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# Maintenance Optimization Programme for Nuclear Power Plants

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# MAINTENANCE OPTIMIZATION PROGRAMME FOR NUCLEAR POWER PLANTS

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# MAINTENANCE OPTIMIZATION PROGRAMME FOR NUCLEAR POWER PLANTS

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# FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Changes in the electricity industry brought about by market liberalization, privatization and deregulation have given rise to a highly competitive market environment. To ensure nuclear power plants are well managed and operated economically, nuclear operators should continually strive to optimize maintenance, operations and fuel costs. The primary purpose of nuclear power plant maintenance is to ensure the availability of structures, systems and components necessary for safe and reliable power production. Thus, an optimum maintenance programme is essential for the overall performance and competitiveness of nuclear power plants.

This publication describes the latest nuclear power plant maintenance optimization programmes, including key requirements, and provides strategies for their successful implementation. In the development of this publication, Member States shared proven maintenance optimization methods and techniques. These are included throughout the publication, with more detailed examples on the CD-ROM accompanying this publication, which updates IAEA-TECDOC-1383, Guidance for Optimizing Nuclear Power Plant Maintenance Programmes. It restructures best practices in light of new operating experience and new trends, reflects current practices, new concepts and technical developments, and will serve as an excellent starting point for nuclear power plant operators who wish to benchmark maintenance optimization against their current processes and practices.

The IAEA wishes to thank all participants and their Member States for their valuable contributions. The IAEA officer responsible for this publication was J. Mandula of the Division of Nuclear Power.

EDITORIAL NOTE

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# 1. INTRODUCTION

## 1.1. BACKGROUND

The maintenance programme includes all preventive and corrective measures to maintain design functions of structures, systems and components (SSCs) at an acceptable level. Maintenance activities include service, overhaul, repair and replacement of parts, and can also include testing, calibration and in-service inspection.

Maintenance optimization helps to ensure that the right tasks are being performed on the right equipment at the right time. A systematic and continuous approach in establishing which maintenance tasks and at what frequency are to be performed on which SSCs help to optimize the use of resources, increase equipment reliability and minimize risks to workers and to the environment. This can be used to establish a preventive maintenance programme and condition based maintenance (CBM) programme. The process seeks to make the best use of CBM to avoid unnecessarily costly actions and associated error induced failures. Probabilistic risk assessments can be used to help to identify the important SSCs. Within the maintenance optimization programme, nuclear power plants generally use some form of reliability oriented or risk informed maintenance to meet maintenance targets concerning safety, reliability and cost. This optimization should be a constant concern to the organization, whether driven by a will to reduce maintenance costs, extend the economic life of the plant or optimize the use of limited human resources.

This publication updates an earlier IAEA publication on maintenance programmes (see Ref. [1]). With regard to reliability, practically all plants follow the equipment reliability process described by the Institute of Nuclear Power Operations (INPO) [2]. The optimization strategy covers the following:

— Development of a structured approach to maintenance based on the equipment's significance. When resources are not targeted to critical equipment, the maintenance strategy deals with the remedy instead of the equipment degradation control.
— Increased use of predictive maintenance at the expense of time based preventive maintenance.
— Transition from preventive to corrective maintenance on equipment functionally and economically insignificant.
— Optimization of the preventive maintenance cycles and scope.

Preventive maintenance can help to control equipment degradation. Informed equipment classification can significantly improve equipment reliability and reduce the corrective maintenance cost. When a problem emerges, it is necessary to return to the optimization process and to determine what has been incorrectly pre-set.

The equipment classification performed in the optimization process is also used by many plants for the purposes of corrective maintenance prioritization, such as the prioritization of the spares, selection of equipment, modifications and replacement methods, and human resource allocation. Although various methods can be used to optimize maintenance, they have the following common features:

— Optimum maintenance levels should be determined from the beginning, without waiting to accumulate years of operational experience.
— The programme should be defined on the basis of real operating conditions.
— The programme should cover, as a priority, critical equipment identified by its degree of redundancy and the effects of its possible failure on safety, production and cost.
— The reasons for choosing the type and periodicity of elementary tasks should be documented so that the knowledge can be transferred and the maintenance programme can be challenged based on the experience gained.
— The programme's effectiveness should be checked periodically, so equipment failure data should be available on the methods of detection, causes and the nature of corrective actions.

### 1.2. OBJECTIVE

The objectives of this publication are:

(a) To provide a starting point for nuclear power plant operators to improve plant performance, safety and economic competitiveness through maintenance optimization;
(b) To increase capabilities in optimizing maintenance programmes and to share best practices to improve the overall performance and competitiveness of nuclear power plants;
(c) To specify principles for optimizing preventive maintenance programmes and to explore best practices in the light of recent experiences and the current state of technology;
(d) To provide examples of maintenance optimization activities and to compile operating experiences and lessons learned.

### 1.3. SCOPE

In exploring the various maintenance methods, references are made to publications from the IAEA [3–7], INPO [2, 8] and the Electric Power Research Institute (EPRI) [9–15]. This publication does not cover the related subjects of long term operation (LTO), outage optimization, maintenance cost and maintenance safety culture (see Refs [16–28] for further information on these topics). This publication is intended for use by staff, managers, engineers, operation and maintenance personnel of organizations involved in maintenance optimization programmes, supplier organizations for maintenance services, technical support organizations, and vendors and equipment suppliers.

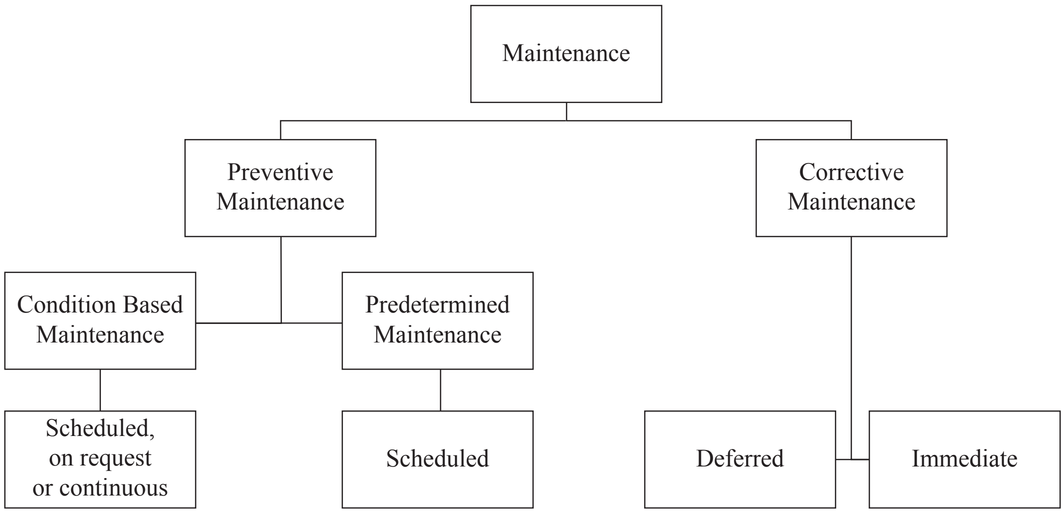
Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

### 1.4. STRUCTURE

Section 2 provides an overview of maintenance processes and definitions of key terms. Section 3 establishes the requirements and objectives of maintenance optimization, and analyses its drivers, barriers and benefits. Section 4 deals with methods for critical component identification and classification and with methods for developing maintenance strategies. Section 5 explores best practices for maintenance optimization and describes the tools and methods for its implementation. Section 6 examines work management and on-line maintenance. Sections 7 and 8 describe the importance of performance and condition monitoring for maintenance effectiveness and the application of the corrective action programme, respectively, and Section 9 concludes. Case studies and lessons learned from the practical implementation of maintenance optimization are presented on the CD-ROM accompanying this publication.

## 2. MAINTENANCE PROCESSES

Maintenance is the organized administrative and technical activity of keeping SSCs in good operating condition. Maintenance activities are divided into preventive and corrective maintenance (see Fig. 1). Maintenance terminology used in this publication is defined in the Glossary and by the British Standards Institution [29]. Preventive maintenance is “carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item” (i.e. SSC functions) [29]. Corrective maintenance is “carried out after fault recognition and intended to put an item [i.e. SSC] into a state in which it can perform a required function” [29].




**Source:** See annex A of Ref. [29].

*FIG. 1. Strategic maintenance activities.*

The aim of maintenance is to keep equipment reliable and functional, and it is essential for long term, safe and economic operation of a nuclear power plant. The main stages are:

(a) To define the strategy and the preventive maintenance programme, then methodically optimize them;
(b) To plan the work schedule carefully and to ensure the necessary skills are maintained;
(c) To ensure feedback based on experience can be efficiently recorded and organized.

## 2.1. MAINTENANCE OPTIMIZATION

Maintenance optimization is driven by the imbalance between maintenance requirements and resources used, and is continually improved by lessons learned (see Fig. 2). The process includes how maintenance techniques are selected to ensure the most appropriate type of maintenance is performed on SSCs and to determine at what periodicity on account of regulatory requirements and maintenance targets concerning safety, reliability, and plant availability and cost. Maintenance techniques can also check the status of components that are not malfunctioning and seek to increase the interval of inspection or redefine the type of maintenance applied to the SSCs.

Maintenance optimization is useful in establishing an effective maintenance programme to achieve plant reliability based on a systematic approach that encompasses safety and a cost effectiveness to operations. In this approach, it is necessary to prioritize the systems to be optimized and to select the correct tool for the optimization process. Consideration should be given to the following key aspects:

— Safety and risk significance to determine the relative importance of SSCs based on probabilistic and deterministic information;
— Regulatory requirements governing intrusive inspections of components;
— Reliability and availability to ensure the plant is available when required;
— Establishment of realistic targets for maintenance;
— Increased necessity to analyse and optimize costs.

### 2.1.1. Requirements, objectives and drivers

Utilities have various corporate goals that translate into plans for efficiencies to ensure the safest, most reliable and most cost effective operations and maintenance. Embedded in utility management models, the plans consider LTO and how to spread maintenance requirements and costs over the lifetime of the plant in the most efficient manner. Requirements vary according to the country and type of utility and, depend on the regulatory environment and equipment design.

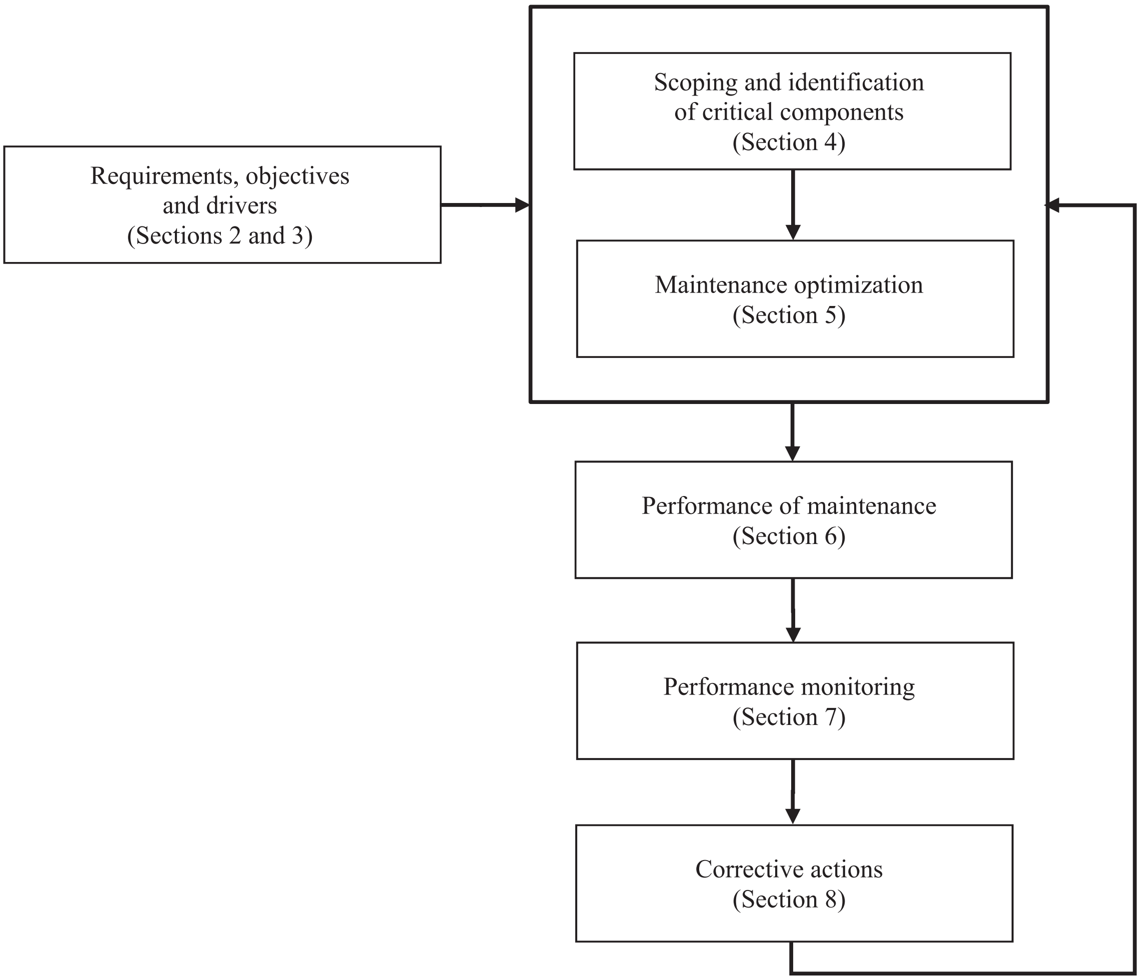



*FIG. 2. Maintenance optimization.*

### 2.1.2. Identification of critical components

Integral to maintenance optimization is the identification of components that affect the safety and reliability of power generation. When developing a preventive maintenance programme, this identification plays a key role in determining which maintenance will be applicable and effective for a given component.

### 2.1.3. Programme optimization

Programme optimization includes development and use of preventive maintenance templates, continual adjustment to preventive maintenance tasks and their periodicity based on plant and industry experience, and documentation of preventive maintenance technical bases. This process is at the heart of maintenance optimization, as it allows a review of maintenance activities to identify applicable and effective tasks for components. The process uses methods such as reliability centred maintenance (RCM), streamlined reliability centred maintenance (SRCM). The use of maintenance templates helps to promote consistency for like items and provides a documented basis for the changes being made.

