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Guidance for optimizing nuclear power plant maintenance programmes

Report prepared within the framework of the Technical Working Group on Life Management of Nuclear Power Plants

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FOREWORD

Current changes in the electricity industry in many countries, such as market liberalization and privatisation processes, have led to a highly competitive market environment. The well managed nuclear power plants (NPPs), with their low fuel costs and permanently declining operation and maintenance costs, are often among the least expensive base load power plants to operate. In a competitive regime this situation encourages, but also forces NPP owners to further reduce their operation and maintenance costs, but of course without compromising safety which is, as always, a paramount consideration.

Since the primary purpose of NPP maintenance is to allow nuclear operators to use all those functions necessary for safe and reliable power production by keeping them available, an adequate maintenance programme is essential. The maintenance programme covers all preventive and remedial measures, both administrative and technical, necessary to identify and mitigate degradation of a functioning system, structure or component, or restore the design functions of a failed system, structure or component to an acceptable level. Maintenance activities include servicing, overhaul, repair and replacement of parts and may, as appropriate, include testing, calibration and in-service inspection.

As plants strive to reduce costs and increase equipment reliability, it becomes necessary to be sure that the right tasks are being performed on the right equipment. Many differing techniques are used to decide what work to do and many of these techniques create unnecessary expenses and take equipment out of service at the wrong times. When equipment fails to function or causes system or plant outages, one of the first impulses for corrective actions is to increase the number of predefined maintenance tasks (preventive maintenance) and increase the frequency of the tasks that have already been established. Many of these actions may cause more failures and decrease the overall plant reliability.

A systematic evaluation approach to establishing what maintenance tasks are to be performed on which systems, structures or components and at what frequency, however, can optimize the use of resources (maintenance costs, personnel doses, equipment and tools, competent personnel, etc.) allocated for maintenance and plant availability. In addition, a systematic method of prioritizing which systems should be worked on and what combination of systems can be worked on at the same time. This approach can be used in establishing a preventive maintenance programme and for the optimization of the ongoing maintenance programmes. The process seeks to make the best use of condition-based maintenance where unnecessarily costly maintenance actions and associated maintenance error induced failures can be avoided. If a probabilistic risk assessment has been performed, its result can be used to help define the important systems and components. This optimization process can lead to the achievement of nearly all maintenance targets concerning safety, reliability and cost.

The objective of the project on Optimization of Nuclear Power Plant Overall Performance within the IAEA's subprogramme on Nuclear Power Planning, Implementation and Performance is to systematically improve the overall performance and competitiveness of nuclear power plants with due regard to safety through the application of technological and engineering best practices, including quality assurance/quality management, and the utilization of relevant databases. As an integrated part of this project, the Technical Working Group on Life Management of Nuclear Power Plants deals with the managerial and engineering aspects of NPP maintenance; its optimization process, with special regard to the importance of condition monitoring in maintenance strategies; and the contribution of maintenance to managing lifetime of operating NPPs.

The current publication was developed within the above framework with the objective of collecting and analyzing proven maintenance optimization methods and techniques (engineering and organizational) in Member States. Annexes 1–10 of this TECDOC comprise selected papers on maintenance optimization presented during the preparation of this document.

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

CONTENTS

1. INTRODUCTION

The primary purpose of a NPP maintenance programme is to ensure that equipment and components are 'fit for purpose' and provide the required functionality to enable safe and reliable power production. The maintenance programme covers all the preventive and remedial measures, both administrative and technical, necessary to identify, prevent and/or mitigate degradation of a functioning structure, system or component (SSC), or to restore the design functions of a failed SSC to an acceptable level. The range of maintenance activities includes servicing, overhaul, repair and replacement of parts and may include, as appropriate, testing, calibration and in-service inspection [1]. Typical relationships among these basic components and types of maintenance are shown in *Figure 1-1*.

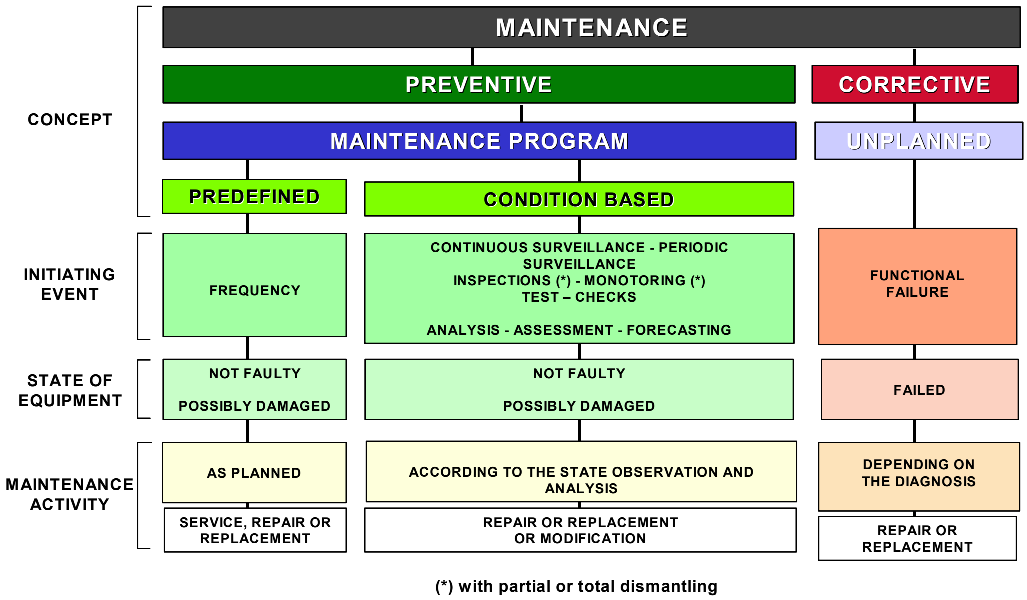

Figure 1-1. Strategic maintenance relationships.

Historically, NPP maintenance programmes were based on manufacturers' recommended inspection intervals where often the function and availability of the component or systems were never considered. This basis for maintenance programmes find utilities with a large maintenance catalogue of predefined tasks, where these tasks are based on a preventive maintenance (PM) approach. This has resulted in large numbers of predefined tasks associated with each system, with many of these tasks not improving the system or component reliability and often reducing the reliability and availability by introducing the increased probability of maintenance induced human errors.

Often with a non-defined or un-optimized maintenance catalogue the number of corrective maintenance (CM) activities is significantly disproportionate to the comparison against the number of PM activities on a system. It is possible to extrapolate a simple comparison between PM versus CM tasks. This PM to CM ratio should be determined for either or both working-hours or cost and these values should be compared on a periodic basis to measure how things are progressing.

Traditionally, when systems malfunction or components fail, the reactive approach is that the numbers of predefined (basically PM) tasks are increased and the inspection interval of existing tasks is decreased (or as equivalent, the inspection frequency is increased) to remedy such occurrences. Experience can now demonstrate that by reacting with an increase in predefines and or a decrease in the inspection interval of existing predefines can actually cause an increase in component failures and thus a decrease in component reliability and, as a consequence, a decrease in the overall plant availability.

The need for NPPs to optimise their maintenance process can be attributed to a number of factors. A significant driver is the revolutionary changes that are taking place with electricity market in many countries. Deregulation and the privatisation of NPPs have led to a highly competitive market environment. As NPP operators strive to reduce costs and increase equipment reliability, it becomes necessary to ensure that the right tasks are being performed on the right equipment at the right time. Many differing techniques are used to decide what type of maintenance will be applied, however, this selection requires that the decisions be based on a proven methodology with an effective process to avoid unnecessary plant unavailability and down time.

In addition to the pressures applied by cost related drivers, issues relating to equipment reliability or concerns relating to safety related SSCs may drive the optimisation process. Additional motivation may be applied by the need to maximize the asset life cycle (in fact, the operational life of the component and plant).

Maintenance optimization is performed principally to achieve two major business goals:

1. To improve ‘critical’ plant availability that will result in an enhanced safety margin, improved plant availability and increased load factor.

2. To optimize costs by undertaking the right maintenance on the right SSC at the correct interval.

This describes the goal of performing focused maintenance tasks on critical or significant equipment before it fails, but not before the maintenance is needed. This philosophy also means that non-critical equipment or equipment that is not commercially significant may be allowed to run until it fails with only minimal maintenance activity prior to the failure.

The effective application of maintenance optimization and the techniques described in this technical document can lead to the optimization of resource use (maintenance costs, personnel doses, equipment, materials and spare parts usage, etc.) allocated for maintenance and availability of plant. In addition, a systematic approach to the prioritization of SSCs is required to establish the combination of systems/sub-systems that can be worked on at the same time.

This approach can be used to establish a robust maintenance programme, which facilitates the optimization of the forward maintenance plans. The process seeks to make best use of different maintenance techniques where unnecessary costly maintenance actions and associated maintenance induced failures can be avoided. The introduction of probabilistic risk assessment (PRA) into the maintenance programmes ensures that critical systems and components are accurately established.

The optimization process can lead to the achievement of many maintenance targets, including safety, reliability and optimized costs. In addition NPP life management is also considered as a major business driver and the optimized maintenance programme has significant bearing to this including extending the operational life of the plant and its components.

NPPs can monitor their performance before, during and after the optimization by following the trends of a set of indicators. These indicators can be used by members of the maintenance organization to show how the plant performance in various areas compares to the performance of other similar NPPs, other plants in their company or to themselves when reviewed over time. In order for this comparison to be valid, it is imperative that these indicators represent realistic measures of the performance of the maintenance organization and provide leading indicators of performance in a timely fashion.

The purpose of the current technical document is to provide guidance for optimizing maintenance at NPPs by relating internationally recognized good practices and methods in these areas. It is not intended that the content of this guideline replace the good judgement and experience of the individual NPP operators. The technical document is intended to be used by maintenance professionals, plant engineering staff, plant management and other knowledgeable individuals responsible for the successful operation of a NPP maintenance organization. Individuals in regulatory organizations, vendor and consulting companies and other organizations that support NPP maintenance may also find this technical document valuable.

Preceding documents in this field are the IAEA-TECDOC-928 entitled "Good practices for cost effective maintenance of nuclear power plants"[2], IAEA-TECDOC-960 on "Regulatory surveillance of safety related maintenance at nuclear power plants" [3] as well as IAEA-TECDOC-1138 on "Advances in safety related maintenance" [4].

2. OBJECTIVES OF NPP MAINTENANCE OPTIMIZATION

2.1. MAINTENANCE OPTIMIZATION PROCESS

The maintenance optimization is recommended to see as a process, which is driven by the imbalance between maintenance requirements (legislative, economic, technical, etc.) and resources used (people, spares, consumables, equipment, facilities, doses, etc.). The process includes details as to how selection of maintenance techniques is achieved to enable the most appropriate type of maintenance is performed on SSCs and at what periodicity to achieve regulatory requirements, maintenance targets concerning safety, reliability and plant availability and cost. The techniques used as part of the maintenance optimization process also carry out health checks against components that are not problematic and seek to increase the interval of inspection or to redefine the type of maintenance applied to the SSC. The NPP maintenance optimisation process is continuously improved by learning experiences. *Figure 2-1* shows the flowchart of the optimization process.
Maintenance optimization is not a fashion, but a useful tool in the establishment of an effective maintenance programme based on a systematic approach to achieve plant reliability, which encompasses safety and a cost effective approach to operating the business. Before reviewing the maintenance of any SSC, background effort is necessary to establish the existing data on the SSC. This information should consist of:

- PM programme vs. CM programme – maintenance catalogue at system level
- Materials costs
- Resource costs
- Plant unavailability
- Function.

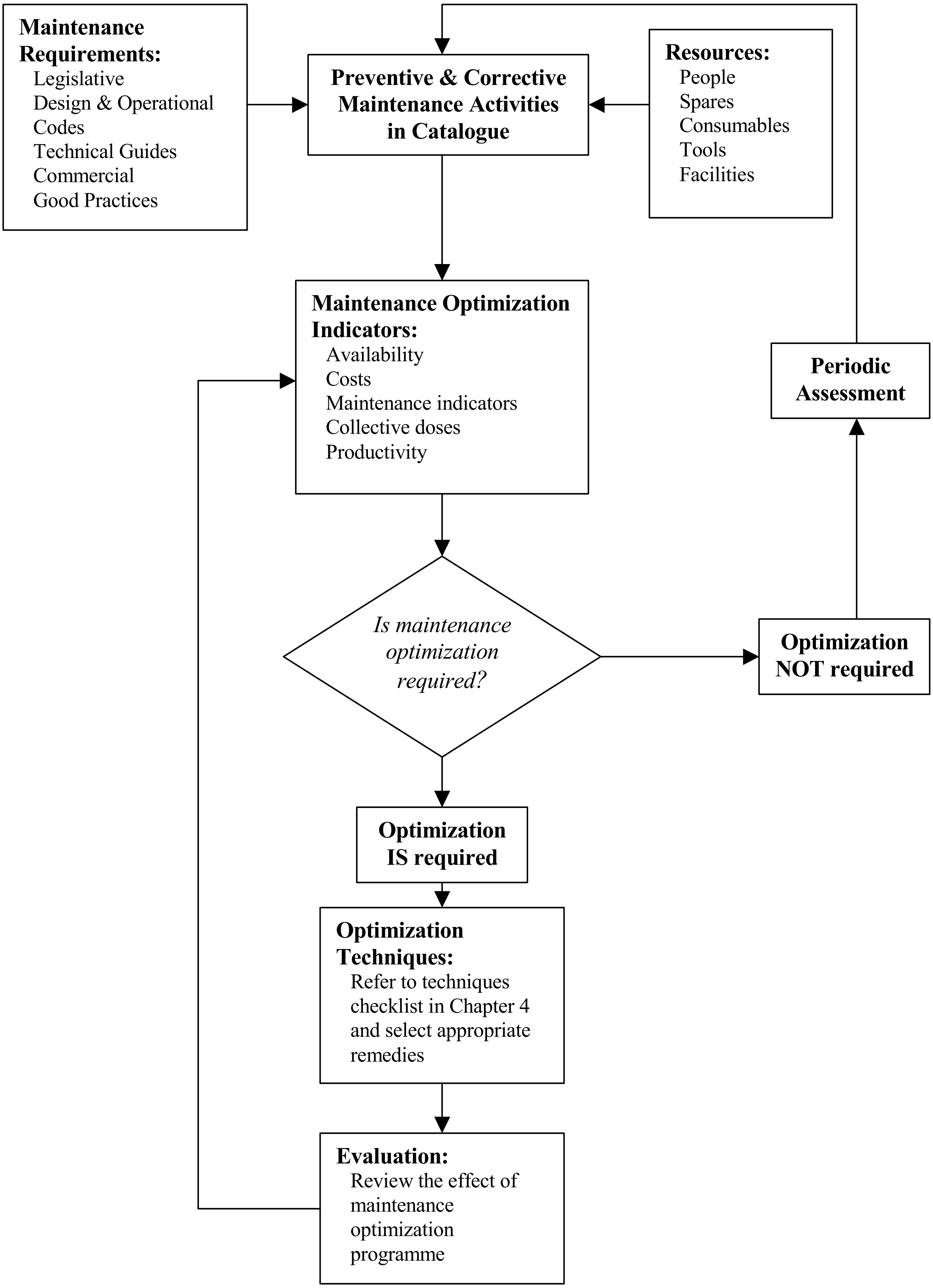

Figure 2-1. The maintenance optimization process.

This approach is necessary to prioritize the systems that are to be optimized. This is also necessary to enable the correct selection of the tool to be used to carry out the optimization process. This initial step provides the benchmark for the indicators that will be used to recalculate the benefit of the maintenance optimization programme.

Consideration must be given to the following key aspects:

- *Safety/Risk significance*
  Relative importance of a SSC based upon probabilistic and deterministic information.

- *Regulatory requirement*
  There may be a regulatory requirement to undertake intrusive inspection of a component due to the regulatory burden that exists due to original design or the inability to mitigate any consequences of failure.

- *Reliability/Availability*
  Ensuring that the plant is available if called upon for service, either during any phase of plant start up or availability as a critical component during the post trip cooling regime.

- *Maintenance targets*
  Establishing realistic targets for maintenance

- *Costs*
  It is becoming more necessary to analyze total costs and optimize.

2.2. ESTABLISHING THE PROGRAMME GOALS

It is essential to define the goals to establish the critical elements for success in all the phases of the maintenance optimization programme. These goals help staff maintain a sense of purpose and enable clear focus on areas of work. *Table 2-1* shows typical goals of a maintenance optimization programme.

These goals should not stifle any evolvement of the maintenance optimization programme. There is always the unknown as to which tools may be used and how they will be implemented during the course of the development phase, however, clear objectives will provide the solid foundation upon which the maintenance optimization programme is established.

2.3. MANAGEMENT COMMITMENT AND SUPPORT

Management commitment and support are an essential success element in all the phases of the maintenance optimization programme, including the budgetary approval and maintaining an overall view of the benefits that are to be optimized by a successful implementation of a maintenance optimization programme. The clear managerial support for the programme will avoid any soft approach by the plant systems groups and will demonstrate the programme is sponsored by the management team.

2.4. ORGANIZATION, ROLES AND RESPONSIBILITIES

The maintenance optimization team should be structured with full time staff and bring in key area staff as and when the systems where they have a particular knowledge are being optimized. The roles and responsibilities of the team should be clearly defined such that core staff provides the necessary infrastructure including the specialist skills associated with various maintenance techniques. This will enable the team to focus on the maintenance optimization programme goals and use the systems based knowledge and skills to focus on specific area of the programme.

TABLE 2-1. TYPICAL GOALS OF THE MAINTENANCE OPTIMIZATION PROGRAMME

Goal	Key Target
Safety	Prevent safety system challenges through failure prediction
	Reduce radiation exposure
	Reduce risk to core damage
	Reduce risk due to uncontrolled release of coolant.
	Reduce risk due to uncontrolled radiological release
Reliability	Prevent critical equipment failures
	Improve equipment performance
	Reduce unplanned load reductions
	Minimize risk due to safety and protection system testing
	Early detection of ageing mechanisms
Cost Reduction	Reduce overall maintenance costs
	Improve plant efficiency
	Optimize outage schedules
	Eliminate unplanned loses
	Optimize spare parts usage
	Achieve a return on investment for all maintenance techniques employed
Availability	Reduce unavailability of equipment due to maintenance activities
	Reduce unavailability of components due to failure
	Improve safety system performance indicators
	Maximize unit availability
	Optimize outage duration
Technology Enhancement	Use of enhanced maintenance techniques
	Enhanced use of non intrusive maintenance techniques

2.5. SYSTEM SIGNIFICANCE

It is necessary to establish the safety significance of the system. By this it is necessary to look at the impact of the system to the NPP's ability to be safe and its ability to operate at full capacity. This will determine both the need for caution and techniques available for optimization. It may be necessary to receive regulatory approval to undertake the implementation of the maintenance optimization programme in an area that is highly significant with respect to nuclear safety.

2.6. ESTABLISHING CURRENT PERFORMANCE

A plant system register has to be established. This process enables assessment of which components fall within which systems. Systems should be defined to include major components, i.e. pumps, motors, breakers, heat exchangers, motor or air operated valves, instruments, cabling etc., which perform a specific function in the safety/operation of the NPP. No specific component can fall into two systems where there are interfaces between systems and it should be clearly defined which components fall into which systems.

Having established the baseline detail, this can then be used to prioritize the maintenance optimization process. Plant maintenance history data is an essential data element for this process. Poor plant history can sometimes assign the wrong priority to systems and in some cases specify an incorrect optimization tool, for the system.

2.7. ESTABLISHING THE MAINTENANCE COSTS OF THE SYSTEM

The actual cost of maintenance of a plant item should include:
- Technician working hours spent on PM and CM
- Proportion of team leaders, engineering and other support staff
- Cost of materials including consumable items
- External spend – outage contractors.

Should the cost data be unavailable, it will be necessary to use an alternative assessment method. This can be established by appropriately apportioning budget costs against components within systems. From a cost comparison basis, the benchmark costing process must be used as the review cost comparison value.

3. MAINTENANCE OPTIMIZATION REQUIREMENTS AND MAINTENANCE PERFORMANCE INDICATORS

3.1. MAINTENANCE OPTIMIZATION REQUIREMENTS

The cost of effectively planning, implementing and evaluating maintenance optimization is considerable and it is necessary to offset this cost with the benefits that are achieved following effective implementation. This cost must be underpinned by a clear requirement to implement such a rigorous change programme.

3.1.1. Strategic company business objectives

NPP owners must operate their plants safely, reliably and economically to be able to compete and secure a market for their product. Owners are considering all aspects of ‘plant life cycle management’ as they establish a solid platform in which to operate. Some of the main issues being considered are operational, technical, engineering, maintenance, spare parts management, strategic spares management, obsolescence and human resource implications.

The capital cost of a NPP is such that owners are looking at maximizing the value and contribution of the asset in an approach to gain maximum output from existing plants. This approach also considers ‘remaining’ operating life with the introduction of asset management techniques where extension to the operating phase is considered.

The current state of the deregulated markets provides an environment where NPPs compete with conventional forms of generation. This market place has a tendency to secure lowest costs generators, with penalties for not achieving generation targets.

3.1.2. Regulatory influences and requirements

The increased market influences have underpinned the regulatory requirement to operate NPPs within their safe operating envelope and to demonstrate the safety margins contained within their operational safety cases. Regulatory requirements, however, may often lead to increased maintenance costs in the maintenance of NPPs without any direct increase in safety. Government authorities impose requirements, which are aimed at protecting employees, the public or the environment. Over the years, in many Member States, the number and cost of these requirements has grown substantially.

It has been demonstrated that some of these requirements are sometimes redundant or conflicting. In some case plant owners who adopt a conservative approach when implementing the regulations create unnecessary requirements. It has also been demonstrated in a number of Member States that these requirements can be modified or deleted with negligible or no impact on either safety or the environment. It is recognized by the regulator that an optimized maintenance programme if effectively implemented using the recognized techniques and methodology results in an improved availability of safety critical components and also supporting systems of lower nuclear safety significance.

However, the use of the different maintenance techniques available based on non-intrusive inspection/assessment instead of the former intrusive process may not be consistent with the requirements for physical assessment especially where degradation mechanisms may be apparent and influential in any refurbishment decision as part of life extension.

All optimization programmes should seek to assure the regulatory requirements, but with the ability to reduce the regulatory burden. In order to reduce the regulatory burden while maintaining adequate safety margins one should first identify excessive regulatory requirements.

It can be important when the regulatory authority tends to include more and more components or systems under regulatory control. The advent and application of Maintenance Rule of the United States Nuclear Regulatory Commission (US NRC) is an example of controlling effectiveness and performance. Appendix 1 presents the text of the US NRC Maintenance Rule.

3.1.3. Commercial drivers

The cost of undertaking any change in the programme needs careful assessment and measuring against the tangible benefits that are stated. The market forces significantly influence the acceptability of high financial investment. The cost of undertaking a maintenance optimization programme is significant. To achieve a successful maintenance optimization programme, the 'total' process must be applied, see *Figure 2-1*, if the real benefits of a maintenance process are to be achieved.

In establishing the time scale and the budget for undertaking such a programme, there must be managerial commitment to the total budget for undertaking the process. Member States have experienced budget constraints during such major optimization programmes and this has resulted in a less effective programme, which fails to deliver the overall benefits claimed at inception.

Commercial drivers, which may influence decisions to embark upon an integrated maintenance optimization programme, are as follows:

- *Current market price of electricity*
  This is the price that the generator is paid for their electricity. This price is then compared against internal generation cost and can be used to influence the decision to instigate improvements such as maintenance optimization. This figure can only be used as a realistic indicator if the electricity price becomes a constant. This value may have limited use in a non-competitive environment.

- *Necessity of cost reduction*
  In the competitive market environment, plant owners may be looking at a cost reduction exercise. These costs fall into two areas, fixed and variable. Maintenance costs fall into the variable costs and hence the overall maintenance costs can be seen as an area for optimization. However, this publication emphasizes that maintenance optimization should not be used purely as a means of cost reduction, as there are circumstances where maintenance costs may rise as a result of an effective maintenance optimization programme.

  Typical triggers for cost reduction efforts are:

  - Imbalance between resources and work
  - Using resources in an inefficient way
  - Market competition
  - Overall production charges, etc.

3.1.4. Market influences

Over the last decade, in a number of Member States there has been a move from 'nationalised' ownership of electric utilities whose objectives were aligned towards full and stable employment. This move has created private enterprise where the utilities operate within competitive markets with pressure to reduce costs, staff numbers and the engineering workload. The focus now is on meeting the targets set by shareholders rather than governments. Some Member States have not seen such market changes, however, these changes are indicative of the direction of the world's energy market.

This market climate has resulted in a change of focus in the operation of NPPs where previously tolerated unreliable and low load factors can no longer be accepted in the current market conditions. This change has required a shift in the operational culture at NPPs and the requirement to internally assess performance based on the design output of the NPP and the economic benefit of increased availability and higher load factors.

3.1.5. Good practices

Member States have been optimizing their processes for a number of years. This has resulted in the sharing of the successes and failures or weaknesses of particular improvement programmes. By the nature of the IAEA, it is an objective for the sharing of good practices and the safe and effective use of nuclear energy including generating electricity. This publication seeks to include examples of experiences of selected Member States who have implemented maintenance optimization programmes. These are contained within the appendices.

3.2. MAINTENANCE PERFORMANCE INDICATORS

3.2.1. Lessons learned from historical maintenance programmes

Within the Member States, there is a wide range of different approaches to maintenance, many of which have been based on the recommendations of original equipment manufacturers or based on some preconceptions or conservative interpretations to the regulatory requirement.

The techniques currently practiced for maintenance optimization programmes effectively challenges the historical regulatory approach where 'more is better'. The previous requirement to apply additional controls, collate more detailed reports or collect additional data is being challenged by demonstrating the availability of plant with the use of Reliability Centered Maintenance (RCM) techniques.

It should also be considered the impact of the reactive approach to equipment failures as well as creating unnecessary regulatory burden has often been accompanied with reduction in interval for intrusive maintenance practices. This reaction of plant owners to incidents and failures has often been focused on a generic remedy and has often failed to focus on the specific causes of an incident.

However, there are opportunities to reduce work scope following sufficient operating history and experience that demonstrate similar causes with recognized and approved corrective actions.

3.2.2. Maintenance performance indicators

Before embarking on maintenance optimization, it is necessary to establish the overall performance of the plant and to test the maintenance performance indicators. The following maintenance performance indicators are recommended to be considered by the IAEA's Quality Assurance Code and Safety Guide 50-C/SG-Q [5]:

- Unit forced outage rate,
- Availability of the same component in other systems,
- Availability of safety systems,
- Unplanned automatic scrams,
- Radiation exposure to personnel conducting maintenance activities,
- Injuries and accidents to personnel conducting maintenance,
- Maintenance backlog (CM and PM),
- Overtime worked by personnel involved in plant maintenance,
- Assessment results in maintenance areas.

Member States have established internal 'indicators/metrics' to assess their effectiveness. These are based upon recognised world standards. An example of maintenance indicators can be found in EPRI document 'Metrics for Assessing Maintenance Effectiveness.'

For the purpose of assessing performance to establish a benchmark for undertaking a programme of maintenance optimization, the following key performance indicators should be considered:

- *Overall energy availability factor against the planned one*
  Is the plant performing to the planned availability and output criteria? If not can this be attributed to the maintenance process by identifying failure of key components or systems? Can these component failures be attributed to 'intrusive maintenance techniques' that have resulted in post maintenance defects or the need for rework?

- *Unplanned losses*
  Has the plant had to operate at reduced power levels due to maintenance related problems? This can be the unplanned power reduction as a percentage of the total expected generation or a total of the unplanned lost generation. Allowances can be made for reductions due to environmental effects or other uncontrollable causes. What are the other reasons of reduced energy availability? E.g.: outage duration, unavailability of critical components, inadequate maintenance programme, ageing of plant components, regulatory burdens.

- *Plant capacity factor*
  How does the above compare with similar plant type? Is the actual capacity as designed? Is the plant providing the amount of electricity to the transmission grid that it was intended to? If not, is this reduced capacity is due to maintenance related problems?

3.2.3. Maintenance statistics

To implement an effective maintenance optimization programme, it is necessary to establish the current position and assess the overall maintenance effectiveness of the existing programme. These measures will form the basis of the review of the maintenance optimization programme as well as providing a health check for the maintenance process. The following questions are recommended to assess and answered:

- *'Emergent work' as a percentage of planned maintenance work*
  Emergent work is defined as work that must be completed in a specified short period, typically 24 hour, from identification. How does this compare to previous reporting periods?

- *Trends in PM vs. CM*
  The value of this comparison should reflect the positive impact of PM on the failure of components. CMs that are performed to correct degraded conditions for equipment that is still serviceable should not be included. The ratios can be separated into the various maintenance areas, i.e. systems and sub-systems or component level and can be broken down into discipline-based statistics e.g. I&C, mechanical, and electrical, for focusing the optimization effort. How does this compare to like types of plant?

- *Actual outage duration compared to planned one*
  What is the reason for the difference if any? Can this be compared to like type of plants? This should reflect the actual duration as compared to the planned duration. Both positive

and negative variations should be examined as shorter than planned outages could indicate a weakness in the planning process.

- *Quantity of reworks*
  Any repeat of a work task because the original work was not done correctly should be included as rework. A useful calculation is “rework as a percentage of all work”. A repeat of work within the PM interval can be a candidate for being rework. A final determination should be made by responsible maintenance personnel to determine if it is rework or PM intervals are not correct.

- *The PM/CM backlog*
  Of more significance, what is the trend? Is the backlog increasing or is it decreasing? If it is increasing, an evaluation of the maintenance work process is warranted. Work orders generated while on line that require an outage should not be included as backlog.

- *The maintenance staff overtime level*
  What is the % to full time hours. Hours worked during exceptional periods such as trip recovery are excluded.

3.2.4. Other performance measures

There are other measures, which should be considered as part of the overall maintenance process. These measures are human factor measures and not direct correlation of a maintenance task.

- *Average collective dose compared to international statistics*
  A higher than average collective dose could indicate an area where remedial action is required, e.g. dose planning, work arrangement and control, work procedures, personnel training, radiation protection.

- *Industrial accident rate compared to standards*
  A higher than standards value may indicate an area that requires action.

- *Quantity of generated waste*
  Both radioactive and non-radioactive (scaffold, lagging etc.) waste should be considered. Particular attention should be paid to solid waste such as protective clothing, gloves, rags, etc. generated during the maintenance activity. Reusable insulation and scaffolding are areas for improvements.

- *Gap of work achieved against work planned*
  This count of the work performed as a percentage of the total work planned during a specific period, one week is typical.

- *Overall maintenance costs compared against like plants*
  This indicator should be used carefully as costs are often differently interpreted. In addition, benchmark values are difficult to achieve. The most useful comparisons are among the plants in the same company.

- *Technical specification/operating rule non-conformance statistics due to maintenance activities*

The number of violations of Technical Specifications in a reporting period that is attributable to maintenance. A high value clearly indicates that regulatory requirements are not sufficiently taken into account during the preparation and/or the implementation of maintenance activities.

4. KEY ELEMENTS OF MAINTENANCE OPTIMIZATION PROGRAMMES

There are key elements that require careful consideration when introducing a maintenance optimization programme. It is necessary to identify these key enablers and understand what they are and how they will impact upon the maintenance optimization programme implementation and can determine the overall success of the programme.

