etc. apply and when errors in execution could lead to reactor trips or any other undesired plant conditions (see Section 6.1: Control of preparation).

The different maintenance activities – corrective, preventive, predictive – are synchronized with all other activities, including Operations activities, through centralized schedules (daily, weekly, monthly, three-month rolling, etc.). The activities are scheduled via work orders in the work management system. The work orders contain the detailed work description and identify the required resources, parts, tools, consumables, supporting tasks incl. isolations, scaffolding, etc., to help to define the critical path of the activity and take corresponding risk mitigating actions. The good practice is to have comprehensive, ready-for-use pre-planned work orders for both preventive and corrective maintenance activities.

Further guidance and good practices in delivering short-term schedules under the process for work management are given in IAEA publication Ref. [27].

4.3. MID-TERM SCHEDULE

The time considered for mid-term schedules of outage activities is typically 2–5 years, corresponding to 2–5 refuelling/maintenance cycles depending on required intervals for maintenance on reactors with on-line refuelling or the adopted fuel cycle for the others. The time considered for mid-term schedules for on-line maintenance is usually shorter, but it is good practice to develop a strategic schedule 2–5 years ahead for large components such as emergency diesel generators, circulation/cooling pumps, start-up boilers, transformers, condensate tanks.

The activities in the mid-term schedule are optimized and coordinated considering long lead components, resources, required competences on the mid-term, cost models, and projections of equipment failures based on assumed/actualized likelihood.

While developing the mid-term plans and associated schedules, opportunities for optimizing on-line maintenance and outage maintenance are considered. Examples include:

- Addition of on-line work in anticipation of the upcoming outages that helps to freeze the outage scope[22] and reduce the risks posed by tasks on the critical path;
- Execution of non-outage work during the outage, for example:
  - To restore flexibility for the coming cycle (e.g. repairing defective pump isolation valves that allow pump maintenance to be again performed on-line as expected);
  - To optimize resources especially when multiple work groups/teams (instrumentation and control, mechanical, electrical) are supposed to carry out

[22] Typically, 9 months before an outage (and sometimes up to 12 months). A good practice is to carry out walkdowns to validate planning assumptions are still valid as close to the outage as possible.

preventive and/or corrective maintenance on the same components within few months;
  - To reduce unavailability of safety related systems over the coming cycle as work was transferred from on-line to outage;
- Prioritization (anticipation) of technical improvements, of tasks that address ageing, of large maintenance activities, and of large design changes identified in the long-term plan, considering the challenges of securing critical resources for such work versus the challenges posed by long lead time for the needed spare parts.

To ensure alignment throughout all stakeholders, the mid-term plan can be documented and distributed to the other departments inside the utility (departments of operations, engineering, etc.) and externally to contracted vendors, typically as a report alongside schedules from the work management system. Such report is regularly revised and reviewed by all stakeholders.

4.4. LONG TERM PLAN

The time considered for long-term plans is typically 5–12 years, up to 20 years ahead.

An effective long-term plan requires a clear outage strategy and life cycle management. The preventive maintenance activities are synchronized with the different outage types (e.g. 'long for maintenance' vs 'short, refuelling only') together with the plans for technical improvements and major refurbishments. The long-term plan is the result of a working asset management process in the plant.

The long-term maintenance plan includes activities to be carried out during outages and normal operation of the plant, considering requirements for long term operation. It also encompasses activities up to the end of lifetime and, for specified parts of the plant, the period of shutdown and decommissioning. A good practice is to have these activities identified and integrated in the work management system.

The long-term plan contains less details than a mid-term plan. A typical long-term plan is a report that is updated (bi-)annually. As additional operating experience is gained, the details of the plan will be enhanced providing more surety for future economic decisions. The long-term plan allows owner-operator organizations to adequately forecast major expenditures (i.e., reactor coolant pump motors, turbine spindles, large transformers, etc.) and resource commitments well in advance.

5. DOCUMENTS

Maintenance is carried out based on established process procedures and task-specific procedures. SSR-2/2 [28] and SSG-74 [4] sets out requirements and recommendations for managing documentation in the maintenance organizations. This section outlines good practices in implementing those overarching guidance.

5.1. DEVELOPMENT OF DOCUMENTS FOR MAINTENANCE

Maintenance documentation is any schedule, procedure (e.g. instruction for maintenance and tests), work package, record, manual, drawing in computerized form or on hard copy that is essential for the optimized and safe maintenance of an NPP. Broadly, maintenance documents can be classified into (a) those documents that are essential before undertaking maintenance (PM schedules, manuals, procedures etc.,) and (b) those that are created based on the maintenance activity carried out (history records, feedback on procedure, etc.).

Maintenance procedures are prepared, reviewed, approved by competent persons designated for the purpose. Good practice is to assign an owner, an individual or a team, for each procedure. It is also essential to have a systemic process by which feedback from maintenance teams is captured and the procedures modified, to be once again validated and authorized for subsequent use. If persons outside the plant organization (e.g. contractors, equipment manufacturers) prepare procedures – especially for infrequent work or first-of-a-kind work, the assigned plant teams (including the quality assurance team) closely monitor the process of writing, making sure the documents are of the same quality as the documents developed by plant staff.

It is good practice to categorize maintenance procedures to risks posed by their use, for example adopting the same risk categorization as the one for defining high risk maintenance tasks (e.g. tasks on critical components and SPV – see Section 3.1) and for planning the tasks (see Section 4.1), and to use logos/stamps on the cover page of the procedure that reflect the risk level[23]. In maintenance procedures and work documents, critical steps are identified or annotated to raise awareness of workers on what is important and to allow for specified personnel to witness performance of those steps to ensure quality. Critical steps are maintenance tasks, which, if not performed with high quality, could adversely impact safe/reliable equipment performance. It is good practice to proceduralize the definitions of critical steps.

For evolving maintenance, troubleshooting, and work for which a standard procedure does not exist, a document containing guideline can be prepared, incorporating appropriate caution, checks and review in the maintenance steps to be performed. On completion of the work, based on the experience gained and a review, the document can be converted into a standard procedure if it is felt that such work might be needed in future.

Maintenance procedures ought to be prepared – normally based on the original manufacturer's specifications – in coordination with the designers, the equipment suppliers/manufacturers, and NPP personnel provided they are suitably competent and experienced in writing maintenance documentation.

5.2. SCOPE AND CONTENT OF DOCUMENTS FOR MAINTENANCE

Maintenance documents and procedures are duly developed for every SSC managed in the plant asset management system, and include step-by-step instructions and verification methods essential for maintenance tasks such as:

- Pre-requisite before starting work (e.g. plant conditions are met);
- Safe work sequence;
- Sequence of dismantling/assembly;
- Fault finding methods and tools for identifying potential deficiencies through exceedance/drift of indicators, parameters and limits (this could be under the responsibilities of engineering functions);

[23] Sections 4.2.2, 4.2.3 and tables 2 and 3 of IAEA TECDOC Ref. [45] provides detailed examples of a graded controls applied to procedures and records.

- Pre-authorized intervention options to correct deficiencies;
- Non-destructive tests and inspections;
- Criteria for testing the post-maintenance condition and sanctioning return to service.

Activities which are not critical to safety and operation of the plant, or which are within skills of craft of maintenance technicians, may not need detailed step-by-step instructions – see for example a determination chart in attachment 2 of annex B in Ref. [46]. However, such activities are assigned to personnel only after a proper assessment of their skills/experience in performing similar activities.

Work instructions and procedures ought to be:

- Clear, descriptive, and unambiguous;
- Technically accurate;
- In a language that is understood by maintenance technicians, especially where multi-cultural/multi-lingual work force operate, without complex language forms;
- Containing step-by-step instructions avoiding multiple instructions in a single step, with a level of detail so that 'the individual carrying out the work can follow the procedure without further guidance or supervision' [4];
- In a logical sequence that can be adhered to;
- Validated in a suitable mock-up or in a controlled set up, especially for complex or high-risk maintenance tasks;
- Incorporating appropriate quality assurance steps, clearly identifying critical steps, hold points and reporting requirements;
- Addressing human factors and referring to appropriate human performance tools for the key steps, following the approach to error prevention presented in Section 7.2;
- With work specific cautions on industrial hazards and measures for their mitigation to guarantee protection and preservation of personnel's life, health and to ensure operational safety;
- With work specific cautions on radiological hazards and means to achieve the 'as low as reasonably achievable' principles;
- Visibly showing the level of risk (to nuclear safety, to equipment reliability) if the execution is not as expected;
- Referring to or containing all references, drawings, interfaces, and other procedures that are needed, or likely needed in case of abnormal as-found conditions, for the successful completion of the maintenance work;
- Referring to or containing the list of tools, consumables and spare parts, required, or likely needed in case of abnormal as-found conditions, to perform the work;
- Adapted to the level of use at workplace – see also Section 5.3.

Experience has showed that work packages can contain multiple, intricated and lengthy procedures where only a fraction of written instructions is needed and, therefore, used. Having the overview of what work packages contain, how procedures refer to each other, and experience in implementing procedures enable procedure writers to optimize the content.

A good practice is to have a writer guide that includes all the above – see for example guidance in annex A of Ref. [46].