### 2.1.4. Maintenance and work management

The performance of the maintenance process incorporates the preventive maintenance programme, documentation of ‘as found’ equipment condition, equipment condition feedback and post-maintenance testing. The work management process focuses on performing and reporting routine maintenance tasks. The corrective maintenance is analysed in the evaluation and performance monitoring process.

### 2.1.5. Performance monitoring

Performance monitoring incorporates system (and component) performance monitoring and trending, predictive maintenance trending, operations walk down monitoring, and analyses of testing and inspection results. The data collected and analysed are used to identify systems that are performing poorly. To recover the systems health, the causes are determined and an action plan is created. This is conducted within the process of corrective action and can identify the need for the maintenance optimization to be reviewed.

### 2.1.6. Corrective actions and plant life management

Corrective actions and plant life management incorporate corrective maintenance, cause determination, corrective action and prioritization of equipment problems. This process is largely dealt with in the corrective action programme (CAP), which includes determining the cause of adverse conditions and generating appropriate actions to resolve the problem.

### 2.1.7. Management commitment and support

Management commitment and support are essential to success in all phases of the maintenance optimization programme, including budgetary approval and maintaining an overview of the benefits of successful implementation. Management's clear support demonstrates endorsement of the programme.

### 2.1.8. Roles and responsibilities

The maintenance optimization team will comprise full time staff, with other key staff brought in as and when their particular knowledge is required. The roles and responsibilities of the team should be clearly defined to enable the team to focus on the goals of the maintenance optimization programme and to use the systems based knowledge and skills to focus on specific areas of the programme.

## 2.2. OPTIMIZATION OF THE MAINTENANCE PROGRAMME

Maintenance optimization is vital to asset management. Figure 3 depicts the optimization concept as applied to maintenance programme drivers. The following sections outline the problem screening process, maintenance programme drivers and the optimization process (for more in-depth description and specific examples, see the Loviisa case study on the CD-ROM accompanying this publication).

### 2.2.1. Problem screening process

Causes and contributors are identified during the problem screening process. The depth of the screening process is based on equipment criticality and the severity of the particular failure. The causal factors and conclusions from the evaluation of the findings should be logical and comprehensive.

Root cause analysis (RCA) is typically used as a reactive method of identifying events, causes, revealing problems and solving them, which is conducted after the event has occurred. It is not a single, precisely defined methodology, and there are many different ways to perform it. Effective RCA is conducted systematically, often as part of an investigation, supported by documented evidence. RCA normally requires cooperation between plant organizations.

Investing in a rigorous evaluation to identify the causal factors can be unnecessary for identified problems that are less significant. Here, focus is on correcting the immediate or apparent cause without addressing the root cause. If similar problems occur, trending will assist in identifying any common causes.

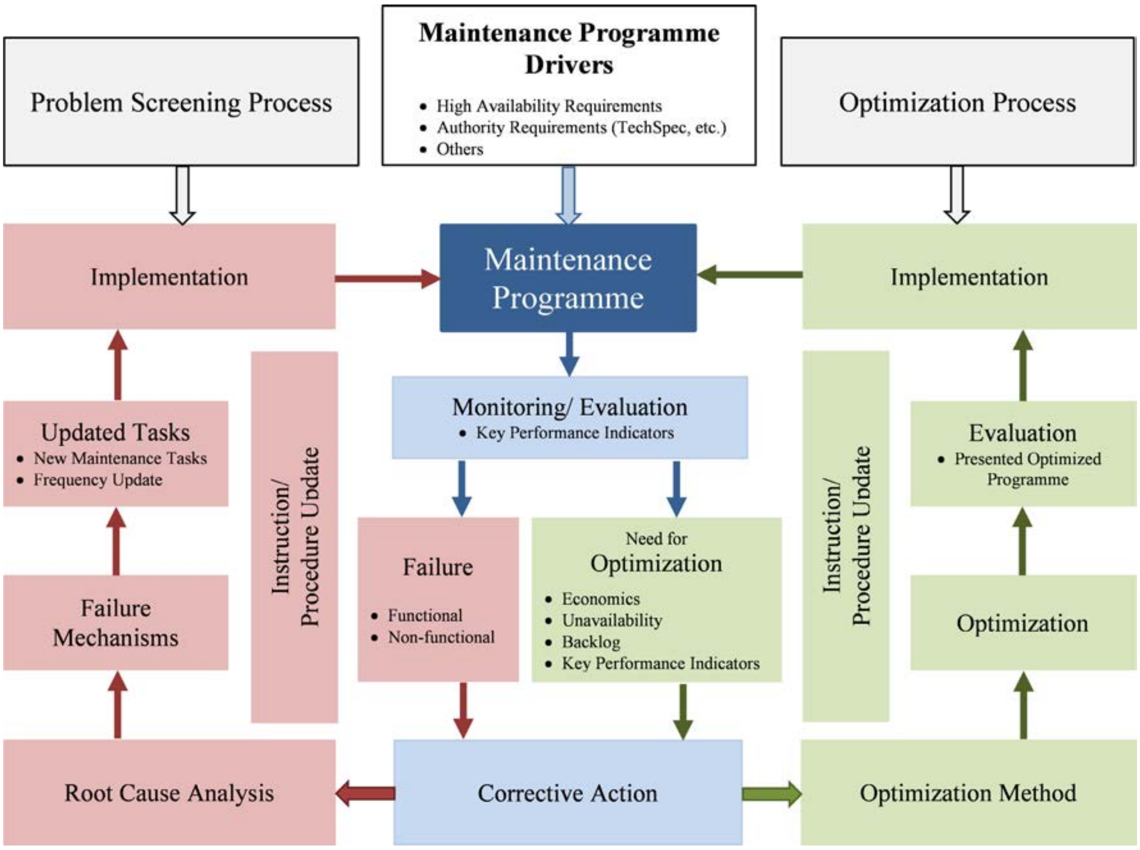



*FIG. 3. Lifecycle of the maintenance programme.*

### 2.2.2. Maintenance programme drivers

The drivers include corporate and plant goals as well as regulatory requirements. The main goal of the programme optimization is to focus the resources on the right areas to ensure plant safety and reliability for the short and long term operation.

### 2.2.3. Optimization process

Optimization tools and methods should be selected and assessed based on equipment criticality and maintenance costs. The most extensive tools, such as RCM analysis, should be applied to the most critical equipment or equipment with the most significant cost. For non-critical components, maintenance history analysis can be used instead of RCM.

Maintenance optimization is a continual process, and based on analysis the maintenance programmes can be changed if necessary. Current and optimized programmes should be compared at regular intervals. The comparison is performed by analysing key performance indicators (KPIs) of the maintenance, which include equipment availability and maintenance costs. Corrective actions should be based on the analysis. Maintenance programmes should be supported with the plant computerized maintenance management system (CMMS) based on the results of optimization and evaluation. Implementation should also include maintenance instructions and procedures, and training of maintenance personnel.

# 3. PREREQUISITES OF MAINTENANCE OPTIMIZATION

## 3.1. DRIVERS AND GOALS

Each plant should tailor maintenance optimization to the realities of its market and regulatory environment as well as its current performance. Plants operating in liberalized electricity markets, called merchant plants, might seek to improve competitiveness and to maximize near term financial returns. Plants in regulated or single utility dominated markets can seek to optimize plant availability for seasonal demand and integration with other generation assets. Some plants will need to account for load following. Plants in a multifleet environment should be optimized for this circumstance — not necessarily delivering a top capacity factor on a plant level but ensuring maximum availability and efficient use of resources across the fleet. All plants will of course seek to maximize safety and to fulfil regulatory requirements.

Maintenance optimization programmes carried out by Member States have many demonstrated benefits, including:

- Improved plant safety through prioritization of critical component systems;
- Improved overall plant availability through a reduction of unplanned energy losses and a shorter outage duration;
- Improved equipment reliability and performance, including better failure prevention, reduction in the number of post-maintenance defects and early detection of ageing mechanisms;
- Reduction in costs from fewer personnel requirements and more efficient use of spare parts and consumables;
- Improved work and outage scheduling;
- Reduction of emergent work;
- Reduction of low level waste generated;
- Reduction of collective dose;
- Improved integration of maintenance with other plant programmes such as asset management planning;
- Improved technology and innovation integration;
- Improved staff performance and maintenance culture;
- Increased staff engagement and motivation;
- Improved management and transfer of skills and knowledge;
- Creation of conditions for an implementation of equipment performance monitoring and condition system;
- Documenting of the plant readiness for LTO.

Taken together, the benefits make maintenance optimization a very attractive proposition to any plant yet to undertake such a programme, especially since it does not require any major component upgrades. Not all benefits will be realized, however, and the results will greatly depend on management goals. For example, reducing maintenance costs is not always necessary or even desirable, since increases in safety and availability might be the objective. Outage duration might not be affected by the optimization, but a reduced frequency of unplanned losses could more than justify the effort.

After establishing the goals of the maintenance optimization programme (see Table 1), the first step is to evaluate the current maintenance programme and then identify those targets which are not currently in alignment. With tens of thousands of SSCs in the maintenance programme and acknowledging the fact that it is not possible to optimize the maintenance strategy for all SSCs, it is necessary to carefully define the SSCs which fall under the maintenance optimization programme. Focusing on these will then provide the best results. The identified SSC criteria should correspond to the overall goals of maintenance optimization.

TABLE 1. TYPICAL GOALS OF THE MAINTENANCE OPTIMIZATION PROGRAMME

| Goal | Criteria/objectives |
|---|---|
| Safety | Prevent safety system challenges through failure prediction<br>Reduce radiation exposure<br>Reduce risk to core damage<br>Reduce risk due to uncontrolled release of coolant<br>Reduce risk due to uncontrolled radiological release |
| Reliability | Improve equipment reliability<br>Prevent failures of critical structures, systems and components<br>Reduce unplanned unavailability and load reductions<br>Minimize risk due to safety and protection system testing<br>Early detection of ageing mechanisms |
| Cost optimization | Optimize overall maintenance costs<br>Improve plant efficiency<br>Optimize outage schedules<br>Optimize spare parts usage<br>Achieve a return on investment for all maintenance techniques employed |
| Availability | Reduce unavailability of equipment due to maintenance activities<br>Reduce unavailability of components due to failure<br>Improve safety system performance indicators<br>Maximize overall plant availability<br>Optimize outage duration |
| Technology enhancement | Use of enhanced maintenance techniques |

## 3.2. KEY PERFORMANCE INDICATORS

Maintenance KPIs are the metric for monitoring maintenance effectiveness and efficiency, and they identify the issues causing maintenance defects. Well defined maintenance KPIs enable the right strategy to be selected in order either to support the actions producing the expected results or to correct these actions if KPI trends indicate downward performance. It is important to select a range of maintenance KPIs that can facilitate an improvement in equipment reliability and maintenance performance and optimization. Maintenance KPIs should represent several levels so that an indicator and its associated performance can be traced from upper to lower levels (e.g. from unit level to supervisor level, or system level to component level). Examples include the following (see Refs [23, 30] for further information):

— Availability and unavailability (planned and unplanned);
— Mean time between failures, mean time to repair and mean waiting time;
— Maintenance and functional failure costs;
— Reworks;
— Maintenance backlog;
— On time delivery.

## 3.3. COMPUTERIZED MAINTENANCE MANAGEMENT SYSTEMS

A key requirement of effective implementation of the maintenance optimization programme is the CMMS, which should fully support the defined and selected maintenance strategies and activities, as well as the range of KPIs. As part of the CMMS, the following functions have important roles in the development and implementation of an effective maintenance programme:

— Site and work management and planning;
— Design and system and component engineering;

— Material supply;
— Operations and maintenance;
— Radiation protection;
— Security, safety and emergency planning;
— Technical inspections and diagnostics.

### 3.3.1. Requirements

All plant equipment should be registered in a master equipment list, and each piece of plant equipment should be assigned to a functional system. The individual records should provide a sufficient level of detail and include the following information:

(a) Equipment:
  — Type and model identification;
  — Category and criticality identification;
  — Service parameters and service cycle;
  — Changing (monitored) parameters;
  — Location and ambient parameters.

(b) Legislative requirements identification:
  — Safety classification;
  — Limiting conditions for operation (LCO).

(c) Preventive maintenance template identification.

(d) Manufacturers' documents identification:
  — Technical specifications;
  — Inspection plans.

Preventive maintenance templates as well as relevant quality related documents provided by manufacturers should be handled as controlled documents. Tools for equipment performance data monitoring and analyses are available and can be incorporated as functions of the CMMS or, alternatively, through analytical systems.

### 3.3.2. Plant asset data

The CMMS should contain the following plant data to ensure the success of the maintenance optimization programme:

— Technical details of locations and assets;
— Spare parts;
— Preventive maintenance programmes;
— Work orders;
— Failure history of components;
— Costs;
— Asset downtime;
— Condition reports;
— Criticality classification.

### 3.3.3. Maintenance programme setting

Within the CMMS, all preventive maintenance tasks should be unambiguously identified by the reasons for their implementation (technical basis), national legislature, regulatory requirements or any other reasons. Furthermore, all preventive maintenance tasks from the templates should be transferred to preventive maintenance predefined parameters pursuant to their defined cycles.

In the case a system or maintenance engineer decides not to perform a preventive maintenance template task, a corresponding preventive maintenance parameter is deactivated within the CMMS and it is obligatory to provide reasons for the decision. The preventive maintenance programme also incorporates documented operation and maintenance personnel tasks, even if not based on work orders.

# 4. SCOPING AND CLASSIFICATION OF STRUCTURES, SYSTEMS AND COMPONENTS

This section describes a process that facilitates the timely completion of critical SSC lists. This process is a simplification of the techniques used in RCM and SRCM. By not performing the more in-depth portions of the evaluation until the critical components and their requisite functions are defined, effort is significantly reduced with little or no impact on the quality of the results. The process described also explores the questions and format of an interview that can be used by the optimization team to schedule the development of the critical SSCs according to need. This can also improve the involvement and response of the system engineers in the process.

Many nuclear power plants in the United States of America have developed their critical component list based on criteria to meet United States Nuclear Regulatory Commission requirement 10 CFR 50.64, Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants [31], known as the maintenance rule. A similar criterion has been developed by INPO [2], and other similar criteria are used at nuclear power plants that are not subject to US regulations or assessment by INPO.