4.1. MANAGEMENT ASPECTS OF MAINTENANCE OPTIMIZATION PROGRAMMES

4.1.1 Asset life management

Plant owners are now looking at nuclear power as a commercially viable safe and reliable means of generation of electricity. The need for environmentally friendly generation of energy has created an environment where governments are now considering nuclear energy to play a part in an environmentally friendly balanced energy policy.

As part of the commercial equation, it is necessary to consider operational life extension. Through effective maintenance programmes, inspection techniques can now indicate the impact that degradation and damage mechanisms have on the operational life and by assessing such inspection results the options can be explored which influence the operational strategy of the plant. This process is the principle of asset life management, whose main elements are as follows:

- Identify SSCs critical to safety and production. This process can be achieved by the critical structure/system/component selection.
- Identify degradation mechanisms.
- Monitor degradation (in-service inspection, condition monitoring.)
- Take appropriate actions to increase residual life. Identification of degradation mechanisms may result in deployment of additional protection, which has the arresting function.
- Reduce stress factors/cycles to increase residual life. Where possible assess the operational load factor and consider different operating strategies as part of life extension.
- Assess residual life of SSCs.
- After limits are reached repair/replace – components replaced based on reaching service limits.

- Replace components that have become obsolete – management of obsolescence is an integral part of asset life management. However, this process must take account of reliability data in conjunction with the different component failure patterns.

- Replace components with better/improved versions with reduced maintenance requirements and increased life time reliability.

4.1.2. Assessing the requirement to undertake maintenance optimization

The purpose of maintenance optimization is to improve the business. The typical business drivers are improved safety, reliability, load factor, output and to reduce maintenance costs. The strategic drivers may also include extending the operational phase of the life cycle. For any maintenance optimization programme to be effective, the data collection and analysis is fundamental. Data sources may be plant operating history, plant maintenance history, system drawings, engineering judgement, operator experience etc.

The diagram in *Figure 4-1* demonstrates the need to establish structures, systems and components to enable easy identification of areas, which may give the greatest benefit such that maximum benefit may be obtained whilst understanding the significance and associated risk.

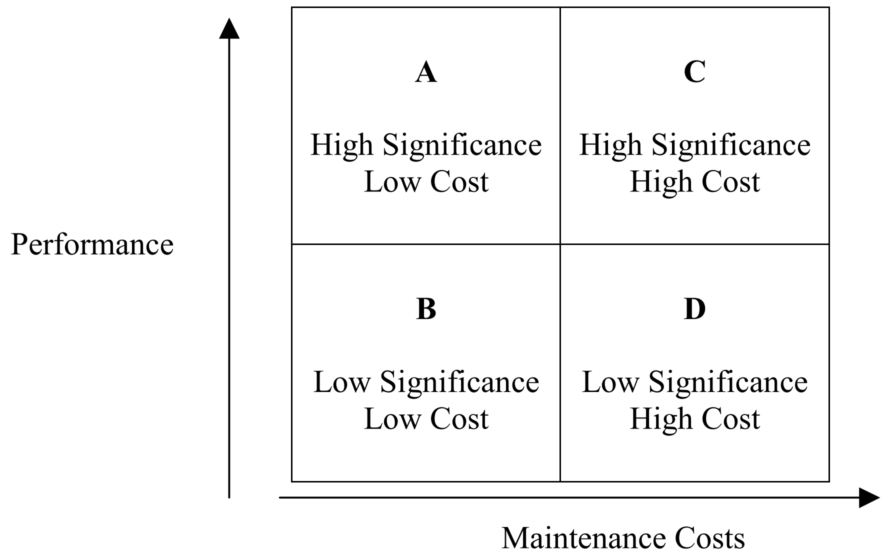

Figure 4-1. Cost/benefit diagramme.

The maintenance performance indicators can be viewed individually and used to determine the requirement to optimize. These can however be considered as a composite set. It is suggested that it is easier to make a realistic evaluation by treating each indicator separately and avoid trying to gain any overall performance measure by any complex algorithm or formulae which joins the indicators to produce an inferred measurement.

4.1.3. Assessment approach for maintenance optimization

After establishing a maintenance optimization assessment team, review of operating and maintenance histories and documents has to be carried out. It may include interviews with operators, system engineers, maintenance technicians and if appropriate contractors and where applicable original equipment manufacturers to establish factual information on the system. Also the ‘as found’ current state of reliability/maintenance costs etc. has to be established.

The next step is to perform a gap analysis which means comparison of the measures against ‘as required’ targets. The targets may not just be financial or cost, but may be safety, reliability or asset life management. As a cost reduction programme compare the maintenance catalogue in its before and after state. Establishing the maintenance performance indicators pre maintenance optimization and comparing these to the maintenance performance indicators post maintenance optimization can achieve this.

The need for review of the maintenance programme, based on reliability, will create a platform for effective asset life management programmes.

Having identified a system that would benefit from a maintenance optimization programme, the next stage is to select the review methods that would be most appropriate to optimize the maintenance catalogue. The decision on which method to use should be based on the following criteria:
- Safety importance
- Energy availability factor
- Cost

Define the ‘Threats’ to optimization which include management commitment, funding, etc.

4.2. METHODOLOGIES FOR SUPPORTING MAINTENANCE OPTIMIZATION PROGRAMMES

4.2.1. Preliminary activities – Critical component selection

A key element of maintenance optimization is to manage the work scope. This is undertaken by establishing a list of critical SSCs. To establish the list of critical components, NPPs should use the operating experience and knowledge base of a team approach consisting of field specialists. Sending specific questionnaires where a structured review is carried out is an accurate data collection method. Alternatively, structured interviews can be undertaken.
It is usually within an NPP for one or more documents to exist that specifically identify a plant inventory systems. These lists may be regulatory documents or could be part of a plant system inventory or drawings listing.

Structure/System/Component attributes for a critical system list may consist of the following:

- It is safety related,
- It is not safety related but it mitigates an accident or transient,
- It could prevent safety related SSC from fulfilling their function,
- Its failure could cause a plant trip,
- Its failure could result in a plant transient,
- It is used in unplanned operational events/emergency procedures.

4.2.2. Reliability centered maintenance

RCM is a process to specify preventive maintenance requirements for critical components and equipment in order to prevent potential failures or to control failure modes. This method uses logic tree analysis to identify maintenance requirements according to safety and operational consequences of each failure. By assigning priorities to components, this method establishes optimized maintenance programmes and provide necessary technical basis. Maintenance resources are then used in effective manner focussing on functional reliability of these components

RCM provides a methodology aiming at identifying the critical components for assuring a high level of safety and reliability therefore optimizing the resources to concentrate on critical components and accord less priority on other components. Past experience is used in justifying the decisions made based on the RCM method.

Application of RCM for optimizing plant maintenance involves answering the following questions:
1. What are the functions and the associated performance requirements of the selected component, considering its present operating environment?
2. In which ways does it fail to fulfill its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to prevent each failure?
7. What should be done if a suitable preventive task cannot be found?

The RCM process

The focus of RCM is in the functionality and reliability of each component in supporting the functions of the system. The resulting maintenance plan is prioritized based on the functionality and optimized based on a combination of experienced and postulated component failures. Maintenance tasks are developed to monitor or maintain only those components whose failure would interrupt an important system function.
All other components are run to failure when it is safe and economical to do so. In addition to a documented basis for the resulting “optimum” maintenance tasks, the process also produces a set of recommended changes to the existing maintenance program.

Engineering judgement is part of the RCM process, which is a considered engineering input based on component performance/availability and a continuous evaluation of maintenance activities. The engineering judgement collects and uses data from maintenance databases, performed maintenance tasks, original equipment manufacturer data and engineering experience.

The benefits of RCM can be summarized as follows:

- Concentrate maintenance resources where they will do the most good.
- Eliminate unnecessary and ineffective maintenance.
- Devise the simplest and most cost-effective means of maintaining equipment, or testing for degradation, focusing on predictive or condition monitoring activities, where applicable.
- Develop a documented basis for the maintenance program.

- Make use of plant maintenance experience when determining PM tasks and frequencies.
- Provide a greater synergy between Operation & Maintenance teams.

The logic for the RCM process is shown in *Figure 4-2.*

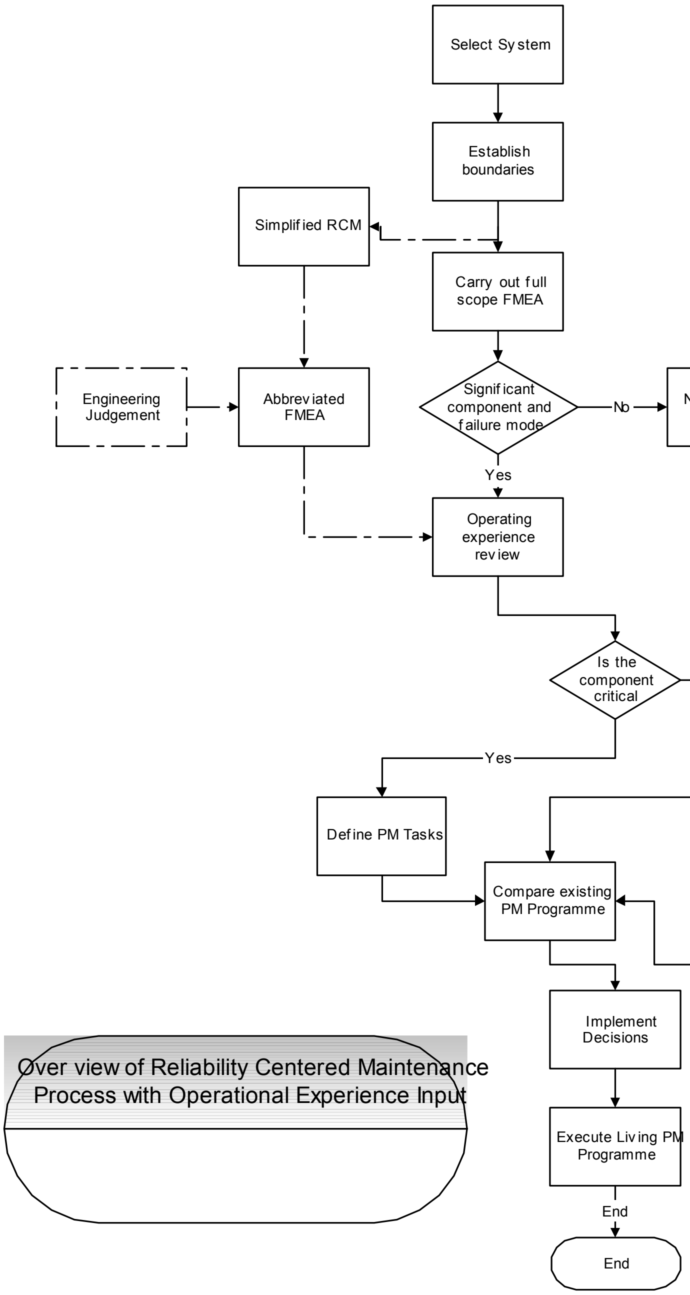

Figure 4-2. Overview of the RCM process.

RCM analysis

The identification of key functions involves specifying those functions that are essential to plant operation and safety. Only the important functions go through the critical analysis, while all the components that support the non-important system functions go through the non-critical analysis. This process allows the analyst to list multiple failure modes for a specific component and only identify the dominant plant effects. If the component is determined to be critical the analyst identifies the appropriate failure causes and the applicable PM tasks.

Components that are initially optimized in the critical analysis but are identified as non-critical will get evaluated again during the non-critical analysis. Most standard RCM processes have individual entries for each component failure mode with local, system, and plant effects identified. The RCM technique can significantly reduce the amount of time required to perform both the failure modes and effects analysis (FMEA) and logic tree analysis (LTA) portions of the analysis.

There is opportunity for adopting a simplified approach where SSCs are of a lesser significance. This approach uses an abbreviated version of the FMEA tool that is less costly to implement.

The non-critical analysis provides an evaluation using economic criteria for those components that were identified as functionally non-critical in the critical analysis. In the non-critical analysis, several questions are used to determine the cost-effectiveness of providing some level of PM vs. allowing the component to run to failure. These are:

- Is there a high repair/replacement cost if the component is run to failure or is there excessive corrective maintenance performed on this component?
- Is there a simple cost-effective task that can be performed to prevent component degradation?
- Can failure of this component induce other failures?
- Is there an increased personnel or environmental hazard if the component is run to failure?
- Is this component required to perform or in support of other recommended maintenance activities?

During the critical and non-critical analysis steps, CM data from the plant is reviewed. Interviews are held with plant operations and maintenance personnel to obtain additional information regarding component performance and maintenance. This data appears in the analysis in the form of assumptions which are verified during the plant reviews of the analysis.

Plant reviews and interviews are also used to verify the classification of a component as critical or non-critical, the existence and performance of PMs, and the potential for design changes to reduce CM or PM or improve the ability to perform PM.

Combining the tasks as they appear in the criticality analysis, the non-critical analysis and the existing maintenance program creates the comparison of the RCM analysis results with the existing maintenance programme. For each component, the existing and recommended tasks are compared. A determination is made to:

- "Add" a new task from the critical or non-critical analysis when there is no existing task;
- "Retain", "Delete", or "Modify" the existing task based on the critical or non-critical analysis;
- Identify redundant existing tasks.

- Implementation of changes takes into account a number of factors, including:
- Existing PM bases (code, insurance or regulatory requirements);
- Obtaining approval for changes to any required tasks, if determined to be cost-effective;
- Pioritizing changes based on task frequency, impact on plant availability and reliability and the impact on maintenance cost reduction.

Implementation of RCM

For implementation of RCM, a multi disciplinary team is formed. This team then selects a system and lists equipment and components in that system, carries out FMEA and assign the priority for each of the equipment and component. The methodical approach makes use of special forms, decision diagrams and decison worksheets. The method defines and analyses functions and performance standards, functional failures, failure modes, failure effects, failure consequences and preventive actions. Critical and non-critical components are defined.

Performance of RCM on any plant system entails a coordinated effort between plant personnel and the analyst. The plant personnel involved include craft, engineering, operations personnel, as well as those directly responsible for the project (core team). Typically, the core team make-up consists of personnel from engineering, operations, planning and maintenance (including supervisors, foremen and craft personnel). These personnel are empowered to make decisions and implement changes in the maintenance programme (change existing PM tasks, add new tasks, purchase condition monitoring technology/equipment, etc.).

In order to obtain the most thorough and accurate information about the system under analysis, the analyst must solicit input from these various organizations. For this to happen, the project manager must coordinate schedules such that, for the most favorable impact on the project, the personnel most knowledgeable are available for analysis reviews (criticality, task selection and task comparison) and maintenance interviews. This can, at times, be a substantial investment of human resources into the RCM analysis; therefore, it is vital that the reviews and interviews be conducted efficiently, without sacrificing quality for speed.

The core team will also know which personnel are "expert" on a particular system, and will ensure that these experts are available to participate in the analysis. Most often, the analyst will perform the analysis with predetermined steps identified as review points. Usually, these points are the criticality analysis, task selection and task comparison.

The analyst with the core team and any other personnel as appropriate usually conducts the reviews. Quite often, the analyst reviews the criticality analysis with only a representative from operations. This is acceptable, as criticality is a functional determination based on the effects of failure on the operation of the plant. However, the criticality review and determination should involve all members of the core team, as this will ensure that all members of the group understand the reasoning behind a component's criticality. Task selection and task comparison, however, require full core team participation in the reviews.

4.2.3. Risk-informed maintenance

Maintenance optimization can be based on a risk-informed approach, where the consequential impact is considered against the principle objectives of safe, reliable and cost effective operation. A risk-informed approach to maintenance optimization decision-making represents a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus the maintenance organization's attention on maintenance issues commensurate with their importance to safety and generation.

Using this risk-informed approach, definition of all activities for securing component functions can be achieved as follows:

Effort for monitoring, inspection and maintenance	~	Risk to safety or generation	x	Consequences of Failure

The risk-informed decision can be shown on a diagram of risk versus consequences. On *Figure 4-3* risk increases in the vertical direction and the consequences increase in the horizontal direction. For high-risk components, a comprehensive PM approach is suggested. For low risk, low consequences components, the decision may be to run them to failure or to perform minimum PMs because the component has a high cost, is difficult to access, or has other importance. For low risk high consequences components a simple, comprehensive PM programme is suggested.

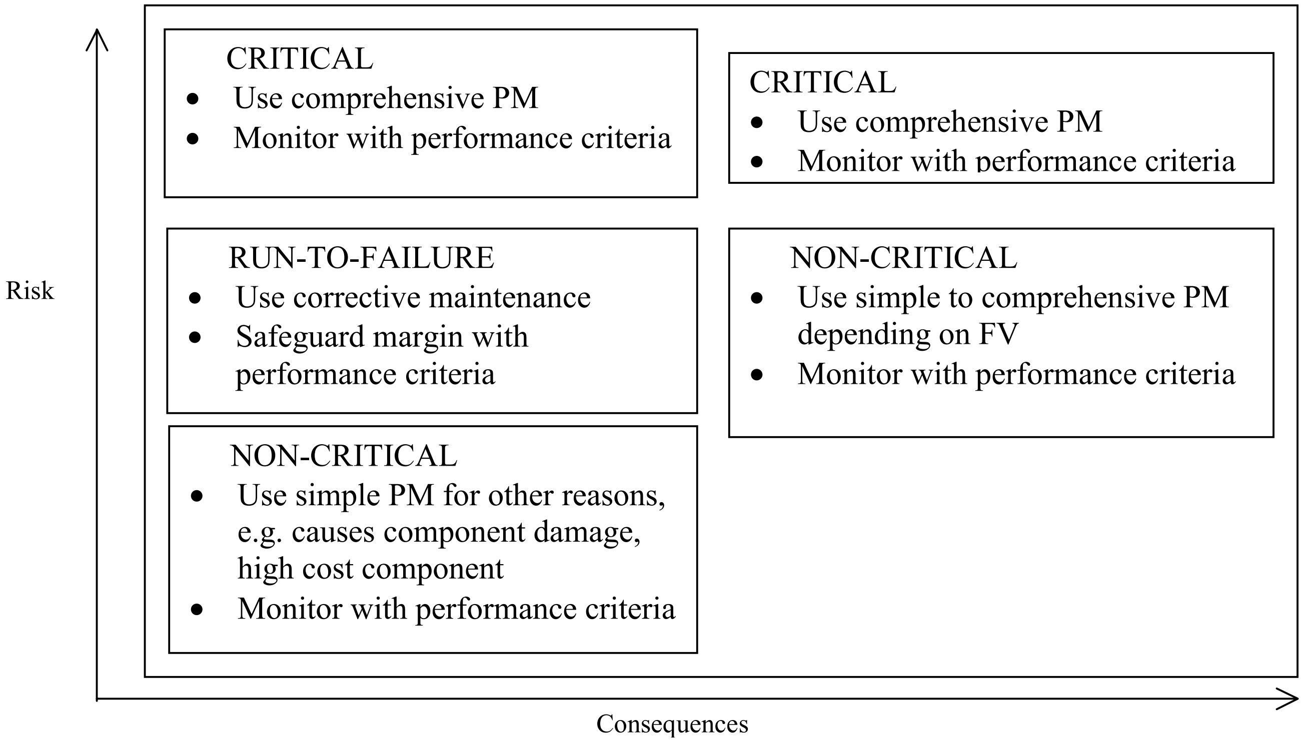

Figure 4-3. Risk informed maintenance objectives diagram.

This enables the plant/components significance to be established based on a risk to the operation of the plant. In order to establish the criteria for monitoring, inspection and maintenance activities for components relative to safety and availability of the plant as a whole, it is necessary to determine the significance of each constituent component.

This is done probabilistically in a fault tree analysis where the result of the analysis demonstrates this component significance. If it is sufficient to know qualitatively if a function is necessary or not, FMEA can be performed. The effort to be invested in monitoring, inspection and or maintenance and also analysis to undertake the optimisation depends on the results of the probabilistic analysis.

4.3. TECHNIQUES AND TOOLS FOR UNDERTAKING MAINTENANCE OPTIMIZATION PROGRAMMES

4.3.1. Time based maintenance

Interval Approach

Time based maintenance is the process where the maintenance interval is based around a calendar and has little relationship to the condition of the item. Time based activities are usually components of high safety significance where the risk associated with component failure cannot be tolerated.

Running Approach

As part of an integrated optimized maintenance catalogue, it is also deemed acceptable to use a maintenance technique that is based on running hours and not on any other criteria. Running hours is another mean of establishing a time basis for maintenance. Running hours/days etc are the driver for the maintenance activity.

It is possible to deploy maintenance based on running hours for some standby critical plant. However, as part of the operational tours, it is necessary to ensure that the plant is available by a process of testing where possible. Plants, which cannot be tested as being fit for purpose due to disturbances to the operating system, should not be based on running time maintenance.

Generally there is sufficient supporting evidence to select an appropriate maintenance interval based on the function, availability and historical/failure/degradation information.

4.3.2. Condition based maintenance (CBM)

CBM is one of the integrated approaches to adopting an optimized maintenance strategy. The process of intrusive maintenance is mitigated against the condition of the equipment/component and is not time driven. Instead of carrying out maintenance on a time-based interval we would be carrying out maintenance based on SSCs' condition and ability to perform their function. CBM can be used for all classes of component (both safety related and production related).

CBM or predictive maintenance (PdM) is a process where the condition of the component is monitored using either installed equipment or mobile test equipment. With generic failure, components typically show to patterns of failure such as catastrophic, in-service degradation (wear out) etc. Typical component failure happens between the failure patterns. A majority of components demonstrate different characteristics as they approach imminent failure but the component is still capable of delivering its desired function

To start the CBM the following steps may be followed:

- Determine the component to be monitored,
- Determine its significance,
- Determine the failure mechanisms,
- Determine the parameters to be monitored for each of the component,
- Develop and fix limiting values for each parameter, (alarm & action),

- Determine the frequency of monitoring,
- Monitor the condition as per the schedule, (manufacturers performance data),
- Intervene and correct when ever alert levels are reached,
- Add more condition monitoring tools to obtain accurate information.

The PdM process requires the collection of diagnostic information and process measurements from a family of technologies. An "equipment and technologies" matrix is established for each individual plant containing the recommended technologies, data collection frequency, and equipment performance inspections and observations. The equipment and technology matrix becomes the basis for selection and investment in new diagnostic technologies.

A PdM programme is a structured process. It routinely collects, analyzes, trends and stores data from selected plant equipment to assess their condition. When any of the measured parameters are determined to be unacceptable, an investigation is initiated to analyze equipment condition. Once an undesirable condition is determined a work request or condition report may be generated to correct or document equipment condition.

To sustain continuous improvement of PdM implementation it is necessary to provide periodic review and coaching of the plant PdM Teams. This enables problems to be established and discussed and solutions to be identified for troublesome equipment problems. This aids in sustaining the work culture of an effective PdM program.

PdM programs recently implemented in industries began automating the analysis and reporting process through the use of the equipment and technology matrix and establishing a condition status report. Test results are entered into the spreadsheet and colour coded green, yellow or red based on the severity level.

The PdM team meets each month to review the technology assessments and assign a single condition status to each component on the spreadsheet. While effective, this process is resource intensive to consolidate the copious data from all the disparate sources of data to perform the assessments. It also does not provide a historical perspective by facilitating learning from past assessments, or from sharing experiences with others.

4.3.3. Tools for condition based maintenance

In this chapter a list of potential condition monitoring technologies, as examples, will be briefly presented [6]. Each technology is limited to specific types of equipment and is useful in identifying specific types of problems. Each technology also provides different short and long term economic benefits.

- *Vibration analysis*
  Vibration analysis is used to determine the operating condition of rotating equipment (e.g. turbines, motors, pumps), identifying developing problems before they cause serious failures and unplanned shutdown. Problems can include deteriorating or defective bearings, mechanical looseness, worn or broken gears, misalignment or unbalance. Vibration monitoring can be periodic utilising portable vibration probes and data collectors and may also be done with a permanently installed system. A continuous vibration monitoring system has the capability to assist the vibration specialist in not only tracking but also diagnosing vibration related problems.

- *Shock pulse method*
  The shock pulse meter using piezoelectric accelerometer detects the mechanical shock waves caused by the impact of two masses, without being significantly influenced by factors such as background vibration and noise. The method can be used to identify subtle

changes in any rolling element bearing condition or lubrication, prior to substantial bearing deterioration or failure (e.g. rotating machinery with anti-friction bearings, motors, large pumps, turbines).

- *Oil analysis*
  Oil analysis can be used on machines that have a circulating oil system (e.g. turbines, generators, hydraulic systems, diesel engines) to identify the condition of fluids and lubricants, and determine if they are suitable for continued use or should be changed. It usually consists of periodically sampling selected oil streams for detection of particulates or contaminants that can indicate bearing failure, overheating, or other machine problems. Analysis of the oil samples is usually done off-site, and trending of the data over time will indicate the component condition, and can be used to predict the optimum time and way of corrective actions.

- *Wear debris analysis and ferrography*
  Wear debris analysis can be used to determine the type, location and severity of component wear occurring within the lubrication or hydraulic system. It is based on periodic samples or in-line measurement. The debris analysis will allow to determine the number, size, composition and shape of ferrous and some non-ferrous wear particles.

- *Acoustic leakage monitoring*
  A compressed gas or fluid forced through a small opening creates turbulence with strong ultrasonic components on the downstream side of the opening, which is detectable with a scanning ultrasound device. In steam, air or pneumatic, hydraulic and vacuum systems, the acoustic monitoring enables to identify leaks, improper seal or gasket installation. Poorly seated valves can also be detected. The leak detection systems can be permanently installed with function of alarming, trending and approximating the leak location, or simple portable devices.

- *Thermography*
  Thermographic analysis using infrared scanners provides a non-contact temperature indication for components such as bearings, motors,, electrical connections, or conductors. This information can be particularly important in electrical equipment where circuits and connections may show no visible signs of deterioration until moments before a complete failure. Thermography can also detect cracks or deterioration in roof or wall insulations as well as in concrete structures, which can increase heat loss. A termography programme usually utilises a walk-around survey procedure.

- *Computer modelling for Erosion/Corrosion analysis*
  The computer simulation of erosion/corrosion is applied to predict the state and well timed replacement of sections of pipe made of carbon steel. The computer simulation takes account of:
  - size and geometry of pipes
  - type of medium
  - parameters
  - chemical composition
  - time

- *Visual inspection*
  Visual observation, listening and touching are the oldest and most common condition monitoring techniques. In many cases human observation helps to identify a problem that was undetected by other predictive techniques or maintenance inspections. This can

include loose, visibly worn or broken parts, oil leaks, chattering gears or hot bearing housings. Typical applications include less critical or balance of plant machines.

- *Plant performance monitoring*
  Performance monitoring or trending can be used on any equipment or component with permanently installed instruments which measure pressure, temperature, flow, rpm or electrical power consumption. It can also include readings taken by portable instruments on less critical components. The real value of performance trend data is to confirm a problem identified by other monitoring techniques, and provide further information on the location or seriousness of the problem. The advantage of performance trending is that the data is usually readily available and relatively inexpensive to collect.

4.3.4. Integrated maintenance management systems

It is now common for NPP operators to deploy integrated maintenance management systems as a core function within their processes. The advent of modern systems enables significant benefits to be claimed based on the integrated approaches now available. However, such systems can be deployed without achieving the benefits offered by such systems. This is largely due to the lack of core data necessary to achieve 100% of the benefit offered.

The hub of the maintenance management system is the management of maintenance activities and the different operational and maintenance tasks that are necessary for compliance management.

- *Full plant inventory*
  It is essential to be able to determine individual systems and components either individually or in a parent/child relationship. It is not necessary to move the detail to the extent where sub components are listed as individual items as these will be detailed within the materials listing e.g. a pressure transmitter is the lowest level of identification necessary within the plant inventory, it is not necessary to identify the components within the pressure transmitter such as the bourdon tube assembly, micro-switches etc.

- *List of all activities (PMs & CMs)*
  There is a requirement to store information about corrective orders and any other type of periodic maintenance. This ability should include resource (materials and labor both direct and indirect,) activity data, periodicity, owner etc.

- *Assess availability of resources*
  A resource availability should be available which details the daily resource pool of different crews. This system should take account of core training activities, sickness and leave.

- *Scheduling system*
  For the creation of daily schedules which take account of the Probabilistic Risk Assessment (PRA) for plant maintenance and the available resources within crews.

- *Integrating materials management with maintenance tasks*
  Spare parts management is an integral part of maintenance optimization and can be used to assess the materials/spare parts usage of the different components. Generally the data can be linked by a vendor code to the plant component. This enables accurate costing

against PMs/CMs or by SSCs. The usage patterns can also be used by extrapolation to infer ‘type faults’.

- *Computerized PM management*
  The integrated maintenance management system can be interfaced to bespoke scheduling packages such as P3/Artemis or MS Project being but a few of the available systems. This enables detailed scheduling to be undertaken showing any critical links to interactive activities or operational requirements. Generally these systems enable detailed plans based on high level plans and can be effectively used for system outages. They enable resource tracking, progress tracking, cost analysis, materials tracking and enable users to develop work breakdown system and cost breakdown system for overall process management.

5. BENEFITS

By undertaking a maintenance optimization further benefits may be expected as a result of the effective execution of the programme.

5.1. DIRECT BENEFITS

- *Improve plant safety*
  Optimizing maintenance programmes ensures that the ‘correct’ type of maintenance is undertaken at the optimum interval and on components that have safety significance.

- *Improved component/system reliability*
  An optimized maintenance programme ensures that the correct maintenance is undertaken on specific SSCs. This will lead to a reduction in down time and post maintenance defects.
  The use of on-line monitoring, performance monitoring, improved maintenance techniques, complemented by improved training and competencies will contribute to a reduction in component failures.

- *Cost management*
  The effective implementation of an optimized maintenance programme can deliver resource savings. To ensure maintenance programmes are optimized, it is necessary to implement a continuous review of the maintenance programme such that the measures are checked regularly and the appropriate maintenance techniques are applied within the life cycle.

  By reviewing all existing maintenance activities the techniques used will establish the base costs of undertaking maintenance tasks, establishing the cost of activities (activity based costing), this can be used as a more accurate indicator for maintenance optimization.

- *Save time/do more*
  Reducing the maintenance on components that are lower graded and replacing resource intensive activities with more appropriate maintenance techniques. This will release resource to undertake more significant components maintenance.

- *Improved planning and scheduling*
  The optimized maintenance catalogue will assign an accurate activity priority, making work scheduling more effective.

- *Less waste – environmental management*

The volume of the maintenance tasks requiring consumable items and creating radioactive waste can be reduced, thus resulting in an overall year on year reduction of contaminated waste. This can also apply to non-contaminated waste. There can be a year on year saving on consumable such as non re-usable lagging materials.

- *Reduce collective dose*
  The elimination of low priority maintenance tasks and more appropriate maintenance techniques will result in a reduction in the collective dose.

- *Increased unit energy availability*
  The maintenance optimization process can reduce the high risk of scram or reduced output. This may never be eliminated, but there will be increased justification for undertaking such activities.

- *Reduction in emergent work*
  The maintenance optimization process will reduce emergent work through application of the most appropriate maintenance technique.

- *Improved justification*
  The maintenance optimization process uses techniques to establish the type of maintenance and the safety significance of the plant component. This coupled with the costing information, enables a clearer justification to be made as to why the management decisions are made on a day to day basis.