Where maintenance is performed on NPP equipment offsite by external organizations (for example, at manufacturer's premises), the procedures, the testing and inspection requirements, and the requirements for reports and records are clearly enumerated, agreed upon in advance and documented. The final inspection and test reports are reviewed to ascertain that the tasks have been carried out as per plan and that equipment meets the performance criteria before the equipment is returned to service.

5.3. USE OF DOCUMENTS AT WORKPLACE

It is good practice that provisions are made to make sure that only the latest revision of work instructions and documents is made available before work commences. Such provisions can be enshrined in the documentation management system or be specific verification steps (e.g. verification by the users on the day of execution).

Adequate understanding of the instructions and procedures by the personnel responsible for the work is verified, especially before the execution of work that could lead to events if not properly delivered. A good practice is to allow time for staff to read through the instructions and procedures at the preparation stage and to check this at the PJB.

The level of use at workplace depends on the nature/type of document and the risk posed by human errors. While a continuous use procedure[24] is at the workplace and continuously referred to during work, a reference use[24] or information use[24] procedure might not require the same level of rigorous procedural adherence. The principles for using and adhering to the procedures and the role of managers and leaders for evaluating their effective implementation are defined for each type of procedures and work – see for example guidance and good practices defined in INPO 09-004 [47][25].

As a general rule, the following documents are available in the work area:

- A written work-specific authorization that complies with health and safety requirements;
- Work related documents, including, if applicable, sketches, lifting and rigging plans, layout, etc.;
- Means to record and follow-up on work progress and evolution of plant conditions when the work spans over multiple shifts, so that shift handovers are effective;
- Measurement charts, forms, step-by-step check records (when required), etc.

Even as multiple documents are made available at the work location, there is a clear guideline on the primacy of one document over another to resolve any conflicts between documents.

6. CONTROL OF ACTIVITIES

Once maintenance activities are identified, planned, and scheduled, the challenge is to deliver first-time, event-free maintenance – this requires both qualified and experienced staff (see Section 7) and effective control steps to ensure event-free maintenance will be/has been

[24] Definitions as in chapter 2.4.2 of Ref. [46] and INPO 09-004 [47].
[25] Publicly available at: https://www.smartprocedures.com/pdfs/inpo-09-004-use-and-adherence-guidelines.pdf

delivered. This section presents examples of control steps[26] taken at the preparation, at the execution and closure (before return to service) of maintenance activities, including control steps taken when procuring and managing spare parts.

6.1. CONTROL OF PREPARATION

At the time a team is assigned to the work, there is a transition from maintenance planning to preparation by the work team. When assigning a team, supervisors and managers ought to be certain that the assigned team possesses and will apply the specific technical skills and fundamentals necessary for first-time, error-free execution of the work in the moment.

Preparation tasks include checks whether the required resources (e.g. supplemental workers, inspection team, consumables, spare parts, tools, and supporting tasks) are identified and available. The work team checks the actual conformity of consumables and spare parts as there could be labelling errors or damage to the items when they were stored or handled – see also next section, the quality of documentation (work package, documents related to environmental, health and safety requirements) and the job place conditions.

The checks are ideally carried out in advance by the team that will execute the work, in line with the plant work management process. Any change of schedule is clearly communicated to the workers in good time.

Good practices are to:

- For managers to allow a fixed window (e.g. each week, half a day) for workers to get prepared for upcoming work;
- Allow for 'just-in-time' training, desktop practice with a highly skilled/experienced worker (incl. mentor, reference worker, trainer) or rehearsal for high-risk activities[27];
- Confirm and formally allocate the required resources when assigned to work, ideally days in advance, especially for high risk activities to personal safety (see for example recommendations in WANO document SOER 2024-01 [48]) and to equipment reliability;
- For workers to take into consideration the challenges and conflicts that may hinder the completion of work activities ('what can go wrong?') and consider contingency plans or adding control steps to mitigate the risks;
- Identify work group interfaces, especially when multiple activities are carried out simultaneously in a room (as often during maintenance outages), and coordination points with the other departments before the implementation.

To further prepare for effective and efficient work delivery, some owner-operator organizations develop task-specific standardized hourly maintenance schedule, use maps (or mats) to optimize lay-down areas[28] for each maintenance steps and prepare for videorecording of

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[26] Overall guidance on how to develop graded control steps applied to maintenance is given in IAEA TECDOC Ref. [45] – table 5.

[27] As for the initial training of personnel on work simulators (see Footnote 36 in Section 7.1.1), new technologies such as augmented reality (e.g. through a camera installed on helmets with goggles being wore) can be used to carry out just-in-time training and rehearsal at the work place, if conditions permit.

[28] For example, a thin mat (easily reusable) can be used to materialize and visualize the laydown areas for tools (sorted by frequency of use and type), procedure hard copies, spare parts, dismantled parts and their sorting boxes.

sensitive steps and tracking of completion time. Further good practice and recommendations are extensively captured in references [13], [49], and [50].

For major work, a good practice is to carry out the engineering walk-down with maintenance representatives (and ideally with operators) about 6 months before the execution of activities of interest for the plant health and the equipment reliability programme, so that the engineering functions can feedback on their needs and the potential issues to look at.

Good practice for carrying out the work site preparation is to have walk-downs carried out with the other departments (operations, logistic for tools and scaffolding, fire/radiation/industrial protection departments) in the days/weeks before execution to ensure:

- Effective support will be provided as needed;
- Risks are identified and eliminated, or if not, mitigated across the organization;
- Laydown areas and temporary storage areas are available and suitable, and will be appropriately labelled and cordoned off;
- Interferences (insulation, cable trays, etc. in the job environment) will be effectively managed;
- Interface with other activities (other maintenance teams, lineups by operators, etc.) that can affect work execution are evaluated, risked-assessed, and controlled.

Templates can be used for such walk- downs.

Hold points on key steps, typically related to quality of execution, nuclear safety, and industrial safety, are identified in the work package. Conditions and resources for waiving the hold points are identified and reviewed beforehand. This can be again checked during the PJB.

In case of troubleshooting, urgent work or fix-it-now team activities, the steps described above are implemented, but on a compressed timescale.

6.2. CONTROL OF PROCUREMENT AND INVENTORY

Procurement plays a significant role in the maintenance of nuclear facilities by ensuring high quality parts and materials (e.g. consumables, chemicals) are available to meet the requirements of the NPP during both normal operation and outages. In addition to ensuring all components meet the appropriate specifications and quality assurance standards, procurement needs to balance the costs involved in maintaining a large inventory vs moving to a more just-in-time delivery method. The balance is influenced by regulations, geographic proximity to vendors, NPP cost/financial models, and vendor relationships.

As delivery time of spare parts can affect the timely execution of work, good practices are to:

- Identify the needs for procurement in the very early stages of maintenance planning[29];
- For procurement organizations to notify maintenance planners of any material/part issues that could affect the planning and the execution of work activities;

[29] Special attention needs to be paid to items with long lead procurement time and discontinued items (such as obsolete – see for example Ref. [51] for mitigating actions). Organizations and staff involved in procurement activities need to anticipate demand for such components years in advance (5–10 years) and manage the procurement against strict risk and project management practices.

- Define the roles of the procurement staff at each stage of the purchasing process and the interface with the maintenance organizations;
- Ensure that the procurement staff has sufficient time for receipt of parts and services.

For items critical to safety and production (especially for SPV) it is good practice[30] to:

- Carry out inspections of source materials and end-of-manufacturing steps as practical;
- Require thorough and extensive factory acceptance tests[31], witnessed by duly qualified inspectors and documented in reports submitted for approval to NPP staff, so that the owner-operator organization can exercise an intelligent customer capability (as defined in Ref. [7]);
- Specify and ensure necessary controls for FME;
- Specify and verify conditions for preservation and protection that are consistent with the specifications on materials, consumable and chemical authorized for use in plant's systems, especially when the items are used on systems connected to the primary system;
- Ensure continuity and consistency between conditions in the package, interim storage at NPP before installation and 'end user' cleanliness requirements;
- Check that the requirements for transporting big components, such as coolers, pumps, transformers, etc., are aligned with the safety claims (e.g. accelerations are monitored and always lower than a set value).

For all SSC, challenges and good practice in detecting and eliminating counterfeit and fraudulent items are given in Ref. [52].

Furthermore, challenges, good practices and recommendations to control supply chain and quality of procured items are extensively captured in references [53] and [54].

Before installation, site acceptance tests and inspections (e.g. FME) are again carried out. After installation, adequate and representative post-installation/commissioning tests (see Section 6.4) are also carried out to confirm the quality and the performance of the procured items.

Reserves of long lead items and of items required for maintaining SPV and critical SSC (from minor but urgent work through to unexpected failures) are developed to exclude waiting for necessary spare part procurement and finally avoid outage or maintenance activity extensions. It is critical to determine proper inventory for those items, for example, using cost-informed risk analyses. In countries with numerous NPP or for owner-operators of large fleet, pooled inventory may be beneficial (e.g. an emergency diesel generator set that can be used by all owner-operator organizations in the country or at all units in the fleet).

When determining what spare parts, including subset/whole set of equipment, to keep in inventory and quantity, consider operating experience, lead time, consumption rates over a long period of time, expert reviews, and manufacturer recommendations.

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[30] Section 4.2.1, table 1 and annex VI of IAEA Ref. [45] provides detailed examples of a graded controls applied to procurement.