## 4.1. OBJECTIVES FOR SCOPING

An effective strategy can be developed to determine a hierarchy for components requiring maintenance. Developing a strategy for each of these components can overwhelm a maintenance organization and cause it to lose focus on the primary objectives of its mission. An important factor in effective maintenance optimization is the level of classification of the components based on their functional importance to nuclear safety, power generation and economic parameters. Maintenance activities are focused on the most functionally important equipment.

To become more competitive, many plants have reduced staffing levels and have made more informed decisions with regard to maintenance activities. In some Member States, nuclear power plants have to focus their efforts on ensuring important equipment is able to meet its design purpose and, if not, efforts are to be taken to remedy the cause of the low performance. The unique aspect of the maintenance rule is that it allows plants to determine the equipment and to set their own level of acceptable performance. However, there are a few caveats that bound performance goals. These self-imposed criteria and levels of performance should be compared with similar equipment in similar applications across industry. Such comparison brings some checks and balances to the self-imposed performance criteria.

In some Member States, there have also been attempts to lower the prescriptive nature of regulations, and plants have been working to make their activities ‘risk informed’, so that there is a technical basis for making decisions that go beyond the requirements of the traditional technical specifications established when the current plants were designed. These processes rely on a reasoned approach to determine which equipment should be the focus of this attention.

The objective of the maintenance optimization programme can be summarized as the right work on the right equipment at the right time. This describes the goal of performing focused maintenance tasks on critical or significant equipment before it fails but not before some expected degradation has occurred. This philosophy also means that equipment which is not critical or not commercially significant can be allowed to run degraded until maintenance resources are available or until the equipment no longer can perform its intended function, with only minimal maintenance activity occurring prior to the failure. Section 4.2 describes a process that facilitates the creation of a list of equipment that can be used to determine which components are critical and which can be allowed to run until corrective maintenance is required.

## 4.2. DEVELOPING THE LIST OF CRITICAL STRUCTURES, SYSTEMS AND COMPONENTS

The key to having an effective maintenance process that optimizes the use of nuclear power plant resources and provides optimum equipment reliability is the proper classification of equipment and the allocation of resources according to that classification. INPO [2] define the following classifications:

(a) Critical: If a failure of the component, or its structural supports, defeats or degrades an important function or a function that is redundant to an important function, then it is a critical component.
(b) Non-critical: A classification of equipment between critical and run to maintenance for which cost effective preventive maintenance makes sense. On account of the relatively low impact of failure of these components, a limited number of failures should be expected for non-critical components.
(c) Run to maintenance: A run to maintenance component is one for which the risks and consequences of failure are acceptable without any predictive or repetitive maintenance being performed, and for which there is not a simple, cost effective method to extend the useful life of the component. The component should be run until corrective maintenance is required. Since most equipment is maintained before it actually fails, some States used to call it run to failure; however, run to maintenance is now the preferred term.

The task of reviewing the entire master equipment list can seem overwhelming. However, it can be greatly simplified by reducing the list to a manageable size. First, it is necessary to determine which SSCs are significant in terms of safety, capacity factors or cost. Although creating this list is simple, it can be time consuming and challenging to achieve consensus among functions such as operations, engineering and maintenance.

### 4.2.1. Initial preparation

The nuclear power plant should have a list of SSCs that are part of the plant. This list may exist as a licensing document or plant drawings. An effective method to prepare the list of critical SSCs is for managers to schedule an interview with the person responsible for each of the systems on the list. The system engineer can enlist the assistance of the most knowledgeable person in the operations organization and component specialists on each particular system.

The interviewees should be advised that they are going to be questioned on what the functions of the system are, what the system is used for, and how the system can fail. The functions and uses of the system need to go beyond those listed in engineering documents and should include any uses that operations have. Any uses during startup, shutdown and emergencies not included in engineering documentation should be listed at this point, with the help of the operations expert.

Another preparatory item is to decide on the attributes expected for SSCs to be considered critical, for example:

- It is nuclear safety related;
- It is not nuclear safety related but mitigates an accident or transient;
- Failure could prevent nuclear safety related SSCs from fulfilling their functions;
- Failure could trip the plant or reactor, or result in a plant transient;
- It is used in emergency operating procedures.

The information required to apply these criteria should be available to the engineer from sources such as the design basis documents, facility licence descriptions, safety analysis reports, system descriptions, and emergency and operating procedures. The criteria and definitions assigned to each item should be provided to all those involved in the meetings, such as system engineers and operations personnel.

### 4.2.2. System function review

The key to timely completion of the critical system and component list is an efficient collection of the information necessary to decide whether or not the SSCs are critical. Additional information relating to the basis for the decision should also be documented. As a follow-up, it is helpful to collect information on the types of failure that can cause SSCs not to meet their intended functions and to use this information to establish procedures that will prevent or mitigate the occurrence of these failures.

The process can begin with the system engineer brainstorming all of the system functions. This should be a simple list of everything that the system does, regardless of the perceived importance. It is then determined whether it is a significant function. Each listed function should be a single, defined function. If there are multiple flow paths, each should be a function, but separate trains or divisions should be listed as separate functions only if each has a distinctly different function. Actuation signals and other control related functions should be listed separately from the actual controlled function if there is a manual override for the automatic function.

The exercise of listing functions should be free flowing and should include any possible functions from all sources. In the next step, the inconsequential functions drop out. There is the chance that some obscure functions might have a significant impact on safety or commercial considerations. It is helpful to examine the accident recovery or scram recovery flow path to ensure that any references to the use of the system or portions of the system have been listed as functions. If significant accident mitigation guidelines have been implemented at the plant, some system functions might have been used that are not normally considered.

Once the brainstorming has been completed, the list of function duplications are reviewed, as well as complex functions that need to be separated into more than one function. Once the list is complete, a master form is compiled and each function is assigned with a unique alphanumerical designator.

#### 4.2.3. Screening the functions

When the criteria for determining which functions are critical and a list of functions has been established, each function is evaluated on whether it meets the criteria (see Table 2). In the example, the functions are: (A) provide cooling water to the control building air handlers; and (B) provide cooling water to the office building air handlers. The criteria are: (1) mitigates the consequences of an accident; (2) prevents the release of radioactivity after an accident; and (3) could cause a plant trip.

TABLE 2. FUNCTION SCREENING

| Function | Criterion | | | Critical function |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| A | Yes | No | No | Yes |
| B | No | No | No | No |

This screening shows that only A is a critical function under the assumption that the criteria were properly selected and that the functions were properly defined. If, during the screening, the response to the question “Does this function meet this criterion?” is “sometimes”, then the function needs to be separated into two or more functions that allow each to be answered either yes or no. It is important to record the reasons why functions were so screened: yes answers are very often obvious, but no answers might need documenting.

#### 4.2.4. Determining functional failures

After the functions have been screened, a description of what constitutes a functional failure is required. This might seem a trivial task, but many maintenance hours are spent resolving issues that have no bearing on the ability of SSCs to perform their critical functions. For example, if there is a valve in the system with a packing leak, and the procedure necessary to allow maintenance technicians to repack the valve is very time consuming. If the packing leak does not prevent the SSC from providing cooling water flow, the maintenance task should be scheduled as a routine maintenance task. If the packing leak is so bad that the SSC cannot provide cooling water flow, the maintenance task should be scheduled on a priority basis.

Many components can be in more than one state. For example, a valve can be open, closed or throttled. Similarly, a circuit breaker can be open, shut or tripped. Not all of these states are necessarily critical and therefore the failure of the component to achieve this state might not be a failure that affects its critical function. For example, Valve 1 needs to be open to perform the critical function of providing cooling water to a heat exchanger. The normal state of the valve is open, and it is only closed to take the pump out of service. If someone attempted to close the valve but it did not close, the critical function could still be accomplished because cooling water could be provided to the heat exchanger, and hence it would not be a listed failure. On the other hand, if the valve could not be opened, the critical function would be lost. In this example, a failure that would cause a loss of critical function is if Valve 1 fails to open. This definition of failure should be noted where the screening results are documented to make it easier to determine whether or not the SSC has indeed failed.

Once the list has been created, it can be used to develop the maintenance strategy for the specific equipment. This strategy will consist of the preventive maintenance plan, the performance and condition monitoring and predictive maintenance strategy, and the work scheduling strategy.

## 4.3. TIERED APPROACH TO MAINTENANCE

A maintenance tier is a degree or level of maintenance applied to a component based on factors such as the degree of criticality, safety significance and economic significance. The objective of a tiered maintenance approach is to apply maintenance resources to a level commensurate with the component's safety, economic significance and other factors. A tiered maintenance approach is conceptually similar to RCM programmes (see Refs [12, 13]). Although this section suggests one approach to tiered maintenance, there is no single, correct programme. A maintenance programme for one plant can be either inadequate or excessive if applied to other plants. There are other valid techniques or means of applying the tiered maintenance concept. Tiered maintenance programmes will, and should, vary between plants. The number and nature of maintenance tiers, the level of maintenance applied in those tiers, and the criteria for classifying SSCs into tiers will vary based on various plant specific factors.

Each plant should first list all equipment to classify them. The tiered maintenance process comprises the following steps:

(1) Determine the criteria for classifying SSCs;
(2) Determine maintenance tasks and periodicity;
(3) Classify each SSC in the programme.

The criteria for classifying components into separate maintenance tiers should be well defined. A tiered maintenance programme examines each of the following programmatic considerations as a minimum. This is not a comprehensive list and other plant specific considerations need to be taken into account (a detailed example of a tiered approach to maintenance can be found in the Loviisa case study on the CD-ROM accompanying this publication):

— Safety significance;
— Economic significance and reliability;
— Component history;
— Availability of spares;
— Regulatory issues;
— Environment impacts;
— Radiation environments and seismic qualifications;
— Component design and construction;
— Accessibility;
— Repair costs;
— Duty cycle;
— Maintenance philosophy;
— Auxiliary equipment;

— Plant resources;
— Plant outages, modifications and other plant considerations;
— Operational requirements.

# 5. APPROACHES TO MAINTENANCE OPTIMIZATION

## 5.1. DESCRIPTION OF VARIOUS METHODS

Maintenance optimization means finding a good mix of time based, condition based and corrective maintenance tasks and setting the periodicity of these tasks so that the safety and economics are acceptable and in line with company strategy. Of course, maintenance includes mandatory regulatory tasks, the periodicity of which cannot be easily extended. A systematic approach can be adopted if adequate data are available to achieve the goals of the maintenance optimization programme. Even if data are not available, operators can still use non-systematic approaches to improving maintenance programmes, such as maintenance programme adjustment. Indeed, some operators use only non-systematic approaches, since they have few component failure data and want to adjust their maintenance programme without waiting for failures to occur. One non-systematic approach is the analysis of production losses, LCO entries and licensing events. Equipment that has caused the most problems is identified, root causes are analysed and specific solutions are found.

In maintenance optimization programmes, the systematic approach uses the following:

— Reliability centred maintenance, of which there are several variations;
— Ageing mechanisms analysis;
— Risk informed maintenance.

Equipment is first ranked according to importance, based on its functions and the consequences of failure. Importance to safety is established using probabilistic safety analyses. Other equipment is also included in the optimization process on account of the importance of its function for plant availability or its costly repair.

### 5.1.1. Reliability centred maintenance

Originally used in the aircraft industry, RCM focuses on preventing critical failure modes of important equipment. In the nuclear industry, some operators apply it only to important equipment. It is a systematic and documented approach to defining the maintenance programme of a system, and includes the following steps (see Ref. [4] for further information):

— Define system boundaries;
— Identify important system functions;
— Identify component failure modes and their effects;
— Determine the criticality of component failure modes;
— Identify condition based or time based maintenance tasks deemed to be technically effective to prevent critical component failure modes;
— Select economically justified tasks.

The analysis relies on operating experience but is not limited to failure modes that have already occurred. It also aims at identifying all possible failure modes of importance. It can result in recommending design modifications when an effective preventive maintenance task to prevent the failure of an important piece of equipment is not known.

To assess whether a preventive maintenance task is economically justified, a qualitative judgement, or a finer quantitative analysis if necessary data are available, can be used. For instance, the product of cost of failure and the probability of occurrence can be compared to the cost of performing the task itself to determine which is more effective and the most frequent. In any case, economic risks resulting from the choice of an equipment inspection or test should be assessed. If that periodicity is extended, the equipment failure rate will increase to some extent as well as associated costs (repair or replacement and loss of production) but inspection and test costs will be reduced.

#### *5.1.1.1. Equipment reliability process goals*

Equipment reliability process goals are defined in Ref. [2] as follows:

(a) Equipment performs reliably through the operating cycle, and standby safety equipment operates properly on demand.
(b) Critical equipment is identified based on its importance to safety, safe shutdown capability and power generation capability.
(c) Equipment and system performance criteria are established, performance is monitored, adverse trends are identified, and corrective actions are implemented and verified for effectiveness.
(d) Failures and failure causes of concern are identified for critical equipment, and measures are established to prevent them.
(e) The need for in-depth analysis of equipment failure is commensurate with the equipment's importance to plant safety and reliability and the likelihood of recurrence.
(f) Predictive maintenance technologies are implemented to detect equipment degradation well in advance of potential failure and to optimize equipment performance.
(g) Equipment ageing is managed using preventive maintenance techniques and life cycle management, including mitigation of environmental stressors (i.e. temperature, radiation and moisture) or operating stressors (i.e. duty cycles and vibration).
(h) Documented technical bases exist for preventive maintenance activities and ageing management programmes.
(i) Equipment performance data and associated trend information are uniformly collected and are readily accessible to support the prompt identification of problems and root causes.
(j) Minimal in-service failures of critical equipment occur between scheduled maintenance intervals.
(k) Equipment unavailability associated with preventive maintenance activities is balanced by the resulting improved equipment reliability and availability from prevented failures.
(l) Changes to the process are timely and responsive to user feedback.

#### *5.1.1.2. Preventive maintenance basis database templates*

RCM is an optimization method based on equipment reliability (i.e. the probability SSCs will fulfil minimum performance requirements (functionality given by the plant project) when requested). It is a graded approach to equipment reliability and lifetime management based on the equipment pertinence to plant functional systems, and identification of system functions and their failure modes. Equipment items are examined in light of all plant system functions to identify component significance for the system functions. Typically, plant equipment is divided into three or four categories, including critical and non-critical.