5.2. INDIRECT BENEFITS

- *Improved maintenance culture*
  Maintenance optimization will generate a greater level of staff involvement in core decision-making and will result in ownership of the process being transferred to a lower level.

- *Communication and awareness*
  The maintenance optimization process is a very powerful vehicle for change. It therefore increases staff awareness of the business need to optimize processes and brings with it a sense of business awareness and familiarization of the maintenance techniques.

6. EVALUATION

To assess the effectiveness of the maintenance optimization programme, it is necessary to evaluate the overall performance. This evaluation process may be undertaken at any time during the maintenance optimization programme as either a health check or can be carried out on completion of the programme.

As part of the definition phase of the maintenance optimization programme, an assessment of the maintenance performance indicators will have been carried out. During this process, either specific indicators will have been used or a selection from the table of indicators.

The evaluation process should be undertaken to compare the following:

Test	Source Information
1	Original maintenance performance indicators vs. maintenance performance indicators [MPI] post maintenance optimization programme
2	Maintenance performance indicators post optimization vs. expected maintenance optimization indicators

Figure 6-1 shows a flow chart of maintenance optimisation evaluation.

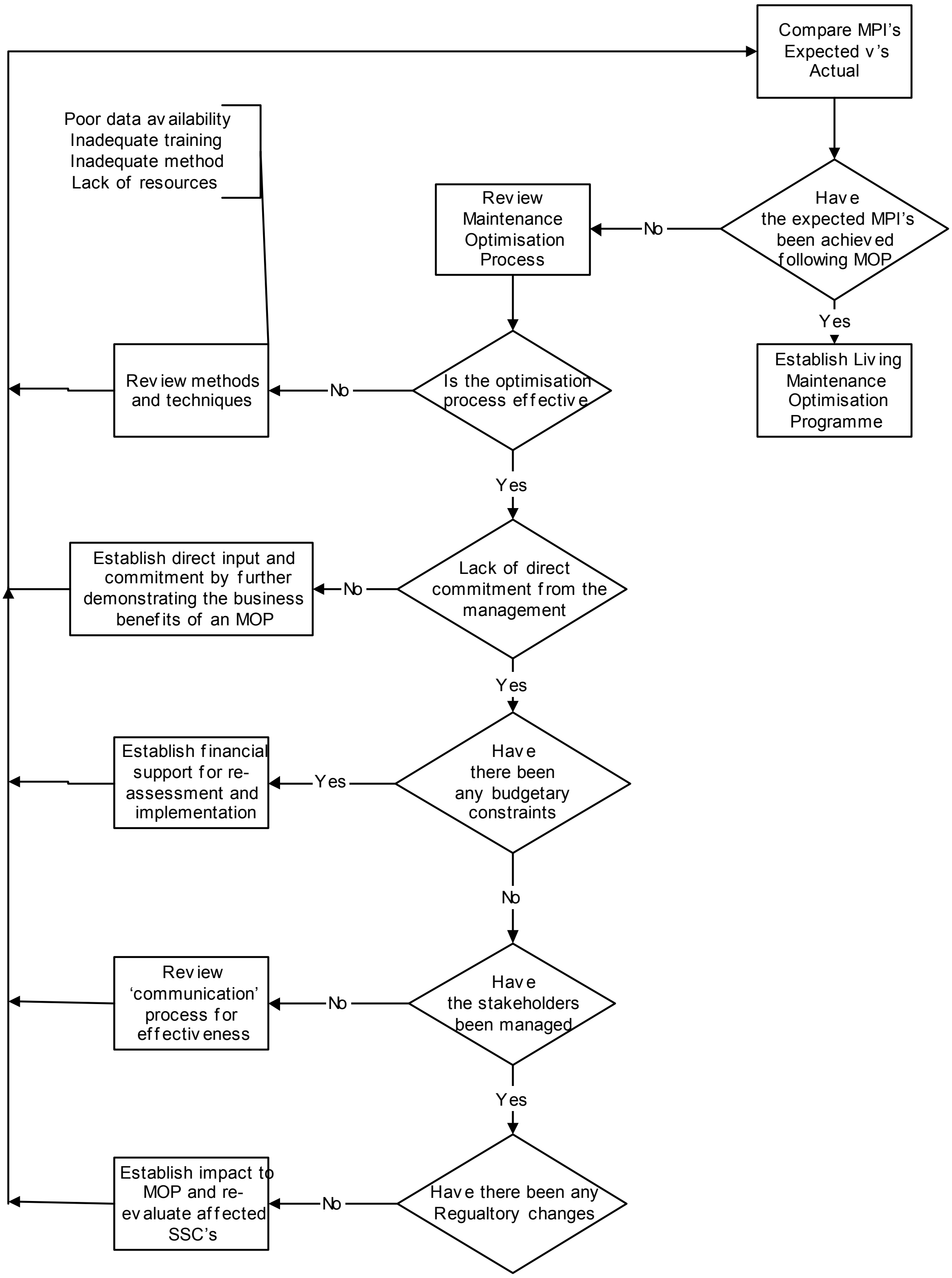

Figure 6-1. Evaluation process.

Appendix 1

THE US NRC MAINTENANCE RULE

10 CFR §50.65 Requirements for monitoring the effectiveness of maintenance at nuclear power plants.

(a)(1) Each holder of a license to operate a nuclear power plant under §§50.21(b) or 50.22 shall monitor the performance or condition of structures, systems, or components, against licensee-established goals, in a manner sufficient to provide reasonable assurance that such structures, systems, and components, as defined in paragraph (b), are capable of fulfilling their intended functions. Such goals shall be established commensurate with safety and, where practical, take into account industry-wide operating experience. When the performance or condition of a structure, system, or component does not meet established goals, appropriate corrective action shall be taken. For a nuclear power plant for which the licensee has submitted the certifications specified in §50.82(a)(1), this section only shall apply to the extent that the licensee shall monitor the performance or condition of all structures, systems, or components associated with the storage, control, and maintenance of spent fuel in a safe condition, in a manner sufficient to provide reasonable assurance that such structures, systems, and components are capable of fulfilling their intended functions.

(2) Monitoring as specified in paragraph (a)(1) of this section is not required where it has been demonstrated that the performance or condition of a structure, system, or component is being effectively controlled through the performance of appropriate preventive maintenance, such that the structure, system, or component remains capable of performing its intended function.

(3) Performance and condition monitoring activities and associated goals and preventive maintenance activities shall be evaluated at least every refueling cycle provided the interval between evaluations does not exceed 24 months. The evaluations shall take into account, where practical, industry-wide operating experience. Adjustments shall be made where necessary to ensure that the objective of preventing failures of structures, systems, and components through maintenance is appropriately balanced against the objective of minimizing unavailability of structures, systems, and components due to monitoring or preventive maintenance.

(4) Before performing maintenance activities (including but not limited to surveillance, post-maintenance testing, and corrective and preventive maintenance), the licensee shall assess and manage the increase in risk that may result from the proposed maintenance activities. The scope of the assessment may be limited to structures, systems, and components that a risk-informed evaluation process has shown to be significant to public health and safety.

(b) The scope of the monitoring program specified in paragraph (a)(1) of this section shall include safety related and non safety related structures, systems, and components, as follows:
(1) Safety-related structures, systems and components that are relied upon to remain functional during and following design basis events to ensure the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, or the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposure comparable to the guidelines in §50.34(a)(1), §50.67(b)(2), or §100.11 of this chapter, as applicable.
(2) Non afety related structures, systems, or components:
(i) That are relied upon to mitigate accidents or transients or are used in plant emergency operating procedures (EOPs); or
(ii) Whose failure could prevent safety-related structures, systems, and components from fulfilling their safety-related function; or
(iii) Whose failure could cause a reactor scram or actuation of a safety-related system.

(c) The requirements of this section shall be implemented by each licensee no later than July 10, 1996.

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GLOSSARY

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 per cent.

energy availability factor:
The ratio between the amount of energy available to be produced during a period versus the maximum amount of energy the plant could have been able to produce during the same period.

unplanned capability loss factor:
Unplanned capability loss factor is the percentage of maximum energy generation that a plant is not capable of supplying to the electrical grid because of unplanned energy losses (such as unplanned shutdowns, forced outages, outage extensions or load reductions). Energy losses are considered unplanned it they are not scheduled at least four weeks in advance.

risk informed approach:
Philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety.

***condition monitoring*:**
Continuous or periodic tests, inspections, measurement or trending of the performance or physical characteristics of SSCs to indicate current or future performance and the potential for failure. Condition monitoring is usually conducted on a non-intrusive basis.

***inspection*:**
An examination, observation, measurement or test undertaken to assess SSCs and materials, as well as operational activities, processes, procedures and personnel competence.

***maintenance*:**
The organized activity, both administrative and technical, of keeping SSCs in good operating condition, including both preventive and corrective (or repair) aspects.

***corrective maintenance*:**
Actions that restore, by repair, overhaul or replacement, the capability of a failed SSC to function within acceptance criteria.

***preventive maintenance*:**
Actions that detect, preclude or mitigate degradation of a functional SSC to sustain or extend its useful life by controlling degradation and failures to an acceptable level.

***periodic maintenance*:**
Form of preventive maintenance consisting of servicing, parts replacement, surveillance or testing at predetermined intervals of calendar time, operating time or number of cycles.

planned maintenance:
Form of preventive maintenance consisting of refurbishment or replacement that is scheduled and performed prior to unacceptable degradation of a SSC.

predictive (condition based) maintenance:
Form of preventive maintenance performed continuously or at intervals governed by observed condition to monitor, diagnose or trend a SSC's condition indicators; results indicate current and future functional ability or the nature of and schedule for planned maintenance.

reliability centered 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 RCM 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.

item important to safety:
An item that is part of a safety group and/or whose malfunction or failure could lead to radiation exposure of the site personnel or members of the public.

protection system:
System which monitors the operation of a reactor and which, on sensing an abnormal condition, automatically initiates actions to prevent an unsafe or potentially unsafe condition.

safety actuation system:
The collection of equipment required to accomplish the necessary safety actions when initiated by the protection system.

safety related item:
An item important to safety which is not part of a safety system.

safety system:
A system important to safety, provided to ensure the safe shutdown of the reactor or residual heat removal from the core, or to limit the consequences of anticipated operational occurrences and design basis accidents.

safety system support features:
The collection of equipment that provides services such as cooling, lubrication and energy supply required by the protection system and the safety actuation systems.
structures, systems and components:
A general term encompassing all of the elements (items) of a NPP which contribute to protection and safety, except human factors. Structures are the passive elements: buildings, vessels, shielding, etc. A system comprises several components, assembled in such a way as to perform a specific (active) function.

ABBREVIATIONS

CBM	condition based maintenance
CM	corrective maintenance
FMEA	failure modes and effects analysis
I&C	instrumentation and control
LTA	logic tree analysis
MPI	maintenance performance indicator
MOP	maintenance optimization process
PdM	predictive maintenance
PM	preventive maintenance
PRA	probabilistic risk assessment
NPP	nuclear power plant
RCM	reliability centered maintenance
SSC	system, structure and component

Annex 1

WORK OPTIMISATION — A FASHION OR A USEFUL TOOL?

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Abstract. Since the early days of the commercial nuclear power, the energy market within many countries has evolved, introducing the need for reliable operation and production of energy sources at a more competitive price. In UK in the '80s a government owned company was established to created a change in the operational culture within the industry such that the nuclear power plants could be proven to be safe, reliable and a cost effective alternative to fossil generation. A programme was launched contained many improvement techniques and culture changes along with remedying many of the outstanding technical and engineering problems with the AGR plants, including optimization of the maintenance programmes. The purpose of this paper is to look at the overall business requirements for embarking upon such an optimisation of nuclear power plant maintenance programmes, considering the benefits and discussing what an optimisation programme cannot achieve.

1. INTRODUCTION

Since the early 'hay-ho' days of the commercial nuclear power programme, the energy market within many countries has evolved. This silent evolution has introduced the need for reliable operation and production of energy sources at a more competitive price.

The United Kingdom has 3 generations of nuclear plants that are still operational, with the earlier 'Magnox' reactors approaching end of life, the AGR's many of which are at mid-life point and a single PWR unit at Sizewell B.

The early days of the nuclear power programme in the United Kingdom saw the 'driver' being 'engineering excellence' with many different designs of NPP being submitted by a large number of suppliers. The nationalised supply industry supported a balanced energy policy; where nuclear was seen as a means of diversification within the energy portfolio.

The effectiveness and efficiency of the nuclear power plants was masked by the overall availability of supply and the effectiveness provided by the central electricity generating board's balanced energy sources.

The change in government in 1979 was accompanied by a policy for the privatisation of the many of the nationalised industries, including the 'electricity supply industry' (ESI), which consisted of fossil, renewable and nuclear plants.

During the second term of government for the conservative party, a white paper was presented before the house to provide the necessary legislation for privatisation of the 'ESI'.

During the preparation for the privatisation, a last minute change of policy excluded the nuclear plants from the 'floatation' due to a concern within the 'financial institutions' (the city) that the nuclear stations were neither reliable or a cost effective means of supply of electricity.

This sudden change resulted in the government forming a wholly owned company to operate and maintain the nuclear power plants. The main purpose of this new company was to created a change in the operational culture within the industry such that the nuclear power plants could be proven to be 'safe, reliable and a cost effective alternative to fossil generation.

Nuclear electric embarked upon a programme of investment and change, to realise the targets set by the government and with the potential future privatisation of the AGR's and the PWR considered as a realistic target.

The programme contained many improvement techniques and culture changes along with remedying many of the outstanding technical and engineering problems with the AGR plants.

One of the programmes deemed an 'enabler' to improve reliability was the review of the maintenance programmes. This was labelled the 'work optimisation' programme. It was based on a 'simplified' reliability centred maintenance' technique and was used to evaluate the existing 'pre-defines' within the maintenance programme.

During this specialists meeting, we will be hearing about the different approaches and techniques used by utilities and support organisations for undertaking optimisation of nuclear power plant maintenance programmes. The draft outline of the IAEA Tec Doc focuses on all aspects of an optimisation programme.

The purpose of this paper and the accompanying lecture is to look at the overall business requirements for embarking upon such a programme and not to explore the techniques (both new and old) of how optimisation can be achieved.

We will consider the benefits and also discuss what an optimisation programme cannot achieve. The basis being that a maintenance optimisation programme needs to have a clearly identified purpose.

2. ESTABLISHING A BUSINESS REQUIREMENT

2.1. The historical maintenance programmes

The maintenance programmes of many of the United Kingdom nuclear power plants evolved from the recommendations of component manufacturers and did not solely consider either system performance or safety related function or any in- service operational indicators.

I would suggest that the main reason for this is for the lack of operational experience due to the construction programmes all being unique, with different plant configuration, operational limits and some fundamental differences in design.

The maintenance programmes were therefore largely based on a conservative approach where many plant items have been over maintained. ***During 1960 – 1980, many maintenance techniques were based on intrusive methods where it was deemed necessary to 'take equipment apart' to find out why it was working?***

This statement may be viewed as a cynical approach, but from my experience as a station planning engineer, I was regularly placed in a position of having to schedule major intrusive maintenance programmes on safety related equipment. It was also not unique to experience plant unavailability and programme over run due to post maintenance defects.

2.2. Core business values

It is the responsibility of all operators of nuclear power plants to operate their plants '**safely**'. The safe operation of the nuclear power plants must not in any way be subjected to any initiative that may have any effect on overall plant safety.

My experience within the United Kingdom nuclear industry supports that at no time any optimisation has taken place, which degenerates the overall safety of the nuclear power plants. The converse has actually been achieved; where there is has been a renewed awareness of the requirement to operate nuclear plants safely.

It is necessary to operate nuclear plants cost effectively, especially as there is an increasing requirement for reduction in energy prices on a global basis. In my opinion a maintenance optimisation programme may result in an increase in availability and reliability.

I would also stress that my companies view is that maintenance optimisation programmes ***should not be used as a cost reduction technique***. To explain this statement, I would suggest that to introduce optimised maintenance techniques may require an increase in maintenance and not necessarily a reduction in maintenance.

One simple but very important rule is:

'there should not at any time be any changes (as a result of a maintenance optimisation programme) to the 'safe' operation of the nuclear power plant.'

However, it may not be unusual that the cost of optimization techniques will result in some cases an overall increase in maintenance costs. As a result of this, I consider that a business requirement of reducing maintenance costs cannot substantiate the adoption of maintenance optimization techniques.

The selection techniques and processes that are necessary to effectively apply and implement optimization of maintenance should identify the benefits of an integrated maintenance programme.

If a utility were only looking to undertake changes where a positive cost saving is achieved, this would result in a disjointed approach where overall synergy with an effective maintenance programme could be sacrificed.

3. A REQUIREMENT TO IMPROVE

3.1. What are the indicators that suggest optimisation may be required?

There are many different reasons which would suggest a requirement for changing the maintenance programme and by changing, we do not necessarily mean that we need to reduce maintenance, but possibly change maintenance techniques based on the new assessment or non intrusive techniques available.

I would propose to consider the following as a list (not exhaustive) of indicators that may result in a maintenance optimisation programme;

- Plant performance – availability factor
- Unplanned losses – actual generation against planned generation.
- Overall capacity factor – compared to similar or like types of plant. Maintenance statistics – 'trend analysis'
- Corrective work
- Predefined v's corrective
- Maintenance programme duration
- Outage duration
- Post maintenance defects
- Predefined backlog
- Maintenance staff level of working
- Maintenance effectiveness – gap analysis
- Maintenance costs
- Other performance measures – 'trend analysis'
- Average collective dose rate
- Accident frequency rate
- Waste
- Non conformances
- Electricity price
- Overall production charges
- International bench marking
- Regulatory requirements

As previously mentioned, the above are not exhaustive and there are many lower level indicators that must be used for assessment of sub systems and components. However, to be able to use the above indicators, it is necessary to record these. My experience with presented indicators has been to find some figures extensively massaged (this is not exclusive to any country where I have worked.)

It is necessary to establish a standard for arriving at the indicators within the Tec Doc. This will ensure that the results of any analysis are correctly used. It will also ensure that the 'benefits' of a maintenance optimisation programme are achieved and that there is some ability to 'bench mark' between different countries.

This is very important, as the cost of a maintenance optimisation programme if undertaken correctly can be expensive and require a large revenue or capital outlay. As a manager, I would be looking for effective investment that leads to a positive contribution to the business.

It is possible to massage financial savings with what I call a smoke and mirrors approach. This smoke and mirrors approach ends up claiming benefits that have **not** been realised. I present for you a simple example;

If you optimise the predefines and identify these as a major saving to the business based on the indicators selected, you must first ensure the following;

- ***The work is actually undertaken***
- ***When it was last undertaken***
- ***What were the FTE requirements***
- ***What have been the spares requirements***
- ***PMD – post maintenance defects***
- ***Losses due to plant unavailability***

I have seen many large claims of savings made by removing predefines that have never actually been undertaken. This I would suggest is a process of rationalisation and not optimisation. To rationalise there is a requirement to use similar modelling, but it is much simpler.

In a case where Pd are not undertaken (and may never of been undertaken), to optimise and use the models effectively, would not give any real added value to the business.

4. OTHER NECESSARY COMPONENTS FOR AN EFFECTIVE MAINTENANCE OPTIMISATION

4.1. Maintenance History

As well as all the indicators mentioned in the previous sections, we must also remember the need for 'high quality' maintenance history. This detail is usually supported or entered into the nuclear power plants maintenance management system.

I have had personal experience where the plant history has been of a very low standard and has not given the level of detail necessary for the maintenance optimisation techniques be effectively deployed.

The plant history such as 'job completed or task concluded' is not good enough and makes the process of optimisation more costly due to the supporting analysis that is required to make the necessary decisions as part of the optimisation technique.

The advent of more complex work management systems has also enabled electronic naivety to prevail. An explanation of this is where 'major failure or major action undertaken' detail is required. It is not unusual to find full stops (.) or commas (,) where a mandatory input is required.

4.2. Compliance Checks

Maintenance management programmes have evolved over many years. Many of these maintenance programmes are comprehensive and are in some circumstances based on the system function and not the component function.

This must be taken account of when undertaking optimisation. It is also necessary to consider overall compliance. An example of some of the compliance requirements within the United Kingdom from a maintenance perspective consists of;

- Maintenance schedule – The programme of maintenance agreed with the regulator.
- The pressure systems regulations – The programme of inspection and testing required for pressurised systems.
- Mandatory maintenance – such items as 'bolt life' and overspeed testing of large rotating machines.
- Environmental compliance – discharge of CO_2, effluent discharges etc.

Following a comprehensive maintenance optimisation programme, it is essential to ensure that all necessary maintenance is being undertaken. I have been made aware of minor irregularities that have occurred in compliance activities due to errors that have resulted from maintenance optimisation. These irregularities although minor demonstrate that it is possible to create unnecessary problems if adequate quality assurance is not applied.

One of our company products has been the recent development of 'audit and monitoring' software that assesses the requirements of 'compliance documentation' and then compares these against the maintenance management system.

There is a view that this level of checking should be contained within the maintenance management system and not as an external check. My response to such an insular view is that you can only monitor 'what is there' within a maintenance management system.
This system of checking for compliance activities is independent to the maintenance management system, but compares internally held data on compliance with the maintenance management system.

5. CONCLUSIONS

I wish to conclude with this short paper on 'A fashion or a useful tool' by making the following observation:

Predefined maintenance optimisation is by default episodic, this means that it must be a continual process. You cannot apply PMO as a one off process, as with in service effects on equipment, the maintenance techniques have to be dynamic to achieve the optimum balance.

A first pass of PMO establishes the benchmark, which can be used to continually optimise maintenance programmes for the duration of the plant life management. Maintenance optimisation is established as a core process and not a one off. If correctly implemented maintenance optimisation programmes can be a very useful tool within the overall plant life extension matrix.

I wish to recommend to the specialists meeting that you consider the following for inclusion in the TECDOC on PMO:

- Clearly define the indicators and how the indicators are to be achieved.
- Compliance monitoring external to the maintenance management system.

Annex 2

THE EPRI PREVENTIVE MAINTENANCE BASIS PRODUCTS

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Abstract. Electric utilities need a technical basis to support preventive maintenance (PM) tasks in all types of power plants for common major components. This paper describes and demonstrates the PM basis products which have been developed by EPRI to provide the utility user with an essential reference for PM tasks and intervals for 45 component types. These products also provide in-depth technical basis information to adapt the PM tasks and intervals to plant conditions. Data for each component type embodies all the PM tasks, intervals, task objectives and scope, and the most important influences on equipment degradation and maintenance for that specific component. The data were developed by expert groups of utility maintenance and vendor personnel, who provided information on equipment degradation and PM options in workshop sessions. The EPRI PM basis products consist of, 1) 40 published reports and a project overview report, 2) a stand-alone Access 97 database, 3) a web-site hosting a server-based version which permits use of the database, and feedback of utility PM experience, 4) a PM basis working group of about a dozen utilities, and 5) documentation and training materials. The electronic databases contain an integrated application guideline which provides state-of-the-art guidance on technical decision making to support a PM program. These topics include use of the database to, 1) evaluate PM tasks and task intervals, 2) improve predictive maintenance usage, 3) make decisions on task deferrals, 4) provide source material for as-found condition reporting and evaluation, 5) provide completeness checks on failure cause evaluation, and 6) to conduct quick PM assessments at a plant. The showcase of the web site application is the vulnerability analysis tool which analyzes the complete set of recommended tasks and intervals, shows the overall effectiveness with which each degradation mechanism is addressed by each task, and summarizes the extent and depth of protection afforded by the PM program. The evaluation can be repeated for any subset of the recommended tasks with user-defined intervals, and alerts the user to gaps in the coverage, and the potential effect on reliability.

1. EPRI PREVENTIVE MAINTENANCE BASIS

Maintenance personnel at many US plants are attempting to reduce preventive maintenance (PM) costs, and improve equipment performance, to an extent consistent with the functional importance of the equipment. To inform these decisions, utilities require information on the most appropriate PM tasks and task intervals for important equipment types, while making allowances for duty cycles and service conditions. Most PM programs have evolved piecemeal from vendor recommendations using historical experience, but the historical reasons for specific PM tasks are usually poorly documented, if at all. The result is that relationships between the tasks, and the justifications for task intervals, are not well known. Utility members of the former EPRI reliability centered maintenance users group (1994-1998) pointed out the need for this kind of information.

Over a period of two years, approximately 20 small groups (3 to 8 individuals) of experienced maintenance personnel from EPRI member utilities and manufacturers, formulated the technical bases of recommended PM task options for selected component types, under the purview of a utility oversight committee. This data is available, 1) in published reports, 2) as an Access 97 database, and 3) on the EPRI preventive maintenance information repository (PMIR) web site.

1.1. Published PM basis reports

The database first appeared as a set of 40 published EPRI reports, EPRI TR-106857, Volumes 1 to 40, November 1998, known as the EPRI Preventive Maintenance Basis Reports. An overview report, EPRI TR-106857R1, Final Report, November 1998, contains a comprehensive account of the methods used to develop the data, and describes key features of the data. These reports are also available as a set of Acrobat PDF files on CD as EPRI Product Number AP114875-CD. The reports, and the electronic Access database, address the following 40 component types:

Battery - Flooded Lead Acid - Lead Calcium/Antimony
Battery - Flooded Lead Acid - Planté
Battery - NICAD
Battery - Valve Regulated Lead Acid
Battery - Charger
Battery - Inverter
Compressor & Pump - Rotary, Liquid Ring
Compressor - Reciprocating
Compressor - Rotary Screw
Heat Exchanger - Main Condenser
Heat Exchanger - General Tube Type
Heat Exchanger - Feed Water Heater
HVAC - Air Handling Equipment
HVAC - Chiller & Compressor
HVAC - Dampers & Ducting
Instrumentation And Control Components
Motor - Direct Current
Motor - Low Voltage - 480V
Motor - Medium Voltage - <5kV
Motor - High Voltage - >5kV
Pump - Horizontal with Couplings
Pump - Positive Displacement
Pump - Vertical
Relay - Control
Relay - Protective
Relay - Timing
Turbine - Feed Water Pump (Main)
Turbine - Main Turbine EHC Hydraulics
Turbine - Terry - Single Stage
Switchgear - Motor Control Centers
Switchgear - Low Voltage
Switchgear - Medium Voltage - 1kV to 7kV
Transformer - Station Type, Oil Immersed
Valve - Air Operated - AOV
Valve - Check
Valve - Motor Operated - MOV
Valve - Power Operated Relief - Pneumatic Actuated
Valve - Power Operated Relief - Solenoid Actuated
Valve - Pressure Relief - Spring Actuated
Valve - Solenoid Operated – SOV

The following five additional component types have recently been added to the web site version of the database. Further additions are expected.

Air Dryer - Unheated
Air Dryer - Heated
Air Dryer - Heat Of Compression Drum Type
Compressor - Centrifugal
Diesel - Small Standby

The objective of the database is to present a moderately conservative set of PM task and task interval recommendations which are suitable for a plant which does not have much operating experience with the equipment, or a plant which can not easily recover its operating experience because of lack of time, lack of resources, or lack of good record keeping. The database information is not in the form of event-based records, but has already been filtered and summarized through the experience of the plant personnel who compiled it. Because of the small size of this group of individuals, it is not an industry consensus database. However, the extensive experience of the group members should contain most of what it is useful to know about the equipment for PM planning purposes.

The technical experts were charged with recommending the best technically justifiable PM programs, not necessarily the programs which already existed in their plants. The technical justification had to be at the level of equipment failure mechanisms, sufficient to enable translation to different plant conditions, and with additional input, to variants of the generic equipment types. For each component type, the PM recommendations cover critical applications (i.e. those which provide extremely important safety or generation functions), as well non-critical applications (i.e. those which do not provide extremely important functions but which nevertheless require some level of PM protection). The recommendations also cover high and low duty cycles, and severe and mild service conditions.

Data for each component type consists of:

1. All the subcomponents within the component boundary, which are the sites of degradation and failure,
2. The degradation processes for each failure location, and the main factors which influence them,
3. The timing characteristics of the deterioration processes,
4. The failure locations and mechanisms most commonly encountered,
5. Actions which could be taken to detect equipment condition and to prevent or address the degradation,
6. The PM strategic level task packages which could contain these activities,
7. The intrinsic effectiveness (High, Medium, Low) of each task at addressing the targeted failure mechanisms,
8. An outline of the scope and content of each PM task,
9. Definitions of duty cycle and service conditions which influence PM,
10. Typical ways additional sources of failures are introduced while performing maintenance,
11. A statement of how all the above factors support the choice of tasks and intervals,
12. Recommended combinations of PM tasks and task intervals, depending on functional importance, duty cycle, and service conditions -- the PM Template,
13. The principle objective of each PM task, and the degree to which the recommended task intervals are constrained by the underlying failure timing information,

14. A table showing the overlap between tasks in the PM program, and gaps in the coverage provided by all the tasks.
15. Useful industry references.

Much of this information is to be found in Tables 1 and 2.

Table 1 Flooded Lead-Acid Batteries - Failure Locations and Degradation Mechanisms

Battery Plates:

Degradation Mechanism	Degradation Influence	Progression Of Degradation	Failure Timing	Discovery Or Prevention Opportunity	PM Strategy
Corrosion or growth of grid	- High temperature - Cycling - Overcharging (high float voltage) - Age - Too high specific gravity (S.G.)	Continuous	- Depends strongly on temperature (every 15 degrees F above 77 degrees F reduces life by 50%) - Greater than design life - Long term effect over -5-10 years - Expect to be failure free for 10 to 15 years - May shorten life to -5 years	Electrolyte temperature/ Material on bottom of jar/ Appearance of Grid/ Positive post higher than negative/ S. G. measurement/ Float current and voltage high/ Trend of internal resistance/ Capacity test results/ Area temperature	- Cell Inspection - Detailed Inspection - Battery Capacity Test - Battery Monitoring
Copper Contamination of negative Plates	-Post corrosion - Manufacturer defect of post	Random	Rapid (can be as long as months)	Inspection/ Capacity test results	- Detailed Inspection - Battery Capacity Test
Sulfation	- Under-charging - Low temperature - Improper storage (open circuit)	Continuous	Expect to be failure free for 6 months (chronic undercharging) to several years (both limits are highly temperature dependent)	Inspection/ S. G. measurement/ Capacity testing/ Internal ohms/ Area temperature/High float current and voltage	- Cell Inspection - Detailed Inspection - Battery Capacity Test - Battery Monitoring
Hydration	- Battery left in discharged condition Undercharging At low S.G. - Vibration - Cycling - Overcharging	- Random - Continuous - Random or continuous - Continuous - Random	- Can be very rapid (days) - Will occur in months - Expect to be failure free for at least 5 years - Expect failures after about 50 cycles - Long term effect, expect failure after 5 to 10 years	Visual bath tub ring/ S.G. measurement/ High float current and voltage Inspect for mossing / Shorted, individual cell voltage/ Capacity test results/ High float current and voltage/ S.G. measurement	- Detailed Inspection - Cell Inspection - Battery Monitoring - Detailed Inspection - Cell Inspection - Battery Capacity Test - Battery Monitoring
Mechanical failure (broken or buckled)	- Corrosion - Vibration - Shock (electrical or mechanical) - Manufacturer defect	- Continuous - Random	- Expect to be failure free for at least 5 years - Random, could be rapid	Visual evidence/ Capacity test results	- Detailed Inspection - Battery Capacity Test

1.2. Access 97 database

An electronic database is available which contains essentially all the data in the published reports. This enables the user to display and query the information on a Microsoft Access platform using Windows 98 or Windows NT. The Access database is obtainable on CD as EPRI Product Number 1001447, under license, from the EPRI Program Manager, Martin

Bridges (704-547-6175). The User Manual is available as EPRI Product Number 1001448, May 2000. The main advantages of the electronic database are that, 1) it enables users to apply data filters to distinguish, e.g. all the degradation mechanisms which are not addressed by any combination of PM tasks, and 2) it contains a hyperlinked application guideline.