[31] For example, experience captured by WANO shows that defects of items such as relays, programmable devices, encapsulated items in resins when used on are regularly not discovered or appropriately looked at during factory acceptance tests.

Minimum stock levels[32] are defined for all items (with priorities given to critical system/equipment), balancing lead time, costs and criticality to plant operation and safety – see the simplified model for determining such levels in Fig. 3. It can be zero for non-critical components, 'run-to-maintenance' components and parts available in large quantities in the industrial sector. Note that the same approach is taken for determining maximum stock levels. The EPRI guideline Ref. [55] contains detailed guidance on how to assess risks before procuring 'contingency' spare parts (the ones that may be needed for maintenance tasks) and on how to define the stocking plan against demands raised by the maintenance organizations and actual usage of parts – see also appendix IV in Ref. [53].

The responsibilities described above may be under the engineering function or any other centralized function in an organization. In all cases, the maintenance organizations are informed on issues that can have consequences on the scheduling and timely execution of maintenance work.

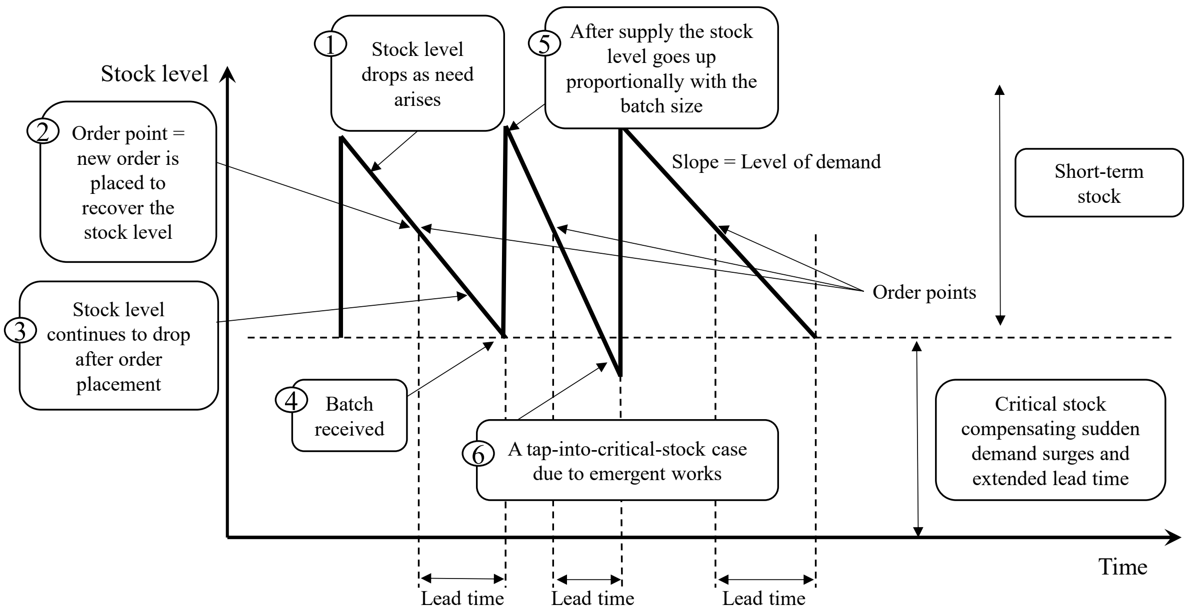

FIG. 3. Simplified model for inventory stock management.

6.3. CONTROL DURING EXECUTION

In addition to the control steps under the responsibility of operators set out in SSG-74 [4] (e.g. authorization for work, communication with control room), specific steps to control quality of executed work are put in place by the maintenance organizations. These steps can be as follows:

- PJBs and PJDs are carried out – see Section 7.3;
- Work execution is supervised against the fundamentals and expected skills of craft, where the level and intensity of supervision is higher for critical steps;

[32] This could be termed safety stocks (EPRI terminology) or critical stocks depending on the organizations.

- Work progress is frequently checked by a supervisor or/and by any remote work control centre[33];
- Hold points are readily reviewed and waived by the designated supervisors or third-party experts with utmost caution;
- Delays, issues and challenges are swiftly communicated to the supervisor or managers and actions taken accordingly;
- Engineering/OEM support is duly provided when needed, especially while carrying out complex activities, including complex troubleshooting[34];
- Any deviations/gaps between work as prepared and work as executed, issues (incl. potential for human errors), and challenges encountered during work are systematically reported by work executors and supervisors, assessed to lessons learned, translated into suggestions and changes to the work procedures, nurturing a learning organization. Work executors contribute to a better maintenance process by raising suggestions for improvement. Required changes are agreed by the responsible supervisor or manager, prior to the execution of the changes.

The maintenance managers and technical leaders perform walkdowns, observations, and, where necessary, intervene to correct individual actions or support resolution of issues.

Across the organizations, emphasis is given to performing work safely and correctly over schedule pressure. As such, maintenance work supervisors stay focused on their team without being distracted by secondary tasks.

6.4. ACCEPTANCE OF ACTIVITIES AND RETURN TO SERVICE AFTER WORK

SSG-74 [4] defines the concept and purpose of post maintenance tests performed before SSC is returned to service. Post maintenance tests ensure that no new issue arose, and that identified deficiencies were fixed. The corresponding procedure defines the scope and the sequencing of the tests depending on the extent of the work[35], preferably following the logic part → component → system (or function), and considering connected systems that may have been affected.

To expedite effective post maintenance tests , it is crucial to ensure, from the perspective of the maintenance and operations organizations, that:

- Expected test results (against criteria for safe and reliable operation), data to be collected (related to the criteria and, as practical, to any unexpected abnormal behaviours), and the potential failures (incl. those possibly caused by the specific maintenance activity carried out) are clearly defined, and the relevance of test criteria to those potential failures are substantiated and checked;
- SSC performance under normal operating conditions is actually verified and also that safety margins have not been eroded;

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[33] In high dose rate areas, based on a careful risk assessment, supervisors may not attend in person and supervise work execution through other means such as video transmission (e.g. from fixed cameras or video goggles worn by the workers). Note that a remote work control centre can also be used for observing/overseeing work carried out on SSCs critical to equipment reliability.

[34] To make readily available, high-quality OEM support for complex troubleshooting possible, good practice is for owner-operators to actively seek for OEM support to stay abreast of industry trends, to actively engaged OEMs and to maintain their services.

[35] Apart from the planned work, other work such as unplanned repair, unanticipated replacement of a significant number of parts, etc. that might have been carried out is considered while defining the post maintenance tests.

- SSC will perform on demand in accident conditions, as per design intent [56];
- Potential unexpected/unforeseen conditions that warrant an immediate termination of the post maintenance tests are identified;
- Issues are documented and swiftly resolved;
- Accurate and detailed records/reports are produced and duly sanctioned.

At those tests, it is good practice to:

- Collect baseline data for future reference, for example, for on-line monitoring and equipment behaviour prediction systems;
- Capture learnings and health status of the SSC (from the maintenance organizations' perspective) into the test records/reports;
- For responsible equipment performance engineers and maintenance experts to evaluate work performance, and attend the PJD carried out by the team responsible for the post maintenance tests.

EPRI report Ref. [57][36] provides more than 200 pages of examples of test matrices, testing guides, and test definitions for basic components in an NPP.

7. MANAGEMENT OF SKILLS AND QUALIFICATION FOR ERROR-FREE PERFORMANCE OF WORK

Alongside effective control steps to ensure event-free maintenance (Section 6), possessing highly skilled, suitably qualified, and experienced maintenance personnel [58] is paramount for maintenance organizations. This section presents good practices in managing skills and qualification, and in deploying human performance tools to prevent errors.

Typical skills of maintenance personnel and guidelines on how to qualify maintenance personnel are provided in references [12] and [13], where Ref. [11] is an example of maintenance fundamentals to be exhibited by maintenance personnel.

7.1. TRAINING AND QUALIFICATION

Experience shows that a systematic approach to training is efficient for managing skills and qualification. Detailed guidance for training maintenance personnel is given in chapter 13.4 of Ref. [58], with table 9 detailing typical generic training sessions. This section outlines the key elements to be considered by managers, including the specific elements for supplemental personnel.

7.1.1. General approach

A common practice is that requirements for training personnel are defined through training needs analyses, ideally over 5–8 years, which consider both the skills/qualification needed and

[36] This report was published in 2004. The table of content is translated into three languages (French, Japanese and Spanish).

the number of individuals required to support the plant specific maintenance programmes and all corresponding tasks.

Parameters to be considered in the training needs analysis include:

- Human resources-related parameters: workforce attrition, succession plans, average number of years of experience, budgeted headcounts;
- Maintenance mid-term and long-term plans, as new needs may arise from major refurbishments, overhauls and design changes of SSC;
- External parameters considered when maintenance strategies are revised – for example, decreasing availability of contractors and vendors that used to deliver specialized maintenance tasks or upcoming deployment of condition-based maintenance (see other parameters in Section 3.1).

Establishing those analyses is a dynamic process. The analyses are frequently updated.

To develop the required skills and qualification, alongside vendor training and utility-developed class-room training, thorough on-the-job training, and mentoring programmes[37] are key to qualify maintenance workers, work supervisors, work preparation engineers and maintenance first line managers.