For critical and non-critical equipment, preventive maintenance tasks are selected using preventive maintenance basis database templates. Where these templates are not available, plant specific failure modes and effects analysis (FMEA) or consultation of an expert panel is performed to define preventive maintenance tasks. In case sufficient plant failure data are not available, generic failure data are used [14]. Preventive maintenance templates are assigned to equipment based on its operation cycle, service conditions and service cycle. The specified preventive maintenance tasks are then compared with the existing preventive maintenance programme.

#### *5.1.1.3. Streamlined reliability centred maintenance equipment registration*

Using SRCM (the next phase of RCM) techniques for systematic evaluation of SSCs and maintenance processes and requirements helps to reduce operating cost while maintaining plant availability and reliability. The streamlined version reduces the cost for both RCM analysis and development of the preventive maintenance work plan and its registration in the plant's CMMS. SRCM equipment registration includes the application of the SRCM methodology and supporting software to determine which components are to be added to the list of equipment with sufficient history records to provide successful project results and to compile experiences in a less burdensome manner.

### 5.1.2. Ageing mechanisms analysis

This method focuses on identifying ageing mechanisms and explaining how they are detected — adding or removing tasks as a consequence. Some operators whose plants have accumulated many years of operational experience give the upmost importance to understanding equipment ageing mechanisms for their maintenance optimization programmes. Once ageing mechanisms and diagnostic methods have been identified for each component, maintenance programmes are reviewed without the necessity of having available data, contrary to RCM. The method includes the following steps:

— Identify safety significant components which can be affected by ageing degradation;
— Systematic search for ageing mechanisms based on equipment history;
— Identify possible diagnostics methods;
— Review completeness of maintenance programmes to deal with this ageing.

### 5.1.3. Risk informed maintenance

This method, which is applied on selected types of safety related equipment, calculates changes in plant risk, plant availability and cost savings when preventive maintenance intervals are extended and postulated component failure rates increase as a result. The assessment should also take into consideration the operating and failure history of the plant item, the current maintenance regime and the future operating profile required. Using sound engineering judgement, experience and best practice, the identified risks are then compared to the current maintenance and monitoring effort and where there is a clear imbalance, recommendations for a change to the maintenance and monitoring regime are made. A further assessment is then made to determine the impact the proposed change is likely to have on the risk of failure. This is an iterative process, and it is important that changes in the maintenance regime are monitored and risks reassessed on a regular basis.

The risk calculation is the product of the event's likelihood and impact (risk = likelihood x impact).

The method assesses the likelihood of the occurrence of the event leading to the failure of a subsystem or component, and its impact on a number of key parameters in power generation, including health and safety, the environment, plant availability and reliability.

An example of how the risk assessment is recorded is in Table 3 (for a risk matrix, see the Paks case study on the CD-ROM accompanying this publication). The likelihood of failure and impact was scored 1 to 5. The calculated risk falls in the range 1 to 25, where 1 is low and 25 is high.

#### *5.1.3.1. Risk scoring criteria*

The definition of the risk scoring criteria can be a matter for a significant debate. It is important to choose criteria that are meaningful for the plant or unit operating regime being assessed, and the reviewer should take account of the following:

— Current maintenance regime;
— Component failure history;
— Information on plant condition and operation (e.g. recent inspection and operation records);
— Any available life assessment of the component;
— Consequences for unit operation if the component fails;
— Equipment redundancy or availability of spares to prevent or limit any outage;
— Knowledge of the behaviour of similar components in other units or other plants.

Each of these areas will have been reviewed during completion of an appropriate questionnaire and discussions with respective asset management and system engineers.

TABLE 3. RISK ASSESSMENT SPREADSHEET

| Group of components: Exciters | | Main exciter | Field switch | Automatic voltage regulator |
|---|---|---|---|---|
| Failure mode | | Insulation<br>Brushgear<br>Bearings<br>Short circuit | Insulation<br>Overheating due to poor contact resistance<br>Operating mechanism failure due to wear/frequent operation | Insulation<br>Contactor failure<br>Short circuits<br>Overheating of devices |
| Consequence | | Loss of unit | Loss of unit | Run unit on manual with loss of income for voltage control<br>Unit becomes unstable and is driven outside of rating parameters with consequentially loss of unit |
| Current likelihood | | 2 | 2 | 2 |
| Current risk scores | H&S | 6 | 2 | 2 |
| | ENV | 2 | 2 | 2 |
| | PROD | 8 | 6 | 4 |
| | REL | 10 | 10 | 4 |
| Current maintenance and monitoring | | Daily inspection and routine brushgear maintenance during opportune plant outages | Annual inspection and outage maintenance | Outage maintenance as required |
| Potential relaxation of maintenance | | Every 2–4 years | Every 2–4 years | Every 2–4 years |
| Resultant likelihood | | 3 | 2 | 2 |
| Resultant risk scores | H&S | 9 | 6 | 2 |
| | ENV | 3 | 2 | 2 |
| | PROD | 12 | 8 | 4 |
| | REL | 15 | 10 | 4 |
| Change recommendation and justification | | No change<br>Maintain current maintenance regime<br>High risk of failure if cleaning of slipring yokes extended | Consider moving on to every 2 years<br>Review moving on to 4 years after next inspections<br>Low operating regime exercises equipment without overstressing | Consider moving on to every 2 years<br>Review moving on to 4 years after next inspections<br>Static equipment and reliability generally high |
| Comments | | Current maintenance regime takes account of brushes wearing, sticking if not exercised and the risk of carbon buildup as a result of brushes wearing<br>There is no potential for change in this area | None | Automatic voltage regulator to be stored in a clean and dry environment |

**Note:** ENV — environment; H&S — health and safety; PROD — production and availability; REL — reliability.

*5.1.3.2. Evaluation of risk score*

The recommended relaxation of maintenance activities in the nuclear island can only be performed if the risk score is less than, or equal to, a specified value and has to be approved by the safety department. A high risk score is likely to indicate that no relaxation in maintenance is feasible. A significant increase in risk associated with a potential change in maintenance score is likely to indicate that the proposed change will not be acceptable.

## 5.2. ADVANTAGES AND DISADVANTAGES OF VARIOUS OPTIMIZATION METHODS

### 5.2.1. Reliability centred maintenance

While addressing all potential failures of importance, particular advantages of RCM include the approach per function rather than per equipment to defining maintenance, the detailed analysis of operating experience (equipment failures and maintenance costs) and the involvement of operations and maintenance staff in defining preventive maintenance programmes. The method also contributes to improving maintenance culture through better knowledge of the production process by maintenance staff, more cohesive operations and maintenance teamwork, and improved experience feedback. It does not necessarily result in reducing costs but it does lead to higher maintenance effectiveness.

Applying RCM, even if streamlined, is deemed to be time consuming — around 500–1000 worker hours per nuclear power plant system for a team of technicians from various departments led by a specially trained engineer. In any case, the value of RCM is reduced when data on equipment operating experience are not available, since using generic data can be misleading. This means that the method is not well suited to unique plants with infrequent equipment failures.

While maintenance programmes should be dynamic (i.e. regularly updated based on experience), the RCM method does not lend itself easily to such a process. For example, an error of judgement can occur when the operator launches a project to reduce maintenance using only negative feedback received from the plant, neglecting positive feedback.

### 5.2.2. Ageing mechanisms analysis

This method focuses on understanding ageing mechanisms and is based on engineering judgement, so there is no need for reliable data. Another advantage is that it not only covers adjustment of preventive maintenance and intervals but also equipment replacement and backfitting. As a result, it is better suited to mature plants.

A disadvantage is that the method exclusively addresses components important to safety. Hence, it should be complemented by maintenance optimization with regard to production losses, unless the strategy is to perform only CBM or corrective maintenance on equipment that has no impact on safety (i.e. to take more availability risks).

### 5.2.3. Risk informed maintenance

This method considers both the likelihood of a plant failure occurring and the impact that the failure would have on the unit in terms of loss of production, reliability, safety and effects on the environment. The method has two main disadvantages:

(a) It requires the plant operator to define what is an acceptable increase in plant risk with the agreement of the safety authority, which aims naturally at risk reduction.
(b) Maintenance should not be geared only to the core damage frequency, as it is in risk informed maintenance.

These are offset by the advantages: risk informed maintenance is less time consuming than RCM; however, its costs are greater. It has straightforward criteria for decisions relating to maintenance relaxation, and a lack of failure modes and effect analysis.

### 5.3. OPTIMIZING THE PROCESS

#### 5.3.1. Identification of areas for improvement

Areas for improvement should provide the greatest benefits for the plant or where there is clear potential for optimization. Identification can be done in many ways and methods include the following:

— Maintenance KPI analysis;
— Costs, availability, failure rate, and as found and as left conditions;
— Utilizing maintenance templates for the current plant maintenance programme;
— Utilizing operation and maintenance history;
— Benchmarking other similar plants.

By using these methods to identify the most beneficial areas for improvement, maintenance management can allocate resources to optimize those areas.

#### 5.3.2. Determination of maintenance programme health

It is of key importance to establish a complete picture of the health of the preventive maintenance programme, including well defined goals for the site optimization effort. This provides a complete picture of the maintenance programme life cycle. Specific metrics and performance measures that track the effectiveness and progress of the optimization effort should be included. All maintenance programmes should include future maintenance resource demands.

#### 5.3.3. Transition to optimized programmes

If the current maintenance programmes are not being deployed effectively to minimize plant risk, the implementation of the new elements of the optimized programme could create confusion and sometimes duplication or omission of work. The new tasks and schedule can result in several maintenance activities becoming overdue, resulting in a large backlog of planned work.

This potential for conflict can be reduced by establishing a complete picture of the preventive maintenance programme, including well defined goals for the optimized programme, before starting the process. An orderly plan for the transition to the new programme should be developed. This plan should address how new maintenance tasks should be integrated into the current programme, and it should also describe how tasks currently planned for execution should be addressed if they are to be deleted.

During the implementation phase, it is important that necessary work on critical components is conducted as originally planned, and that the work being deleted or rescheduled does not create the possibility of increased failures of critical equipment. It is also important that the new tasks do not add maintenance tasks that are being deleted or significantly changed by the new, optimized programme.

The revised maintenance tasks should be implemented as they are completed to prevent the maintenance process from being overwhelmed by a flood of new tasks. This also facilitates the verification of the interaction of the revised task with the current tasks because the maintenance programme for the component is fresh in the minds of the maintenance personnel.

#### 5.3.4. Preventive maintenance templates

Preventive maintenance activities are usually based on the time to failure for a component. The initial periods for preventive maintenance is initially recommended by the vendor and then adjusted for the nuclear power plant’s operating history. In the 1990s, the United States Nuclear Regulatory Commission determined that it wanted a method for evaluating maintenance effectiveness, and issued regulation 10 CFR 50.65 [31], known as the maintenance rule. Earlier, EPRI was asked by a group of utilities in the 1980s to adapt a technique originally used by the aircraft industry. At the request of these utilities, the collective results of the RCM analyses were compiled into a database of components, failure modes and maintenance tasks, which became known as the EPRI preventive maintenance templates (see Fig. 4 for a sample template). These templates are being modified by utilities to reflect their specific maintenance histories and are being used in the maintenance optimization programmes specific to the utility.

Nuclear power utilities are expected to improve the templates with the following methodology:

— Establish corporate subject matter experts;
— Develop standard preventive maintenance templates;
— Utilize an expert panel;
— Use templates developed by others (e.g. EPRI preventive maintenance templates);
— Classify components as critical, non-critical and run to maintenance;
— Compare preventive maintenance template recommendations to existing preventive maintenance;
— Examine work history;
— Modify preventive maintenance (additions, deletions or frequency changes);
— Monitor preventive maintenance template implementation and performance indicators;
— Utilize software to facilitate the process.

**Horizontal Pumps**

| Component Classification Categories | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | LEAD SME:<br>BACK-UP SME:<br>Template Approved by<br><br>Release Date: **7/26/2004** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Critical | Yes | X | X | X | X | | | | | | |
| | No | | | | | X | X | X | X | | |
| Duty Cycle | High | X | | X | | X | | X | | | |
| | Low | | X | | X | | X | | X | | |
| Service Condition | Severe | X | X | | | X | X | | | | |
| | Mild | | | X | X | | | X | X | | |
| **Condition Monitoring Task** | | | | | | | | | | **Failure Codes** | **Comments** |
| Vibration Analysis@ | | 1M | 1M | 1M | 1M | 3M | 3M | 3M | 3M | OC | EPRI TR-106857-V13 Application Note 2.3.1 |
| Performance Trending | | 6M | 6M | 6M | 6M | 6M | 6M | 18M | 18M | OC | EPRI TR-106857-V13 Application Note 2.3.3 Monitor in accordance with ER-AA-2003 |
| Oil Analysis | | 3M | 18M | 3M | 18M | 18M | 18M | 18M | AR | DA FL OC | EPRI TR-106857-V13 Application Note 2.3.2 |
| **Time Directed Task** | | | | | | | | | | **Failure Codes** | **Comments** |
| Coupling Inspection | | 24M | 5Y | 24M | 5Y | AR | AR | AR | AR | DA FD GL UD | EPRI TR-106857-V13 Application Note 2.3.5 |
| Nozzle NDE Inspection | | 10Y | AR | 10Y | AR | 10Y | AR | 10Y | AR | CO ER | EPRI TR-106857-V13 Application Note 2.3.6 Time based inspection should be performed at frequency specified. If data is available from inspection of like equipment in similar service indicates more or less frequent inspections are required,then frequency of inspection should be adjusted accordingly. |
| Refurbishment* | | AR* | AR | AR* | AR | AR* | AR | AR* | AR | AG CO ER IW NO OC | EPRI TR-106857-V13 Application Note 2.3.9 * Refurbishment of non-redundant (no installed spare), power production pumps (Condensate, Condensate Booster, Feedwater) should occur on the following time based schedule: - Condensate Pumps: 8 years - Condnensate Booster Pumps - 8 years - Feedwater Pumps - 10 years |
| Oil Filter Change,Clean and Inspect | | 24M | AR | 24M | AR | 24M | AR | 24M | AR | DA FL OR | EPRI-TR106857-V13 Application Note 2.3.4 Oil change frequency may be modified by application of CBM technologies (Delta P. particle counts)etc. |
| External Visual Inspection | | 1D | 1D | 1D | 1D | 1W | 1W | 1W | 1W | BF CO DA FD GL LC OC OR SL | EPRI TR-106857-V13 Application Note 2.3.7 |
| Partial Dissassembly | | AR | AR | AR | AR | AR | AR | AR | AR | BS FD GL OC OR PL SL | EPRI TR-106857-V13 Application Note 2.3.8 |
| **Surveillance Task** | | | | | | | | | | **Failure Codes** | **Comments** |
| Functional Testing | | AR | AR | AR | AR | AR | AR | AR | AR | XX | EPRI TR-106857-V13 Application Note 2.3.10 |

* Refurbishment of non-redundant (no installed spare), power production pumps (Condensate, Condensate Booster, Feedwater) should occur on the following time based schedule: - Condensate Pumps: 8 years - Condensate Booster Pumps - 8 years - Feedwater Pumps - 10 years @ For canned/wet motor pumps, consider supplementing normal vibration monitoring with current monitoring.
This template is the controlled revision. Please refer to MA-AA-716-210 & MA-AA-716-210-1001 for additional guidance.