Table 2 PM Template For Battery - Flooded Lead Acid - Lead Calcium/Antimony

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
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**
PM Task								
Battery Monitoring	NA	1M	NA	1M	NA	3M	NA	3M
Cell Inspection	NA	3M	NA	3M	NA	3M	NA	3 M
Detailed Inspection	NA	1Y	NA	1Y	NA	1Y	NA	1Y
Battery Capacity Test	NA	5Y	NA	5Y	NA	5Y	NA	5Y
Battery Service Test	NA	NR	NA	2Y	NA	NR	NA	NR

* The template does not apply to the Run-To-Failure components; non-critical here means not critical but important enough to require some PM tasks.

1.3. Application guideline

The integrated application guideline shows in detail how the database can inform many of the day-to-day decisions which PM coordinators and system engineers must make. The application guideline contains extensive procedural guidance which incorporates lessons learned from the experience of implementing PM optimization plans, generic modeling and charts of the effect of changing task intervals, as well as database features such as the use of data filters, and application tools in the web-site version, such as the vulnerability evaluation, and performance criteria evaluation.

The seven decision areas covered by the application guideline are:

1. PM Task Evaluation – Do you have the right task(s) – either as part of a PM program optimization or for a single task?
2. Task Interval Evaluation – Are the tasks being done at the right intervals?
3. PM Assessment – Make a quick assessment of how your PM tasks and intervals compare with the database recommendations.
4. Evaluation Of As-Found Condition - How to use as-found condition data to adjust PM tasks and intervals.
5. Task Deferral – Justify a one-time task deferral, and place limits on the duration of a task deferral.
6. Cause Evaluation – Use the database to support cause evaluation.
7. Predictive Maintenance Enhancement – Develop and justify increased usage of predictive PM tasks.

1.4. PMIR Web Site

EPRI management recognized that the format of the database could support continued accumulation of utility PM experience over an extended time, to become a PM information repository (PMIR) for the power industry. To accomplish this, a web site version was required to enable utilities to feed information back to EPRI.

The web site version of the database also supports the application guideline, but provides enhanced tools, more component types, the ability to feedback review comments to EPRI, the capability to post plant PM program information for other utility members, and the ability for a user to download changes to the data which have occurred since a previous version. The latter capability will permit users to maintain configuration control when they have previously exported information from the database to their own plant data systems.

The most important additional capabilities available in the web version are, 1) feedback by utilities of review comments, 2) view posting by utilities of additional related documents, e.g. their own PM templates and task descriptions, 3) bulletin board, 4) view data updates since a previous version, i.e. configuration control, 5) the vulnerability evaluation, 6) set-up and evaluation of reliability performance criteria, and 7) download of data to utility databases (planned). The vulnerability evaluation tool evaluates any subset of the EPRI task recommendations selected by the user, with corresponding user-supplied task intervals, and highlights failure mechanisms where the degree of protection provided by the chosen tasks is only medium or low. It provides an approximate measure of the reliability impact of adopting less than the full set of recommended tasks and intervals. The web site is in beta testing, and is expected to be fully functional by the end of 2001.

2. TECHNICAL ASPECTS OF THE DATA

2.1. Degradation and PM strategies

Questions about how well a PM task protects against component failures, and the best time to perform a task for maximum effectiveness, are best handled at the level of individual line item PM activities, and individual failure mechanisms affecting specific sub-components. The data tables therefore contain records at the level of subcomponent degradation mechanisms –split into “Failure Location”, “Degradation Mechanism”, and “Degradation Influence”, as shown in Table 1 for a single failure location. The idea is to state which piece of hardware fails, how it degrades, and what causes it to behave in that way. The PM activities which can address such a condition, are first inserted as specific line item symptoms, activities, or tests, which are the candidate “Discovery Or Prevention Opportunities” (such as Inspection, Audible Noise, or High Resistance). Almost always these are discovery opportunities, but some are indeed truly preventive. In the database, not all of them may be selected as the most effective options for a broad range of practical situations. The items which are recommended usually appear as line items in a higher level, or strategic PM task – the kind of PM task for which a PM package would be generated, such as “Detailed Internal Inspection”. In general, the “Discovery Or Prevention Opportunities” which are included in a higher level PM task, reappear as items in the task contents, and outline the scope of the PM task.

2.2. Degradation progression and failure timing

All equipment degradation is considered to fall approximately into one of two types – wear-out and random. Wear-out is characterized by a more or less continuous accumulation of degradation which eventually reaches a threshold corresponding to failure (e.g. wear of a sliding surface). This is referred to as a "continuous" progression. The actual time of failure is by no means random, because it will be fairly certain that failure will not occur during the period before the degradation reaches the failure threshold. The continuous type of degradation is accompanied by a statement of this expected failure free period.

In contrast, "Random" degradation occurs with no expectation of a failure free period, and can happen any time, even shortly after a subcomponent has been replaced. If possible, the random type of degradation is accompanied by words which indicate additional timing features or the approximate rate of failures, such as "can be immediate" or "on a scale of 5 years". The scale simply indicates the mean time between failures (MTBF).

Random degradation mechanisms (typically a human error) can also be the result of a wear-out mechanism, which proceeds so erratically that a failure free period can not be assigned. From a practical point of view, such mechanisms are random.

The reason these two cases are distinguished, is to enable the true value of condition monitoring to be appreciated, and to show when time-directed tasks are appropriate. When a degradation mechanism is random, there is no good time to perform an infrequent task. For example, if a time-directed task is performed at an interval which approximates the mean time between failures (MTBF) of a random mechanism, actual failure times will frequently be much shorter than the task interval.

Even so, the random mechanisms may still display a short-term signature of the impending failure. This offers the only way to defend against random failure mechanisms, that is, perform a task very frequently, and hope to pick up the signature of impending failure. Such a condition monitoring task therefore has to be inexpensive to perform, and it has to be essentially non-intrusive, otherwise the frequent performance of the task will lead to the generation of additional failures, through various kinds of errors and the introduction of defects. Random failure mechanisms form a large fraction of the total, underlining the importance of understanding the potential effectiveness or ineffectiveness of condition monitoring.

These characteristics of the degradation mechanisms and failure timing are used by the application tools provided with the database, to evaluate the quality and reliability impact of the proposed set of PM tasks and task intervals.

2.3. Common degradation mechanisms

The degradation mechanisms in the database are limited to those which are known to occur at least once in the life of the equipment, and can lead to failure. Because of good maintenance, failures from these sources may not actually be encountered very often, but they would certainly occur if maintenance were not performed. Degradation mechanisms which frequently lead to a significant level of degradation despite maintenance are tagged as "Common" mechanisms by being labeled with a "C". They are encountered much more frequently than the other degradation mechanisms. The common mechanisms are the ones, which any experienced maintenance professional will be certain to watch out for.

2.4. Task effectiveness

PM tasks are assigned an intrinsic task effectiveness (High, Medium, or Low) for each degradation mechanism and failure location for which they provide protection. The term intrinsic means the effectiveness of the task at discovering that some degraded condition exists (but not necessarily identifying the degradation explicitly), *given that the task is performed while the condition exists in a detectable form.* The intrinsic task effectiveness is therefore independent of task type and task timing considerations. For example, an operator may, or may not be able to hear a worn bearing in a motor in a noisy environment – depending on the conditions, and his skill level. This might therefore be given a medium or low level of task effectiveness, rather than a high level. In contrast, meggering a motor might be given a high task effectiveness for discovering breakdown of the insulation.

An application tool in the database converts these intrinsic task effectiveness assignments into overall task effectiveness assignments by taking account of the task interval and task type. For example, a time-directed task with high intrinsic task effectiveness for a random degradation mechanism, would be downgraded in overall effectiveness because the task is unlikely to be performed at the right time. Similarly, a task which addresses a wearout degradation mechanism, but at a task interval which exceeds the expected failure free period, will also be downgraded in effectiveness.

2.5. Template

Table 2 shows the task intervals assigned to the eight combinations of critical or non-critical application, high or low duty cycle, and severe or mild service conditions. NA means not applicable (in the example shown, no station batteries were thought to have high duty cycles – defined elsewhere in the database), and NR means Not Recommended. In other Templates, AR means As Required, e.g. when a functional test has an interval determined by technical specifications.

3. APPLICATIONS OF THE PM BASIS DATABASE

There have been several applications of the database to its most obvious purpose, the improvement and standardization of PM tasks and intervals. The most aggressive utility in this regard has been Exelon (ComEd + PECO Energy), which has used the database extensively in standardizing preventive maintenance across all its nuclear plants. The database can also assist with finding the solution to a persistent equipment reliability problem, in recommending corrective actions after failing to meet performance criteria in the maintenance rule, or in justifying why a component PM program is already good enough, and should not be changed. Additionally, utilities have realized that the PM basis database can provide reliable answers to more elusive questions such as:

1. Is it possible to identify quickly where there may be gaps or over-kill in existing PM programs? This can be valuable in providing a sense of perspective and direction to program improvement.

2. What constitutes an adequate technical basis for the PM program, and can this be put in place efficiently? There is now more emphasis on the technical basis because increasing safety regulation and cost pressures make PM changes more likely, and their justification more necessary than ever.

3. Which information should be obtained from the crafts to monitor equipment condition, and how should it be evaluated? Condition information provides an attractive alternative to increased regulatory monitoring of failures, because the latter is reactive, and supplies potentially inaccurate inputs to maintenance improvement.

These three areas were among the first applications of the EPRI PM Basis by U.S. utilities. They are considered in more detail below.

3.1. PM assessments

PM assessments have been carried out using the database at the Sequoyah, Duane Arnold, Millstone, Robinson, Susquehanna, and Fort Calhoun nuclear plants, by performing quick vertical-slice PM assessments of the major equipment in two or three systems. They have evolved into an efficient process that is completed in little over one week. If the process is structured as a vertical-slice, major equipment is sampled from three systems. One contractor and one to two plant personnel complete the assessment during four days on-site, with a final report that is produced within the next week. The assessment team selects all components from the three systems that are covered by the EPRI PM Basis Database, and classifies them as having high or low functional criticality, high or low duty cycle, and whether they encounter harsh or mild service conditions.

All the PM tasks being applied to the equipment are listed, and questions are formulated to clarify the scope of the tasks. These first steps can be quite labor intensive, depending on the accessibility, consistency, and completeness of plant databases, and the degree to which previous PM optimization has been carried out. It has been found that an early interview with the relevant system or component engineers can usually speed up the process, particularly in finding out duty cycle, service conditions, task scope, and tasks and intervals which may not be in the databases. Predictive maintenance tasks, scheduled PM tasks, surveillance tests, and equipment qualification tasks are included.

The plant tasks and intervals are then entered into standard forms (see Table 3), into which the EPRI recommended tasks and intervals have already been entered. The EPRI intervals are taken from the database Template using a dialog which asks for the criticality, duty cycle, and service conditions. The two sets of tasks and intervals are compared one by one. Significant differences focus attention on whether the plant has a valid technical basis for the use of the task at the current interval, or for the fact that the task is not being done at all. Typically, historically poor performance with a particular component can demonstrate the need for additional or more frequent tasks, whereas good performance over a long period for a group of components may support why some tasks are not done. Draft findings and recommendations are entered on the forms.

A follow up interview during the same week with the relevant system or component engineers resolves remaining questions and produces a set of recommendations. The recommendations are grouped according to equipment types, along with general findings on the overall PM program, such as the degree of integration with the maintenance rule program, usage of predictive maintenance techniques, and whether or not there is an adequate technical basis for equipment which is run to failure. A typical assessment report produces a 25 page document with about 20 data sheets covering 30 to 50 individual components. A typical worksheet is shown in Table 3.

Table 3 Completed Data Form For A PM Assessment

Component ID's: 1A1 & IA1-7		**Component Type:** MV Breaker Category: Critical, Low Duty, Mild Service
Current Plant Program:	1	Thermography - Connections to bus - 18M
	2	Breaker - Visual Inspection - No Task
	3	Breaker - Detailed Inspection - 18M
	4	Breaker – Overhaul - No Task
	5	Cubicle - Detailed Inspection - 4.5Y - part of bus inspection.
	6	Cubicle – Overhaul - No Task
	7	Protective Devices - Calibrate-Out of Scope
	8	Functional Test - 18M at present, included in Detailed Inspection.
Industry PM BasisTasks And Intervals:	1	Thermography - Breaker and Cubicle including bus - 1Y
	2	Breaker - Visual Inspection - AR
	3	Breaker - Detailed Inspection - 6Y
	4	Breaker – Overhaul - 10Y focused on lubricant condition; was very necessary for Magneblast breakers.
	5	Cubicle - Detailed Inspection - 6Y
	6	Cubicle – Overhaul - 10Y
	7	Protective Devices – Calibrate - 5Y
	8	Functional Test - 2Y
Plant Basis For The Differences:	1	Thermography task can not view the breakers.
	2	Visual not needed while Detailed Inspection is so frequent.
	3	Detailed Inspection at 18M is recommended temporarily by ABB. Extension to 3Y is being implemented. If this extends even further, might consider adding a visual inspection at a shorter interval.
	4	ABB claims they have everlasting grease - so currently no overhaul. This claim is being viewed with some reservation and a timing test to evaluate the integral performance of the breaker is being considered.
	5	Cubicle inspection similar to reference.
	6	Suggests cubicle overhauls at 10Y. These are being considered.
	7	Out of review scope.
	8	Need to cycle every 18M when Detailed Inspection is extended to 3Y and more. Consider cycling the breaker as a functional test. This could be the opportunity to do a visual inspection as well.
Recommendations:	1	Consider a timing test to evaluate the integral performance of the

Component ID's:		Component Type: MV Breaker
		breaker to give confidence the overhaul is not needed.
	2	Consider adding a cubicle overhaul at around 10Y.
	3	Consider cycling the breaker as a functional test when the Detailed Inspection is no longer at 18M. This could be the opportunity to do a visual inspection as well.

3.2. Developing a plant PM basis

Most current PM programs at US plants do not have a complete PM Basis in documented form. Where it exists, the most typical basis consists simply of the PM tasks performed on each component, the task intervals, and whether a task is part of a technical specification, equipment qualification, management commitment, or other regulatory requirement, or plant programs such as life-extension, maintenance rule, check valve program etc.

Additional information which would be beneficial, but which is almost never present includes:

a. The main objectives of the task; e.g., "This task is mainly focused on the condition of bearings”.
b. Latitude for interval extension; e.g. “The interval is not closely determined by known degradation rates and failure timing information”.
c. Dependence on other tasks; e.g., "Frequent oil sampling and vibration analysis enables Internal Inspection to be at 7.5 years rather than at 4.5 years which is common in the industry."
d. Summary of equipment history that supports intervals; e.g., "Sand from the intake forces this valve seat inspection at every major outage."
e. Justification for not having a particular task; e.g., "Separate Visual Inspection is not needed because of the Shaft and Guide Inspection at 3 years."
f. Justification for run-to-failure (i.e. no PM tasks at all); e.g., "No PM tasks are cost-effective for non-critical 480 volt motors less than 125 horse power, unless they are equipped with brushes."

The EPRI PM Basis documents provide data to support all these additional items. In particular, it is not difficult to derive a brief summary statement that expresses the main focus of a task and any particularly noteworthy features, such as:

"The battery float current is monitored monthly to provide assurance the correct charging conditions are being maintained. Incorrect charging conditions are responsible for the majority of battery problems. Monitoring the float current removes the need to sample the specific gravity of some cells every 3 months, and for measuring all cell specific gravity values at 1 year."

Similar summary basis statements were derived using the EPRI PM Basis reports, by Duke Engineering Services, the PM program optimization contractor for Northeast Utilities, for Millstone Units 2 and 3. They have since been added to the database as the Task Objective.

Additional information, such as the important system functions which are lost by failure of the component, and how critical the functional failures are with respect to safety, power production, and other important criteria, may become available from other industry databases. Links to additional databases are under consideration.

3.3. Information on equipment condition

Opportunities to gather information on equipment condition exist when preventive maintenance (PM) or corrective maintenance (CM) is being performed. In power plants, and in many other industries, only a fraction of the useful information potentially available from craft personnel is actually recorded, often in the form of vague and inconsistent entries in maintenance work orders. If consistent and specific information were available from all PM and CM activities it could be used to modify PM tasks so that only the right kind of maintenance would be performed at the right times. Such information would be a key input to improving a PM program, and could reasonably be expected to result in improved reliability at reduced maintenance cost. The use of such information would increase the capture and use of plant experience by a large factor.

To start addressing this problem, American Electric Power Company, in a joint project with EPRI, used the PM Basis Database to develop condition feedback checklists for the D. C. Cook plant, for all PM tasks for 20 specific component types. The checklists only contain items pertinent to the task at hand, so do not distract and discourage the craft personnel with irrelevant requirements for information. It is expected that the use of these data collection sheets will take little time on the part of maintenance personnel during the performance of a PM task, will not require handwriting (and in fact, is easily adapted to handheld electronic devices for direct field use), and will capture the interest of crafts personnel by prompting them for observations which they make instinctively and know to be important.

The reporting items were derived from the hardware locations of degradation and failure, the degradation mechanisms and influences, the task content, and the main reasons for doing the task. Items checked during a PM task will represent, 1) extremely degraded condition which indicates the need for prior action, 2) expected condition which indicates the task is timed appropriately, or 3) exceptionally good condition which indicates the task need not be performed as frequently. The reporting format needs to be in a form suitable for computerized data recording.

Further customization and focusing of the checklists, and extension to include all database component types is planned for 2002. An evaluation process has also been developed by EPRI to make use of this information when completed feedback documents are in hand. The most general objective of the evaluation process will be to decide if the equipment condition is indicative of a preventive maintenance program that is technically appropriate and properly implemented, or whether some changes are justified in the task content or timing. In the short term the objective might simply be to decide if a task interval can be extended on a single occasion. In the optimal situation a task interval might be increased or decreased on a permanent basis. Timely decisions of this kind can make the difference between a smoothly adaptable PM program, which keeps pace with the plant's changing needs, as opposed to a PM program, which rapidly falls behind advances in technology, and aging of the equipment.

4. STATUS AND CONCLUSIONS

No further PM Basis reports will be published by EPRI. Future development will be focused on the web site version which will complete beta testing during 2001. In addition there will be a convergence between PM information obtained during NMAC projects, which is published in new NMAC component reports, and data updates to the PM Basis Database. Additional features which are scheduled to be added during this time are:

1. An application to assist with setting up and evaluating performance criteria used to monitor reliability in the Maintenance Rule, 10CFR50.65.
2. Additional components, most notably I&C components.
3. Component updates on horizontal pumps, main condenser, and HVAC air handlers.
4. Subsets of the recommended PM tasks for each component in the database will be ranked as to the effectiveness of the protection they provide, in order to provide assistance to plants which do not intend to implement the full set of tasks, and to provide alternatives useful for improving the balance between reliability and availability.

Future potential enhancements might include:

1. A database of equipment condition checklists, as described in section 3.3, above.
2. A tool to evaluate the balance between reliability and availability, according to a criterion recently developed by EPRI, and using information on the relative effectiveness of various combinations of PM tasks, as described in item 4 above.
3. Links to other databases related primarily to the Maintenance Rule, such as the EPRI SysMon database developed by Plant Support Engineering, which links important system functions which are lost by failure of important components, and their importance to safety, power production, and other criteria.
4. Graphic data related to specific degradation mechanisms to enhance craft training. Much of this information currently exists, but is distributed across a wide variety of sources.

As utility personnel learn more about the database and become adept in its uses, it is expected that its accuracy, completeness, and breadth of equipment coverage will rapidly approximate an industry consensus database. It has already become a de facto repository of industry PM experience and insights, and a standard tool and reference in improving preventive maintenance in power plants.

Annex 3

A METHOD FOR DETERMINING THE CRITICAL SYSTEMS/COMPONENTS FOR MAINTENANCE OPTIMIZATION PROJECTS

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Abstract. The objective of maintenance optimization projects can be summarized in just a few words, "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 the maintenance is needed. This philosophy also means that non-critical equipment or equipment that is not commercially significant may be allowed to run until it fails with only minimal maintenance activity prior to the failure. This paper describes a process that facilitates the creation of a critical SC (SC) list that can be used to quickly determine which components fit into the critical component category. Many nuclear power plants (NPP) in the United States have developed their critical component list based on criteria mandated by their regulator, the U. S. Nuclear Regulatory Commission, to meet the requirements of the "Maintenance Rule." Similar criteria can be used at other NPPs not subject to regulation under the "Maintenance Rule." However, the process that is used to develop the list is as important as the criteria. If left to its own momentum, the process of developing the critical SC list will fall to the bottom of the priority list and will not be completed in a timely period. This paper will describe a process that facilitates the timely completion of a critical SC list and provides for the effective utilization of the system engineers' time in developing the list. This process is a further simplification of the techniques used in reliability centered maintenance (RCM) and streamlined RCM. By not performing the more in-depth portions of the evaluation until the critical components and their requisite functions are defined, the effort is significantly reduced with little or no impact on the quality of the results. The process described in this paper will also provide guidance in the types and content of questions and the format of an interview that can be used in this process. The use of the interview process allows the optimization team to schedule the development of the critical SC according to their needs. It will also improve the involvement and response of the system engineers in the process.

1. THE RIGHT WORK, ON THE RIGHT EQUIPMENT, AT THE RIGHT TIME

As maintenance managers strive to improve the reliability and availability of systems and equipment, the pressures of the competitive energy markets are forcing costs down. Many times these two forces seem to be at odds with each other and can create tensions in an organization. It is important to develop strategies to allow these forces to work together to strengthen the maintenance organization and its performance.

If cost were no object, it would be relatively simple to implement a maintenance program that all but assures maximum reliability and availability. But, cost is a very important component of any nuclear power plant operating strategy. Large maintenance organizations with large amounts of money can perform many preventive maintenance tasks on all of the equipment in the plant. This work can be performed on a frequency that assures that a failure of the equipment rarely, if ever, occurs. But, there are several significant issues with this approach.

Performing more PM tasks than are necessary creates more opportunities for human error. The more opportunities that are available for human error to occur, the more errors will occur, given a constant error rate. These errors include using the wrong part, performing the right task wrong, performing the wrong task, or performing the right task on the wrong equipment. Additionally, any time equipment is being worked on; it is unavailable to perform its intended function. This means the probability of the component failing to operate when called on is 100% because it is out of service. Finally, performing unnecessary maintenance is costly in that it uses parts that are not needed, requires work that does not need to be done, and causes component/system unavailability needlessly.

The opposite situation is that not enough preventive maintenance is performed due to limited resources. If this scenario develops, equipment breaks, systems fail, and power plants do not generate electricity. Component availability and reliability, and consequently system availability and reliability, suffer. Costs increase because it is now necessary to replace entire components rather than just parts. Maintenance personnel must work extra hours and they must work hours outside of the normal workday because of unplanned failures. This situation can develop for any of several reasons. The maintenance budget may not be large enough. There may not be enough people in the maintenance organization. The current staff may not be properly trained. Incorrect or out of specification parts may be used. Preventive maintenance programs may not be effective.

The major goal of a maintenance optimization effort is to create a program that will perform the right work on the right equipment at the right time. This means that the plant has developed a list of the equipment that must have optimum reliability and availability; the correct tasks that must be performed on this equipment have been identified; and the interval between these tasks has been optimized. At the completion of this effort, the maintenance process has been optimized for the first time, and it is time to start the "Living Maintenance Program" process.

2. DEVELOPING THE LIST OF CRITICAL SYSTEMS/COMPONENTS

At first glance, the task of reviewing the performance of the systems/components in a NPP is overwhelming. However, this task can be greatly simplified by reducing the list of SCs to a manageable size. There is no need to spend a lot of time and effort on systems/components that are of little significance relative to safety, capacity factor, or cost. A simple process can be used to develop a list of only those systems/components that are important to the safe and economical operation of the NPP. Although the process is simple, it can be time consuming, and if it is not properly managed, it can be the item that causes the most trouble and creates the worst feelings.

The most knowledgeable people to prepare the critical SC list are the system engineers, but, in most cases, they are among the busiest people in the plant. If the system engineer is sent a questionnaire or a list to review, he will generally set the list aside and will give the task a low priority. A more effective method is to use an interview format, and schedule interviews with the system engineers. This allows the project manager to control the timing of the meeting and to more accurately schedule his end date.

2.1. The Starting point

The logical starting point is the beginning, but if this is the first time an effort is being made to optimize the maintenance process, it may be hard to figure out where the beginning is. One or more documents in the NPP contain a list of the systems that are part of the plant. This list may exist as a licensing document, as part of a list of plant drawings or some other list of systems. Using this list and a list of the assigned owners of the systems, schedule an interview with the person responsible for each of these systems. The schedule should be aggressive and should allow 2–4 hours per system. It is also suggested that the system engineer enlist the assistance of the most knowledgeable person in the operations organization on each particular system for this meeting.

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 and all uses that operations may have. Obscure uses during startup, shutdown and emergencies should be listed. An operations person should be included to help with this effort.

Another preparatory item is to decide on the attributes that are expected to be present for a SC to be considered a critical SC. Some suggested attributes are:

- System/component is nuclear safety related
- System/component that is not nuclear safety related but it mitigates an accident or transient
- System/components could prevent nuclear safety related SCs from fulfilling their function
- System/component whose failure could trip the plant or reactor
- System/component whose failure could result in a plant transient
- System/component used in emergency operating procedures

Note:

The term "nuclear safety related" is taken from U. S. terminology and is used to define systems/components that meet the following criteria:

Systems/components that are relied on to remain functional during and following an event to ensure:

- The integrity of the reactor coolant pressure boundary
- The capability to shutdown the reactor and maintain the reactor in a safe shutdown condition
- Prevent or mitigate the consequences of accidents that could result in potential significant offsite exposure

These attributes are taken from guidance on the implementation of the U.S. Nuclear Regulatory Commission regulation 10CFR50.65, "the Maintenance Rule".

This information on the functions of the system should be available from sources such as the design basis documents, facility license descriptions or safety analysis reports, system descriptions, or emergency and operating procedures. These criteria and the definitions that are assigned to each item should be provided to all system engineers, operations personnel, and other involved personnel prior to the interview meetings.

2.2. The Interview

The key to timely completion of the critical system/component list is an efficient collection of the information necessary to make a decision as to whether the SC is critical or not. Once this information is collected, additional information relating to the basis for the decision should be documented. As follow-on, it is helpful to also collect information on the types of failures that can cause a SC to not meet its intended function and to use this information to establish the tasks that will prevent or mitigate the occurrence of these failures.

Note: Attachment 1 provides an example of a format for documenting the information collected during the interview.

It is suggested that a dedicated room be established for this effort. It should be equipped with a whiteboard or several flip charts and a personal computer. If possible, having an LCD projector for the PC would be helpful. Also, it would also be helpful to have copies of the system descriptions and procedures available. In addition to the persons conducting the interviews, it is also suggested that a person be provided to record the information as it is provided.

2.3. The Functions

Begin the process by having the system engineer, the operations representative, and the members of the panel "brainstorm" the functions of the system. This should be a simple list of everything that the system does no matter what the perceived importance. The list should be provided without comment. Once the list is made, it can be edited to consolidate functions but functions should not be deleted. The next step will determine if it is a significant function and minor functions will be noted as such and no further action will be required. Deleting a function before it has had the screen applied will potentially eliminate functions that should be considered.

Each listed function should be a single, defined function, example – Provide cooling water to the control building air handlers. If there are multiple flow paths, each flow path 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 over-ride for the automatic function.

The exercise of listing functions should be free flowing and should include any and all possible functions from all sources. When the next step is performed, the inconsequential functions will drop out. There is the chance that some obscure functions may have a significant impact on safety or commercial considerations. It is helpful to walk through the accident recovery/scram recovery flow path to make sure 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, there may be some functions for the system that have been used in these guidelines that are not normally considered.

Once the brainstorming has been completed, review the list of functions for duplication of functions, complex functions that need to be separated into more than one function, and for reasonableness. Once all parties are satisfied that the list is complete, compile the list onto a master form and assign each a unique alphanumerical designator.

2.4. Screening the functions

You now have criteria for determining which functions are critical and you have a list of functions for the system. Each function should now be screened to determine if it is a critical function for the system. The screening process should be a simple "Yes/No" review.

Evaluate each function as to whether it meets the criteria or not by asking the question, "Is this function required to..?"

Example:
Function:

A. Provide cooling water to the control building air handlers.
B. Provide cooling water to the office building air handlers.

Criterion:

1. Mitigates the consequences of an accident.
2. Prevents the release of radioactivity after an accident.
3. Could cause a plant trip.

Questions:

1. Is Function A required to mitigate the consequences of an accident?
2. Is Function A required to prevent the release of radioactivity after and accident?
3. Could the failure to provide Function A cause a plant trip?

It is helpful to use a table format as shown in Attachment 1 to document the responses. For example:

Function Screening

	Criterion			Critical Function
Function	1	2	3	
A	Yes	No	No	Yes
B	No	No	No	No

From this screening, we can see that Function A is a critical function and Function B is not if we assume that the criteria were properly selected and that the functions were properly defined. If during the screening, when we ask the question, "Does this function meet this criteria?" and the answer is "Sometimes", then the function needs to be separated into two or more functions that allow each to be answered, "Yes" or "No." If it is not obvious how to answer the question, the function should be rewritten so that a yes/no answer can be given.

At this point, it is important to document the reasons that function were screened the way they were. Many times the "Yes" answers are obvious, but the "No" answers may need documenting. It is not necessary to write a long discussion, but one or two sentences should be written for each function.

2.5. Determining the failures

Now that the functions have been screened, it is necessary to describe what constitutes a functional failure. This may seem like a trivial task, but may times, maintenance hours are spent resolving issues that have no bearing on the ability of a SC to perform its critical function. Preventive maintenance tasks are performed to improve the reliability of a component, but the incremental improvement is more than offset by the amount of unavailable time necessary to perform the maintenance. If airplanes were maintained on the same frequency of many NPP SCs, they would load passengers, taxi out to the runway and taxi back for maintenance.

Example

Function: Provide cooling water flow.

Assume there is a valve in the system that has a packing leak and the tasks necessary to allow maintenance technicians to repack the valve are very time consuming. If the packing leak does not prevent the SC 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 SC cannot "Provide cooling water flow", the maintenance task should be scheduled on a priority basis.

For this portion of the process, it is helpful to have a flow diagram and a wiring diagram to mark the function on. For the example of "provides flow to the control room air handlers" use a colored pencil to mark the flow path that provides this function. Next list all of the components that are important to the flow path to provide the flow. Finally, note any changes of state that must occur. This means any closed valves that must open, any open valves that must close, any equipment that must start and run and any electrical components that must open or close.