Work simulators[38] and mock-ups can also be an integral part of initial training or used as ‘just-in-time’ training or rehearsal prior to a significant/complicated work activity. Mock-ups generally include steam generators water channel heads, reactor coolant pump seals, seal tables, high-voltage switches, etc. The initial investment in mock-ups can be significant, requiring a detailed cost-benefit analysis that considers the complexity of the task and the consequence of error (potential impact to nuclear safety, personal safety, radiation dose, environmental damage), and potentially partnership with the OEM as part of long-term service agreements or sharing mock-ups with other owner-operator organizations and companies.

To maintain high levels of proficiency in maintenance and supplemental personnel, initial qualification must be followed-up by a requalification/refresher programme tailored to the specific skill set. The requalification/refresher interval will be dependent on several factors: frequency of work, criticality/impact of error, negative trends in performance, industry experience, country specific standards, self-identified gaps, and regulatory requirements (as for review of training programmes).

The arrangements to train and qualify maintenance staff can, in practice, depend on ‘hard’ factors such as costs, practical availability of contractor/vendors to deliver initial training/refreshers, geographical location, and restrictions to access to the services.

Throughout the implementation of training, good practice is that maintenance managers and technical leaders:

- Proactively design and set up the training programmes, partnering with training teams;
- Proactively engage vendors and training providers, gaining intelligence on the opportunities offered by the market and new technologies;

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[37] Ref. [59] presents experience with coaching and mentoring programmes in nuclear installations.
[38] that simulate real work environment (incl. high radiation, temperature, noise, etc.). These simulators can benefit from new technologies, such as virtual reality or augmented reality, 360-degree videos, three-dimension models, process simulators, e-learning.

- Sponsor the development of mock-up and hands-on facilities at site;
- Understand certifications for specific maintenance activities, such as non-destructive testing, welding, heavy lifting, ice plugging, high-pressure injection of sealing compound, use of high-pressure tools and equipment, etc., and certifications for activities that pose a risk to personal safety, such as driving forklift, working at height and rope access, working in confined space or in highly contaminated areas, erecting scaffolding, etc.;
- Attend the training evaluation sessions (collecting feedback and unaddressed needs).

7.1.2. Specific approach for supplemental personnel

As outages and large refurbishment projects result in a large influx of supplemental personnel specific steps are taken to ensure plant expectations will be met by these personnel. Before starting work, the level of skills and experience can be checked by the work supervisor and mitigating actions can be taken (see Section 8). In addition to the general training to access the NPP, additional training can be provided to certain individuals/groups of supplemental personnel such as those involved in complicated/ high risk activities, infrequently performed maintenance tasks and activities that include oversight of other workers. This could imply temporary training facilities for general maintenance tasks (human performance-tools, FME, etc.) to be deployed before the outage, systematic hands-on tests to be passed by supplemental personnel, and, therefore, an adequate planning for gaining supplemental trainer resources.

To secure highly skilled and experienced supplemental personnel, the strategy can include ordering contractors for 'long' periods (more than 3 years) so that efforts and cost to augment and secure competences and skills of supplemental personnel can be spread over a longer period and so that companies are incentivized to bid. Long-term contracts and service level agreements combined with penalties and incentives (e.g. associated with requirements for high percentage of retournee staff) are commonly used tools to obtain engagement of contractors in continuously improving safety culture and quality of work.

Further guidance is given in IAEA documents references [58] (see chapter 14 for high level principles), [60], and, in the broader picture of knowledge management for supplemental personnel, [61].

7.2. ERROR PREVENTION

One of the key elements affecting maintenance quality is the human performance of workers executing the activities. Good practice is to start with the philosophy that errors in maintenance are preventable as it is very likely that thorough analyses will show that the error could have been prevented – see chapter 2.2 of Ref. [62]. Through an effective error management, a lot can be done to identify error-likely conditions and take actions to eliminate/mitigate them to prevent the chance of errors. By thoroughly investigating causes of human errors the real drivers of human error can be identified and addressed by proactive actions. Examples of tools used to identify gaps in human performance are given in chapter 3.4.1 of Ref. [62]. A simple tool is to ask 'five why questions' that also investigates why certain behaviour is witnessed. Guidance on how to enhance root cause analysis is given in Ref. [63].

Errors and error-likely conditions are the result of several factors at different levels (organizational, local, individual), and, thus, a systematic approach is needed to identify those factors. Organizational factors that can influence the probability of errors occurring are e.g., decisions, processes, values, and culture while factors, at a ‘local’ level, can include competencies, procedures, tools, hazard awareness, spares availability, team beliefs, time pressure, documentation, demanding work environment (heat, noise) and housekeeping. Examples of factors at the personal level can be fitness for duty (fatigue, stress), information overload, personality types or biases in thinking and decision making.

In deploying an effective error management, maintenance organizations ought to focus on mental skills (e.g. thought process) as well as technical skills, and on improving the conditions under which people work. To be successful, such measures are systemic, and cover person, team, workplace, task, and organization.

7.3. HUMAN PERFORMANCE TOOLS

Human performance tools are tools designed to prevent human error and eliminate/mitigate error-likely conditions. Typical human performance tools include pre-job brief (PJB), post-job debrief (PJD), procedure use and adherence (PU&A), self-checking (incl. read-touch-verbalize, stop-think-act-review), effective communication (i.e. use of the phonetic alphabet and 3-way communication), and independent verification. A comprehensive, publicly available reference describing those tools and their recommended usage is Ref. [64].

It is good practice to implement a comprehensive human performance programme that applies equally to all staff that access and work at the NPP including all supplemental personnel.

WANO guideline GL 2002-02 [65] provide recommendations for using human performance tools, widely implemented in NPP. Regarding the execution of tasks, 3-way communication being recommended for (a) communication with operators, (b) direction and correspondence of procedure steps, (c) parameter reading and recording, (d) any directions by a supervisor. Phonetic alphabet is recommended for communicating equipment identification. Stop-think-act-review/read-touch-verbalize are used for manipulating switches and valves or identifying equipment to work on. Peer check is used for critical steps.

PJB and PJD are widely used human performance tools to prevent errors and safety issues in maintenance activities in NPPs, following a graded approach to risk and complexity of the tasks. To perform effective PJB, plants have developed templates to be used by all workers. Experience has showed that specific training and coaching are needed for new work team leaders to make sure they appropriately address topics such as work scope, qualification of staff, risks, mitigating actions and worst-case scenarios when conducting PJBs. Some plants have adopted the practice of a reverse PJB, at supervisors’ discretion. In this case the workers brief the supervisor on all aspects of their work activity including safety, operating experience, human performance tools to be applied when executing and closing out the work, alongside the technical details of the task. The reverse PJB is a tool to confirm to the supervisor that the work team has a clear understanding of the risks, roles and responsibilities while still providing the supervisor the ability to add instructions/coach/reinforce specific expectations and address any gaps.

Evidence of high quality PJB include that all work team members attend the PJB, the supervisor encourages everyone to be engaged, workers confirm the purpose of the job, identify critical steps and time-off, identify conditions to stop work, identify risks associated with the job and jobsite, are self-aware and transparent on their level of proficiency (against the defined fundamentals), discuss the worst case scenario (and the mitigating actions), and discuss operating experience that increases their risk awareness (where the examples of operating experience do not have to be related to the specific task). For PJD, good implementation can be identified when there is discussion on potential improvement in the job process and the procedure for the next occasion, and when all workers candidly provide feedback to enhance teamwork and mutual trust.

The desired state that demonstrates how deep the use of these tools is enshrined into the staff practice is when, always (e.g. without being observed or coached, or being directed through procedures), workers are committed to use human performance tools, and work supervisors consistently act as a role model and demonstrate effective use by exemplary implementation.

Experience shows that human performance tools are better suited to an environment where specific traits of a healthy nuclear safety culture are well embedded. Nuclear safety culture is defined in Ref. [30]. The traits that mostly support high human performance are raising concerns, questioning attitude, and work process (the latest advocating for a strong procedure use and adherence) – see Ref. [30] for the corresponding attributes. Those traits ought to be emphasized in training delivered to plant and supplemental personnel.

8. OUTSOURCING OF ACTIVITIES

Outsourcing is a common practice for maintenance at NPPs for several reasons. For instance, NPPs are often staffed with in-house personnel to support a steady-state on-line maintenance workload. Supplemental maintenance workers are needed to support higher volume work – mainly during outages – or for implementation of project work/modifications where a significant number of additional resources are needed over a short period of time. In addition, NPPs sometimes require specific knowledge, skills, competencies[39], and OEM knowledge (i.e. software update, sensor maintenance) which in-house personnel may not possess. This section outlines good practices to keep control of outsourced maintenance, excluding procurement services covered in Section 6.2.

8.1. THE CHALLENGES OF OUTSOURCING

The plant is ultimately responsible for the safety and quality of all work performed by supplemental personnel, exercising an intelligent customer capability (as defined in Ref. [7]). For this reason, it is important to ensure outsourced work is executed to the same standards as in-house maintenance to ensure safe/error free maintenance.