*FIG. 4. Preventive maintenance template.*

## 5.4. EFFECTIVE UTILIZATION OF CONDITION BASED MAINTENANCE

An effective way to improve equipment reliability is to base the maintenance on the condition of the equipment. This approach reduces the number of unnecessary intrusive activities that can cause component unavailability and uses fewer maintenance resources, thereby reducing the overall cost. It can be conducted using normal equipment monitoring techniques to provide information on the condition of the equipment, and includes the following:

— Operator rounds;
— Engineer walk downs;
— Performance monitoring;

— Functional tests;
— Predictive maintenance activities.

These activities are collectively called condition monitoring. When used to serve as the basis for deciding when to perform restoration maintenance activities, it is called CBM. Experts strongly recommended that structured guidance be given to personnel who provide condition monitoring activities. Effective use requires that organizations use vendor information, operating experience and other resources to develop a list of conditions and symptoms that should be monitored so that condition monitoring personnel and supporting staff are able to provide information. Industry groups such as EPRI, INPO, the Nuclear Energy Institute and WANO also provide information on this topic.

In addition to predictive maintenance, condition monitoring covers a broad area and also includes wireless equipment and on-line monitoring, and prognostic health monitoring (PHM). Each comprises inspections, monitoring and trending, and technologies that provide insights into the condition of the plant equipment. Careful analysis of the data collected during these activities will allow component experts to determine whether the component has degraded to the point that maintenance is required. By using this approach, unnecessary maintenance can be avoided, and equipment reliability and availability can be maintained. This form of maintenance can also be added to the time based maintenance strategy for critical components, so that failures resulting from random events (i.e. human error) and time based wear out can be minimized as well.

Because CBM can significantly improve equipment reliability and simultaneously allow limited resources to be focused on the critical safety significant components, vendors are developing some very exciting new products, such as large data analysis and machine learning as well as improved sensors and processors used to monitor the equipment. These advances are creating new opportunities for using condition monitoring to focus the maintenance strategy on doing the right work at the right time.

### 5.4.1. Predictive maintenance

Predictive maintenance technologies monitor equipment and component health so that planned maintenance can be performed prior to equipment failure. Sensors installed on the component can provide continuous monitoring of parameters such as vibration, temperature and pressure, and periodic monitoring can be performed by technicians using hand held sensors. Predictive maintenance includes the application of condition monitoring technologies such as vibration monitoring, lube oil analysis, thermography, non-destructive examination and non-destructive testing as well as the process of evaluating all equipment condition indicators to make timely decisions regarding the maintenance requirements of plant components. An important component of the successful use of predictive maintenance technologies is the use of effective analysis techniques to evaluate the data collected from the monitoring sensors and determine the condition of the component and the remaining useful life until maintenance intervention is required.

### 5.4.2. Predictive maintenance expert groups

Expert groups are often formed to evaluate the entire maintenance programme (i.e. as found data, maintenance history and monitoring results) and then to adjust the maintenance programme accordingly. Technicians and analysts in such groups are responsible for collecting and diagnosing plant equipment. It is important that they work directly with the engineering organization to monitor and assess effectively the condition of the plant equipment to maximize reliability and availability.

It is also important for this organization to work closely with the maintenance organization to obtain the necessary data, and to properly schedule the maintenance intervention to assure the optimum reliability and availability of the units. An effective partnership between engineering and maintenance departments is an absolute necessity for successful maintenance optimization.

### 5.4.3. On-line monitoring and wireless equipment monitoring

A number of nuclear power plants, such as the Comanche Peak Nuclear Power Plant and the Byron Nuclear Generating Station, have installed wireless equipment and sensors to improve and optimize on-line monitoring capabilities. The key benefit of wireless equipment monitoring is that once the infrastructure is installed, wireless sensors can be fitted to components and structures at a fraction of the cost of a hardwired sensor. Additional benefits can also include the following:

(a) Better on-line monitoring for engineers to plan and implement processes to increase equipment reliability.
(b) Spending less time on data collection means engineers can spend more time on data analysis and diagnostics.
(c) Operator rounds can be reduced, along with the associated radiation exposure.
(d) Preventive maintenance can be reduced by switching from time based preventive maintenance to condition based preventive maintenance.
(e) Unexplained equipment failures can be better understood by improved wireless equipment monitoring capabilities.

#### 5.4.4. Prognostic health monitoring

The latest PHM incorporates industry data and data from the CMMS and any other plant monitoring systems, and analyses the information through programs such as:

- Automated troubleshooting processes which capture human knowledge and retain it in digital formats;
- Diagnostic processes which identify impending failures by comparing asset fault signatures with operating data;
- Remaining life estimation of how long an asset will continue to provide a reliable service.

The latest PHM techniques are being designed and implemented by EPRI and Idaho National Laboratory, and a number of pilot projects are in progress (see the Exelon case study on the CD-ROM accompanying this publication).

### 5.5. EFFECTIVE UTILIZATION OF RUN TO MAINTENANCE

An effective maintenance optimization programme requires that work processes be revised to reflect the results of the optimization process. In the past, many organizations tried to achieve maintenance optimization objectives by classifying the functional importance of equipment to reduce the resources required. For this technique to provide a method of maintenance optimization, it is important that the classification of equipment is also translated into how the actions of component degradation, maintenance and post-failure correction are dealt with. If a component is classified as run to maintenance (or run to failure) because it has no negative impact on plant safety, the failure should be treated as such if it fails. These components (and their failures) used to be treated similarly to critical components, and, as a consequence, no resource savings were achieved from any reclassification.

For non-critical and run to maintenance equipment, some failures can be expected, and they are evaluated as failures whose consequences can be tolerated. To achieve the greatest benefit from using the functional importance classifications effectively, the maintenance strategies for the components should be adjusted to reflect the classification. For many components classified as non-critical, the optimum maintenance strategy is only to monitor the equipment and to perform deficiency repair maintenance based on condition. As a matter of policy for run to maintenance equipment, there should be no maintenance performed until the component is no longer capable of meeting its intended function. In other words, preventive maintenance should not be performed on run to maintenance equipment.

In order for classifying equipment based on its functional importance to have an impact in optimizing maintenance strategies, it is important that the performance expectations for the equipment is shared with all necessary personnel. The maintenance optimization programme should then be developed based on the functional importance of the equipment and the risk tolerance of the management team of the nuclear power plant. At many plants, critical and non-critical SSC performance standards and expectations are essentially the same. Managers expect no failures — and as a consequence, engineers and maintenance personnel treat all SSCs the same. The outcome is that maintenance strategies and performance metrics for all SSCs are essentially the same, so there is no advantage achieved from the classification process.

Establishing different expectations for SSCs in different classifications is more than just a procedural change. Extensive managerial and organizational modification is required. In addition, functional importance can be artificially inflated to maintain control of preventive maintenance (i.e. non-critical SSCs classified as critical to ensure engineering ownership or classifying run to maintenance SSCs as non-critical to ensure maintenance is performed). This tendency will need to be addressed. Non-critical equipment failures, while undesirable, are less consequential than critical equipment failures if the equipment has been properly classified. On account of the relatively low impact that the failure of one these non-critical components has, a limited number of failures is to be expected.

Once components have been classified according to their functional importance, the maintenance strategy can be developed. There are several ways of doing this, but one starting point is an evaluation of the current performance of the SSC being considered. The first metric is whether the performance of the SSC is satisfactory, and includes a review of any commitments made to management, regulators, insurers and government bodies. If commitments have been made on which tasks should be performed or to their periodicity, these will have to be addressed as part of the process. An analytical or technical justification for changing maintenance strategies can often result in having the commitment terms revised.

The assessment should focus on the expected performance of the SSC in relation to its functional importance. Since the process focuses on optimizing the performance of non-critical SSCs, it is important to remember that, during the classification process, it was determined that some small number of functional failures could be tolerated. Therefore, if some failures have occurred, it is important to evaluate whether they were expected and whether the consequences were in fact tolerable. This evaluation is more qualitative than quantitative. Input from operations, maintenance and work management is important to validate whether the SSC performance is consistent with the evaluation being used for maintenance optimization.

On conclusion that current performance and reliability are ‘satisfactory’ and that the functional importance of the SSC has been properly determined, the scope and periodicity of the preventive maintenance for the SSC can be reviewed for optimization. There are two potential methods that could be used to evaluate this. One method is to start with the current strategy and to evaluate the impact of eliminating some task, extending the intervals of other tasks, and making no changes to others. A second method is to start with an ‘empty plate’ and to assign preventive maintenance tasks based on identified failures and failure modes specific to the SSC in its current application, service environment and duty cycle (for more details on these methods, see the EPRI case study on the CD-ROM accompanying this publication).

# 6. WORK MANAGEMENT AND ON-LINE MAINTENANCE

## 6.1. WORK MANAGEMENT

On account of the large number of activities and the need to schedule them, an effective work management process is required to ensure that plant management can make the right resources available at the right time [8]. The work management process should ensure that work is well defined, tracked and accomplished in an efficient and timely manner. The data collected during the work cycle should be analysed using plant KPIs and work management specific indicators. The results of which provide information for management to support its decisions.

The plant CMMS should support the work management process, with the following six key requirements:

- Integrate with condition monitoring systems;
- Manage the entire work cycle and associated data;
- Manage all asset history and provide reliable data;
- Manage general and specific plant information;
- Provide system support and configuration of the CMMS to enable maintenance procedures to evolve;
- Provide data for plant specific KPIs.

The work management process is dependent on three successive levels of detail:

- — The top level process map represents an overview of major process elements and how they relate to each other.
- — The intermediate process map expands on the top level process elements and includes the detailed activities necessary to achieve the process objectives.
- — The written process instructions following the intermediate process map provide criteria and considerations for implementing the work management process activities.

### 6.1.1. Work order classification

Maintenance work orders should be classified in the plant CMMS. Work order classification supports maintenance optimization analysis and data collection.

#### *6.1.1.1. Observation hierarchy*

Observation hierarchy identifies the ways in which defects are observed, and examples include:

- — Observation (e.g. process measurements and sensors);
- — Value (e.g. temperature, flow and pressure);
- — Symptom (e.g. too low or too high);
- — Method (e.g. alarm, rounds, condition monitoring and surveillance).

#### *6.1.1.2. Component failure impact*

Failure impact is used to identify the consequence of the component failure and is divided into two categories:

- — Functional failure is when equipment stops performing a required function [29];
- — Non-functional failure is when the equipment's ability to performs the required function is decreased.

#### *6.1.1.3. Work type classification*

Work type classification identifies different work types, and includes:

- — Periodic test;
- — Periodic overhaul;
- — Surveillance;
- — Condition monitoring;
- — Rounds;
- — Modification;
- — Investment;
- — Repair (functional failure);
- — Restoration (non-functional failure).

#### *6.1.1.4. As found and as left conditions*

As found and as left conditions identify a component's condition before and after maintenance work, and include:

- — Unanticipated failure;
- — Repair required — not normal wear;
- — Repair required — normal wear;
- — Outside tolerance;

— Reliability degraded;
— Within tolerance — adjustment required;
— Satisfactory;
— Superior;
— Not applicable.

*6.1.1.5. Action done*

Action done classification identifies the actually maintenance work performed and includes:

— Tightening;
— Cleaning;
— Oil change;
— Adjusting;
— Calibrating;
— Grinding;
— Lubricating.

*6.1.1.6. Failure hierarchy*

Failure hierarchy identifies different failure types (divided into different equipment types):

— Failure class (mechanical/electrical);
— Equipment type (pressure vessels and pipes/rotating machines/valves);
— Failure type (erosion/corrosion/ageing/cracking);
— Failed component (pipe/tube/shaft/bearing/piston).

*6.1.1.7. Failure cause hierarchy*

Failure cause hierarchy identifies the root cause of the failure, for example:

— Cause is assembly/ageing/manufacturing;
— Fault is wrong material/design error/alignment error.

### 6.1.2. Maintenance feedback process

The plant should define a maintenance feedback process and the required feedback information to fulfil the business needs to steer and manage the maintenance activities (see Fig. 5). High quality data is crucial for developing the maintenance optimization programme. Maintenance personnel should understand the importance of this with the help of sufficient training and support of the maintenance management.

The feedback process starts from the observation of deviation or equipment failure. During the maintenance work, much information is generated in many different phases. Well defined processes ensure that very important information is available for the future. Feedback information is used to establish maintenance KPIs, such as reworks, and can also be used for exemplary failure and failure cause tracking, and defining corrective actions.

The plant CMMS should support the plant feedback process. Feedback data should be sent directly to the CMMS by those with the first hand information of who, what, where and when. The quality and sufficiency of data should be ensured by supervisors of the maintenance organization (for a more in-depth description of Fig. 5 and specific examples, see the Loviisa case study on the CD-ROM accompanying this publication).