Many components can be in more than one state. For example, a valve can open, it can close, or it can be throttled. A circuit breaker can be open, it can be shut, or it can be tripped. Not all of these states are necessarily critical states and therefore the failure of the component to achieve this state may not be a failure that affects its critical function. Again, an example – a valve (Valve 1) may need 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 and it wouldn't close, the critical function could still be accomplished because cooling water could be provided to the heat exchanger. On the other hand, if the valve could not be opened, the critical function would be lost.

In the example, we have defined a failure that would cause a loss of critical function as:

Valve 1 fails to open. (Note: Valve 1 fails to close would NOT be a listed failure.)

At this point it is useful to discuss the best future use of this list. Once the critical components are defined the preventive maintenance strategy can be optimized. A tool such as the EPRI PM Basis Database can be used to define the PM tasks and frequencies that can provide the optimum balance of reliability and availability. These products and their use will be described in a later presentation.

3. CONCLUSIONS

The primary objective of optimizing the maintenance program at a NPP is to provide assurance that the right work is being performed on the right equipment at the right intervals. Of equal importance is the need to balance reliability with availability so that the probability of a critical system/component being available to perform its intended safety function is very high. Many tools are available to assist in the determination of the right task and the optimum interval. The process described here can provide a simple method to determine the right equipment in a timely and cost effective way.

SYSTEM SCOPING REVIEW
System :
System Engineer:

Functions:

A. *(List functions from the brainstorming sessions here. There may be more or less that the list shows.)*
B.
C.
D.
E.
F.
G.
H.
I.

Scoping Review *(The listed criteria is for illustration only. Use plant criteria)*

Function	Safety Related	Trip	Inhibit SSC	Actuate SSC	Mitigate	EOP	In Scope	High Safety	Standby	Modes
A										
B										
C										
D										
E										
F										
G										
H										
I										

Functional Failure:

1. *(List the failures that could cause a loss of the critical functions here.)*
2.
3.
4.
5.
6.
7.

Justification and Scoping:

(Provide a brief discussion of why functions were included in the critical list and why they were not.)

REFERENCES

(List any reference documents here. Examples of the types of references are listed below.)

Design Basis Document
System Description
Technical Specifications:
UFSAR
Other

Annex 4

AUTOMATING PREDICTIVE MAINTENANCE WITH WEB-BASED SOFTWARE

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Abstract. EPRI and Progress Energy implemented Predictive Maintenance (PdM) at eight fossil power plants. This included changing maintenance organizations into effective PdM teams, introducing condition monitoring technologies, and developing a web-based tool to automate the PdM process and improve staff effectiveness. Plant PdM Teams now use condition of major equipment to initiate maintenance tasks thereby avoiding incipient failures, reducing time based maintenance tasks, and scheduling maintenance before high market price periods to improve commercial availability. The PdM process is information intensive and involves a cross section of Plant and Department staff in making maintenance decisions. The PlantView PdM Web Based software was developed to automate the process, improving staff performance and information use, and making equipment condition reports accessible throughout all levels of the Department.

1. BACKGROUND

In 1998, progress energy (Carolina Power and Light) and EPRI entered into a collaborative project focused on fossil plant integrated automation technologies. This project was multifaceted, however two key elements of the project involved process information technologies and plant maintenance optimization.

One project task was to create an overall vision for Carolina Power and Light's Fossil Division to optimize the business of maintenance and introduce condition based / predictive maintenance (PdM). The EPRI M&D Center was engaged to introduce the four key elements of predictive maintenance (PdM) implementation; people, process, technology and work culture. Together, vision casting, assessment in use of technologies, implementation of an effective condition based maintenance program, and continuous improvement with coaching and group review were carried out at all the fossil generating stations. The program illustrated how the use of condition based maintenance enhanced maintenance planning, reduced forced outages and improved commercial availability, and reduced production costs.

A second development focused on plant information management systems. Carolina Power and Light had extensive applications of automation technologies at their fossil generating stations. However, key process, design and business information was located in various stand-alone, specialized system applications in various computers throughout their generating facilities and remote corporate offices. Access to information was cumbersome and time consuming and often only accessible locally by "system experts". These automation systems could not pass information between systems or enable key communications between staff. It was evident that with the new emerging business environment it was critical for information to be accessible quickly by many staff at local or remote sites to perform timely assessments, and make decisive decisions. Maximizing resources, and fully utilizing scarce specialists, required the ability for remote access and analysis of information. The project developed an intranet process information system, called "PlantView". PlantView provides a platform as a single source of key high level information for remote access. Additionally, a number of process information application systems were developed to enable automation of operation and maintenance processes. One highly successful application was the PlantView PdM module.

2. PREDICTIVE MAINTENANCE

Establishing an effective maintenance strategy provides a maintenance basis for work task identification. Optimized maintenance programs are developed around a balanced plan of corrective, preventative and predictive maintenance tasks that focus on high reliability of critical components, and most effective utilization of limited maintenance staff resources. Progressive organizations are evolving into a program that contains a large number of condition directed maintenance tasks in-lue of traditional schedule based tasks or repair upon run equipment to failure. Expensive and resource consuming maintenance tasks are executed only when equipment condition would produce a compelling business case to perform maintenance or before equipment failure would result in unplanned corrective maintenance. This predictive maintenance is essential to reducing maintenance costs and avoiding costly unplanned outages, major repairs, and wholesale replacements.

To aid fossil generating plants with their condition based maintenance task identification, the M&D Center pioneered applications of new condition diagnostic technologies to the generation industry, and evolved a predictive maintenance process based on equipment condition. As equipment wears and degrades toward failure it exhibits operating characteristics that can be detected through vibration, acoustics, heat flux, process measurement, current signature, or contamination detection. The Center worked to establish the cost effective technologies, severity criteria, and experience to make predictions of equipment condition enabling accurate maintenance decisions.

The M&D Center was engaged by Carolina Power and Light Company to introduce the four key elements of predictive maintenance (PdM) implementation; people, process, technology and work culture. Collaboratively, over a two year period an effective condition based maintenance program has been implemented that has resulted in realizing significant production cost benefits, reduced forced outages, and improved commercial availability.

The implementation started with vision casting by conducting a number of PdM workshops. In the workshops management and staff were introduced to the issues surrounding a predictive maintenance process, condition diagnostic technologies, advancements in maintenance task identification and work planning, work culture changes, and the performance measures to validate program effectiveness. A workshop was conducted first for executive management, plant managers, and production supervisors to engage high level support in the program, necessary to ensure a successful launch of this major organizational change within the plants. These were followed by individual plant workshops engaging management and craft staff in vision casting.

After completion of the workshops where all participants understood the definitions and principles of predictive maintenance, individual plant PdM assessments were performed. The M&D Center staff reviewed diagnostic technology utilization, maintenance strategies, task identification and work execution processes, staff organization, and business goals. Additionally, a cross section of plant staff interviews established a foundation to identify pre-existing positive maintenance program practices and identify issues individuals perceive as barriers inhibiting change. These assessments were compiled in a report and a recommended PdM implementation plan was delivered for management to review and authorize an investment to implement the program.

The PdM process requires the collection of diagnostic information and process measurements from a family of technologies. An “Equipment and Technologies” matrix is established for each individual plant. The plant equipment that is included in a PdM program is identified in the vertical axis of a spreadsheet and may be roughly 100 components. The technologies are identified along the horizontal axis of the spreadsheet, i.e. vibration, thermography, lube oil analysis. The spreadsheet is completed with the recommended technologies, data collection frequency, and equipment performance inspections and observations. The Equipment and Technology matrix becomes the basis for selection and investment in new diagnostic technologies.

A Predictive Maintenance program is a structured process. A Predictive Maintenance program routinely collects, analyzes, trends and stores data from selected plant equipment to assess their condition. When any of the measured parameters are determined to be unacceptable, an investigation is initiated to analyze equipment condition. Once an undesirable condition is determined a Work Request or Condition Report may be generated to correct or document equipment condition.

The M&D Center staff helped address the organizational structure, roles and responsibilities, and accountability of plant staff to provide an effective PdM program. Significant is the formation of PdM Teams for each plant and delegating a PdM Coordinator. PdM training was performed to introduce how to use diagnostic technologies and how the PdM Team works to perform condition analysis, make maintenance task decisions, and perform the benefits analysis measurement.
To sustain the continuous improvement of PdM implementation the M&C Center staff provided periodic review and coaching of the plant PdM Teams. Issues carried by the Team were discussed and resolved, and solutions were identified to troublesome equipment problems. This aids in sustaining the work culture of an effective PdM program. Additionally, periodic PdM coordinators meetings were introduced to bring staff from the different plants together. In these meetings experiences are shared, advancements in diagnostics are identified, and continuous training is implemented.

PdM programs recently implemented in industries began automating the analysis and reporting process through the use of the "Equipment and Technology Matrix" (E&T Matrix) and establishing a condition status report. Test results are entered into the spreadsheet and color coded green, yellow or red based on the severity level. The PdM team meets each month to review the technology assessments and assign a single condition status to each component on the spreadsheet. While effective, this process is resource intensive to consolidate the copious data from all the disparate sources of data to perform the assessments. It also does not provide a historical perspective by facilitating learning from past assessments, or from sharing experiences with others.

No commercial product existed to support the effective automation of the PdM process. CP&L and the M&D Center collaborated with PowerVision an Internet software developer to produce PlantView. PlantView automates the business processes of PdM to bridge the gap between technology exams and the CMMS for work order management.

3. PLANTVIEW PdM AUTOMATION

PlantView is an information management system providing an Internet/Intranet architecture that ties the geographically separate plants/departments together, forming a pool of information and experience that is available to all staff as a single source of departmental information. The information will be available from all plant PCs connected to the LAN via Microsoft's internet explorer and the CP&L internal intranet page.

By presenting information in the same way to every computer, an Intranet can do what computer and software makers have frequently promised, but never actually delivered: put all the computers, software and databases that dot the department landscape into a single system that enables employees to find information wherever it resides, hence leveraging access and support from any location.

The PlantView/PdM reporting module will aid in the collection, analysis and condition assessment of PdM related equipment. It provides a department wide intranet based solution that warehouses the individual technology assessments, the monthly component assessments and the case histories that summarize equipment problems. Any user can review open items, items recently closed, a cost-benefit perspective on the PdM program, or problems identified by a particular form of technology. Since a relational database is at the core of PlantView/PdM, data queries and report generation can be provided to meet almost any request.

The PdM Module automates the reporting process of a PdM program by dividing the process into 4 functional sections: technology examinations, equipment assessments, case histories and cost benefits. Multiple technology examinations form the basis for an equipment assessment. A case history consists of any number of equipment assessments and can include multiple cost benefits.

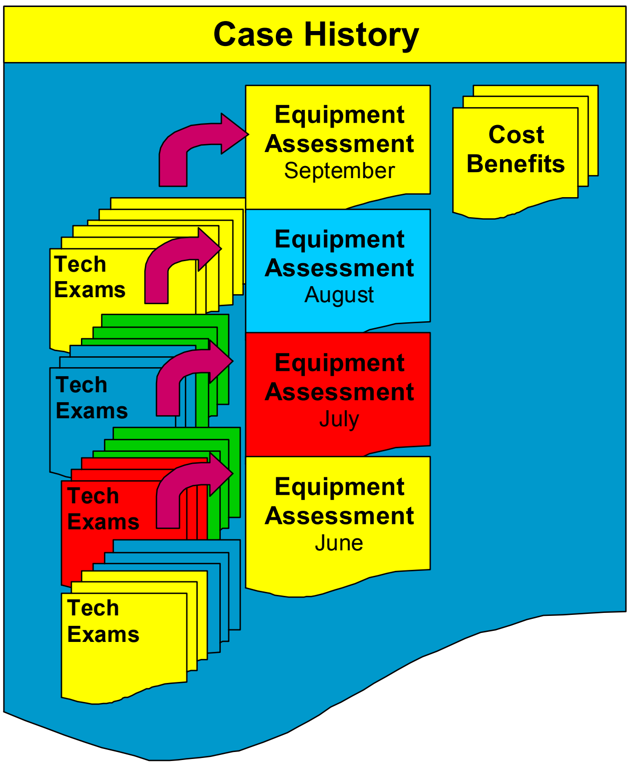


FIG. 1. Predictive maintenance process model.

To aid users in visualizing status of equipment a consistent color coding is applied throughout the program. Technology exams and equipment assessments can be assigned a severity status of satisfactory (green), watch list (blue), marginal (yellow) or unacceptable (red).

Technology owners perform periodic exams on major components and record the results on preformatted templates. Pull down menu fields enhance navigation and simplify data entry. Each component (equipment) within the PdM program will have multiple technologies pre-assigned to it, or new entries can be applied where applicable. The example, vibration diagnostics have been taken for the 2D primary air fan.

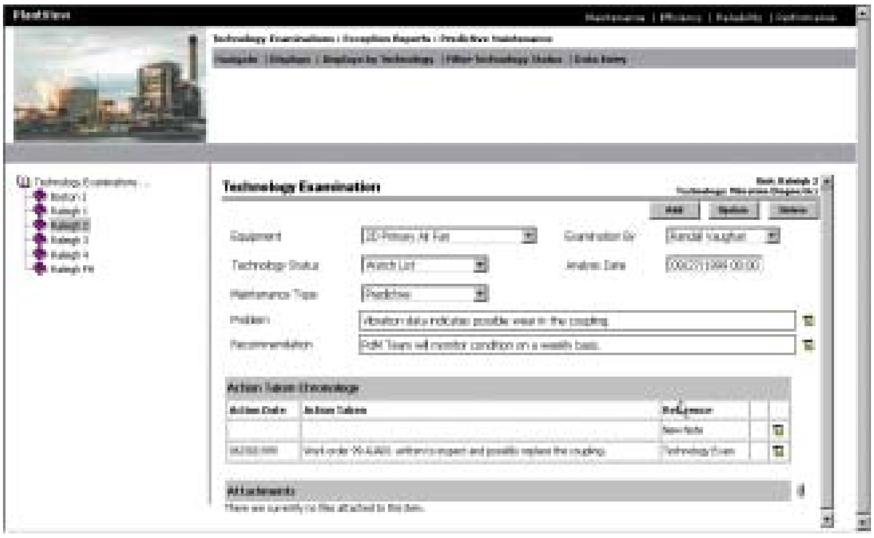


FIG. 2. Example of technology owner data entry template.

Operator inspections and informational entries are also posted as an equipment exam to be reviewed with the component assessment package. Electronic references like thermograms, data charts, digital photographs can be posted with an exam. Data queries are preformatted to identify technology exams that may be backlogged, or a statistical summary of completed versus outstanding exams. Additionally, the exams can be queried by multiple summary criteria, i.e. by component, or technology, or technology owner, or severity status.

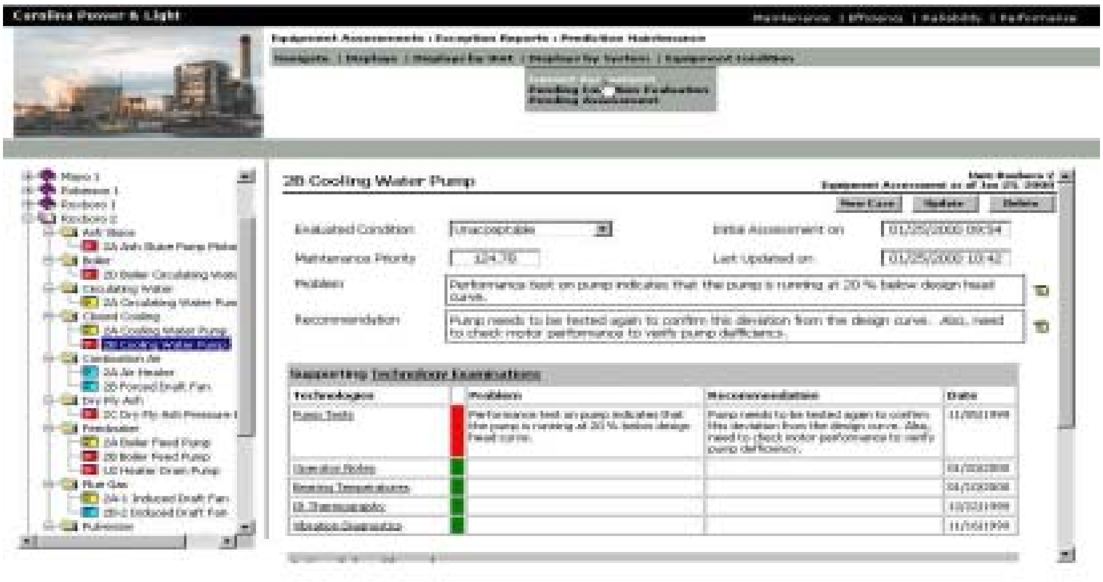


FIG. 3. Example of preformatted template for equipment assessment.

The PdM team has several mechanisms for monitoring the data collection and assessment creation process. Each type of technology is assigned a collection frequency. At any time a technologist can obtain a list of "past due" examinations. The PdM team can also obtain a count of examinations that are awaiting assessment. Technology examinations that have been entered but are not yet part of an equipment assessment are classified as "pending assessment". Examinations that are part of the current equipment assessment are classified as "current". PlantView provides filters to review either the pending or current examinations of a particular technology status.

At regular intervals the system or equipment owners perform the component assessments combining the plant knowledge and engineering experience of the PdM team. PlantView will assign a condition status to the equipment following the simple rule: if all technologies within the assessment are acceptable then the condition status is acceptable. If any examination has a status other than acceptable, the condition status is "pending" which results in an engineering review by the system or equipment owners. Recent assessments can be reviewed, the technology exams are reviewed along with collected logs and inspections, and an equipment status is designated for the component. If any component is beyond satisfactory a maintenance recommendation is applied. For example, the owner can designate the component for the watch list, increase technology exam frequencies, or recommend executing a maintenance task order.

There are many methods for reviewing the current equipment status. The condition status report matrix displays the status of technology examinations and equipment assessments. It can be generated at any point in time as a “visual snapshot” of the equipment condition, or provide a high level illustration of overall plant condition. It is an excellent visual in portraying the overall program with respect to technology exams and equipment assessments. Additionally, with the relational database capabilities, data queries can be requested to display equipment condition based on severity status.

FIG. 4. Example of condition status report matrix.

The equipment condition report is considered to be the end product of the PdM analysis work for a time period and indicates only equipment that are in a non-acceptable equipment assessment condition. It is intended for management view and is to be a summary document describing only the problem, recommended solution, action date required, and responsible person. Many PdM programs generate and use this document as the basis for the plant monthly reliability meeting.

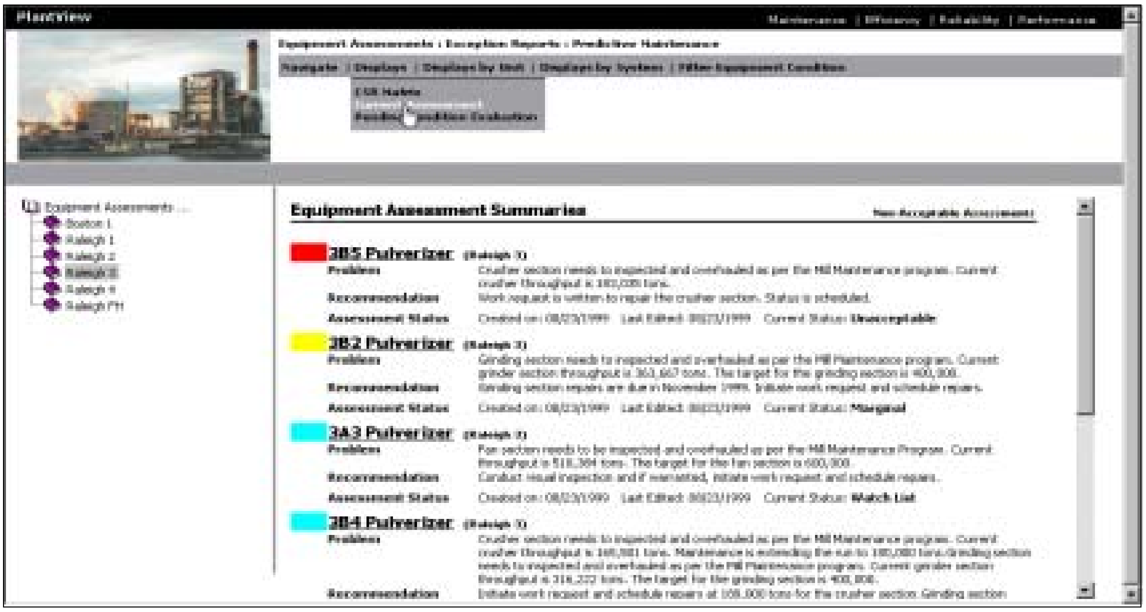
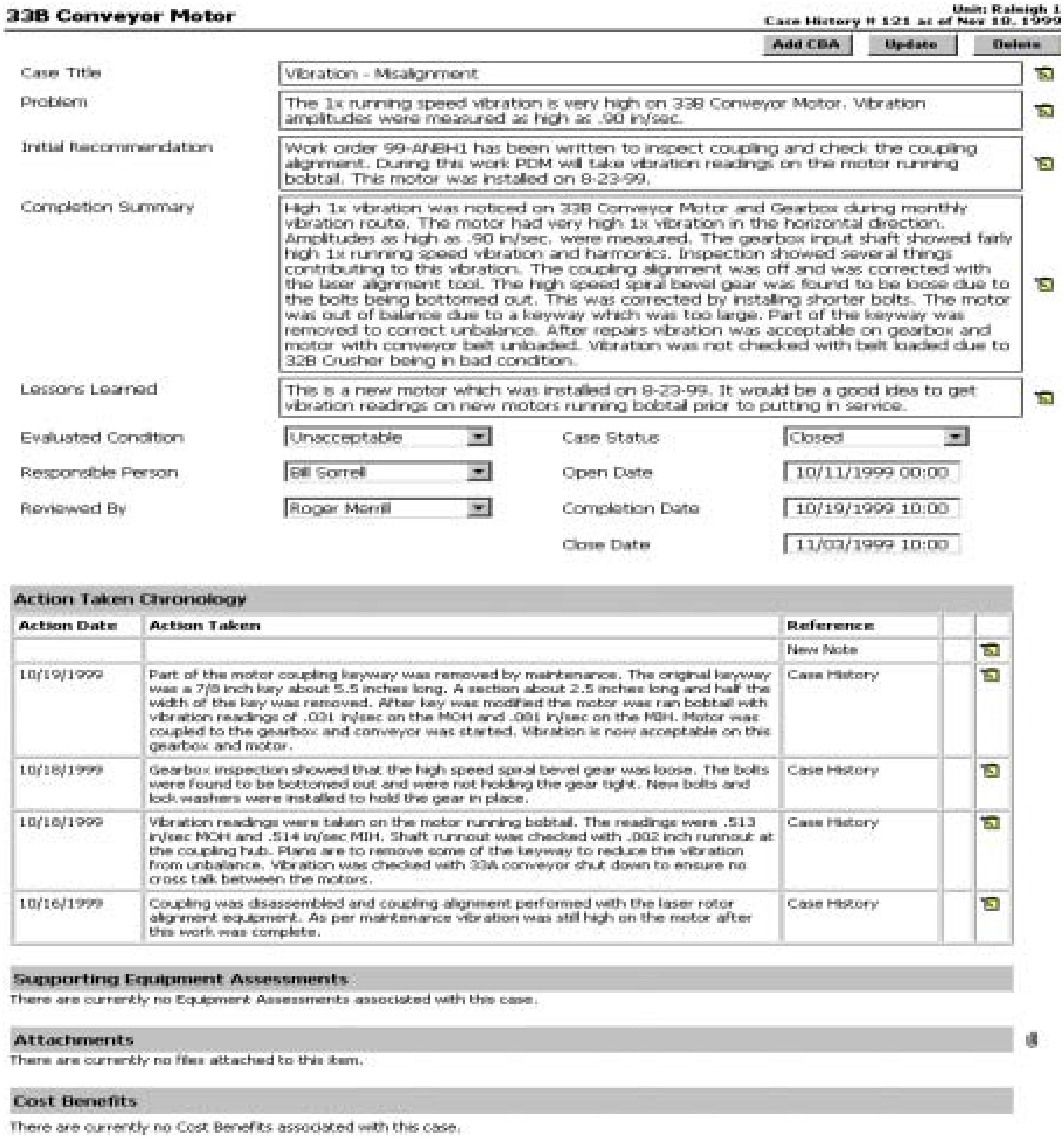


FIG. 5. Example of non-acceptable equipment condition summary report.

The case history is a folder that includes all of the information relating to a specific equipment problem. A case may open and close in a day or extend for several months before a maintenance action takes place. Open cases represent the current equipment problems at the plant. Closed cases are the living record of the maintenance history associated with an individual component. For the PdM program to be effective, the plant staff must identify problems, open and close the associated cases, and then learn from the histories of similar equipment at their plant (or other plants). These case histories are accessible for review in sharing significant event experiences at periodic PdM coordinator meetings as a forum for continuous improvement.

Cases are created when the equipment status is either marginal or unacceptable. Technology exams and equipment assessments will automatically be associated with the case. The owner has the option of storing additional reference documents (word, excel) and images (.bmp., jpg.) to support the case history. A case has several purposes: 1) to capture a significant event for historical documentation purposes, 2) if an equipment condition lasts for several months the case history becomes the folder that captures the periodic equipment assessments, 3) to form the vehicle for sharing of information between remote facilities to better utilize specialists both internally, and from external organizations. A sample case form includes a running log of actions gathered from the examinations, assessments and the case itself. The case display also includes all the contributing assessments and their associated technologies.

A good PdM program provides success metrics and tracking to indicate the effectiveness of the program. One such method is to calculate a cost benefit analysis (CBA) on significant PdM events or finds. The CBA approach used within the PlantView PdM Module uses an EPRI M&D Center developed methodology to determine the potential value of a PdM or proactive discovery; avoided curtailments or replacement power costs, lost performance or increased O&M costs. The net benefit is calculated from comparing probabilities of catastrophic, significant, and minor scenarios with actual cost of repair. The PlantView PdM module provides a form for PdM coordinators to enter and calculate their CBAs with actual case history information.



33B Conveyor Motor

Unit: Raleigh 1
Case History # 121 as of Nov 10, 1999

Add CBA | Update | Delete

Case Title	Vibration - Misalignment
Problem	The 1x running speed vibration is very high on 33B Conveyor Motor. Vibration amplitudes were measured as high as .90 in/sec.
Initial Recommendation	Work order 99-ANBH1 has been written to inspect coupling and check the coupling alignment. During this work PDM will take vibration readings on the motor running bobtail. This motor was installed on 8-23-99.
Completion Summary	High 1x vibration was noticed on 33B Conveyor Motor and Gearbox during monthly vibration route. The motor had very high 1x vibration in the horizontal direction. Amplitudes as high as .90 in/sec. were measured. The gearbox input shaft showed fairly high 1x running speed vibration and harmonics. Inspection showed several things contributing to this vibration. The coupling alignment was off and was corrected with the laser alignment tool. The high speed spiral bevel gear was found to be loose due to the bolts being bottomed out. This was corrected by installing shorter bolts. The motor was out of balance due to a keyway which was too large. Part of the keyway was removed to correct unbalance. After repairs vibration was acceptable on gearbox and motor with conveyor belt unloaded. Vibration was not checked with belt loaded due to 32B Crusher being in bad condition.
Lessons Learned	This is a new motor which was installed on 8-23-99. It would be a good idea to get vibration readings on new motors running bobtail prior to putting in service.

Evaluated Condition	Unacceptable	Case Status	Closed
Responsible Person	Bill Sorrell	Open Date	10/11/1999 00:00
Reviewed By	Roger Merrill	Completion Date	10/19/1999 10:00
		Close Date	11/03/1999 10:00

Action Taken Chronology

Action Date	Action Taken	Reference
		New Note
10/19/1999	Part of the motor coupling keyway was removed by maintenance. The original keyway was a 7/8 inch key about 5.5 inches long. A section about 2.5 inches long and half the width of the key was removed. After key was modified the motor was ran bobtail with vibration readings of .031 in/sec on the MOH and .081 in/sec on the MIH. Motor was coupled to the gearbox and conveyor was started. Vibration is now acceptable on this gearbox and motor.	Case History
10/18/1999	Gearbox inspection showed that the high speed spiral bevel gear was loose. The bolts were found to be bottomed out and were not holding the gear tight. New bolts and lock washers were installed to hold the gear in place.	Case History
10/18/1999	Vibration readings were taken on the motor running bobtail. The readings were .513 in/sec MOH and .514 in/sec MIH. Shaft runout was checked with .002 inch runnout at the coupling hub. Plans are to remove some of the keyway to reduce the vibration from unbalance. Vibration was checked with 33A conveyor shut down to ensure no cross talk between the motors.	Case History
10/16/1999	Coupling was disassembled and coupling alignment performed with the laser rotor alignment equipment. As per maintenance vibration was still high on the motor after this work was complete.	Case History

Supporting Equipment Assessments

There are currently no Equipment Assessments associated with this case.

Attachments

There are currently no files attached to this item.

Cost Benefits

There are currently no Cost Benefits associated with this case.

FIG. 6 Example of equipment case history report

The relational database capabilities within PlantView, enables the overall cost totals to be displayed for equipment, units, plants, and even rollup for departmental totals. These totals can be used to support the success metrics associated with the overall PdM program.

The PdM cost benefit summary is a report generated as a management report to indicate the effectiveness of the overall PdM program and display monthly, quarterly, annual, and program to date views. The report will be focused on plant and departmental summaries and indicate the "net benefit" of the program by comparing program costs (man-hours, technology, training, and contract support) to program savings calculated from the cost benefit analyzes. The report also attempts to indicate adherence to the monthly PdM process by tracking the technology and equipment assessments performed.

3A Condensate Pump

Unit: Raleigh 3
Cost Benefit as of Sep 01, 1999

Calculate | Update | Delete

Background Information

Event Date	04/02/1999	Primary Technology	Pump Tests
Event Description	Performance tests indicate pump efficiency problems		
Assumptions & Comments	Catastrophic - Replace element which includes a new shaft. 4 men * 48 hrs * 21 $/hr Expendables= $385 Significant = replace element. minimal = replace element with no load reduction. Ref WO 99-AGCZ2 uses NPV of 9.18		
Total Avoided Costs	$33,680		

Cost Benefit Calculation

	Occurrence Assumptions			Actual Costs
	Catastrophic	Significant	Minimal	
System Impact				
Energy & Capacity Charges $/MHr	$9.18	$9.18	$0.00	$0.00
Load Reduction MW	350	350	0	0
Hours Offline	48	48	0	0
Loss of Performance	$0	$0	$0	$0
Potential Loss of Revenue	$154,224	$154,224	$0	$0
O&M Impact				
Material Costs	$385	$385	$385	$73,480
Repair Costs	$85,000	$73,345	$73,345	$0
Labor Costs (CP&L and Contractor)	$4,100	$4,100	$4,100	$1,748
Other	$0	$0	$0	$0
System/O&M Impact Sub Total	$243,709	$232,054	$77,830	$75,228
Probability of Occurrence	2%	10%	88%	
Avoided System Costs	$30,845			
Avoided O&M Costs	$2,835			
Total Avoided Costs	$33,680			Calculate

Attachments

There are currently no files attached to this item.

FIG. 7. Example of cost benefit analysis.