Some of the challenges include that supplemental maintenance personnel and their leadership:

- May not be aware of or have the same standards as in-house personnel (in areas such as maintenance fundamentals, human performance, FME, industrial safety, nuclear safety culture, etc.) as they may come from other industries or infrequently work in NPPs;
- May not know the plant, people, procedures, or processes and, therefore, not communicate and report as expected;
- May lack ownership for work and, thus, have more tolerance to errors, workarounds, and inaccuracies.

[39] Highly specialised contractors are often used for ice plug, leak repair injection, etc.

The challenges of outsourcing, alongside generic recommendations, are further discussed in chapter 4 of Ref. [53].

8.2. SUPERVISION/OVERSIGHT OF CONTRACTORS

Since the responsibility for safety and quality cannot be transferred from the operating organization so the need for supervision or oversight of the contractors is important. The operating organization ought to have programmes to ensure sufficient skills and knowledge of supplemental workers and supervision.

Legislation related to outsourcing varies between Member States but usually the regulatory bodies can issue requirements on outsourcing, exercise supervision of hired companies or approve such contractors – see Section 3.2 for examples, and chapters 3 and 5 of Ref. [66] for detailed discussions.

Supervisory oversight of maintenance activities is one of the most effective ways to ensure field activities are being performed safely and correctly. The training and qualification of supervisors is a vital component in the success of the maintenance department and every effort is made to establish and maintain the programme. There are numerous industry forums and benchmarking opportunities available to establish a successful supervisory/leadership programme. The emphasis of the training programme of supervisors is firstly placed on their ability to detect deviations in behaviours and in the implementation of core skills/skills of craft to the specific jobs, irrespective of the complexity of the jobs.

When considering plant supervisors vs contractor supervisors for supplemental personnel (when the option is permitted in the national regulation), it is good practice to carefully review the risks/benefits (nuclear, radiological, industrial, environmental, and economic) and the specificities of the tasks, first of a kind evolution, infrequently performed tasks, complexity, skill level, and familiarity/proficiency of the supplemental workforce.

To address the challenges posed by hiring supplemental personnel, it is important to ensure there is adequate on-boarding/training/demonstration of skills and knowledge through assessment (prior work commences), evaluation (prior to and during work) and supervision (during work) of contractors. Thus, consideration is given to:

- Assessment and evaluation of qualification of contractors' personnel to the specified work (through desk-top review, pilot scheme, simulated work on mock-ups, etc.). A recognized good practice is to regularly evaluate contractor's individual competencies;
- Assessment of knowledge, experience, and the training programmes for human performance, nuclear safety culture and any specific areas identified by the plants;
- Production of high quality technical specifications for contracting supplemental personnel – see chapter 4.3 in Ref. [53] for guidance – that support the implementation of the oversight programme by the plant;
- Adequately scoping/splitting/quoting work in the contracts to ensure the contractor is assigned work within their capabilities and has sufficient capable resources;
- Assessment of management systems for safety and for delivery of the work, including how plant expectations are communicated and reinforced;

- Specific evaluation of contractors' first line supervisor competencies and training programme [67], with attention paid to areas such as human performance, nuclear safety culture, how the supervisor interacts with the work activity (supervise, not participate);
- Observations of contractors' managers to evaluate their conduct of activities;
- Supervision and evaluation of work performed at workplace, implementing an oversight/observation programme that ensures field behaviours of workers and work leads meet plant expectations. This can be recorded in annual supplier feedback sheets40, task-specific performance assessment reports, periodic self-assessment report prepared by plant managers or outage/project critique to ensure feedback and lessons learned from the use of supplemental personnel are captured and retained over time to improve future activities;
- Partnerships with contractors to ensure:
  - Plant expectations are clear to them;
  - Periodic assessment of their performance is widely shared and fully understood across the contractors' organizations;
  - Feedback/communication from the NPP or from contractors' organizations freely flows between the NPP and the contractors, at all levels;
- Milestone tracking to ensure work progress is as expected, and slippage is detected so that compensatory actions are/can be taken as appropriate;
- Processes and procedures in place at the NPP that govern use of supplemental personnel and address the topics listed above.

Evaluation of knowledge and experiences are based on procedures[41] that involves both the operating organization and the contractors in a common evaluation of both good and bad experiences resulting in lessons learned and improved conduct, procedures, or organizational arrangements.

In the oversight/observation programme for work performed by supplemental personnel, special attention is given to critical steps and hold points. They can be witnessed and waived by another worker, the contract supervisor, a plant supervisor, or third-party experts, as appropriate, depending on the potential consequences. When not witnessed/waived by a plant supervisor, it is good practice for plant personnel to plan for a specific observation on that topic in the programme.

8.3. BENEFITING FROM CONTRACTORS

There are several advantages to a long-term relationship. One is the development of the skills and experience of contractors, while another is for the operating organization to benefit from experiences and best practices learned from contractors. Also, a long-term relationship facilitates the fostering of a good nuclear safety culture in the contractor's organization and makes their personnel familiar with safety and quality requirements along with the associated procedures. The use of OEMs for high risk/high-cost activities has proven not only to be efficient but also cost effective based on the risk of a third-party contractor.

As staff familiarity between the owner-operator organization and the contractor grows, the trust and the collaboration environment usually improve. This can provide support to solve problems

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[40] See for example chapter 4.4 in Ref. [53].
[41] These procedures are preferably supported by policies endorsed by the senior leadership teams.

occurring during operation (e.g. for urgent complex troubleshooting), outages, etc. A disadvantage of long-term relationships, however, can be those relations between the owner-operator organization and the contractor might be too relaxed resulting in complacency. Careful consideration should be given when working with long term contractors to ensure mutual benefits. A cause for such scenario might be e.g. replacement of experienced personnel, employment of new personnel, changed organization, procedures, or policies by the contractor during contractual relationships. It is thus important that the operating organization assures that such changes by the contractor are communicated. When properly managed, outsourcing can provide benefit of knowledge transfer to both the contracting organization and the site. This is accomplished by fostering teamwork and openly sharing of information and skills.

8.4. COMMUNICATION

Effective communication between the operating organization and the contractor at all levels is essential to achieve the quality and requirements needed to maintain safety. A good practice is to include them in the routine department meetings and communication.

It is important to be aware of and effectively manage prerequisites that affect effective communication. Differences in culture, legal requirements, procedures, and languages all affect the communication, and thus the quality of services delivered. This is especially important in projects that involves multiple states, countries, languages, or cultures. Therefore, it is important that all these differences are clearly understood so that they can be effectively managed.

The culture of routinely reporting findings, human errors, accidents, and incidents is an important part of the nuclear safety culture (see Section 7.3). It is therefore important for the operational organization to ensure that the contractor follows the policies and procedures in place at the facility. This expectation along with the required training to support a healthy nuclear safety culture will be clearly communicated to supplemental personnel.

9. PERFORMANCE INDICATORS AND THEIR USE

Once all ingredients are set for delivering effective maintenance, it is current practice to monitor and effectively drive performance using representative KPIs. This section presents good practices in selecting and using KPIs in maintenance organizations. Examples of critical KPIs to be considered at NPPs are given.

9.1. PRINCIPLES OF PERFORMANCE EVALUATION WITH KEY PERFORMANCE INDICATORS

Staying on top in maintenance organizations requires maintenance managers to carry out periodic effective performance evaluation and, over a longer time, performance trends to act upon any departure from the objectives. From experience applying to industrial facilities and infrastructure, KPIs are essential ingredients for effective performance evaluations. KPIs are used throughout the shop floor up to the senior leadership team to:

- Materialize and disseminate the objectives;
- Enable timely measurement of the performance;

- Support accurate assessment of the gaps to the desired performance;
- Trigger a response when gaps in performance are identified or persist;
- Monitoring the effectiveness of implemented optimization strategies if it does not show the expected benefits (see also chapters 3.1 and 3.2 of Ref. [2]).

When selecting (and using) KPIs, the most significant challenge managers are faced with is to find the balance between (a) the benefits of having KPIs that foster realization / in-depth discussions on what the real performance is and that appropriately question the daily routine of managing the business (out of the comfort zone toward excellent performance), and (b) the efforts on individuals to administer the KPIs.

Principles for selecting the most relevant KPIs are given in Section 9.2, whereas critical KPIs commonly used for evaluating performance of strategies, processes and topical programmes are presented in Section 9.3. These KPIs are tools maintenance managers can use on their journey to excellent performance in maintenance.

It is good practice that performance of maintenance strategies, management processes, maintenance programmes and action plans are monitored through KPIs against objectives that are challenging/ambitious but realistic in an international and national level comparison. Not only the effectiveness is monitored through KPIs, where effectiveness defines "the extent to which planned activities are realized and planned results are achieved" as per standards 9000 of the International Organization for Standardization [68], but also the efficiency – "the relationship between the result achieved and the resources used" [68].

Ideally KPIs are automatically updated from databases, reflect the physical plant asset (e.g. through decomposition in SSC), made available to all maintenance personnel and periodically and systematically analysed. Displayed information (e.g. in dashboards preferably showing graphs, periodic reports) illustrates the recognition of performance trends at the plant versus industry progress. Quantitative indicators are typically calculated over 3 to 36 months, to support the analysis of performance trends.

Clear rules for data collection intervals, aggregation, analysis, and trending are defined for each KPI, e.g. through KPI definition documents. A good practice is to regularly consider updating the basis and calculation methods for KPIs, while avoiding frequent changes that disrupt data history.