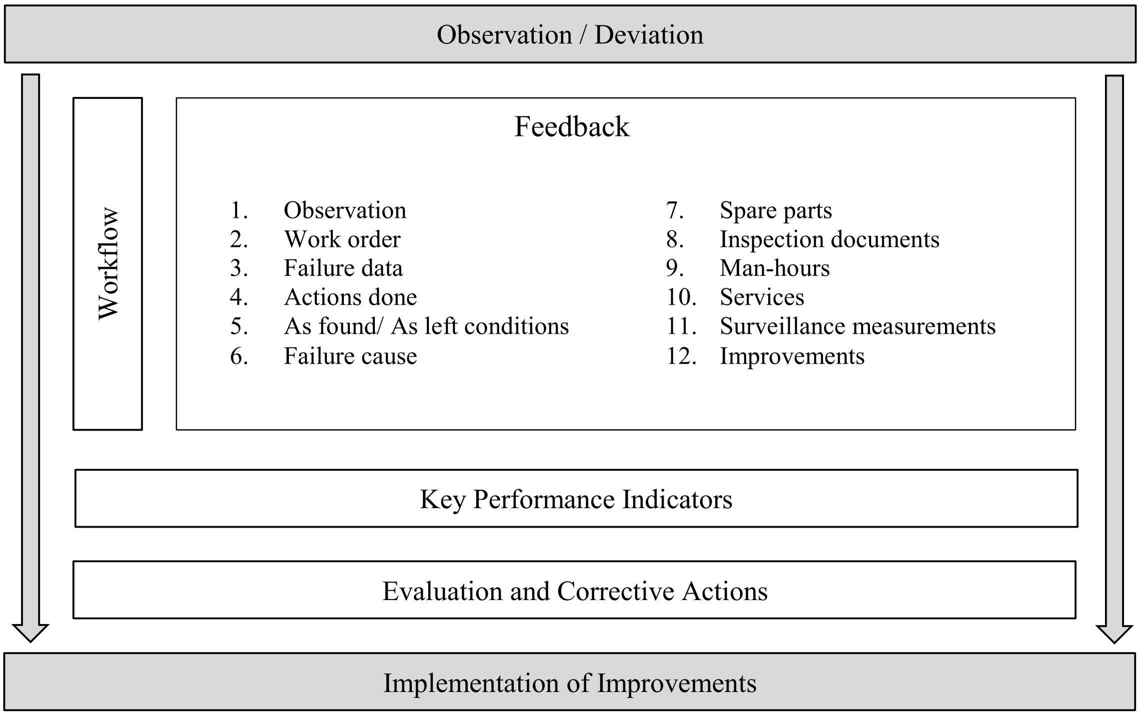



*FIG. 5. Feedback process.*

## 6.2. ON-LINE MAINTENANCE

On-line maintenance takes place while the nuclear power plant is generating electricity [9]. It can provide benefits for plant safety, performance and economics and can contribute to the maintenance optimization programme. There are two categories of on-line maintenance. Corrective on-line maintenance is necessary when SSCs fail and need to be immediately repaired or replaced. This is usually unplanned. Preventive on-line maintenance is planned and is integral to the overall maintenance programme. It serves to evaluate the current status of SSCs as well as to maintain or restore their nominal condition. This section focuses on preventive on-line maintenance.

From an economic perspective, maintenance work scheduling is largely driven by the need to reduce outage duration to optimize availability and thus to reduce generation costs. This can be achieved through an on-line maintenance programme by rescheduling maintenance tasks previously performed during outages. Safety considerations is also a reason to implement an on-line maintenance strategy. Depending on the level of redundancy of a power plant's safety trains, the incremental increase of risk (e.g. large early release frequency) due to maintenance work on a single safety train during power operation can be lower than the incremental increase of risk due to the same work during the outage. An assessment of the associated risks for plant safety and availability as well as adherence to plant specifications and regulatory requirements are prerequisites for any on-line maintenance programme.

### 6.2.1. Benefits of on-line maintenance

The most significant benefit of on-line maintenance is increased equipment, system and plant reliability, resulting in improved plant safety. The main economic benefit is the possible reduction of outage duration. Benefits to the optimization of work planning include the following:

- Anticipation of maintenance work, with appropriate contingency plans;
- Spreading out of the workload from peak outage demand to quieter times during power operation;
- Reduction of occupational and radiation exposure;

- Reduction of stress levels in the work environment (e.g. in the control room) during planning and on-site activities;
- Increased reliability of systems whose availability is essential during shutdowns, startups and outages;
- Maintaining a high level of practical experience of in-house personnel not directly involved with maintenance work often outsourced during outages;
- Lessons learned from on-line maintenance work on one redundancy or safety train applied to other redundancies or safety trains during outages;
- Reduction of risk of common mode failures, as different maintenance teams work on different safety trains at different times.

### 6.2.2. Application of on-line maintenance

The criteria for determining which maintenance tasks can be performed on-line are based on plant operating guidelines, regulations and practical experience, for example:

- Nuclear safety related SSCs that have several redundant backups, allowing for one redundancy at a time to be taken off-line without an unacceptable increase in risk;
- Nuclear safety related SSCs whose availability is essential during shutdown, startup and outage;
- SSCs not essential to the safety or reliability of the plant.

On-line maintenance tasks should comply with plant's technical specifications and national regulations. Technical specifications define inspection periodicity and maximum durations of safety system and equipment unavailability. Unavailability causes an LCO and has a certain completion time, within which the SSCs have again to be available. The completion times are the permissible time periods for corrective on-line maintenance. Depending on the State's nuclear safety regulations, LCO completion times can also be used as a basis to determine the acceptable duration for performing preventive on-line maintenance.

A plant specific document listing the technical specifications of on-line maintenance can be supplemented with lessons learned from operation and past experiences dealing with the unavailability of SSCs or entire redundancy trains. While technical specifications serve as the basis for performing preventive on-line maintenance, this supplementary document can also help to increase system availability beyond the technical requirements.

For plants that have highly redundant safety system schemes (e.g. four 100% safety trains), the maximum permissible durations of safety train unavailability can be quite long, and maintenance tasks can be performed during one week or more on a single train, with a moderate and potentially lower impact on safety than if these tasks were performed during the outage. Most new reactor designs even provide for preventive on-line maintenance in the plant design. Regardless of the number of redundant safety trains, the availability of essential redundancies and electrical power supply needs to be ensured at all times, and each plant needs to be analysed in detail before embarking on an increased use of preventive maintenance during power operation.

### 6.2.3. Implementation of on-line maintenance on safety relevant systems

Effective implementation of on-line maintenance requires the coordination of risk assessment, work planning and maintenance. In the risk assessment, the risk impact of on-line maintenance on plant safety is analysed by deterministic and probabilistic methods.

Proper work planning allows for optimized resource allocation and effective scheduling of tasks. Different departments involved with on-line maintenance should be coordinated by a single responsible representative to facilitate an optimized sequence of tasks. This also helps to avoid unintended plant configurations in which the risk impact of unavailable systems is increased. Knowledge of the technical basis for maintenance tasks is essential, and includes determination of maintenance task intervals. Separate instructions should describe the details of each on-line maintenance measure.

On-line maintenance work should be integrated into the plant's general maintenance programme. Best practice is for a plant internal group, such as a safety review board, to review the proposed on-line maintenance programme. This group should include personnel who were not involved with the initial planning.

#### 6.2.4. Regulatory approach

Internationally, there are divergent regulatory approaches to determine the permissible duration of preventive on-line maintenance. One approach allows part or all of the LCO completion time to be used to perform preventive on-line maintenance. In effect, there is no differentiation made as to the reason for the unavailability of the SSCs. In the context of maximum permitted durations of unavailability as defined in the technical specifications, unplanned unavailability due to SSC failure is treated equally to planned unavailability, since the SSCs have been taken off-line for maintenance.

Another approach does not allow LCO completion times to be used for preventive on-line maintenance. LCO completion times are interpreted as being solely for corrective maintenance on SSCs after they have failed unexpectedly. Under this approach, the possibilities for an on-line maintenance programme are limited, as no allowance is given for deliberate unavailability for the purpose of preventive on-line maintenance.

Among regulators that allow on-line maintenance, the methods to determine whether a specific on-line maintenance programme is permissible can vary greatly. Some regulators use risk assessment criteria such as core damage frequency and large early release frequency as measures of whether or not to allow an on-line maintenance programme. The increase in risk impact due to the implementation of on-line maintenance as assessed by the probabilistic safety assessment may not exceed certain prescribed values. Other regulators make decisions on a case by case basis, and others permit plant operators to perform on-line maintenance only on balance of plant equipment.

# 7. PERFORMANCE MONITORING

There are at least two types of performance monitoring in maintenance optimization. The first addresses the performance of the maintenance organization and the maintenance process. It provides information on the activities being performed and is a means of assessing the organization's effectiveness in accomplishing them. The second addresses the SSCs being maintained. This monitoring provides input on the effectiveness of the activities being performed by the maintenance personnel, and helps with the decisions of which maintenance should be performed on which SSCs. This type of performance monitoring is the foundation of the CBM programme, which is a major component of the overall maintenance programme.

## 7.1. MONITORING MAINTENANCE EFFECTIVENESS

Periodic assessments are performed to determine whether an existing maintenance programme is effective. Most maintenance programme assessments are conducted with self-assessments and peer assessments performed by industry oversight organizations at least every two years, as specified in 10 CFR 50.65 [31]. Although comprehensive and performed by experienced professionals, assessments are mostly qualitative evaluations based on subjective judgements. There are, however, a few objective measurements, known as indicators, that can be used such as rework counts, backlog counts, plant level indicators (e.g. the number of unplanned plant trips) and safety system actuations. The indicators should be consistently defined and uniformly applied, and, for example, they should:

(a) Be complementary to other indicators used by the nuclear power plant and other organizations;
(b) Focus on assessing the maintenance programme on an ongoing basis;
(c) Be suitable for comparison across the industry;
(d) Focus on maintenance activities and their results;
(e) Use data that are available consistently across the industry.

Typical assessments focus on five major areas of the maintenance process:

- — Work identification;
- — Work control;
- — Work execution;
- — Work closeout;
- — Overall maintenance programme.

## 7.2. SYSTEM HEALTH PERFORMANCE MONITORING

System health refers to the ability of individual plant systems to perform their intended function. The first step in a system health performance monitoring plan is the development of a formal programme with the following key aspects:

- — Define roles, responsibilities, objectives, expectations and actions;
- — Establish clear expectations for all levels in the organization;
- — Define consistent and clear scoping criteria that align with the SSC functional importance process;
- — Align performance monitoring goals with system and plant goals;
- — Align the monitoring programme with maintenance optimization;
- — Establish relationships between system health performance monitoring and other plant processes and programmes;
- — Establish a clear owner for the system health performance monitoring programme.

In order to establish system health performance criteria, considerations include the following:

- — Establish performance criteria based on goals already being monitored and on SSC failure mechanisms that can cause a loss of function;
- — Look for leading indicators that predict performance in addition to indicators based on equipment failures;
- — Recognize that component in-service performance might not be a good indicator of component condition and that inspection during component out of service time or plant outages might be required for a comprehensive monitoring programme;
- — Understand the damage mechanisms, effects and leading indicators of damage for critical components;
- — Relate monitored parameters to measurable indications of component degradation;
- — Employ condition monitoring techniques when performance monitoring cannot be related to component degradation and include specific alert values for condition monitoring data in the component performance criteria;
- — Identify the actions required when indicated alert or alarm action levels have been reached;
- — Describe the consequences of a failure if the degradation proceeds to failure.

A detailed discussion of the specific components of industry best practices is addressed in the Equipment Reliability Index of the International Equipment Reliability Working Group (see also Ref. [32]).

## 7.3. USE OF EQUIPMENT CONDITION MONITORING DATA

A condition monitoring programme evaluates the actual operating condition of the equipment to determine whether the equipment can operate reliably until the next scheduled outage. If maintenance is required, the predictive evaluation helps to determine the specific maintenance necessary. Condition monitoring uses advanced monitoring technology for the early detection of machinery faults. Much of the technology has already been successfully deployed in nuclear power plants with proven effectiveness and reliability. The technology, when combined with plant information such as maintenance history and design and process data, monitors the equipment condition and compares it to past performance. A condition monitoring programme would therefore include the entire chain of evidence that would support the diagnosis of machinery problems.

By integrating the results from the various diagnostic tests with information from operations and maintenance, the condition monitoring activities become a vital part of the daily routine at the plant. Variations in condition monitoring data caused by a particular operating technique or maintenance procedure can be quickly identified and resolved. This increases the reliability of the condition monitoring systems to detect changes caused by wear. This integration of condition monitoring information with other plant information will need to be done manually at first, but the process could be automated in the future. With the advances made in networking and standardized hardware and software, plants can gather this information more easily and effectively.

Advanced processing techniques such as expert systems, fault signature analysis and remaining life prognostics can be applied to on-line and historical data to detect automatically any deterioration of plant equipment. An additional advantage is that the corporate knowledge gained through years of operations and maintenance experience is not lost when personnel leave or retire. This library of information can then be used for training and simulations for the next generation of operating and maintenance personnel.

One of the most difficult areas of CBM is sorting through the detected degradation and determining its significance and the priority of each item to repair. However, experience and practice can provide solutions. When reporting machine condition based on a diagnostic test, routine maintenance often becomes emergent maintenance or even emergency maintenance. To avoid this, the programme or system owner should be prepared to answer the question of what will happen if no action is taken. In addition to stating the problem, management will want to know the problem's severity and when they need to take actions. Table 4 provides example repair priority levels.

TABLE 4. REPAIR PRIORITIES

| Level | Condition assessment | Significance description |
|---|---|---|
| 1 | Condition normal | No problems found |
| 2 | Degradation indicated | Not severe<br>Cleared for continued operation |
| 3 | Degradation found | Repair required at next scheduled outage<br>Monitor closely for changes (weekly) |
| 4 | Performance degraded | Repair required at next available work window<br>Increase monitoring frequently (daily) |
| 5 | Performance unacceptable | Repair required immediately |

## 7.4. DATA ANALYSIS

There are five ways in which condition monitoring information can be used to provide information about plant equipment condition:

(1) Comparison of predictive maintenance variable to an absolute known limit (e.g. dissolved oxygen in condensate should not exceed 20 ppb);
(2) Standard practice of plants sometimes employing limits based on previous lessons learned (e.g. bearing temperatures should not exceed 180°C);
(3) Co-incident indication of two or more condition monitoring or process parameters (e.g. tube leak detection system shows increased acoustic activity in one part of the heat exchanger, temperatures are slightly depressed and small leak indicated even though system alarms have not been breached);

(4) Rate of change at which a predictive maintenance parameter changes can indicate the type of fault and allow engineers to curtail a developing fault (e.g. long term trends show increase in vibration);
(5) Statistical analysis used to set repair priorities when no other information is available (especially effective when data are from a large number of machines).

For condition monitoring to be successful, all the necessary information should be gathered on a regular basis. The data should be analysed for signs of deterioration and appropriate corrective actions should be taken in response to indications from the diagnostic systems. Converting data to information and action is at the heart of condition monitoring, and failure to take appropriate corrective action based on the results of the complete analysis wastes the data collection and analysis efforts. If corrective actions cannot be practically accomplished, the monitoring activities should then be redirected to other SSCs where corrective actions can be taken.