PdM Program Cost Benefit Summary

ADMINISTRATOR Scope
01/01/99-11/20/99

Unit	Analyses	O&M Impact	System Impact	Total Savings
Boston 1	4	$61,563	$5,162	$66,725
Raleigh 1	1	$4,080	$0	$4,080
Raleigh 3	4	$44,525	$30,845	$75,370
Raleigh 4	1	$14,439	$0	$14,439
Raleigh FH	2	$0	$0	$0
Totals for Jan 1 - Nov 20, 1999	**12**	**$124,607**	**$36,007**	**$160,614**

1999 PdM Program Summary

Unit	Analyses	O&M Impact	System Impact	Total Savings
Boston 1	4	$61,563	$5,162	$66,725
Raleigh 1	1	$4,080	$0	$4,080
Raleigh 3	4	$44,525	$30,845	$75,370
Raleigh 4	1	$14,439	$0	$14,439
Raleigh FH	2	$0	$0	$0
Totals for 1999	**12**	**$124,607**	**$36,007**	**$160,614**

PdM Program Summary

Unit	Analyses	O&M Impact	System Impact	Total Savings
Boston 1	7	$253,785	$150,775	$404,560
Raleigh 1	1	$4,080	$0	$4,080
Raleigh 2	0	$0	$0	$0
Raleigh 3	5	$53,950	$178,579	$232,529
Raleigh 4	2	$12,101	$281,649	$293,750
Raleigh FH	2	$0	$0	$0
Grand Totals	**17**	**$323,916**	**$611,003**	**$934,919**

FIG. 8. Example of program cost benefit summary

SUMMARY

This paper has illustrated how predictive maintenance was introduced to a major electric generating company. Predictive maintenance is an essential component of reducing costs of operations and maintenance. Equipment problems must be detected and corrected early to avoid costly unplanned outages, major repairs, or wholesale replacements. Significant cost reduction can be obtained by early detection of equipment problems, which reduces the number of emergency and urgent work orders and improves equipment availability. The PlantView PdM helps leverage existing plant resources by automating the business processes of predictive maintenance. It enables effective utilization of limited resources and provides department wide access to key information regarding equipment and plant condition. In addition, PlantView enables PdM coordinators to complete a vast number of component assessments and provide timely reports of the condition of plants for the highest levels of management to review.

Annex 5

MAINTENANCE OPTIMIZATION METHODS FOR NPP CRITICAL SYSTEMS, STRUCTURES AND COMPONENTS

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Abstract. Considerable progress has been made in the development and implementation of the PLiM program [1], with formal processes to systematically identify and evaluate the major critical systems, structures, and components (CSSCs) in the station, and a plan to ensure that the plant surveillance, operation, and maintenance programs monitor and control component degradation well within the original design specifications essential for the plant life attainment. The paper presents a brief description of the most important aspects of the methods used to identify the CSSCs taking into account maintenance activities. The systems structures and components (SSCs) that influence decisively the nuclear power plant (NPP) reliability are considered as critical. Also, for the accident conditions, the SSCs, which have a major influence to the system availability/operability, are considered also as critical. PSA techniques serve as a basis for maintenance optimization. The paper includes: a description of the most important operational/accident events on which the maintenance has important contribution; the steps to establish the systems / components that need maintenance using risk indicators; methods to identify CSSCs taking into account maintenance; the events associated to maintenance activities and presentation of method to determine the significance of the maintenance related events, selection of the most significant maintenance related events; ierarhization of maintenance events (taking into account failure effects or risk indicators); ranking / ordering of the maintenance related events; maintenance optimization of CSSCs and optimization of the maintenance parameters.Specifically examples for Cernavoda NPP Unit 1 are selected and presented in order to state the analytical methods. A computer database using Visual Basic 6.0 language is developed to manage and describe some analysis tasks.

1. BACKGROUND

The events that appear in the power plant or installation operation are recorded then a study is performed to classify and to group them in some categories. The events that have or could have impact on the plant safety barriers or/could affect the operational personnel or the public are selected for further analyses in order to identify the event root causes and to prevent the recurrence of such events.

Usually, for NPP operation, the maintenance department is made up by an electric maintenance section and a mechanical maintenance section and consists of many persons. The significant events are those events that could appear during plants/installation commissioning or during operation of such utilities and have impact on the safety barriers/margins/limits of them.

The analysis methodologies are based on probabilistic/deterministic techniques. The deterministic process of the evaluation of the installation safety is based on the design basis accident identification. These events could consist of extreme conditions (but possible) considered to be possible to appear in the power installation that are analysed. Until now the probabilistic process of analysing the significant events was not specifically considered as part of the significant events analysis methods.

In the analysis of one power plant system or installation/process the first step is familiarisation with this installation/process. Significant events are considered the events that appear during a system operational state and affect the safety barriers leading to undesired consequences and impact to the environment. The main methods to analyse the significant events are based on deterministic and probabilistic approaches.

2. ANALYSIS METHODS

The further analysis of the significant events is done in order to guarantee that in the future the possibility of appearance of such events will be as minimal as possible, and also, in order to identify the related events that could lead to similar events in the power plant.

Ranking of the operational events

The ranking of the operational events were done taking into account the possible applications of such events. One of the questions that could be made is if ranking is the appropriate term to denominate such events processing activities and if classification or screening, sorting, grouping are not more appropriate terms. The decision was took depending of the complexity of understanding thinking to the ranking term. Processing of the operational events means:

selection of the event, sorting of the event, grouping of the event, ranking of the event.

A preliminary judgement is necessary using the event description. Ranking method selection depends on some ranking criteria and application of the ranking results. The ranking criteria are both qualitative and quantitative and additionally refer on safety impact, management and human performance deficiencies, possible accident consequences, likelihood reasons, number and efficiency of available barriers to prevent degradation of plant state.

The operational events ranking criteria considers:

nuclear safety impact, significance of the normal operation perturbation due to operational event, significance of the transient induced by the operational event, common cause impact of the operational event, design deficiencies that were revealed by the operational event, departure of the estimated probability comparing target objective.

Decision to perform a detailed system/unit analysis depends of the significance of the operational event looking to the ranking criteria. Performance indicators like plant availability, numbers of reactor trips, total number of the operational events, number of the events per year, reactor shutdown per year, number of human errors. The most known method to process the operational events is the method to obtain the failure rates of the components.

Processing of operational data to obtain SSC failure rates

The SSC reliability data are an essential component of any probabilistic safety evaluation study. The quality of data could major change the quality of the overall PSA study. A complete PSA database must consists of:

components failure data, SSC test and maintenance data, initiating events data, common cause failures data, uncertainty data, human errors data, SSC aging data.

For the reliability data on make many estimations looking to the SSC failure rates. Development of a reliability database is done by means of elementary rules of mathematical statistics. The types of data are discrete or continuous. Bulk data are processed in order to give a shape that is appropriate to be subject of an analysis. By grouping data part of information is lost but could obtain more clarity and adaptability looking to the data processing operations.

Maintenance programs

The activity of SSC maintenance in an NPP continues to be very important and maintenance management means also to reduce the costs without reducing the specific or overall safety level. A maintenance program is a complex process that provides the efficiency of all NPP's SSC that have safety functions according to the initial project assumptions and that guarantee that the plant safety level will be not affected during normal plant operation. Probabilistic Safety Assessment (PSA) provides a structured and logical approach to identify credible accident sequences, assess the corresponding likelihood and delineate the associated consequences. Using PSA could identify possible weak spots in the design and operation of the plants and could also rank the dominant risk contributors. These insights may directly lead to safety improvements at the plants by means of design modifications or procedural changes.

Maintenance activities are assessed for:

NPP design evaluation, design changes evaluation, optimisation of nuclear safety, NPP life extension.

During plant operation are done several maintenance activities (preventive or corrective) for standby SSC in order to assure their availability.

The maintenance optimisation activities are important also for:

evaluation of induced risk due to maintenance activities, identifying of the plant areas that need high attention due to maintenance, identifying of the plant areas where the maintenance activities don't need high attention.

SSC configuration management

During NPP operation the SSC state change due to failures, maintenance and testing. These changes lead to modifications in plant configuration that affect the plant risk [1].

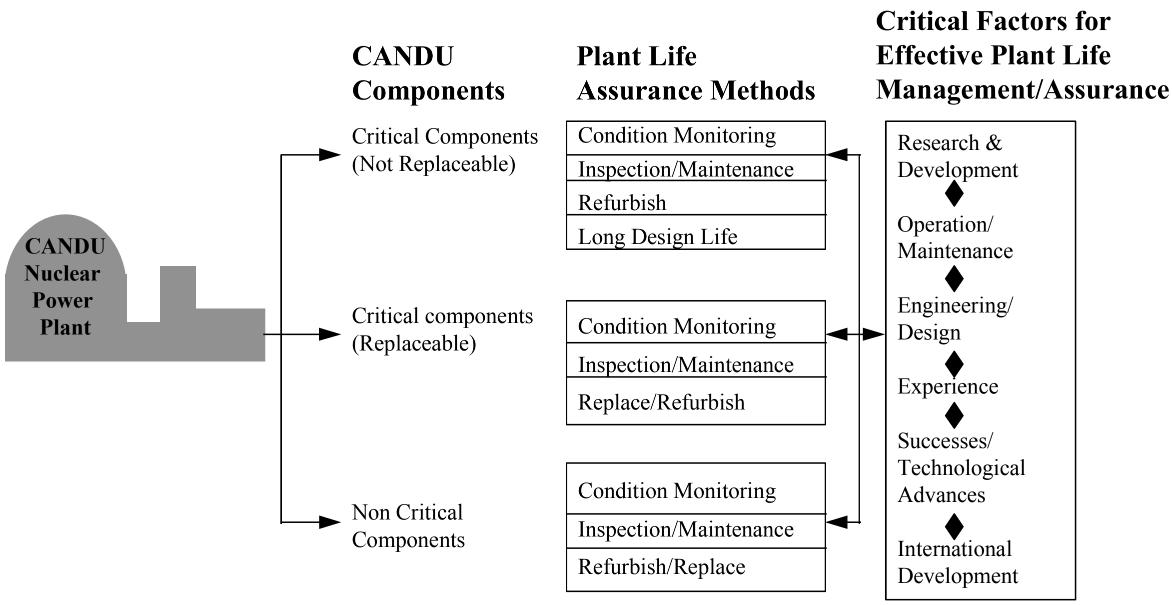

FIG. 1. The screening/prioritization approach in CANDU NPP PLIM.

The management of SSC configuration means: identifying of risk significant configuration and providing of solutions to avoid them and to restore the configuration with an acceptable risk level, assurance of flexibility in NPP operation when the implications on risk are minimum, prevention of high-risk recurrence due to SSC aging generated by maintenance.

Planning of preventive maintenance

Preventive maintenance is applied during normal operation of the plant being a difficult activity for operation/maintenance personnel. PSA can assure the basis for planning the maintenance activities minimising the negative effects on plant risk level due to unavailability of some SSC during maintenance.

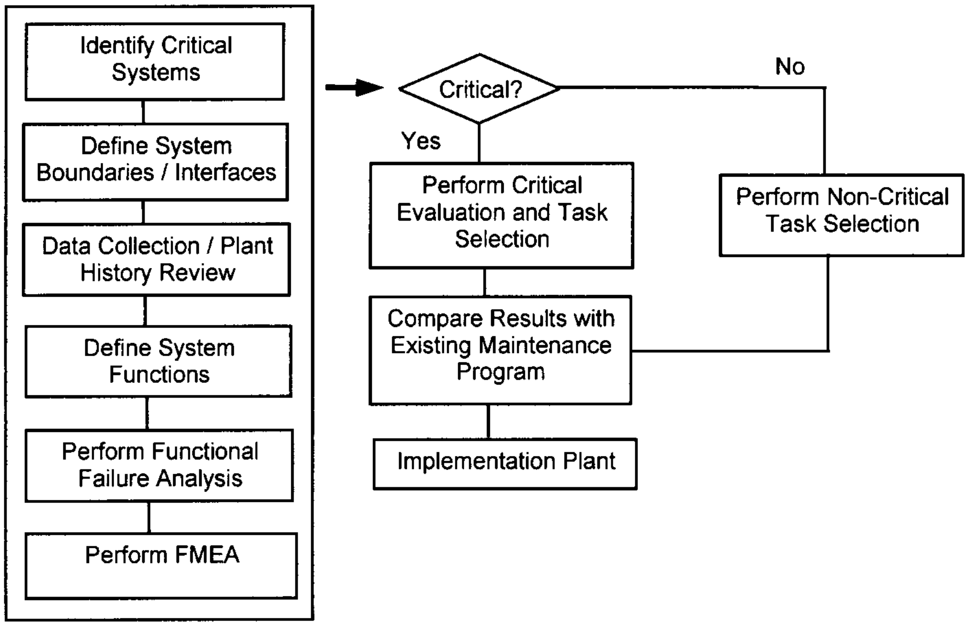

FIG. 2. Maintenance optimisation program.

Modification/Optimisation of AOT

By AOT is defined the time that could be allowed for out of operation of SSC. The necessity to modify AOT appears:

if the failures that appear during operation require a long time to be, if the component AOT is not clearly defined in technical specifications and lead to ambiguity between operation personnel and regulatory body, if it is necessary the monitoring of the risk.

The critical maintenance activities could be identified using some importance factors:

"Risk Achievement Worth" (RAW) = contribution of a function to risk level

"Risk Reduction Worth" (RRW) = contribution of a function to risk reduction level

The functions that have high RAW are important for the quality assurance programs and for inspection activities.

The functions that have high RRW are of interest for the efforts to reduce risk.

In this paper is presented a case of association between operating events and CSSC. The main reference was the PSA study for Cernavoda NPP, Unit1 CPSE B+ [3]. From this study was selected and presented:

- the contributions diagram for the occurrence of one accident (small LOCA) with some severe consequences (e.g. PDS 1-2 – early core damage);
- dominant accident sequence that had been analysed;
- the initiating event that generated the possible dominant sequence;
- the most important accident events;
- qualitative and quantitative results;
- main CSSC identification;
- results validation and proposals for system operation performances improving;
- documentation of the analysis.

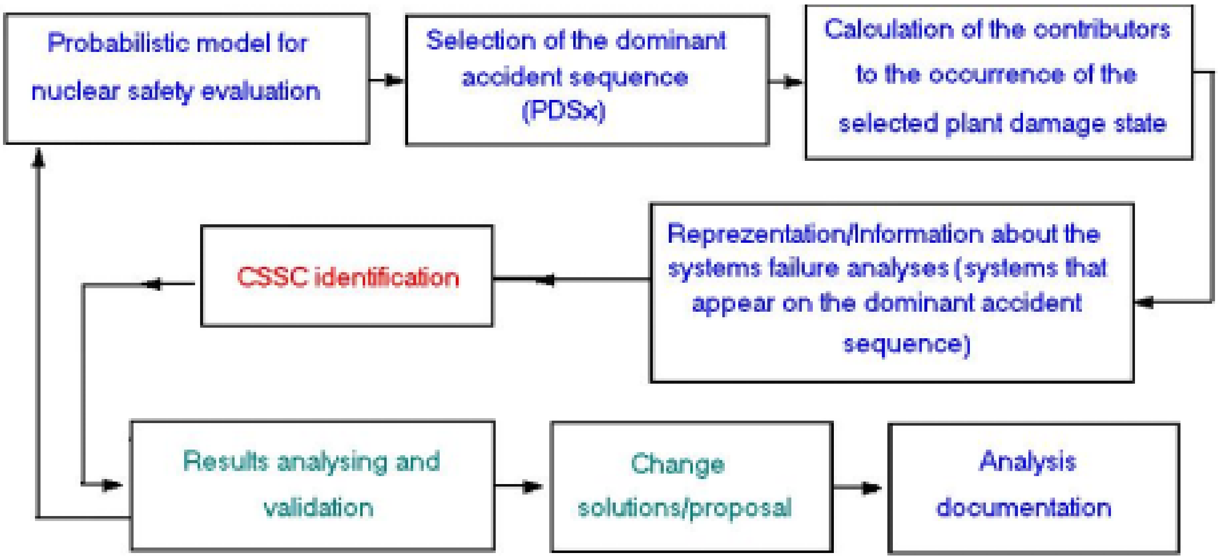

FIG. 3. CSSC Identification Steps.

AOT versus risk

The following steps should be considered to determine AOT: *identify all the SSC for which AOT is assessed, verify if the PSA model contains these SSC, determine the contributions in risk due to AOT, determine the acceptance criteria of AOT contribution, determine AOT that satisfy criteria.*

There are two contributions associated with AOT: *singular AOT contribution and AOT frequency contribution.* Singular AOT contribution is associated with a failure occurrence and AOT frequency contribution is the cumulated contribution due to several successive failures.

Calculation of singular AOT contribution:

F_1 = level of risk with the SSC failed;

F_0 = level of risk with the component available;

d = failure time;

$(F_1 - F_0) \cdot d$ = singular AOT contribution = r_{AOT}

Calculation of frequency AOT contribution:

R_{AOT} = frequency AOT contribution = $w \cdot d \cdot (F_1 - F_0) = w \cdot r_{AOT}$

w = failure rate.

Loss of the process control during system operation could lead to undesirable events and as a result to loss of operational safety.

The factors that generated the event

A graphical representation is used by means of which the events caused. The diagrams use symbols for representation of the initiating event, normal process events, causal factors, root causes, failure/defence barriers, and basic events.

The possible causal factors are focused on the diagrams. Using this technique, the irrelevant causal factors often become evident. Such diagrams are useful for complex situations being more relevant than narrative description.

Using the established symbols is possible to represent actions, modification/deviations, barriers, causal factors and root causes.

The causes that generated the event

The causes could be grouped in causes related of:
management, system/plant design, operation/test/maintenance procedure, activities planning/organization, operation of the plant/system/installation etc.

The effects of the significant events on the plant operation and on the environment

This type of analyses are correlated with different analysis methods: probabilistic analyses, thermo-hydraulic analyses, physique calculation/analyses, others studies/analyses for plant/installation safety.

Significant events analyses types

In the analysis of the significant events are used deterministic and probabilistic analyses. The deterministic analyses are based on the design basis accident identification. Such events include extreme conditions that are possible in the power installation. The design of the safety systems, which have the role to control and mitigate the consequences of the events, is performed based on them. The recommendations that result after utilisation of the deterministic methodology are incorporated in the design, operation standards, procedures and rules. For criteria, standards and safety limits, establishment/development research, standardisation, design, operation activities are performed. The results of these efforts must lead to a high level of safety and a large field of rules and standards comparing to other fields. The deterministic methodology doesn't deny the "*probability*" or "*likelihood*" approach.

The method of assessment of significant events using PSA model/study

Defining the event significance

To define the event significance the following factors must be taken into account: event frequency, the possible consequences of the event, the uncertainty due to the event understanding and the assessment tools.

In this context, the significance of the event is obtained from the event frequency and the possible causes. The method analytical basis is derived from the importance data that are used in the PSA (Probabilistic Safety Assessment) studies. From the point of view of the risk a numerical measurement, S_X, of the event could be obtained from the following relation:

$$S_x = \frac{PDF_x}{PDF_{BL}}$$

where: PDF_x - the updated plant damage frequency related to the observed event "x";

PDF_{BL} - the reference frequency of the plant damage.

The reference frequency of the plant damage results from the plant specific analysis or from the generic PSA results that are applied to a specific plant. The numerical significance of the observed event is designated by an updated fraction of the plant damage that implies the event. The analysis of the updated fraction must take into account the possible differences between the actual frequency and the impact of the observed event comparing with the data and the impact used in the PSA analyses. The method consists of seven steps and is presented in Table1.

TABLE 1. Significant events evaluation using PSA

Step	The activity
1	*The analysis of event impact* Determine the functional impact of the observed event. This could include an initiating event, which lead to plant shutdown, an equipment failure, an unplanned unavailability, human errors or a combination of these issues.
2	*The comparison of PSA impact events* Determine if the observed impact events are evaluated in the available PSA study and check how they were included in the E/T, F/T. In case that the combination of the impact events is not included in the models, determine if similar impact events are included.
3	*The estimation of event frequency* Assess the frequency of the observed event taking into account the actual operation experience of the plant. If the event implies unplanned equipment unavailability is also estimated the period within the equipment was unavailable.
4	*The determination of reference* PDF_{BL} Determine the reference frequency of plant damage PDF_{BL} based on the PSA results.
5	*The estimation of updated* PDF_{BL} *value* Estimate the updated PDF_x value from the sequences that involve the observed event.
6	*The calculation of the event significance* S_X Calculate the event significance $S_x = \frac{PDF_x}{PDF_{BL}}$

The main purpose of this evaluation is to develop a numerical scale that allows events comparison and the analysis of the priorities in order to upgrade the plant. Such a scale is presented in Table 2.

TABLE 2. Event significance ranges

Event significance	S_X range
Very small	< 0.01
Small	0.01 - 0.10
Medium	0.10 - 0.30
High	0.30 - 1.0
Very high	> 1.0

The method for the event significance measurement, based on PSA model, does not substitute but complete the results obtained from a complementary method.

3. MAINTENANCE OPTIMIZATION USING PSA RESULTS

The PSA analysis is capable to evaluate the risk and their safety and operation implications to the nuclear power plant. Risk analysis is the main way to assure the optimisation of the maintenance activity. Evaluation of maintenance activities has to carry out the following objectives:

- Identification of the field of interest for personnel that perform maintenance activities;
- Identification of the fields where the regulation modifications are required, taking into account the plant safety;
- Optimisation of risk/benefits using planning;
- Detection of dependent failures and configurations of the plant with risk significant implications;
- Minimization of dependence between human errors in activities as maintenance, test, repairs, calibration.

The process of optimisation can be done at the component level, the system level and the plant level. The risk-based application enables the maintenance plan to be changed to reduce the risk if necessary or to perform needed maintenance with confidence that safety is adequate.

A quantitative PSA method is used to prioritise or identify risk-significant equipment. The method involves the use of PSA results to prioritise all equipment modelled in the PSA according to objective figures of merit, which merit measure risk-significance. Using importance evaluation, we developed a procedure for identifying risk-significant equipment, which consists of the following steps:

- The initial maintenance program: includes initial list with data referring to components, equipment maintenance activities;
- The list with important components: obtained using risk analysis, important evaluation (Risk Achievement Worth, Fussel-Vesely Importance);
- The comparison between the list of the maintenance programs with the initial list;
- The evaluation of comparison and implementation of the observations using a final form as document.

This procedure will be applied to those systems whose effects result in a significant increase in core-melt risk. Core damage accidents, especially early core damage, are very severe accidents.

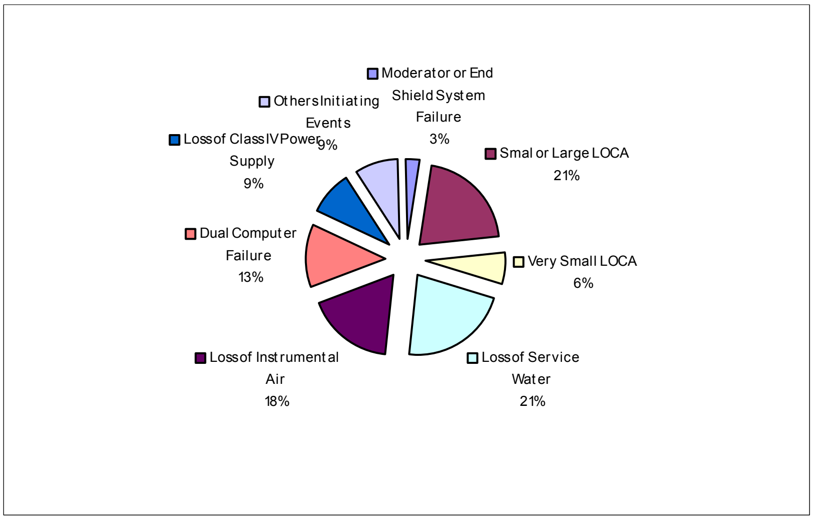

FIG. 4. Initiating events groups contributions to late core damage.

In the CPSE B+ [3] study the late core damage accident was analytically estimated as having an occurrence frequency of 7.4E-05 events/year. The above diagram indicates the contributions of different initiating events groups at the overall frequency. Each initiating events group is has associated as support the probabilistic analyses that leaded to their occurrence frequencies. So, from the accident sequences for 'Small LOCA' (occurrence frequency 6,23E-06 events/year [3], the dominant sequence has a contribution of 8,6 %.

Dominant accident sequence description

Dominant accident Sequence equation is:

LOCA2 * SD*N (CLIV)*LOOPIZ*N (CLIV-OP)*N (MOD-LHS)

IE -, Small LOCA
, Success of reactor shutdown'

'Failure of Class IV power supply'
, Success of PHT loop isolation'

'Operator failure to restore Class IV power supply'

'Moderator System unavailable as the last heat sink'

In case of a small LOCA initiating event occurrence, the Emergency Core Cooling System (ECCS) doesn't supply water make-up in PHTS.
One-failure criteria of this system could be:
No LOCA signal (PHT pressure is low and the pressure in reactor building is high)
ECCS high-pressure circuit, HP-ECC, fails (manually initiated)
ECCS medium pressure circuit, MP-ECC, fails (manually initiated)
8 out of 8 injection valve, on each PHT loop, fails to open
After the system modelling in such conditions and processing of the fault tree the following results were obtained for 'IE – small LOCA'
Top Value: 4.04052445813488E-02 events/year
Quantitative truncation criterion: 0.0000001
Qualitative truncation criterion: 4
Taking into account the following failure criteria the main ECCS critical components were identified to be as follows:

<table>
<tr><th>No.</th><th>System</th><th>Initiating Event</th><th>Critical components (singles or grouped)</th></tr>
<tr><td>1</td><td rowspan="5">Emergency Core Cooling System</td><td rowspan="5">Small IE – LOCA</td><td>Pneumatic Valve PV10</td></tr>
<tr><td>2</td><td>Pneumatic Valve PV11</td></tr>
<tr><td>3</td><td>Relief/Safety Valve RV 85</td></tr>
<tr><td>4</td><td>Relief/Safety Valve RV 86</td></tr>
<tr><td>5</td><td>Relief/Safety Valve RV 102</td></tr>
</table>

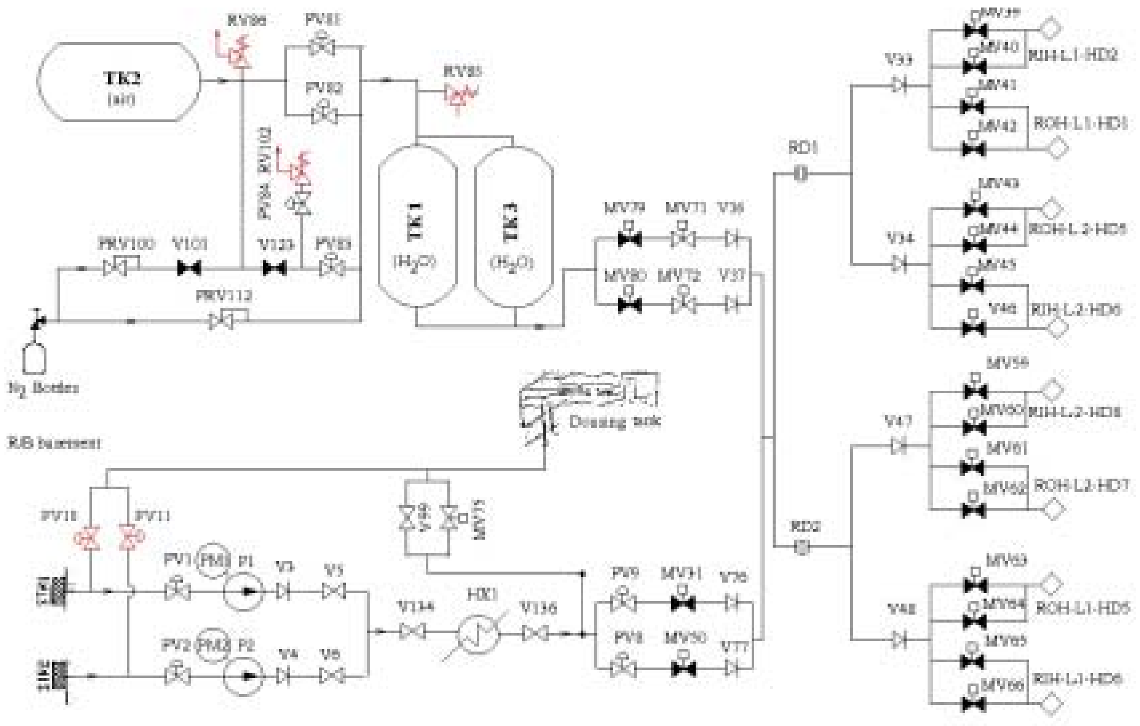

FIG. 5. Emergency core cooling system with the main CSSC.

The second accident event was, Failure of Class IV power supply' for which the probabilistic modelling revealed the following results:

Top event global value: 7.03986781476137E-05 (probability)

Quantitative truncation criterion: 0.0000001
Qualitative truncation criterion: 4

Taking into account the following failure criteria the main Class IV Power Supply critical components were identified to be as follows:

No.	System	Initiating Event	Critical components (singles or grouped)
1	Class IV Power Supply	TE - „failure of Class IV power supply"	Bus BU A
2			Transformer TR 01 and Transformer TR 05

The next event is: 'Operator failure to restore Class IV power supply'. In this case the critical component is the 'operator'.

The last accident event is: 'Moderator System unavailable as the last heat sink'

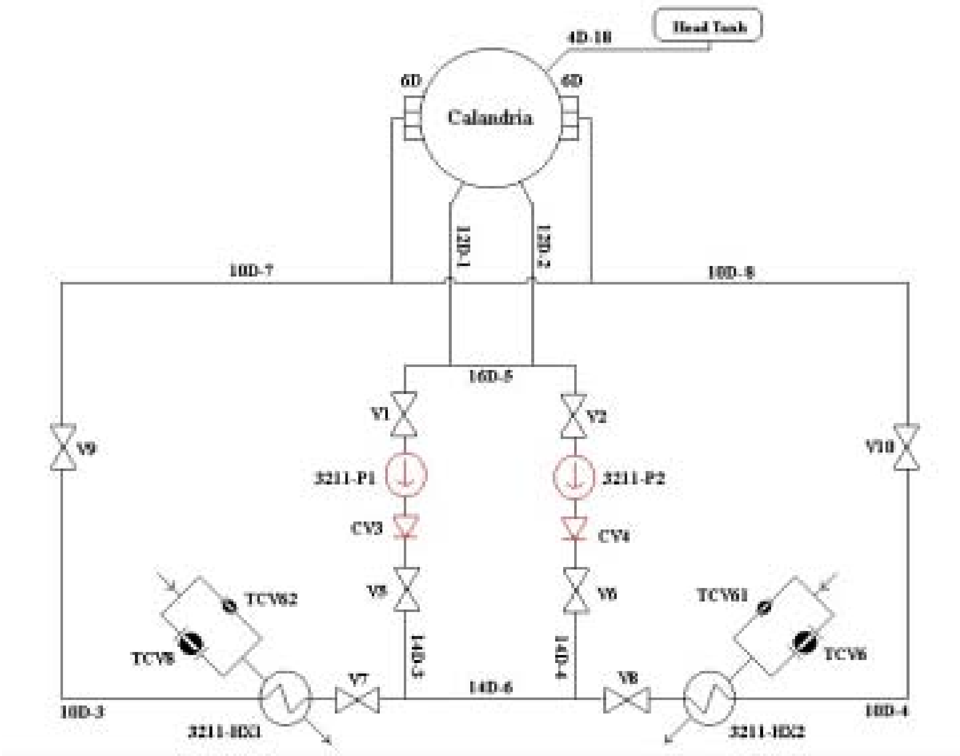

FIG. 6. Moderator main circuit with the main CSSC.