Further discussion of what to achieve through the use of KPIs in Maintenance is provided in chapter 5 of Ref. [69], and chapters 3 and 6 of Ref. [70].

9.2. PRINCIPLES FOR SELECTING KEY PERFORMANCE INDICATORS

It is important to select maintenance KPIs that cover all processes that support the maintenance policies, strategies, and programmes, and, therefore, capture:

- The overall performance of the maintenance strategies and programmes in achieving high plant and component availability (e.g. short outages for maintenance or refuelling);
- The performance in delivering the maintenance tasks that implement the programmes (e.g. event-free preparation and execution of work);

- The performance in delivering the process steps specified in the core processes, supporting processes, and management processes related to maintenance (e.g. work management, documentation, corrective action programmes, event investigation);
- The overall contribution of maintenance organizations to the wider operational excellence at an NPP, in areas such as fire safety, industrial safety, plant security, radiation protection, training, chemistry, and emergency preparedness.

The selected indicators are scrubbed from consequences of errors, events, issues from other functions than Maintenance, and they rely on high quality data. If plant wide KPIs are used, the specific responsibilities of the Maintenance function (as a whole) and the effects of maintenance strategies can be clearly isolated.

It is worth considering using combined KPIs, where lower tier indicators or heterogenous performance indicators are weighted and combined. This enables the production of streamlined dashboards that can be used by senior managers and corporate functions when exercising their oversight.

There are two types of indicators: lagging indicators – looking back at whether the intended performance was delivered – and leading indicators – looking forward at future outcomes and events, both connected and adapted to manage performance improvement, whereas leading indicators, when practicable, are preferred.

Guidance in developing and using KPIs are provided in numerous IAEA and non-IAEA documents – see Appendix A.1 for short literature review, dating back to paragraph 366 of IAEA quality assurance code and safety guide 50-C/SG-Q [71] (1996). The experts that developed this TECDOC identified the 10 most critical KPIs for maintenance organizations (see Section 9.3), whereas Appendices A.2 to A.6 further list KPIs of interest.

9.3. CRITICAL KEY PERFORMANCE INDICATORS

Based on their experience, the experts that developed this TECDOC identified the 10 most critical KPIs for a maintenance organization as follows:

- Regarding the overall performance of the maintenance strategies and programmes in achieving high plant and component availability: Duration of maintenance and refuelling outages;
- Regarding performance in delivering the maintenance tasks that implement the programmes:
  - Number of maintenance-related events, not considering FME and human performance;
  - Extension of work under LCO, in hours;
  - Number of rework[42];
  - Number of FME-related events and issues;
  - Number of active leaks[43];
  - Number of events, non-conformances and issues (combined) related to the use of human performance tools incl. requirements for PU&A;

[42] see example of composite indicator in INPO guideline Ref. [72]
[43] see an example of a composite indicator in EPRI report Ref. [21].

— Regarding performance in delivering the process steps specified in the core processes, supporting processes, and management processes related to maintenance:
  - Work management: schedule adherence, stability of on-line and outage schedules;
  - Corrective maintenance backlog for critical and safety-related SSCs;
— Regarding the contribution of maintenance organizations to the wider operational excellence at an NPP: Industrial safety accident and incident rate, including the number of near misses if a combined indicator is adopted.

Definitions and general levers to improve performance captured by these KPIs are presented in Appendix, sections A.2 to A.5.

10. BENCHMARKING

The nuclear industry has a unique culture of mutual learning. Benchmarking is generally a win-win deal for both the visiting and visited organizations and is complementary to participations of staff in conference and workshops hosted by international organizations. The primary purposes for benchmarking are to find solutions for addressing gaps in performance detected at the plant, while leveraging experiences from other owner-operator organizations and industries, and to identify new ways of improving operating performance. Benchmarks are carried out against best practice/industry standards, exemplary behaviours, and highly effective processes in both quantitative and qualitative ways.

The main benefit of benchmarking in maintenance for the visiting organizations is to identify and to develop improvement action plans by comparing against the industry highest maintenance standards and practices. The sharing of best practice and lessons learned from effective recovery plans after a decline in performance is especially important to maintenance organizations as the drive to lower costs while maximizing safety and reliability is strong.

The typical process steps of benchmarking other organizations are as follows:

— Select areas to benchmark based on performance reviews, recommendations from external organizations (e.g. WANO, IAEA OSART, etc.), LiF observations, or by considering international benchmark tools such as the WANO performance indicators;
— Identify the organizations (e.g. companies, corporate, NPPs, institutes) that achieve the desired level of performance – WANO and owners' groups can help for identifying such organizations;
— Collect and analyse data from these organizations (such as objectives and average actual performance), comparing internal processes and considering national regulations of the organizations being benchmarked. A good practice is to visit the NPP and collect the data at the source. The team that visits the site must include experts in the field so they can rapidly identify the best practices seen on the spot, and decision makers that support the implementation at the plant. The team collects facts, not impressions or projections;
— Identify and validate the most valuable gaps or lessons learned[44]. A good practice is to formalise each identified good practice in the form of a report/sheet shared throughout the organization (especially in large fleet);

[44] The visited organizations may consider sharing their learnings from the visit with the visiting organizations, to foster mutual learning.

- Select areas of interest and perform in-depth assessment of the gaps or lessons learned in the selected areas;
- Develop a sustainable action plan for implementing the improvements for the identified/selected benchmarking parameter and deliver the action plan under the CAP.

It is important for managers, technical leaders and workers who participate in benchmark studies to understand what good performance or excellence looks like and what ambitious but achievable objectives can then be set to their organization on short- to long-terms.

Benchmark visits help to see what practice, culture and behaviours are key to success, while desk-top benchmark studies help to figure out what procedures, processes and organizational setup can be implemented to support the desired improvement of performance.

Typical areas and parameters that are considered for benchmarking maintenance include:

- Preparation and conduct of major SSC refurbishment work, such as replacement of steam-generators, in-service inspection of reactor pressure vessels and steam generator tubes, overhaul of emergency diesel generators, rewinding of stator, building tightness test;
- Execution of complex work, such as disassembly or reassembly of complex SSC (high-pressure pumps, main steam valves, high-power motors, etc.), lifting of heavy items, complex welding, and the roles and responsibilities of managers, technical leaders and supervisors when such work is carried out;
- Development and implementation of strategies to streamline maintenance and to support transition to long-term operation;
- Preparation and execution of emergent and high priority work;
- Training sessions on mock-ups;
- Programmes such as FME, leak management, human performance in the maintenance organizations;
- Recovery plans after a significative decline in performance at an organization that now achieve good performance or remarkable performance.

The KPIs that can be benchmarked are as follows:

- Number of rework;
- Number of maintenance-related events – significant safety event reported to the national regulator or ranked on the IAEA scale, breaches of technical specifications, extension of LCO, failed post-maintenance tests, failed periodic tests, low-level events by category of deficiency (e.g. FME-related, human performance-related, etc.);
- Outage duration and extension;
- Maintenance backlog;
- Schedule adherence to work plan established 6 to 12 weeks before and outage work schedule established 6–9 months before;
- Number of active leaks.

Examples of KPIs that can be compared to understand the context and the performance in the conduct of maintenance of the benchmarked organizations include:

- Total staff (or hours per 100 MW rated capacity as defined in chapter 4.5.9 of Ref. [70]) and ratio of managers to preparation engineers and workers;
- Hours and percentage of outsourced activities, for safety related and non-safety related SSC, alongside the approach and resources for oversight and supervision;
- Number of work orders, on-line and off-line (outage) and number of equipment (safety-related and non-safety-related, critical, non-critical and run-to-maintenance);
- Number of leader-in-the-field observations and findings, positive and negative;
- Average training hours for key positions;
- Expected time to complete priority actions from the CAP and average age of the backlog.

EPRI report Ref. [70] presents a series of benchmark values in its table A-2 such as total number of work orders served a year, wrench time (percentage), annual number of work orders attributable to rework, annual direct maintenance cost.

11. MOST SIGNIFICANT GOOD PRACTICES

The good practices set out in this section are derived from industry lessons learned, operating experience, and considerations presented in Sections 2 to 10. The good practices are presented in the same order as the sections of this Publication.

Regarding the conduct of maintenance (details in Section 2), good practice for managers is as follows:

- To establish a well-defined conduct of maintenance policy based on industry good practices, which is communicated and reinforced to all personnel, including contractors;
- As maintenance is delivered in the field, for maintenance managers, supervisors, and technical leaders to spend significant quality time in the field to observe, provide positive feedback, coach/correct maintenance personnel, detect organizational weakness and identify opportunities for improvement;
- To fill managers and leader’s positions with well qualified individuals based on a combination of their technical, managerial, and personal attributes. Critical technical attributes are competence and knowledge in maintenance techniques/practices, maintenance management, contractor supervision, risk and work assessment;
- To recognize the importance of first line/contractor supervisor and for senior management to ensure qualified individuals are developed, groomed, and mentored to hold these roles as a part of succession planning.