# 8. CORRECTIVE ACTION PROGRAMME

The CAP is a key component of an orderly optimization process and ensures that the actions needed to define, control and document the steps used in the optimization process are followed. This section describes the processes in a CAP that are used in the maintenance optimization programme and the typical corrective actions. The CAP incorporates corrective maintenance and cause determination of adverse conditions, to correct and prioritize the problem (see Refs [10, 11, 25, 26]).

## 8.1. ANALYSING DEVIATIONS AND CORRECTIVE ACTIONS

Most nuclear power plants use CAPs to identify problems or issues, evaluate its causes, establish corrective actions and review their effectiveness (see Fig. 6).

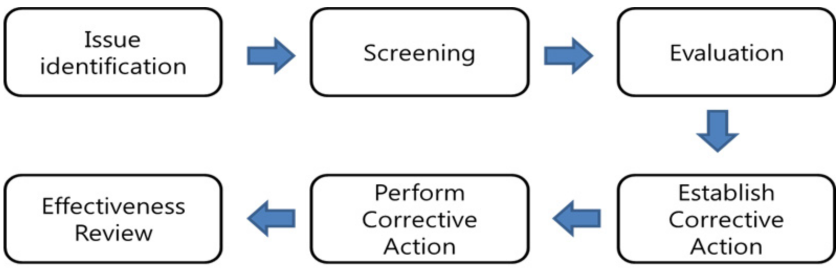



*FIG. 6. Simplified corrective action programme.*

### 8.1.1. Issue identification

This occurs when somebody working at the plant identifies a condition that does not meet requirements or that can be improved. It can be any kind of problem, event or adverse trend that affects plant safety, reliability, operation and regulatory requirements. Together with all relevant data and evidence, the issues should be documented in a condition report — electronically or on paper — to review and track progress.

### 8.1.2. Screening

All condition reports should first be reviewed to determine whether the issue affects plant safety, technical specification limitation and operability, and whether it needs to be reported to the regulator. It should also be reviewed for possible quarantine, prompt investigation and immediate actions. If the condition report requires field work, a work order is created.

### 8.1.3. Evaluation

The evaluation depends on the level of significance determined by the screening committee. Most CAPs include detailed trending codes which, when assigned correctly, identify trends in events which might be more significant than they appear individually.

### 8.1.4. Establishment of corrective actions

When the cause of the failure is identified, corrective actions should be established to address the adverse condition of the SSCs and to solve the cause of the failure. The corrective actions should be documented, monitored and tracked.

### 8.1.5. Completion of corrective actions

Corrective actions are assigned to supervisors, who reviews the actions and assigns them to an individual. If for any reason, the action cannot be completed as assigned, any alternate actions should receive the same level of analysis, review and approval as the original action it replaces. Once the worker has completed the action, and it has been approved by the supervisor, the status of the action on the tracking system is changed to closed.

### 8.1.6. Effectiveness review

For all root cause evaluations, an effectiveness review is conducted on completion of all associated corrective actions. The review determines whether the desired change has been accomplished and that no new problems have developed as a result. The acceptance criteria should be established at the time of the evaluation and be based on best industry practices (see Fig. 7).

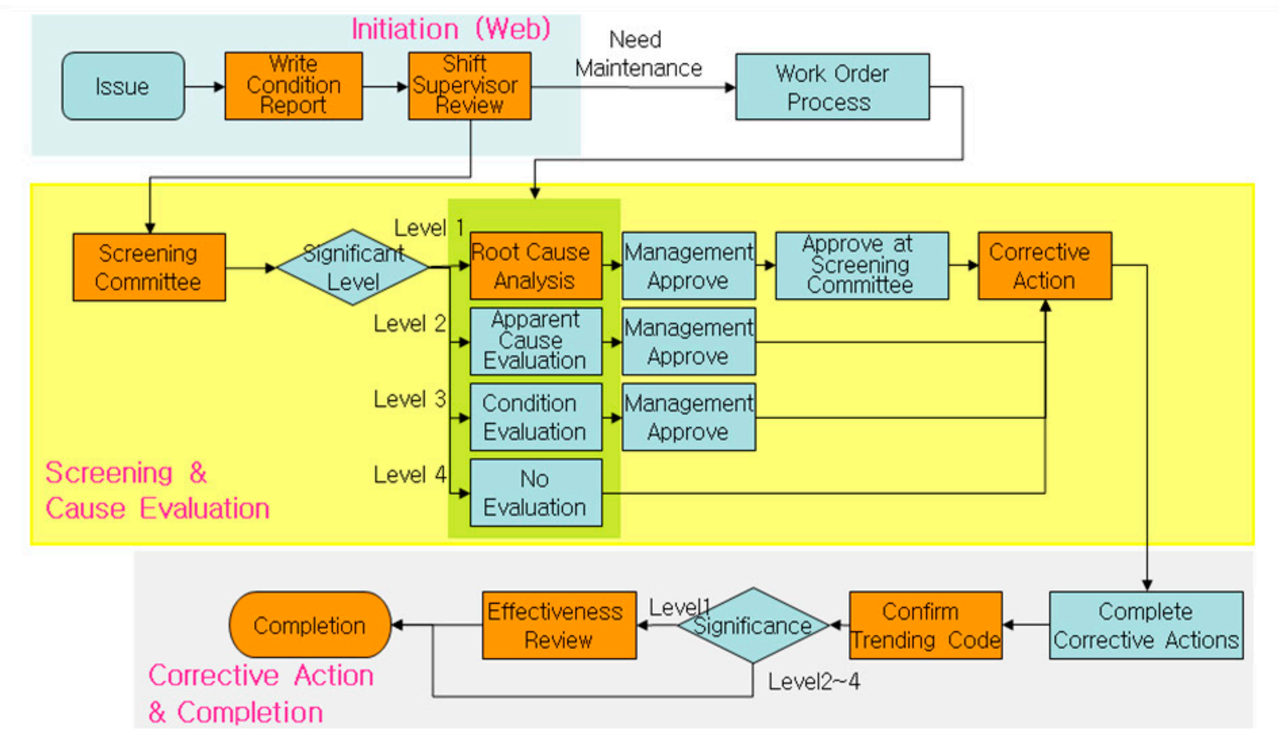
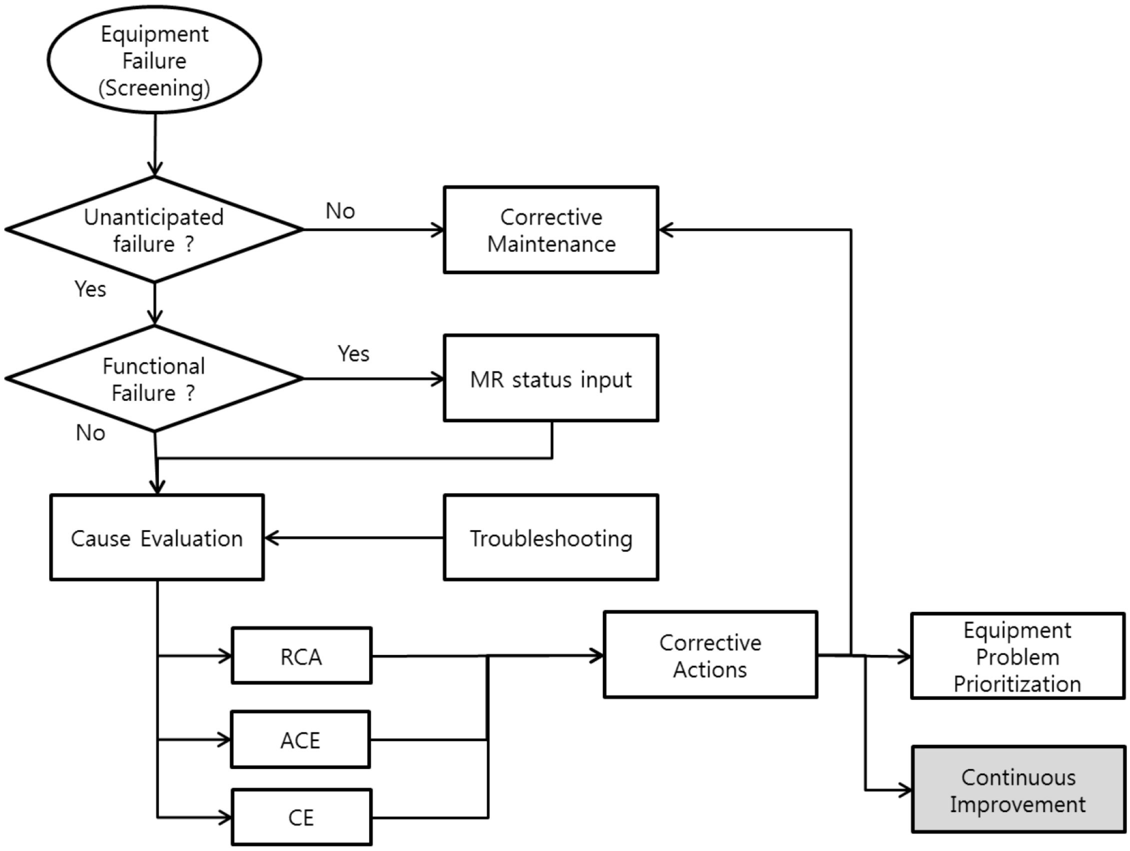



*FIG. 7. A typical corrective action programme.*

## 8.2. TRACKING CORRECTIVE ACTIONS: EQUIPMENT FAILURE SCREENING

When equipment failure or equipment performance degradation occurs, it needs to be determined whether or not the condition is acceptable. All unanticipated and preventable failures should be reviewed by a screening committee (see Fig. 8).




**Note:** ACE — apparent cause evaluation; CE — condition evaluation; MR — maintenance rule; RCA — root cause analysis.

*FIG. 8. Typical flow chart of corrective action for equipment failure.*

The screening committee is composed of department representatives, and it reviews the condition reports to determine their significance level. This level in turn determines the type of cause evaluation required, so guidelines should be provided. An example of a significance scale is as follows:

- — Level 1: Root cause analysis.
- — Level 2: Apparent cause evaluation.
- — Level 3: Condition evaluation.
- — Level 4: No evaluation.

Most nuclear organizations provide supporting criteria that the screening committee can use in assigning the significance level. For example, level 1 criterion might include events that: (i) affect core reactivity; (ii) cause loss of generation for more than one full power day; (iii) cause or could cause an enforcement action from the regulator; and (iv) any unplanned plant scram. The criteria for each level should be developed to reflect the priorities of the organization.

The screening committee identifies a working group responsible for the evaluation and assigns the task and deadline to the appropriate person. The screening committee also reviews the issue to determine whether it needs to be reported to external or domestic sites as part of the operating experience programme. This decision can be reconsidered later as the evaluation provides a more complete understanding of the issue and its broader application. Screening criteria for determining unacceptable failures include the following:

— Unexpected negative effects to plant operation;
— Initiation of an operational transient or degradation of the margin of safety;
— Outcomes such as power reduction, unplanned entry into a shutdown, LCO less than or equal to 72 hours, a failure of a critical safety function or an unplanned initiation of an engineered safeguards features actuation system signal.

If the failure is acceptable and anticipated, corrective maintenance without evaluation is performed as described in Section 8.3. The evaluation of all unanticipated equipment failures to identify the cause and to establish corrective actions is described in Section 8.4.

It is then determined whether the failure is a potential functional failure, based on the following criteria:

— The failed component is associated with a maintenance rule function.
— The failure resulted in actual or potential defeat or degradation of a maintenance rule function.

If any of the above conditions are met, the failure is a potential functional failure. It is then evaluated and compared to the performance criteria in accordance with the plant maintenance rules.

## 8.3. ANALYSING MAINTENANCE FEEDBACK

The failed component or equipment should be fixed and returned to its normal function in a timely manner, based on the criticality of equipment and the plant's priorities. Corrective maintenance of the failed component or equipment should be performed in accordance with the plant's work management process to use resources effectively and to minimize an impact to the plant operation. Corrective maintenance can be categorized into planned corrective maintenance according to a schedule or emergency corrective maintenance requiring immediate repair to ensure safe and continuous operation. The as found condition should be identified and documented during and after corrective maintenance for component type failure trending. If corrective maintenance results from cause determination, then a post-maintenance test needs to be performed to ensure the problem has been resolved.

## 8.4. CAUSE EVALUATION

To prevent recurrence of the failure, cause evaluation should be performed in accordance with the CAP to determine the actions to be taken, and its level depends on the safety and operational significance.

### 8.4.1. Root cause analysis

The first step in the RCA is to assign a qualified individual to lead it, who has been trained in RCA methods and analysis. A team composed of site staff supports the leader and performs the evaluation in accordance with RCA guidance. Once completed, the RCA is reviewed and approved by the assigned supervisor. The approved evaluation is approved by plant management. Management also reviews the RCA to ensure that the fundamental causes have been identified and that the proposed actions will be effective in preventing recurrence of the problem. Once approved by management, corrective actions and due dates are assigned.

### 8.4.2. Apparent cause evaluation

The screening committee assigns the evaluation to a work group with the necessary experience and capability. The supervisor assigns the evaluation task to a qualified apparent cause evaluator. The evaluator should complete the ACE using the guidance provided, usually within 30 days. The ACE is to determine the direct cause of the event, and typically does not generate any corrective actions to prevent recurrence — although if such actions are obvious, they should be included. On completion, the ACE is given to the supervisor for review and approval.

### 8.4.3. Condition evaluation

The assignment follows the same procedure as with the ACE. However, the condition evaluation is to determine what has actually broken or failed, fix only that problem and restore the original functionality. It does not determine the cause of the failure or the extent of the condition; therefore, there are no specific requirements for this type of evaluation. Actions should be very few, with a very narrow scope. On completion, it is given to the supervisor for review and approval. If approved, the evaluation is then included in the process programme documents. It is not necessary to present it to management;

### 8.4.4. No evaluation

When a significance level 4 is assigned, no evaluation activity is conducted. Typically, the screening committee closes the report, provided that sufficient actions have been initiated to remedy the reported problem. If this is not the case, the report is assigned to a supervisor to ensure such actions are initiated and completed according to work priorities.