After probabilistic modelling resulted the following results:

Top Value: 0.161433367940093 (probability)

Quantitative truncation criterion: 0.0001
Qualitative truncation criterion: 4

Taking into account the following failure criteria the Moderator Main Circuit critical components were identified to be as follows:

No.	System	Initiating Event	Critical components (singles or grouped)
1	Main Moderator Circuit	TE – MCS unavailable as the last heat sink	Pump motor for P1
2			Pump motor for P2
3			Check valve CV 4
4			Check valve CV 3

For the critical components, if need periodical maintenance, the maintenance activities must be optimised. In order to do these two relations some sensitivity studies have to be performed. In the system probabilistic models the associated events for the critical components could be the failure events of the component and also the unavailability due to component isolation for maintenance. The AOT is optimised in order to accept risk due to maintenance.

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Annex 6

EXPERIENCE OF RCM ANALYSIS AND EVALUATION METHOD OF ESTABLISHING CRITICAL COMPONENTS IN KOREAN NPPS

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Abstract. The analysis of Reliability Centered Maintenance (RCM) for three pilot system of Yonggwang nuclear power unit #1, #2 had been performed from 1997 to 1999. The objective of this analysis was to optimize the preventive maintenance program. For evaluation of critical component, FMEA(Failure Mode and Effect Analysis) and Instrument matrix method had been used in the analysis. As results of the analysis, about 25% of total component was identified as critical component, and the number of preventive maintenance (PM) tasks has been reduced by about 18% compared with current PM tasks. Also as for the types of PM tasks, time-directed tasks were reduced from 75% to 55%, while condition-directed tasks and failure finding tasks were increased from 2% and 23% to 9% and 36%, respectively. Based on this analysis of pilot system, the RCM analysis on extended 25 systems of the same unit has started from 2000 to 2002. In this study, the evaluation method for establishing critical component that can be used for selection of the SSC(system, structure, component) in maintenance rule has been developed. This method is simpler and cost-benefit than FMEA method. In this paper, the results of RCM analysis on pilot systems of Yonggwang nuclear power unit 1 & 2 and evaluation method for determining critical component used in our nuclear power plant are described. Also the future plan for maintenance strategies on the all NPPs in Korea are described.

1. INTRODUCTION

Korean nuclear power plants (NPPs) have been operated at with higher availability than average values of the world NPPs industry, and many NPPs in Korea have been achieved OCTF (one cycle trouble free) operation. Those achievement results from the feedback of accumulated operation and maintenance experiences accumulated in domestic NPPs industry.
However, current maintenance programs are set up from the vendor instruction manuals or plant engineer's judgments, and these programs mainly consist of time-directed tasks without consideration for the condition of components. Maintenance tasks was also increased as the reactor operation years were added and aging of the NPP's components was progressed. Consequently, it is necessary that systematic and efficient maintenance programs should be reestablished.

For above necessity, the pilot project of RCM (reliability centered maintenance) analysis was performed in 3 pilot systems of Yonggwang NPPs units 1&2 from 1996 to 1999 Based on this analysis of pilot system, the extended RCM analysis on 25 systems of the same unit has started from 2000 to 2002. After this analysis on Yonggwang units 1&2, we have a plan to set about new projects of maintenance optimization on another power units. In the pilot project, FMEA (failure mode and effect analysis) method to screen the critical components and LTA (logic tree analysis) method to determine maintenance tasks are applied. Also RCM analysis methodologies were partially modified for applicable to domestic NPPs' operation conditions. As a result of the pilot project, 18% of maintenance tasks were reduced and the portion of condition monitoring tasks was increased. In the extended RCM analysis, streamlined RCM methodology, criticality checklist, instead of FMEA is being used for the 25 systems.

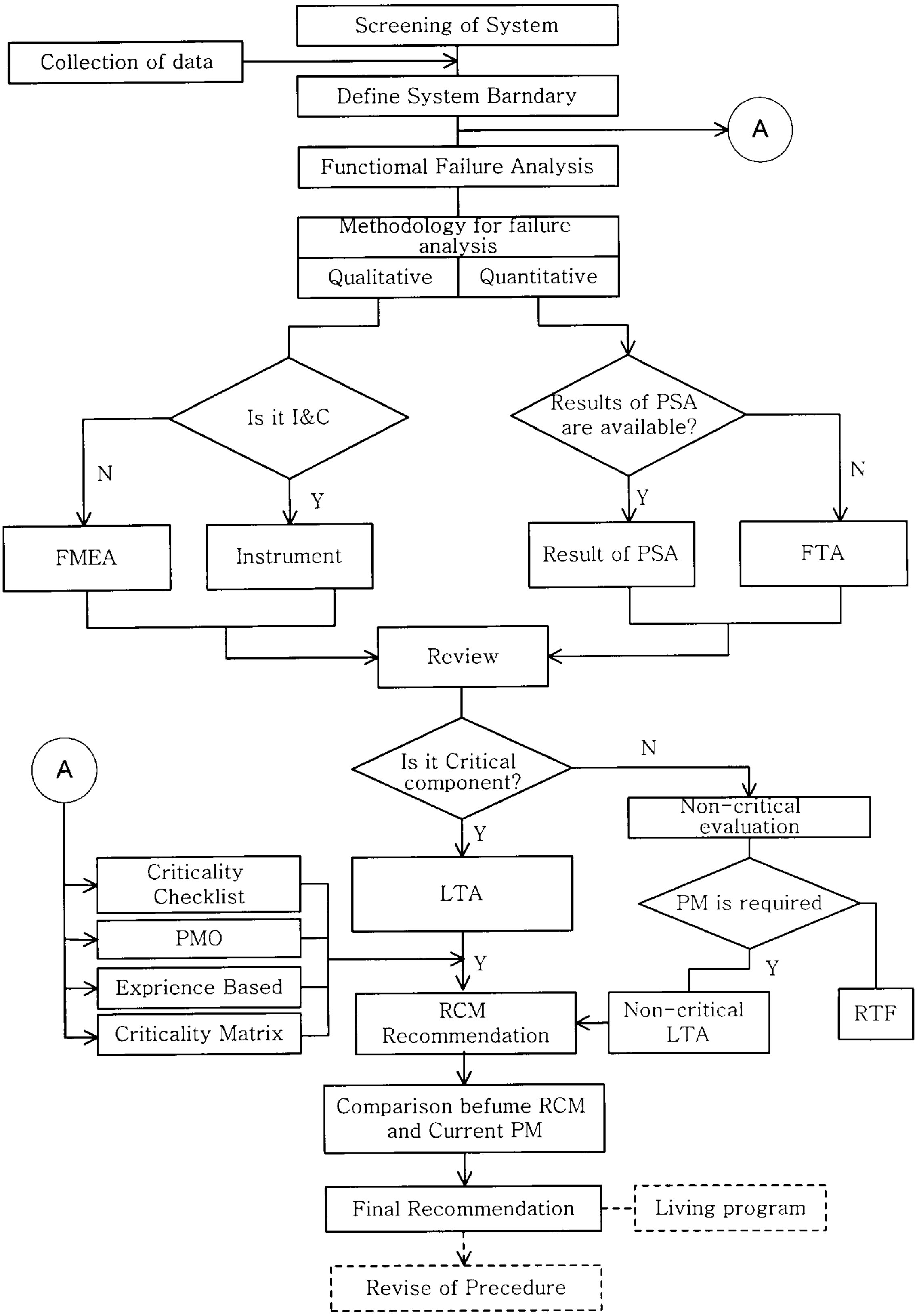

FIG. 1. Flow diagram for RCM analysis in Korean NPPs.

In this paper, the results of the pilots project, the methodologies for determination of critical component, and the future plan for maintenance strategies on the all NPPs in Korea are described.

2. METHODOLOGY OF RCM ANALYSIS ON PILOT SYSTEM

RCM analysis Methodology for the domestic NPPs was mainly based on traditional RCM analysis introduced by EPRI. But some methodology like system screening, determination of critical components, and selection of preventive maintenance tasks processes were modified to suitable to the Korean NPPs. The flowchart of RCM analysis of domestic NPPs is shown in Figure 1.

The step of RCM analysis is consist of 7 steps as follows :

1) System screening for RCM analysis, 2) Collection of operation and maintenance data, 3) Definition of system boundary, 4) System function and functional failure analysis, 5) Determination of critical components, 6) Selection of preventive maintenance(PM) tasks and intervals, 7) Comparison selected PM tasks to the current tasks.

3. DATA ANALYSIS FOR RCM

3.1. Data collection

Maintenance history data were collected from PUMAS/N (power unit maintenance system for nuclear), which is the maintenance tasks management system, and other maintenance related documents were collected to for supplement to the lack of PUMAS data.

(1) Components to be analyzed

In the pilot systems, the total of the components is 8,185, and these components were classified as 68 component type.
The excluded components were mainly manual valve of vent valve smaller than 1/2 inch and root valve. The portion of excluded components for each system were 19.2% in main steam system, 19.8% in chemical and volume control system, and 39.7% in compressed air system.(refer to table 1)

Table 1 Component excluded in data analysis

System(a)	Total No.	excluded in analysis(b)				b/a(%)
		Root valve	Drain valve	Vent valve	Total	
AB	2,056	200	156	40	396	19.2
BG	3,574	362	178	170	710	19.8
KA	2,555	162	851	2	1,015	39.7
Total	8,185	724	1,185	212	2,121	

(2) Functional failure

629 failures in the total 1,447 failures were classified as Functional failures according to functional failure criteria.(refer to table 2)

Table 2 Functional Failure rate

Unit / System	Unit 1		Unit 2		Total		Remarks
	Total	Functional failure	Total	Functional failure	Total	Functional failure	
AB	224	73	163	59	387	132	
BG	292	118	356	148	648	266	
KA	242	127	170	104	412	231	
Total	758	318	689	311	1447	629	

Table 3 Failure rates on Component types

Component types	Failure made	sys.	unit	Demand	Sum of Demand	No of Comp.	Operation hr.	Sum of operation hr.	No failure	Sum of failure	Failure rates	Failure rates (IEEE500)	MTBF
Centrifugal (MPUC)	FTR	BG	H	-	-	16	120,192	120,192	7	7	5.82E-06	7.07E-06	1.72E+04
	FTS	BG	D	3,964	3,964	16	-	-	2	2	5.05E-04	4.73E-05	1.98E+03
AC Motor (EMOA)	FTR	BG	H	-		16	120,192	488,112	2	4	8.19E-06	2.47E-05	1.22E+05
		KA	H	-		16	367,920		2				
	FTS	BG	D	3,964	4,216	16	-	-	1	1	2.37E-04	2.47E-05	4.22E+03
		KA	D	252		10	-	-	0				
Globe valves (MVAL)	EL	AB	H	-	-	282	12,365,136	37,593,144	3	9	2.39E-07	3.53E-06	4.18E+06
		BG	H	-		228	6,709,368		6				
		KA	H	-		248	18,518,640		0				
	IL	AB	H	-	-	282	12,365,136	37,593,144	0	6	1.60E-06	3.53E-06	6.27E+06
		BG	H	-		228	6,709,368		5				
		KA	H	-		248	18,518,640		1				
Gate valves (MVAG)	EL	AB	H	-	-	56	3,191,328	9,906,576	1	1	1.01E-07	1.85E-06	9.91E+06
		BG	H	-		34	1,319,088		0				
		KA	H	-		86	5,396,160		0				
	IL	AB	H	-	-	40	3,191,328	9,906,576	1	3	3.03E-07	1.85E-06	3.30E+06
		BG	H	-		34	1,319,088		0				
		KA	H	-		86	5,396,160		2				

(3) Failure mode and type

Functional failures were classified as failure mode and failure type such as hourly or demand type.

(4) Maintenance time

Maintenance time were extracted from man-hour of trouble report (TR).
But some data needed to be modified.

(5) Operation time and number of demand

After the determination of failure mode and failure type, operation time and the number of demand were derived to calculate the failure rate.

3.2. Results of data analysis

As the results of data analysis, dominant failure mode, mean time between failure (MTBF), mean time to repair (MTTR), frequent failures, and failure rate per failure mode were corrected. Major data analysis results are shown as table 3.

Failure rates for the 38 component types including centrifugal pump were produced and compared with generic data(IEEE 500), and the result was that most failure rates were similar to generic data except solenoid valve actuator.

4. RESULTS OF RCM ANALYSIS ON PILOT SYSTEMS

As a results of pilot system, a current preventive maintenance program has been changed as maintained as much as 46%, modified as much as 17%, and deleted as much as 37%, added as much as 24%.

The total the number of preventive maintenance (PM) tasks has been reduced by about 18% compared with current PM tasks. This is described in figure 2.

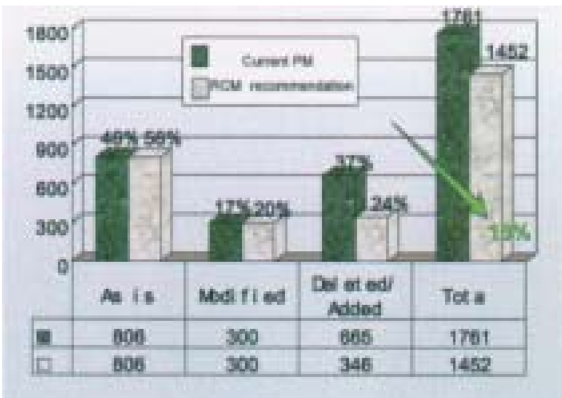

FIG 2. Comparison of number of maintenance tasks before/after RCM analysis on pilot systems.

Many of modified tasks are in case that the interval of maintenance are modified. Many of the deleted tasks are consisted of number of overhaul for manual valves and calibration tasks of local indicators.

In the case of newly added to present PM program, packing replacement, overhaul of manual valve, visual inspection of lubrication oil of motor operated valve and load tests of motor of

MOV were the mostly added tasks. The change of the number of PM tasks showed that maintenance cost could be reduced through the optimized maintenance program by the RCM analysis. The 20% of newly added PM tasks means that safety related critical components should be considered carefully in the maintenance program to improve the overall reliability of plant.

The results of RCM analysis in terms of maintenance type were that time directed tasks were reduced from 75% to 55%, while condition monitoring and failure finding were increased from 2% and 23 % to 9% and 36% respectively. This is described in figure.3. The causes of reduction of time directed tasks were that time directed tasks were replaced by condition monitoring and failure finding tasks, and many time directed tasks were evaluated to deleted from the maintenance program. Furthermore the above reduction of time directed tasks resulted in still less portion of condition monitoring nevertheless the RCM analysis. Although condition monitoring tasks were recommended by the RCM analysis, it could not be implemented because of lack of proper monitoring equipment. These tasks were replaced with the appropriate time directed tasks. As a result, if the equipment for the condition monitoring tasks are provided, condition monitoring tasks will be increased as compared with time directed tasks, and then the effectiveness of RCM analysis will be enlarged apparently.

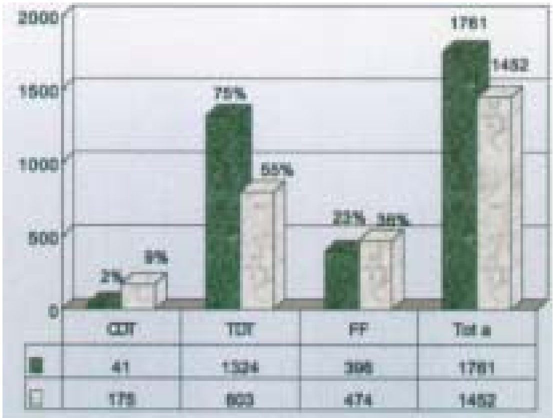

FIG 3. Comparison of maintenance tasks before/after RCM analysis on pilot systems.

From the RCM analysis of pilot systems in Yonggwang units 1&2, many improvement items were found out. Exclusion of 37% of maintenance tasks from present program in the 3 pilot systems means that the present maintenance program had been established much more conservatively. Also, the difficulty in implementing of condition monitoring had been found out because of lack of equipment and skilled personnel. It is necessary that the framework of maintenance program should be changed appropriately into the optimized condition monitoring tasks in that maintenance effectiveness. And then the optimization of preventive maintenance would be achieved rapidly.

5. EXTENDED RCM ANALYSIS

5.1. Screening of 25 systems

a. Key elements of evaluation for screening of 25 systems

Following elements are used to select 25 major systems.

 Functional important system
- Function of Reactor or turbine trip
- Function of power reduction or inefficient function
- Included of LCO (limiting condition for operation)

 Maintenance history
- Preventive maintenance (PM) tasks
- Preventive maintenance tasks per components
- Ratio of preventive maintenance to total maintenance tasks (PM/PM+CM)
  (CM: corrective maintenance tasks)

b. Result of evaluation for screening of system

It is described in table 4.

Table 4 Result of screening of systems

System ID	System Description	Evaluation			
		tional import	tenance his	Sum	Priority
BG	Chemical & Volume Control	9	27	36	1
AE	Feed Water	9	26	35	2
EG	Component Cooling Water	9	25	34	3
GL	Auxiliary Building HVAC	7	27	34	4
EF	Nuclear Service Cooling Water	8	25	33	5
MA	Main Generator	10	22	32	6
CH	Turbine Valve & Hydraulic Control	10	22	32	7
EA	Turbine Plant Open Cooling Water	9	23	32	8
DC	Traveling Screen and Screen Wash Pumps	8	24	32	9
AD	Condensate Water	8	24	32	10
AB	Main Steam	10	21	31	11
KC	Fire Protection	7	24	31	12
KJ	Stand-by Diesel & Diesel Fuel Oil	7	24	31	13
RL	Control Board(SSILS)	10	20	30	14
DA	Circulating Water	9	21	30	15
AF	Feed Water Heater Extraction Drain & Vents	7	23	30	16
BB	Reactor Coolant	7	23	30	17
AC	Main Turbine	7	23	30	18
CA	Turbine Grand Steam Sealing	9	20	29	19
GK	Control Building HVAC	7	22	29	20
GT	CV Air Purification & Combustible Control	7	22	29	21
SF	Reactor Control Logic(CRDM)	10	19	29	22
SE	Neutron Monitoring	10	19	29	23
GJ	Essential Chilled Water	7	21	28	24
GN	Containment Heat Removal	7	21	28	25
CE	Generator Stator Cooling	10	17	27	26
CB	Turbine-Generator Lubrication	10	16	26	27
SC	Reactor Instrumentation	10	16	26	28
BH	Safety Injection	7	19	26	29
GG	Fuel Handling Building HVAC	7	19	26	30
AL	Auxiliary Feed Water	7	19	26	31
KA	Compressed Air	8	18	26	32
FC	Main Feed Water Pump Drive Turbine	9	16	25	33
EB	Turbine Plant Closed Cooling Water	9	16	25	34

c. Selected system

The four systems like as chemical & volume control system, main steam system, compressed aAir system, standby diesel system which have already analyzed were excluded. And five systems expected as ineffective system in RCM analysis were also excluded. : main generator, main turbine, main turbine valve & hydraulic control, main feed water pump drive turbine, reactor coolant system.

Additional four systems have been added by discussion through expert panel meeting: turbine plant closed cooling water sys, central chilled water sys, S/G blow-down sys, liquid rad-waste sys, TBN building HVAC sys.

5.2. Determination method for the critical component

Korean NPPs have in-service test (IST) plan and quality assurance (QA) program. IST plan for pumps and valves contains the classification of safety class 1,2,3 pumps and valves. The classification category of safety class is equal to the determination criteria for the safety related critical component in RCM and also equal to scoping criteria for the safety related SSCs in maintenance rule (10CFR50.65). In QA program classified the component into safety-related class (Q), safety-impact class(T), reliability-critical class(R) and industrial standard class(I/S).

The classification criteria of Q-class is applied for safety related equipment which have function to ensure that the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and capability to maintain it's function after safe shutdown, and the capability to prevent or mitigate the consequences of accidents that could result in potential offsite radiation exposure comparable to the described in 10CFR100.

In RCM process, the evaluation of component failure effects is required to determine the critical components that impact on plant safety and power production. For the purpose of this evaluation on 25 systems, we developed the criticality check-list (refer to table 5) and the specific evaluating guideline using plant component classification in the in-service test (IST) plan and the QA program.

Table 5. Criticality Check list

Plant : Comp ID :	System :	
Does failure mode of this component result in		
A. Loss of the following safety function ?	Y	N
a. integrity of the reactor coolant pressure boundary		
b. the capability to shut down the reactor and maintain it in a safe shutdown condition,		
c. the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposure		
B. Effect on plant capacity factor such as power reduction?	Y	N
C. Violation of the LCO of Tech spec.?	Y	N
D. Inadvertent ESF actuation ?	Y	N
E. Prevent safety-related components from fulfilling their safety-related function ?	Y	N
F. Prevent mitigate accidents or transients	Y	N
G. Functional failure that are used in plant EOP or AOP	Y	N
H. Other reason have to classified as critical failure mode?	Y	N
Component Critical ?	**Y**	**N**

The safety related critical components are determined according to following three step as in figure 4.

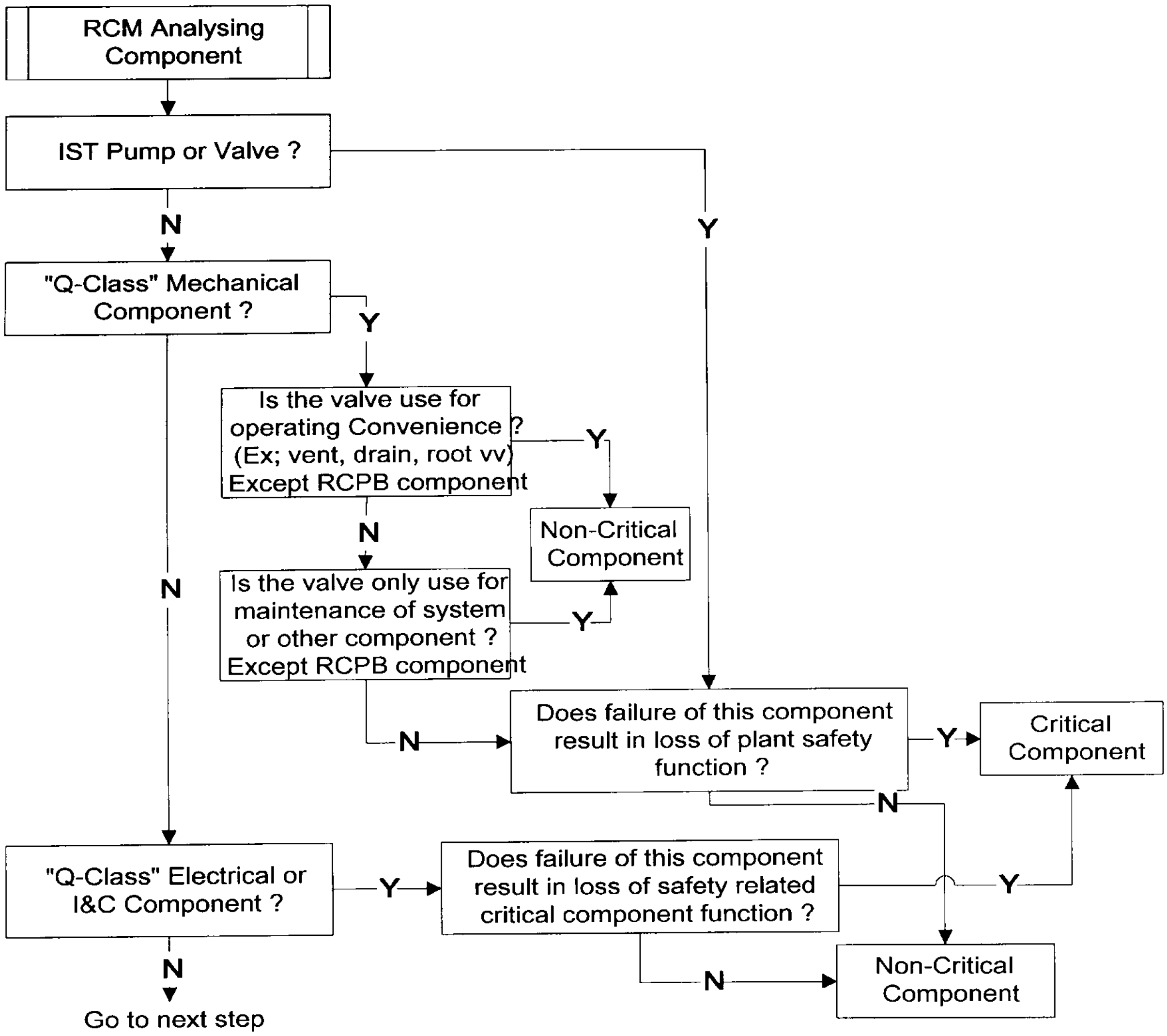

FIG. 4. Decision logic diagram of safety related critical components.

Step 1 is evaluation process for the pumps and valves whether these component are included in in-service test program or not. If the component is in IST program, evaluates the effect of component failure modes on plant safety function.

Step 2 is evaluation process for the mechanical components that is classified Q-class but excluded in IST program. It can be evaluated using the component list in PUMAS program. Although the component is Q-class, the components in following conditions should be categorized in non-critical component.

- Valve that is used only for operational convenience (ex: drain, vent, testing)
- Valve that is used only for a system/component maintenance

Last step is evaluation process for electrical and I&C component that is classified as Q-class. Also it can be checked using the component list in PUMAS program. And it is evaluated that the function of components' effect on the safety related critical component.

6. FUTURE PLAN FOR OPTIMIZATION OF MAINTENANCE

RCM is useful method for preventive maintenance optimization. For more improvement of current preventive maintenance program, monitoring of maintenance effectiveness are required. Therefore it is suggested that several technologies of maintenance optimization for our nuclear power plant should be developed as following items.

- Effective establishment of critical components based on it's function
- Monitoring of system reliability/availability
- Monitoring of component's condition
- Establishing of appropriate maintenance interval/tasks based on reliable database. To achieve above technology, it is required an integrated reliability data system such as data system in the reliability program of EDG (emergency diesel generator). Also, it is recommended that RCM methodology should be focused on more critical components.

For this purpose, it is advisable that research of maintenance optimization for older nuclear unit such as Kori unit 1 or Wolsung unit 1 be performed as next phase.

7. CONCLUSION

RCM analysis in Korea have been performed for several years on Yonggwang unit 1 and 2. It was found that RCM is useful systematic approach of preventive maintenance optimization. For future plan, the integrated maintenance optimization including monitoring of system performance and condition monitoring of component in addition to RCM analysis are required.

Annex 7

OPTIMIZATION OF MAINTENANCE PROGRAMME AT DAYA BAY NUCLEAR POWER STATION BASED ON RCM ANALYSIS RESULTS

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Keywords: Maintenance and testing systems, RCM analysis results, maintenance program optimization, reliability centered maintenance (RCM).

Abstract

This paper begins with an introduction to Guangdong Daya Bay Nuclear Power Station (GNPS) and gives a simple introduction to the operations and maintenance documentation system at GNPS. It then will review the maintenance program guidelines base and the associated problems prior to the application of reliability centered maintenance (RCM). How RCM was implemented at GNPS, how the results of RCM analysis were used to optimize the maintenance program and test program, and what is the interface between RCM and the existing maintenance program will be shown. Next, it will show the successful implementation of RCM at GNPS resulted in the following changes: A new understanding of equipment failure challenges operations and maintenance beliefs, maintenance concepts undergo a large change, maintenance program and periodic testing program are continuously modified and optimized, new on-condition maintenance technologies are introduced, non-productive scheduled overhauls are discarded, maintenance costs are effectively controlled, maintenance appropriateness has improved, management of hidden failures is more effective and timely. It will show the benefit of greater equipment reliability brought about by all of these changes, which in turn increases the reliability and safety of the entire power station.

1. AN INTRODUCTION TO GUANGDONG DAYA BAY NUCLEAR POWER STATION

Guangdong Daya Bay Nuclear Power Station (GNPS) is located at Da Keng on the coast of Daya Bay in Guangdong Province of China, which is about 45 kilometers from Shenzhen City and 50 kilometers from the Hong Kong border. GNPS plant consists of two 984 Mwe PWR lines, with the major equipment manufactured in France and the UK. Unit 1 and Unit 2 came on line in February and May of 1994 respectively. Since the start of operation, both units have maintained an excellent safety record and have continually improved their standing in the World Association of Nuclear Operators (WANO) benchmark indicators. Of the 10 WANO benchmarks, as of 2000 GNPS is either at or near world leadership standards for capacity factor, thermal efficiency, collective dose, fuel reliability, and industrial safety events, scoring in the top 25 % in these 5 areas. Efforts are focused on placing GNPS in the top 25 % for all 10 benchmarks with in the next 2 years. Average capacity factor is at a all time high for GNPS at 87.04%, with improvement of 0.64% over 1999, and close to world leader performance. In a safety competition with EDF sister plants, GNPS placed first in 1999 and is in the lead for 2000.

2. GNPS DOCUMENTATION HIERARCHY FOR OPERATIONS AND MAINTENANCE

2.1. Document hierarchy

The document hierarchy is broken into 4 groups: Laws & codes, equipment management & maintenance policies, work procedures, reports & records.

LAW & CODES are the base documents. They are the foundation of equipment management and maintenance strategies. By fully analysis and evaluating of the requirements of law & code documentation basic requirements we establish create service inspection program, testing and surveillance program and maintenance program that meet the equipment management maintenance requirements. Maintenance procedures are based on the requirements of the maintenance program. Reports and records refer to all maintenance, test, failure and experience feedback reports, etc.

GNPS documentation hierarchy for operations and maintenance is shown in Fig 1.