Regarding the development of maintenance strategies (details in Section 3), good practice is as follows:

- To periodically assess and revise maintenance strategies, considering technological and organizational improvements, operating experience, life cycle management (ageing), and approaches to long-term operation;

- To foster knowledge and understanding across the maintenance organizations of maintenance management principles and specific maintenance requirements for SSCs critical to safety, when selecting/updating the maintenance strategies at an NPP;
- To ensure availability of OEM parts and services by establishing long term agreements at the construction/commissioning phase of an NPP or when planning for major refurbishments/upgrades of NPP.

Regarding maintenance planning (details in Section 4), good practice is as follows:

- To have dedicated, highly qualified, and experienced resources with well-defined roles and responsibilities for the mid- and long-term planning and scheduling to ensure availability of needed resources (materials, spare parts, services);
- To carry out walkdowns prior to work;
- To regard the schedule as the sacred vehicle that drives all departments to deliver the work on time and on quality;
- To periodically share the long-term maintenance work plan through the organization.

Regarding documentation (details in Section 5), good practice is as follows:

- To develop and implement a policy/programme for PU&A;
- To collect feedback from users and to regularly review, update, verify, and validate procedures/instructions by qualified and experienced maintenance personnel to ensure continuous improvement.

Regarding control of activities (details in Section 6), good practice is as follows:

- To ensure that the workers who will execute the job perform high quality preparation;
- To make sure that maintenance reports and completion remarks (including for work performed by contractors) contains sufficient information and details that accurately reflect equipment as-found/as-left conditions and work performed;
- To keep long lead items, SPV, and critical components/spare parts always above minimal stock levels, considering lead time and potential obsolescence.

Regarding performance of work by personnel and the management of skills (details in Section 7), good practice is as follows:

- To pay utmost attention to qualification and thus to training of personnel;
- To utilize work simulators and mock-ups as an integral part of initial qualification training, re-qualification, or just-in-time training, prior to a significant/complicated work activity being carried out in operation (online) or in outage;
- To start with the philosophy that errors are preventable while understanding that errors can occur and a foreseeable part of maintenance activities;
- To establish and implement an effective error management that considers factors at the organizational level down to local and personal levels;
- To develop and implement a comprehensive human performance programme that applies equally to all personnel that access and work at the NPP, focusing on effective tools, such as PJB and PJD – the latest to learn and the first to prevent;

- To foster a safety culture which encourages open and honest communication, including routinely reporting findings, human errors, near misses.

Regarding how to manage outsourcing of maintenance activities (details in Section 8), good practice is as follows:

- To maintain a strong in-house capability to perform deep/accurate assessment of qualification and knowledge of contractors;
- To prioritize the development of plant and contractor supervisors with ability to detect gaps;
- To make sure supplemental personnel perform and behave as 'good' as plant staff do and to include them in the routine communication;
- To maintain the right balance between in-house and external capabilities, considering maintaining in-house capability to minimize overreliance on outsourcing versus opportunities to diversify suppliers or manufacturers and acquisition of knowledge from external partners.

Regarding the use of KPIs to drive performance (details in Section 9), good practice is as follows:

- To select KPIs that foster realization/in-depth discussions on what the real performance is and that appropriately question the daily routine of managing the business (out of the comfort zone toward excellent performance), while considering the efforts on individuals to administer the KPIs;
- To consider using 'critical' KPIs such as number of safety-related events and unavailability of systems/plant due to maintenance issues, rework, number of industrial safety events, and number of active leaks;
- To use KPIs from international organizations (e.g. WANO, IAEA, European standardization organization, etc.) to allow accurate comparison of gaps and strengths against industry best performance and to form a basis for benchmarking and peer reviews.

Regarding benchmarking (details in Section 10), good practice is as follows:

- To identify and develop plans and areas for improvements against the highest maintenance standards and practices in the industry;
- To embed experts and decision makers in the team carrying benchmarking;
- To foster participation of maintenance personnel – plant staff and supplemental personnel – in international industry meetings, working groups, forums, and conferences (WANO, IAEA, etc.) to exchange and share experience, ideas, and good practices.

APPENDIX. KEY PERFORMANCE INDICATORS FOR MAINTENANCE

This appendix presents a short literature review of documents that provide guidance and good practices in selecting KPIs for maintenance, and lists KPIs and other performance indicators of interest for monitoring the performance in maintenance.

A.1 LITERATURE REVIEW OF DOCUMENTS PROVIDING GUIDANCE AND GOOD PRACTICES IN SELECTING KEY PERFORMANCE INDICATORS FOR MAINTENANCE

Examples of other documents that further provide guidance and good practices in selecting KPIs for monitoring performance in maintenance include:

- Publicly available EPRI report Ref. [70] (2003);
- European Joint Research Centre report Ref. [73] (2008) that provides a solid base of 53 indicators recommended by a panel of European NPP owner-operator organizations;
- The European standard EN 15341 [69] (2019);
- The WANO guideline for the WANO enhanced performance monitoring, Ref. [74] and its appendix II.5;
- Chapter 2 of INPO Guideline Ref. [50];
- IAEA TECDOC-1490 [75] (2006) and chapter 3.2.3 of Ref. [5] dedicated to indicators for managing performance of planned outages;
- Chapter 3.2 of IAEA TECDOC-1383 [51] superseded by IAEA Nuclear Energy Series technical report NP-T-3.8 [2] (2018) on the optimization of maintenance programmes;
- Chapter 4.2.4. of IAEA Safety Reports Series No. 106 [16] (2022) specific to KPIs to monitor performance for long-term operation and ageing management;
- Paragraph 5.20 of IAEA Specific Safety Guide No. SSG-74 (2022) on maintenance, testing, surveillance and inspection of NPPs.

A.2 KEY PERFORMANCE INDICATORS RELATED TO THE PERFORMANCE OF THE MAINTENANCE STRATEGIES AND PROGRAMMES

KPIs that may be used are presented in Table 1. These KPIs enable appropriate evaluation of the overall performance of the maintenance strategies and programmes in achieving high plant and component availability. These KPIs are typically owned and managed by engineering functions under the umbrella of an equipment reliability programme or an outage optimization programme, whereas the effects of errors in preparing and executing maintenance are covered by KPIs presented in the next section of this appendix.

Ultimately, while developing the approach to KPIs for that topic, it is worth considering the qualitative and conceptual indicator that captures the effectiveness of maintenance in restoring the intended performance as follows:

- Effectiveness of 0%: minor maintenance, such as repair, where it is assumed the performance of the SCC after maintenance is as ‘bad-as-old’;
- Effectiveness of 100%: extensive maintenance, such as extensive preventive maintenance or replacement by new, where it is assumed the performance of the SCC after maintenance is as ‘good-as-new’.

This concept is used in renewal models to measure the effectiveness of preventive maintenance (see chapters 3.1.3 and 3.1.4 of Ref. [32]), with intermediate states – low, medium, high effectiveness – between the extreme of ‘bad-as-old’ and ‘good-as-new’ being used. While selecting maintenance strategies, this concept can also be used to verbalize what performance the maintenance strategy is meant to achieve.

Useful questioning of the plant performance and journey to excellence that KPIs help to depict are available in chapter 3.2 of Ref. [51].

TABLE 1. TYPICAL KPI RELATED TO THE PERFORMANCE OF THE MAINTENANCE STRATEGIES AND PROGRAMMES

Indicators	Levers to improve performance
Planned duration of refuelling and maintenance outages, compared with a benchmark of NPPs with a similar design [2] Critical KPI for maintenance. Lagging indicator.	The maintenance organization better prevents degradation of SSC, so that lengthy refurbishments and repair in outage are not required over the lifetime. Event-free on-line maintenance is maximized and the transfer of backlog work to the outage is better controlled and minimized. Modifications and improvement projects better mitigate the impact of the design to the outage duration. Resources for the outages are more efficiently deployed to deliver the planned work in the shortest time. Further guidance is given in Ref. [5]. A good practice is to incentivize staff and managers to raise suggestions for improvement, for example through the LiF programme.
Planned unavailability of systems and components critical to nuclear safety[45] and to production [2], and planned production losses [2] that could have been reduced by more effective maintenance strategies. Lagging indicators.	High performance (high availability) can be achieved through strategies where: — Maintenance is further optimized thank to approaches set out in Section 3.3; — Planned unavailability and production losses are addressed under a maintenance optimization programme [2].
Number of events[46] and number of repeat/corrective maintenance tasks ([16], 1.2.1 in [73]) that could have been prevented by more effective maintenance strategies or more reliable spare parts. Mean time between failure (MTBF) ([2], 1.2.3 in [73]). All lagging indicators.	High performance can be achieved through an effective maintenance optimization programme [2]. Good performance is to find the root causes of each event so that there is no repeat. Maximal attention and utmost scrutiny of possible causes, incl. consideration of potential wear-out and ageing effects, is required. Apparent cause investigations are often considered to be not good enough – systematic root cause analysis is seen as good practice. Excellence is when there is no event, no failure, no unnecessary maintenance tasks.

A.3 KEY PERFORMANCE INDICATORS RELATED TO EVENT-FREE DELIVERY OF MAINTENANCE TASKS

KPIs that may be used are presented in Table 2. These KPIs enable appropriate evaluation of the overall performance in delivering high quality and event-free maintenance that implements the programmes. All KPIs in Table 2 are related to issues in the preparation and execution of

[45] For nuclear safety-related SSCs, also termed planned limiting conditions of operation (LCOs). Similar to the safety system performance indicators from WANO or the concept of downtime (indicators 1.1.1 to 1.1.5) in table 3.2 of Ref. [73], but only when affected by a lack or absence of effective maintenance.