## 8.5. CORRECTIVE ACTIONS

Outlining the content of Ref. [2] on corrective actions, Gregor and Chockie [33] report that:

"An evaluation is required to determine if the failure was preventable, using the following considerations:

- What existing barriers should have prevented the failure (procedure completeness, procedure implementation, craft training, post-maintenance testing, tag-out restoration, use of operating experience, troubleshooting, unavailability management, and human performance)?
- What barriers should be implemented to prevent recurrence? Consider the risk/benefit of the change.
- What other components are susceptible to this failure mechanism; what is the extent of this condition?
- How did the continuing equipment reliability improvement process miss this?
- Could more frequent implementation of existing preventive maintenance actions prevent recurrence?
- Should the scope of the preventive maintenance tasks be increased?
- Is there an ageing or obsolescence concern that should be addressed in the corrective actions?
- Is additional corrective maintenance needed?

…….

- Are similar components affected by the same problem?"

Troubleshooting may be required to identify the equipment problem and to obtain sufficient information to be evaluated to develop an appropriate set of corrective actions. The troubleshooting includes preservation of all physical evidence of the problem, including quarantining the area, and applying a problem solving process.

Corrective actions should be identified according to root cause evaluation to prevent recurrence of the failure. Some can address more than one cause, and corrective actions should be considered to address root causes, contributing causes, failure mode, symptoms, common mode failures and extent of condition. It may be necessary to implement temporary corrective actions to mitigate the consequences if recurrence cannot be prevented. Actions should be assigned priorities according to their importance and risk of operating if not implemented.

Corrective actions are reviewed by the departments assigned to implement them. If the investigators and reviewers believe the actions are necessary but the department does not agree, recommendations are then presented to senior management for approval and assignment. Corrective actions are tracked and their effectiveness reviewed to verify that the actions prevent recurrence of the failure, and typical examples include the following:

- Design modification or change;
- Revision of SSC classification and maintenance strategy;
- Revision of the periodicity of preventive maintenance activities or changes to the types performed;
- Revision of operating or maintenance procedures;
- Change of a monitoring method;
- Addition of a physical barrier or a safety device;
- Installation of warning devices, signs or signals;
- Training.

### 8.6. PRIORITIZATION

Prioritization of equipment problems is based on plant safety and availability. This activity is performed by a cross-functional team of key management representatives from departments for operations, engineering, maintenance, safety and work planning. Prioritization considers the following [2]:

- Key equipment problem list, including pending problems;
- Owners action plan for specific equipment problems;
- Action plan progress;
- Assessment of the aggregate risk impact;
- Integration of the equipment problem resolution into plant processes.

# 9. CONCLUSIONS

The objectives of this publication are:

(a) To provide a starting point for nuclear power plant operators to improve plant performance, safety and economic competitiveness through maintenance optimization;
(b) To increase capabilities in optimizing maintenance programmes and to share best practices to improve the overall performance and competitiveness of nuclear power plants;
(c) To specify principles for optimizing preventive maintenance programmes and to explore best practices in the light of recent experiences and the current state of technology;
(d) To provide examples of maintenance optimization activities and to compile operating experiences and lessons learned.

A considerable amount of effort was invested to provide the most up to date nuclear maintenance best practices to achieve the above objectives. For those utilities looking to optimize and improve maintenance processes, this publication provides an excellent starting point.

The more detailed case studies, found in the Annex on the CD-ROM accompanying this publication, provide additional information against which to benchmark. After utilities have performed an initial benchmark, they should then benchmark the ‘best in the industry’ to gain additional insights to the benefits and potential pitfall that might result from implementing an optimized maintenance process. Utilities are also encourage to benchmark the best in other industries such as aerospace, chemical processing, oil and gas, and large manufacturing facilities, as these industries often test out new technologies before they are utilized in nuclear power.

Optimized maintenance processes should be a living process that is update periodically to incorporate new regulatory requirements, data, economic realities and new technologies.

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## Annex

## CONTENTS OF THE CD-ROM

The case studies in the Annex have been prepared from the original material as submitted for publication and have not been edited by the editorial staff of the IAEA. The case studies remain true to the original reports submitted by the Member State.

The contents of the CD-ROM are available on the IAEA Publications web site. To download, please visit www-pub.iaea.org/books/IAEABooks

# GLOSSARY

**ageing.** The continuous, time dependent degradation of structures, systems and components due to normal service conditions, which include normal operation and transient conditions. Nuclear power plants experience three kinds of time dependent change:

- Ageing is independent of the operating time of the structures, systems and components. It is a physical phenomenon which involves a change of the physical or chemical characteristics of the material.
- Wear out and degradation increases with the operating time or the number of operations of the structures, systems and components or its applied stresses. It is a physical phenomenon which results in a loss or deformation of material.
- Obsolescence of structures, systems and components (i.e. becoming out of date in comparison with current knowledge, standards and technology).

***ageing management.*** The coordination of existing programmes, including maintenance, in-service inspection and surveillance, as well as operations, technical support programmes (including analysis of any ageing mechanisms) and external programmes such as R&D. Demonstration of ageing specific to the plant are clearly identified and documented in the general description of the integral work to counteract all forms of ageing in the safety analysis report throughout the plant's lifetime.

***ageing management programme.*** Any programme or activity that adequately manages and counteracts the effects of ageing (e.g. maintenance, surveillance, inspections monitoring and assessment, and operation programmes or activities).

***managing ageing mechanisms.*** Include operations according to procedures and technical specifications; chemistry control; environmental control; and operating history, including transient record.

**capacity factor.** The net electrical energy produced during the reference period versus the net electrical energy which would have been generated at maximum net capacity under continuous operation during the entire reference period, expressed in percentage.

**condition monitoring.** Continuous or periodic tests, inspections, measurements or trends of the performance or physical characteristics of structures, systems and components to indicate current or future performance and the potential for failure. Condition monitoring is usually conducted on a non-intrusive basis. It can also be an activity, performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the actual state of an item. Monitoring is distinguished from inspection in that it is used to evaluate any changes in the parameters of the item with time. It can be continuous, at intervals or after a given number of operations. It is usually carried out in the operating state.

**corrective maintenance.** Actions that restore, by repair, overhaul or replacement, the capability of a failed structure, system or component to function within acceptance criteria. It can also be maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.

***deferred corrective maintenance.*** Corrective maintenance which is not immediately carried out after a fault detection but is delayed in accordance with given rules.

***immediate corrective maintenance.*** Corrective maintenance which is carried out without delay after a fault has been detected to avoid unacceptable consequences.

**critical component.** The scoping and identification of critical structures, systems and components determining their functions important to maintaining safety, reliability and power generation.

**emergency (**also **emergent) maintenance.** Work to be completed within a short period (typically 24 hours).

**inspection.** An examination, observation, measurement or test undertaken to assess SSC and materials, as well as operational activities, processes, procedures and personnel competence. Also an examination for conformity by measuring, observing, or testing the relevant characteristics of an item.

**long term operation.** Extending the operation of old nuclear power plants beyond the time assumed that they can be used without major problems (also known as plant lifetime extension).

**maintenance.** The organized activity, both administrative and technical, of keeping structures, systems and components in good operating condition, including both preventive and corrective (or repair) aspects. It is also the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.

**modification.** Combination of all technical, administrative and managerial actions intended to change one or more functions of an item. Therefore, modification is not a maintenance activity.

**obsolescence.** Inability of an item to be maintained due to the unavailability on the market of the necessary resources at acceptable technical or economic conditions. Examples of necessary resources include: sub-items needed to restore the item; tools or monitoring and testing devices; documentary resources; and skills.

**on-line maintenance.** Maintenance carried out on the item while it is operating and without impact on its performance. During this type of maintenance, it is important that all the safety procedures are followed.

**operability.** The ability to keep the plant in a safe and reliable functioning condition, according to predefined operational requirements. Operability is closely related to reliability, supportability and maintainability.

**operation.** Plant operation means minimizing expected degradation of a structure or component through careful operation or use in accordance with operating procedures and technical specifications.

**planned (**also **scheduled) maintenance.** A form of preventive maintenance consisting of refurbishment or replacement that is scheduled and performed prior to unacceptable degradation of a structure, system or component. Scheduled maintenance is also carried out in accordance with an established time schedule or established number of units of use (note that corrective deferred maintenance can also be scheduled).

**plant life management.** Integration of ageing management and economic planning: to maintain a high level of safety; to optimize the operation, maintenance and service life of structures, systems and components; to maintain an acceptable performance level; and to maximize return on investment over the service life of the nuclear power plant.

**predictive (**also **condition based) maintenance.** Form of preventive maintenance performed continuously or at intervals governed by observed condition to monitor, diagnose or trend condition indicators of structures, systems and components. Results indicate current and future functional ability and the nature of planned maintenance and its schedule.

**preventive maintenance.** Actions that detect, preclude or mitigate degradation of functional structures, systems and components to sustain or extend its useful life by controlling degradation and failures to an acceptable level. It can also be maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.

**reliability centred maintenance.** A process for specifying applicable preventive maintenance requirements for the safety related systems and equipment in order to prevent potential failures or to control the failure modes optimally. The reliability centred maintenance utilizes a decision logic tree to identify the maintenance requirements according to the safety consequences and operational consequences of each failure and the degradation mechanism responsible for the failures.

**safety actuation system.** The collection of equipment required to accomplish the necessary safety actions when initiated by the protection system, which is a system that monitors reactor operations and automatically initiates actions to prevent an unsafe or potentially unsafe condition after sensing an abnormal condition.

**safety system.** Ensures the safe shutdown of the reactor or residual heat removal from the core, or limits the consequences of anticipated operational occurrences and design basis accidents.

**structures, systems and components.** A general term encompassing all of the elements of a nuclear power plant which contribute to protection and safety, except human factors. Structures are passive elements (e.g. buildings, vessels and shielding). Systems comprise several components, assembled in such a way as to perform a specific function. Components are equipment (e.g. pumps, valves and heat exchangers) or parts of the equipment.

**work management.** The process by which maintenance, modifications, surveillance, testing, engineering support and any work activities that require plant coordination or schedule integration are implemented.

# ABBREVIATIONS

| | |
|---|---|
| ACE | apparent cause evaluation |
| CAP | corrective action programme |
| CBM | conditioned based maintenance |
| CMMS | computerized maintenance management system |
| EPRI | Electric Power Research Institute |
| INPO | Institute of Nuclear Power Operations |
| KPI | key performance indicator |
| LA | life assessment |
| LCO | limiting conditions for operation |
| LTO | long term operation |
| PHM | prognostic health monitoring |
| RCA | root cause analysis |
| RCM | reliability centred maintenance |
| SRCM | streamlined reliability centred maintenance |
| SSCs | structures, systems and components |

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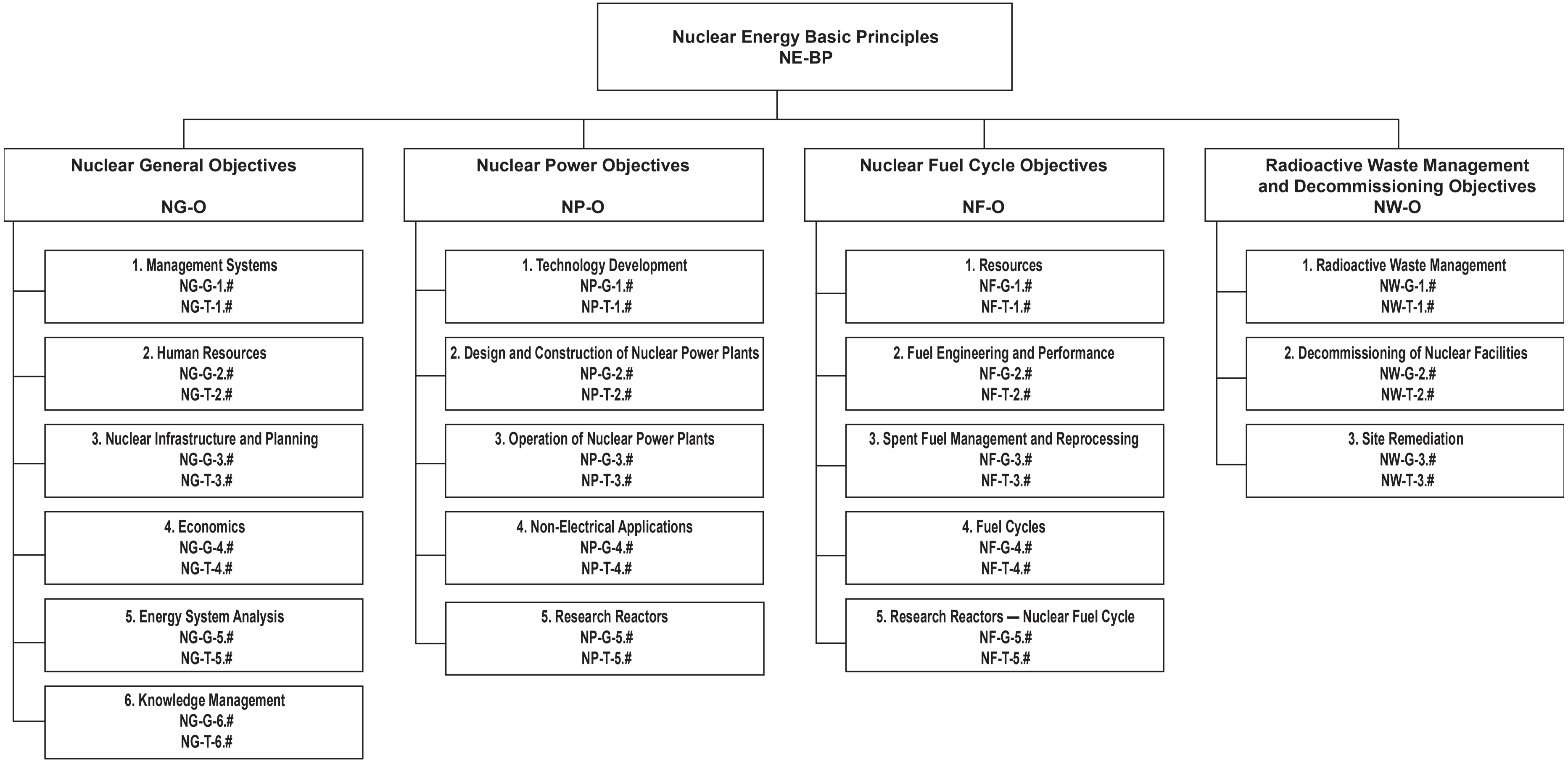


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