[46] Examples of events include safety events including reactor trips (Ref. [71], indicator 1.1.2 in Ref. [73]), breach of technical specifications’ requirement, exceedance of LCO [75] and low-level events, unplanned unavailability of SSCs critical to nuclear safety and production, unplanned production losses [2], post-maintenance tests not passed, periodic tests not passed, inspection criteria not met (indicator 2.2.4 in Ref. [73]), control room deficiencies (i.e. degradation of the performance of an indication, switch or controller), active leaks.

maintenance tasks, such as poor or incorrect work documents, poor or incorrect practice, human error, lack of supervision and lack of skills.

TABLE 2. TYPICAL KPI RELATED TO THE DELIVERY OF MAINTENANCE TASKS

Indicators	Levers to improve performance
Number of maintenance-related events[47]. Critical KPI for maintenance. Lagging indicator.	Actions are recommended in Ref. [5]. A good practice is to identify and protect tasks on the critical path and on sub-critical paths, while deploying outage control centres, extra resources, and oversight of those activities, and carrying out more thorough preparation.
Rework[48] [2] for example consecutive of malfunction, jam, leak. Critical KPI for maintenance. Lagging indicator.	Maintenance fundamentals are better reinforced, supported by better training. The approach to error is a focal point of the maintenance managers' strategic agenda.
Extension of work under LCOs[49]. Critical KPI for maintenance. Lagging indicator.	The delivery of work under LCOs is monitored and managed to ensure that personnel are ready to and will perform tasks in a manner that limits the amount of time critical and safety-related equipment is out of service.
Number of FME-related safety events, internal low-level events and non-conformances detected at in-the-field inspections. Critical KPI for maintenance. Lagging indicator.	Actions recommended are presented in chapter 3.4.3 of IAEA documents references [5] and [17], WANO documents references [19] and [20] and EPRI Ref. [18].
Number of active leaks for critical and safety-related components, non-related to design issues. Critical KPI for maintenance. Lagging indicator.	Actions recommended are presented in Ref. [21].

Other performance indicators of interest as they are leading indicators are as follows:

- Issues and non-conformances related to the use of human performance tools incl. requirements for PU&A;
- Negative findings vs total number of findings, negative and positive, detected through the LiF programme;
- Number of improvements identified during PJD.

A.4 KEY PERFORMANCE INDICATORS RELATED TO THE PERFORMANCE AND COST EFFECTIVENESS IN DELIVERING THE SUPPORTING AND MANAGEMENT PROCESSES RELATED TO MAINTENANCE

The first and most useful set of indicators that can be used is presented in Table 3. They are typical of KPIs used to manage the work management process. The first two KPIs in Table 3

[47] Examples of events include those in Footnote 46 in Section A.2 and extension of refuelling outages due to issues in maintenance. These events include 'maintenance consequential errors' defined by WANO as the sum of all significant and noteworthy events reported to WANO and caused by plant staff or contractor maintenance (supplemental) personnel during a 12-month rolling period.

[48] Any repeat maintenance task when work was not delivered right first time. The period to be considered is ideally up to 2–3 years after work was originally carried out. This indicator is typically the average of monthly weighted rework issues classified by event level for a period of time, normalized by the number of units, for plant staff and supplemental personnel. See Footnote 42 in Section 9.3 for further guidance.

[49] This KPI monitors the deviation in time (usually exceedance) against the scheduled duration (in hours) of the work under LCO. Some owner-operator organizations also trend and compare the ratio between the scheduled/optimized time to complete work under LCOs and the max allowed LCO time, against the ratio between actual time to complete work under LCOs and the max allowed LCO. See also appendix V of Ref. [27] for another example of KPI related to LCO execution.

are generally as in the WANO approach (see next section). Note that KPIs related to cost effectiveness in delivering maintenance are not developed in Table 3 as they are addressed in Ref. [70] (for example, on wrench time: see chapter 4.5.1).

TABLE 3. TYPICAL KPI RELATED TO THE PERFORMANCE AND COST EFFECTIVENESS IN DELIVERING THE PROCESS STEPS

Indicators	Levers to improve performance
Number of delayed preventive maintenance (PM) tasks for critical and safety related SSCs. Critical KPI for maintenance organizations. Lagging indicator.	The cooperation between the maintenance organizations, the work management organizations and the engineering functions is strengthened so that most critical PM tasks are identified (months in advance) and adequately prioritized by the maintenance organizations.
Corrective maintenance backlog ([2], [4], [16], [71], appendix V of [27]) for critical and safety-related SSCs. Critical KPI for maintenance organizations. Lagging indicator.	See generic levers presented in chapters 4 and 5 of Ref. [27] to increase the performance in work management.
Compliance to the gate process in planning and preparing outage work. Lagging indicator.	Levers as presented in chapter 3.3 of Ref. [5], specifically its chapter 3.3.7 and annexes V-3/VI-3 on readiness, including definition/update of reference time for delivering outage work with personnel that executed or will execute work.

Regarding other processes supported by Maintenance, typical KPIs are:

- Documentation: number of maintenance procedures that passed the due date for an update;
- CAP: number of high priority actions overdue;
- Event investigation: number of event investigation reports overdue.

In organizations where dates are assessed to be appropriately managed and due dates extended as needed, the concept of ‘overdue’ is generally replaced by ‘average age’ of completing document updates/ event investigations and of high priority actions.

Note that other performance indicators for outages are suggested in Ref. [75].

A.5 KEY PERFORMANCE INDICATORS RELATED TO THE CONTRIBUTION OF MAINTENANCE TO THE OVERALL PLANT PERFORMANCE

KPIs that may be used are presented in Table 4.

TABLE 4. TYPICAL KPI RELATED TO CONTRIBUTION OF MAINTENANCE TO THE OVERALL PLANT PERFORMANCE

Indicators	Levers to improve performance
Total industrial safety accident and incident rate [51], [71]. Critical KPI for maintenance organizations. Lagging indicator. Near misses. Leading indicator.	More training and coaching, as poor performance is indicative of poor application of maintenance fundamental, low qualification and experience. Follow the recommendations identified in WANO document Ref. [48] and guidance given in the comprehensive IAEA report Ref. [76], especially its Section 8.
Collective dose, on-line and outage, compared with a benchmark of NPPs with similar design, materials and age [4], [51], [71]	Better dose planning, work arrangements that consider optimization of doses, better control and work procedures, personnel training in the area of radiation protection. Note that a higher-than-average outage dose is an indirect indication that there are still too many tasks carried out whereas benchmarked plants were able to reduce the programme thanks to optimization or that too many people are required to carry out the same work compared with benchmarked plants.
Quantity of generated waste [51]	Radioactive waste is to be considered, specifically the solid waste such as protective clothing, gloves, rags, etc. generated during the maintenance activity.

Other performance indicators of interest are as follows:

— Fire safety:
  - Lagging indicators: number of fire safety-relevant leaks of flammable liquids, fire safety-related events such as fire zone compartmentalization breaches or non-conformances against requirements for hot work, number of overdue maintenance tasks on fire safety doors, fire safety-related systems, etc.;
  - Leading indicators: number of fire watches in progress or required on a periodic basis, fire impairments sub-divided by duration (short-term, mid-term, etc.)

— Training: number of staff not having completed the mandatory training or refresher;

— Emergency preparedness: number of overdue maintenance tasks on emergency preparedness relevant SSCs.

A.6 KEY PERFORMANCE INDICATORS USED BY WANO FOR THEIR ENHANCED PERFORMANCE MONITORING

WANO developed an enhanced performance monitoring process that uses a set of performance indicators as part of their action for excellence initiative to detect adverse trends and provide assistance for effective plant improvement to NPPs [74]. The six performance indicators used for forming the maintenance composite performance indicator are given in Table 5.

Data that are based on operating experience are retrieved directly from the WANO operating experience database.

TABLE 5. COMPOSITION OF THE WANO COMPOSITE PERFORMANCE INDICATOR FOR MAINTENANCE USED IN THE ENHANCED PERFORMANCE MONITORING PROCESS

Code	Indicator	Weight in the composite indicator
MA-1	Maintenance-related events	50%
MA-2	Rework	10%
MA-3	Critical preventive maintenance tasks in their second-half of the grace period	10%
MA-4	Deferred critical preventive maintenance tasks	10%
MA-5	On-line critical component defect backlog	10%
MA-6	Outage critical component defect backlog	10%

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ABBREVIATIONS

CAP	corrective action programme
EPRI	Electric Power Research Institute
FME	foreign material exclusion
INPO	Institute of Nuclear Power Operations
KPI	key performance indicator
LCO	limiting conditions of operation, see Footnote 21
LiF	leader-in-the-field (programme), Ref. [21]
NPP	nuclear power plant
OEM	original equipment manufacturer
OSART	operational safety review team
PJB	pre-job brief
PJD	post-job debrief
PM	preventive maintenance
PU&A	procedure use & adherence
RCM	reliability centred maintenance, references [3] and [43]
SPV	single point vulnerability, WANO guideline Ref. [39]
SSC	structures, systems and components, Ref. [3]
WANO	World Association of Nuclear Operators

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