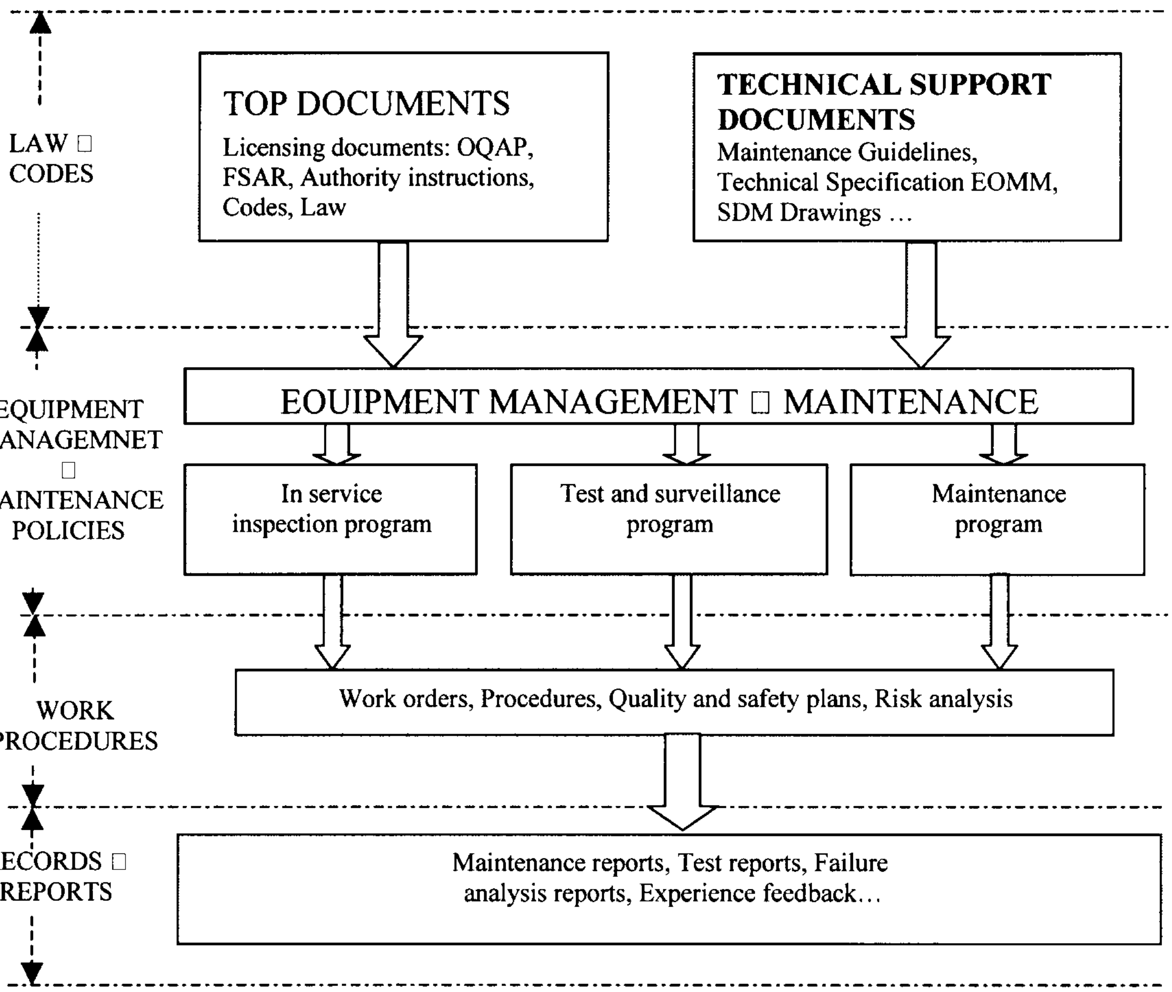

FIG. 1 GNPS documentation hierarchy for operations and maintenance

2.2. Establishment of the maintenance program prior to RCM

Prior to RCM, the maintenance program was based on manufacture's suggested operations and maintenance handbook (EOMM) along with experience feedback in some cases. The maintenance program was not only unscientific, but it was also far from being a living program. Most of our maintenance technology was second generation, with a heavy dependency on scheduled overhauls. Although on-condition maintenance had begun to be applied, the application base was small and concentrated on rotating equipment. Also, our confidence in the use of on-condition techniques was poor. The concept of how to relate the condition of equipment to the potential failure, and functional failure was weak.

Because there was no analysis of equipment requirements, some equipment received no maintenance were it was needed, while other equipment was overhauled even though the equipment was in perfect working order. Based on the new concepts of equipment failure, this not only is expensive, but also does nothing to improve equipment reliability.

3. IMPLEMENTATION OF RCM STUDY RESULTS

3.1. Initial implementation of RCM at GNPS

Although GNPS had established a documentation system for operations and maintenance and our output continued to improve with each year, however we found that a number of problems that were created during the establishment of our maintenance program continued to surface. More and more of these problems seem to arise from imperfect or unreasonable maintenance and we also found increasing cases of infant mortality. This discovery fit well with new concepts on the failure of equipment: namely that rather than just the single bathtub failure curve model, there are 6 types of conditional probability curves for failures. That only about 11% of failure modes conform to curves that can be prevented by scheduled overhauls, and the balance approximate 89% of failure modes cannot benefit from scheduled overhauls.

RCM is an analytical technique that has been well established in the aviation and nuclear industry. In 1999, GNPS completed our first successful RCM study on part of the condensate recirculation system (CEX).

(a) During normal operations at full load, 2 CEX pumps operate with a 3rd pump as back-up. Prior to RCM, the failure rate of the auto-start up of the back up pump (when a working pump tripped) was 66.7% (2 failed back-up pump auto-starts for 3 operating pump trips). The consequences of this failure are reduction to 50%Pn, and in severe cases a turbine trip with a resulting reactor shutdown. After the RCM analysis, it was discovered that our current test program for CEX backup auto-start was flawed: This test is performed after every planned outage. However the test conditions differed from the actual operation conditions stated above. The test was performed during the early stage of start up with a configuration of only one CEX pump in operation and the remaining 2 pumps acting as back-up. The logic control loop was one that selected a primary back-up pump to start first, and if it fails to start with-in 1 S, then the secondary back-up pump is started. However another logic control loop is used for our normal operation under full load where 2 pumps operate with only one back-up pump and the existing test failed to test if this much more critical auto-start control loop was working or failed. The test procedure was modified to correct this flaw. Since then, where 2 pumps were operating and one tripped, there has been a 0% failure rate for auto-start of the back-up pump during normal operations (0 failed back-up pump auto-starts for 3 operation pump trips).

(b) Prior RCM, there were no seal testing tasks for the isolation valves of the CEX pumps. If these valves fail to hold a good seal during normal operation, then the result is no repair work can be done on the failed pump, which may results in the plant having to operate for a long period of time with out a back-up pump, a serious compromise of plant reliability. After instituting a sealing test task, it was found that the isolation valves were incapable of delivering a good seal as designed, with the result that the valves were re-engineered.

(c) The CEX Pumps themselves are highly complex items operating in a rough environment, and hence suffer from infant mortality. Nearly 50% of scheduled overhauls were followed by pre-mature pump failures. By substituting on-condition based maintenance for scheduled overhauls, we were able to extend the average time between intrusive overhauls, which directly reduces the failure rate. Also, the RCM analysis pointed out where critical failure modes could occur. Therefore the accuracy and quality control of repairs has increased, which further reduces the risk of infant mortality and increases equipment reliability.

The success of the CEX study was a critical first step in the development of RCM at GNPS. As more systems have been analyzed and the emphasis on RCM has increased, then use of RCM in equipment management and maintenance strategy has become well accepted by more and more staff. Currently, GNPS has established a RCM section to manage and lead the RCM work. By the end of 2001, 21 systems will have been analyzed.

3.2 RCM analysis process

The following documents are incorporated in the RCM analysis process:

(a) Flow diagram/Logic diagrams/Block diagrams/Piping & Equipment layout/Mechanical drawing

(b) EOMM/System manual

(c) Maintenance base/Maintenance program/Maintenance procedures

(d) Operational periodic testing program/Operational periodic testing procedures/Equipment rotation table

(e) Routine patrol record and report/Alarm card

(f) Equipment failure reports/Reliability data base

(g) General operation rules(GOR9)/Safety analysis report

(h) Performance testing program/In-service inspection program

(i) Internal and external experience feedback

The RCM analysis process includes: Information collection and review, defining the system boundary, writing the operating context, listing the system functions, defining function failures, listing failure modes, describing failure effects, assessing failure consequences, selecting appropriate maintenance tasks and frequency.
RCM Analysis Implementation Process is shown in Fig. 2.

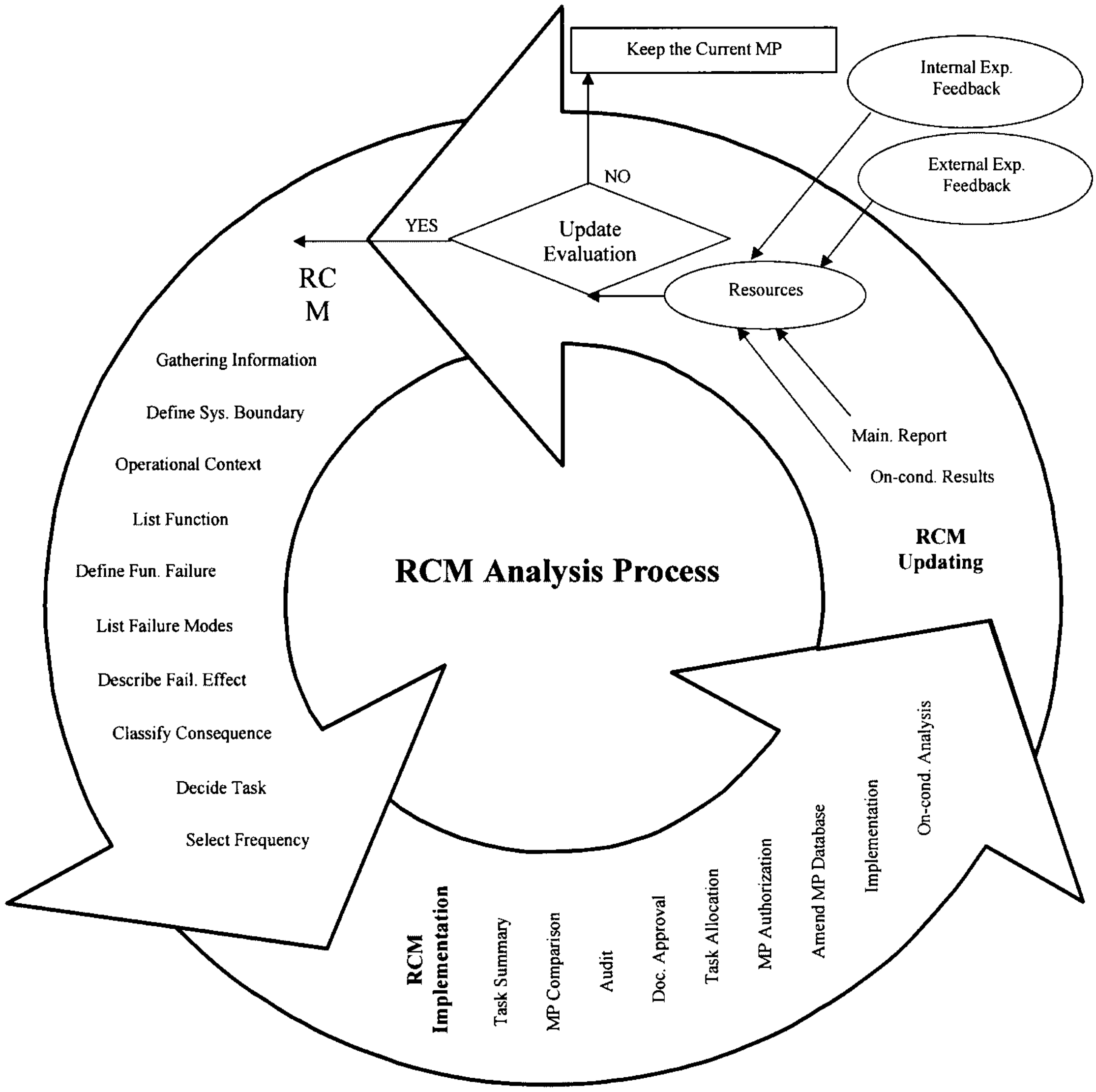

FIG. 2 RCM analysis implementation process

RCM implementation process includes: task summary, maintenance program comparison, audit, document approval, task allocation, maintenance program authorization, amend maintenance program database, implementation of tasks, on-condition analysis.

RCM documentation updating process information sources: On-condition results, maintenance reports, history records and experience feedback from internal and external sources.

3.3. Interface between RCM analysis results and the existing maintenance systems

The interface between RCM analysis results and the existing maintenance systems is shown in Fig. 3.

The maintenance guidelines are directly derived from the RCM analysis results, and directly form the related systems maintenance programs, and also optimize the periodic test program, GOR9, performance testing program, chemistry analysis program and in-service inspection program of the related systems.

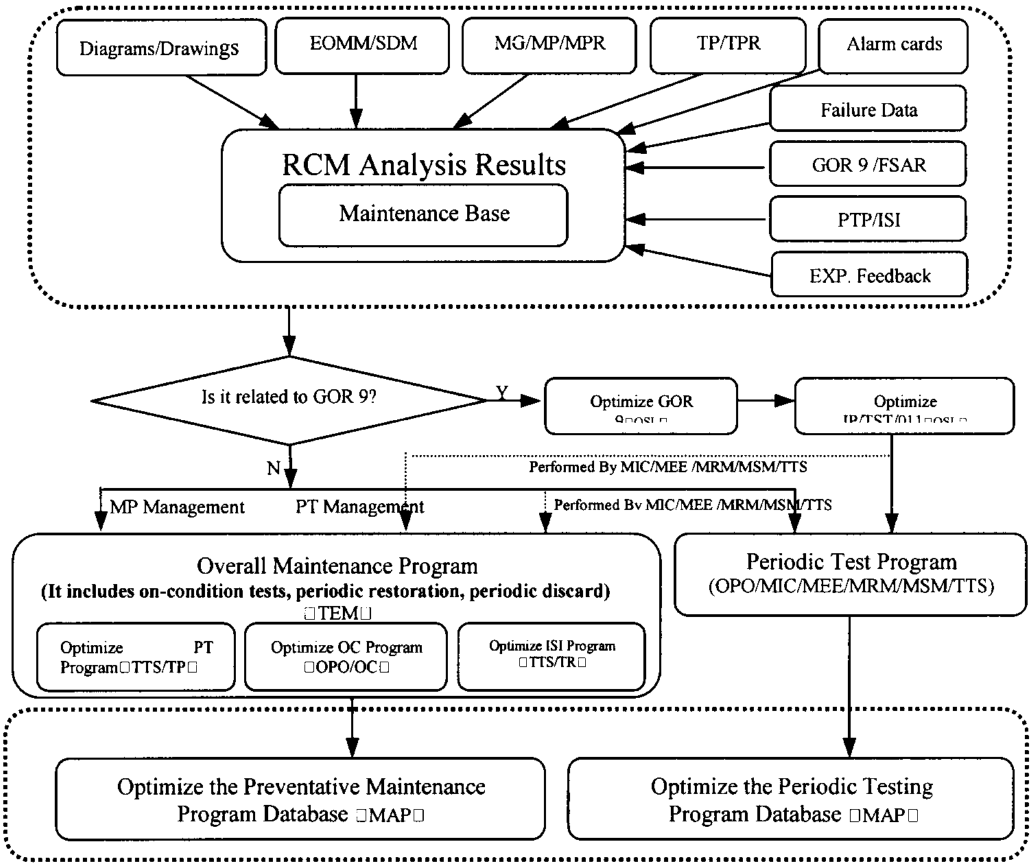

FIG. 3. The interface between RCM analysis results and the existing maintenance systems.

The maintenance planning department amends the maintenance information of the related equipment in the data bases of preventive maintenance program and periodic testing program according to the optimized general maintenance program and periodic testing program.

The maintenance planning department according to the general maintenance program optimizes the 10 years outage program, which then is used to arrange the refueling outages program.

4. BENEFITS BROUGHT ABOUT BY RCM

4.1. Understanding new failure mode conditional probability curves

As RCM analysis work has proceeded, our staff's understanding of new failure mode conditional probability curves has increased. This has resulted in a change in basic beliefs about the relationship between failure and age, in particular that for the majority of equipment a relationship between asset age and conditional probability failure rate is becoming less and less apparent. When early expectations that equipment failures increase with age proved too simple, the bathtub curve was developed to explain infant mortality. However, as more recent studies have shown, failure mode conditional probability conforms not to one curve, but rather to 6 curves, and further that only approximately 11% of failure modes should be managed by scheduled overhauls, and the remaining 89% cannot achieve any benefit from scheduled overhauls.

4.2. A change in the concept of operation & maintenance management

Based upon the above discussion, while 11% of failures may in theory benefit from a limit on operating age, from both economic and safety reasons, the actual percent of equipment failures that can be prevented by a limit on operating age is still lower. One of the earliest RCM analyses at GNPS was the conventional island equipment cooling system (SRI). The RCM analysis team detected 238 failure modes, of which only 4 failure modes are preventable by scheduled overhauls. The question is what to do about the remaining 234 failure modes.

We are now realizing that an overhaul itself in nearly all cases is a form of (induced) failure. An item removed from operation for overhaul is not able to perform the service for which it was acquired during the overhaul. Therefore an overhaul causes the equipment to be in a failed state at a time where the consequences (hopefully) are less drastic, in order to (hopefully) avoid failure later during operation when the effects consequences are much more serious.

Any task that successfully manages the consequence of an equipment failure can be considered a maintenance task. The failure consequence is not the failure of the equipment itself. Rather it is the loss of the function(s) the equipment provides and what it may cost to restore these functions. RCM established 5 classes of operation and maintenance policy to manage these consequences. They are:

(1) Scheduled Overhaul/Discard: as explained above, this policy seeks by a scheduled restorative action(s) to prevent a functional failure during a later more critical time. This policy is normally carried out by maintenance.

(2) On-condition (condition based, predictive) maintenance: This policy seeks to predict when a failure will occur so that some action may be taken beforehand to mitigate the effects of the functional failure. This policy is most often carried out on-line by operations, but where performed off-line or where detailed analysis is required (such as vibration analysis, oil analysis, water chemistry analysis, etc) it is carried out by technical staff. Those parts carried out by operations usually require support from maintenance in determining whether the equipment has reached a potential failure point or not.

(3) Failure Finding (functional testing): This policy seeks to find when hidden failures that can cause the loss of a (protective) function have already occurred, so that protection can be restored. This policy is carried out by both operations and maintenance.

(4) Redesign: This policy seeks to either eliminate the failure, or mitigate its consequence by modification of equipment, operating procedures, or environment/context. This policy is carried out by both operations, maintenance and technical sections.

(5) Breakdown maintenance: This policy reduces seeks either to reduce the possibility of preventative maintenance induced infant mortality or to eliminate expending preventative maintenance resources where they are not justified by the consequence of a failure. This policy is carried out by maintenance.

RCM provides a strategic framework to select when each of the above policies is most appropriate. Further, RCM recognizes that it is not enough to prevent failures that have occurred in the past, but any failure that might possible occur must be anticipated and appropriate policy to manage the consequences of these failures must be decided on before they have the opportunity to occur. In this way RCM delivers a large increase in reliability.

It was apparent to our management, that passively waiting for a failure to occur before formulating policy to prevent it from happening a 2^{nd} time was too much like closing the barn door after the cow has run away. RCM, by providing a method of predicting then managing these failures, has placed our company in a much more proactive position. As was shown earlier, RCM has helped us discover many previously ignored failure modes in our SRI system.

4.3. Successful examples

We first will look as some of the improvements obtained from an RCM analysis of a $125V_{DC}$ supply system (LBA).

(1) (Prior to the RCM analysis) the storage battery type was changed from TSE to TXE, which increased the battery capacity and performance, but the discharge test was kept at 3 months even though it was not clear as to what failure modes this test was suppose to manage. During the RCM analysis, it became clear that the purpose of the test is to monitor a decrease in the battery capacity, for which the TXE type is superior to the TSE. After an exchange of data with EDF, it was determined that the test period at the very least be extended to 6 months. The effect of this extension is not just an increase in time between test, but an increase in the life and reliability of the storage batteries.

(2) By eliminating an unnecessary test on the charger and instituting infrared hot-spot checks, we have eliminated an opportunity for a human error induced reactor trip.

(3) Through careful analysis of a total of 51 load switches, we found that only 3 switches required management by scheduled maintenance. The failure effects of the balance were not serious, which in turn had drastically reduced the amount of time spent on overhauling the LBA system.

(4) The analysis found that our existing annual discharge test was set at 205 A. The same test for the same system at an EDF station after careful load study and calculations has been modified to 73 A. Over discharging these storage batteries shortens the life by 25 % (a normal life to 7-8 years reduced to 5-6 years). Setting battery discharge tests loads requires measurement and calculation of the size of the actual load.

(5) Battery post corrosion is an unavoidable problem, but with proper care and maintenance can drastically reduce the rate of corrosion, extending the life of the batteries. Formerly, our batteries were lasting on average on 3-4 years. EDF was able to obtain 7-8 years from the same battery types. During the RCM analysis, we found that some of our exiting methods were incorrect and actually increased the rate of post corrosion.

Let us now look at some of the improvements obtained from RCM analysis of other systems.

(a) Condensate extraction system (CEX), condenser vacuum extraction system (CVI), conventional island equipment cooling system (SRI), generator stator cooling system (GST), nuclear island equipment cooling system (RRI) equipment train change-over rotation period were extended from the shortest period of 1 month to a optimum period of at least 3 months.

This resulted in a reduction in stress to the system and also decreased the workload of operations staff.

(b) The number of scheduled overhauls of main equipment had decreased significantly, effectively reducing amount of equipment failures due to excessive or inappropriate maintenance. For CRF, CEX, RRA, ASG, DVN, RCP, and other systems, past experience has shown that pumps, fans and valves previously in good condition, have failed after being overhauled simply due to an artificial time limit.

(c) A number of critical failure modes that our previous programs overlook were discovered through RCM analysis, such as some valves in the RRI, CFI, CEX system, failure due to corrosion of the cooling water line and seal water line for the CVI system, a number of critical pipes, supports, expansion joints, snubbers, etc in the conventional island.

(d) Instituting a seal test on the CVI system that allows for more effective location of leaks (which increase oxygen content in the condenser) which has greatly increased plant reliability.

(e) Equipment maintenance appropriateness has increase because of effective analysis and failure mode management. The failure of the 2CEX003PO pump during 2000 was a classic example of inappropriate maintenance.

(f) On-condition maintenance tasks and frequencies are more sound. The condition of major equipment, critical equipment, and sensitive equipment are now receiving truly effective control and management.

5. SUMMARY

The equipment maintenance optimization program at GNPS now proceeds through the RCM analysis results. As the work proceeds for each system; the reliability of equipment, the suitability of maintenance, the management of hidden failures are all improved. The end result is that the overall safety and efficiency of the power station is improved.

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Annex 8

WHY RCM AT RINGHALS NUCLEAR POWER PLANT

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Abstract. This paper describes the reliability centered maintenance (RCM) efforts that have been made at Ringhals Nuclear Power Plant. The paper covers the history of various RCM applications that have been piloted at Ringhals. Both traditional and streamlined methods have been evaluated and found having different benefits. Ringhals latest challenge has been a pilot project where the SRCM™-process from ERIN Engineering has been used. Ringhals project organization, scope of work, results and so on are described. A key area of importance is Ringhals experiences on the reasons for applying some type of RCM approach at Ringhals. The goals and objectives are important. A link between these reasons why to use RCM and the methods selected will be provided. This is a key link in what method to apply and should be understood before embarking on any RCM project.Finally, a summary of results from the current SRCM™ process pilot are presented as available, particularly relative to changes to the current maintenance program and other findings. Also, what decisions need to be made to justify going beyond a pilot effort based on projected results from the pilot effort. These will be presented in the tangible changes to programs, as well as intangible benefits such as having a documented basis.

1. INTRODUCTION

This paper describes the history of reliability centered maintenance, RCM at Ringhals nuclear power plant.

Ringhals started to look at RCM in 1996. The reasons for our interest were two;

1. People seemed to talk about it and perhaps not having a good picture of what RCM really is and how it works.
2. At that time there was a focus on the maintenance process. Ringhals received help from a consulting company to see the potential in the maintenance process. RCM was described, as a tool that it would take time to implement and that would have high potential.

Ringhals started to study literature and articles about RCM. Some people also participated in an open RCM II course given by Mr John Moubray, Aladon ltd. The conclusion after the course and the studies was that the method could be of interest for Ringhals.

2. RESEARCH PROJECT ON RINGHALS UNIT 2

A research project was initiated with the purpose to give Ringhals experience with the method. We learned during our studies that there could be big differences between methods that all called themselves RCM. The decision was therefore to analyze a system in the process twice, using two methods, one “streamlined” and one traditional and to use the same personnel. By doing this Ringhals was supposed to see how the results and the need for resources would differ between methods.

2.1. Selected system

The analyzed system was the main cooling water system on Ringhals unit two, which is a Westinghouse PWR. The system was selected because there had been both maintenance and operations problems, failure of the condensor cleaning system could cause environmental effects and bad publicity. Reduced production could off course also be an effect of system unavailability. The system is relatively small and has no safety function.

The purpose of the research was to see the differences between the two RCM methods, not to maximize return of investment.

2.2. Methods used in research project

The main cooling water system was first analyzed with a “streamlined” RCM method from a company situated in Stavanger, Norway called Rogaland Consulting. They had used RCM ideas in the Off Shore industry for several years with good experience. Ringhals came across their work and method through NUMEX, which is an European organization for exchange of experiences within maintenance.

The second RCM method used in the research project was RCM II. A Swedish Aladon licensee conducted training of participants and facilitated the analysis of the main cooling water system.

2.3. Result of research project

The research project increased Ringhals RCM experience a lot. Both methods suggested a reduced maintenance program, the reduction was minor. Ringhals found neither of the two tested methods suitable for future usage.

The participants felt that the first (Norwegian) method was too “streamlined”. The reasons for the new maintenance program were difficult to follow. The method didn’t collect and store as much information about the components and it’s maintenance program as Ringhals felt necessary.

With RCM II the participants felt comfortable except for the speed. They enjoyed the cooperation and the exchange of experiences and competence between disciplines. Most comments about RCM II was the speed and the level of detail.

The conclusion from the two analyses was that RCM could contribute to Ringhals success. However, an RCM method that’s "something in-between" the tested methods would be best. The conclusion from the research project could be described as “ we need a station wagon” but it wasn’t clear if it should be a big or small or if it should be a Mercedes or a Volvo.

When analysis results were evaluated it became obvious that Ringhals would never get the big savings that had been described in press and expected earlier. Ringhals had already relatively high availability and low costs for production.

It became also obvious that the use of a common and structured method for maintenance optimization also has other benefits than technical aspects and reduced maintenance program.

Attached to the analysis work are a number of “soft factors” that can be considered valuable;

- Competence transfer between disciplines.
- Capture of experiences that are only documented in the heads of Ringhals personnel.
- Comparability through consistent maintenance decisions.
- Documented maintenance program.
- Quality assurance.

The values of the factors above are hard to put a monetary value on, but should not be underestimated.

3. IMPLEMENT RCM-METHOD FOR RINGHALS

During the summer of 1999 a project was initiated with the objectives to give Ringhals a common method for maintenance optimization based on RCM principles. The decision was based on the experiences of the research project (above) and at the time ongoing work with process development at Ringhals.

A small team was put together which started to look into what Ringhals wanted from the RCM work. A set of "guidelines" for the project were defined that were supposed to be considered during the selection of an appropriate RCM method;

- Ringhals shall not "re-invent the wheel" – look for a method that has been tested and validated
- The supplier must have the intention to make Ringhals self supportive
- Ringhals personnel should do the analysis work in order to achieve acceptance for the result.
- The selected method shall be simple and only use computers for documentation.
- Ringhals RCM work shall not be "a one time task". In order to have a continuous development, RCM must be a part of Ringhals everyday life.

With the guidelines above forming a base for the project, Ringhals put an advertisement in the European Commission magazine Official Journal to find possible suppliers. All replying companies were compared with the guidelines above and some other criteria. Those who met the criteria were invited to present themselves, their method and competence. When the presentations of possible suppliers were finished, then the project team evaluated the companies and decided which companies who were qualified and which companies who would be invited to tender. In total there where six companies who qualified, four were invited to tender. The winner in this purchasing process was ERIN Engineering, an US Company seated in California.

While the possible suppliers were presenting themselves at Ringhals, it became obvious that the economical potential wasn't as big as calculated when the project was initiated. This insight forced the project group to produce a cost/benefit analysis for doing RCM.

The work with cost/benefit analysis changed the scope for the implementation project into a **larger pilot project** on Ringhals unit 1. The scope of work was to analyze 5-7 systems to confirm advantages, adopt method and make a good decision possible for the future.

3.1. The reasons to do RCM affects choice of RCM method

During the work with the new cost/benefit analysis, the team was forced to take a step back and rethink **why** and **how** Ringhals would implement RCM. Ringhals talked to others who had tried some kind of RCM. We also studied the different methods and experiences that the possible suppliers presented. It became obvious at that time, that the reasons for a company to do RCM would decide why and how they would do it.
Doing RCM analysis on a plant or a system can be done several ways. The reasons should reflect what the company wants to achieve.

There are a lot of factors that need to be considered;

- How competitive you are, if you already have high availability and low costs for production – you might not earn so much in economical terms.
- Is the company working in an environment where there are small profit margins.
- Does the company have a complete documentation, meaning systems descriptions, vendors manuals, maintenance history and so on.
- Does the company have personnel who have been within the plant for many years and are considered important due to their competence and experience and could be expected to retire in an near future.
- Does the company have multi skilled personnel or is there an ambition to increase competence
- Does the company have good understanding between the disciplines of maintenance and operations

A lot more questions could be asked, the purpose of the questions above is to help you start thinking. There could be several reasons to do RCM, it can also be done in several ways and with different ambitions;

- The “full scope”
- Only analyze the problems
- Go for the safety systems
- Maintain performed analyses so that they always reflects the present situation (RCM a part of your every day life)
- Do the analyses as an “one time task”

Combining the company reasons to do RCM with different scope of work gives many possible alternatives. It is our experience that a lot of effort needs to be spent on this issue in order to get acceptance for the work and to receive required resources.

4. SRCM PILOT PROJECT

4.1. What is SRCM?

The SRCM Process

The streamlined reliability-centered maintenance (SRCM™) process evolved from the reliability-centered maintenance (RCM) techniques developed for the commercial airline industry. The SRCM analysis process combines a reliability analysis with a review of plant maintenance history to develop a recommended maintenance plan. A review of each analysis step by the plant staff, as well as interviews with maintenance and operations personnel, are essential to the success of the analysis.

The focus of SRCM is in the functionality and reliability of each component in supporting the functions of the system. The resulting maintenance plan is prioritized based on the functionality and optimized based on a combination of experienced and postulated component failures. Maintenance tasks are developed to monitor or maintain only those components whose failure would interrupt an important system function. All other components are run to failure **when it is safe and economical to do so**. In addition to a documented basis for the resulting "optimum" maintenance tasks, the process also produces a set of recommended changes to the existing maintenance program.

The goals of SRCM can be summarized as follows:

- Concentrate maintenance resources where they will do the most good.
- Eliminate unnecessary and ineffective maintenance.
- Devise the simplest and most cost-effective means of maintaining equipment, or testing for degradation, focusing on predictive or condition monitoring activities, where applicable.
- Develop a documented basis for the maintenance program.
- Make use of plant maintenance experience when determining PM tasks and frequencies.

The logic for the SRCM process is shown in Figure 1. The documents collected during the "data collection" step include system descriptions, piping and instrument diagrams (P&IDs), functional diagrams, plant operating and alarm response procedures, work procedures, routine surveillance tests, vendor information, corrective and preventive maintenance history and component lists. The identification of key important functions involves specifying those functions that are essential to plant operation and safety. Only the important functions go through the critical analysis, while all the components that support the non-important system functions go through the non-critical analysis.

The "critical analysis' in the SRCM process combines the standard failure modes and effects analysis (FMEA) and the maintenance task selection logic tree analysis (LTA) into one record. This process allows the analyst to list multiple failure modes for a specific component and only identify the dominant plant effects. If the component is determined to be critical the analyst identifies the appropriate failure causes and the applicable PM tasks. Components that are initially analyzed in the critical analysis but are identified as non-critical will get evaluated again during the Non-Critical Analysis. Most standard RCM processes have individual entries for each component failure mode with local, system, and plant effects identified. The SRCM technique can significantly reduce the amount of time required to perform both the FMEA and LTA portions of the analysis.

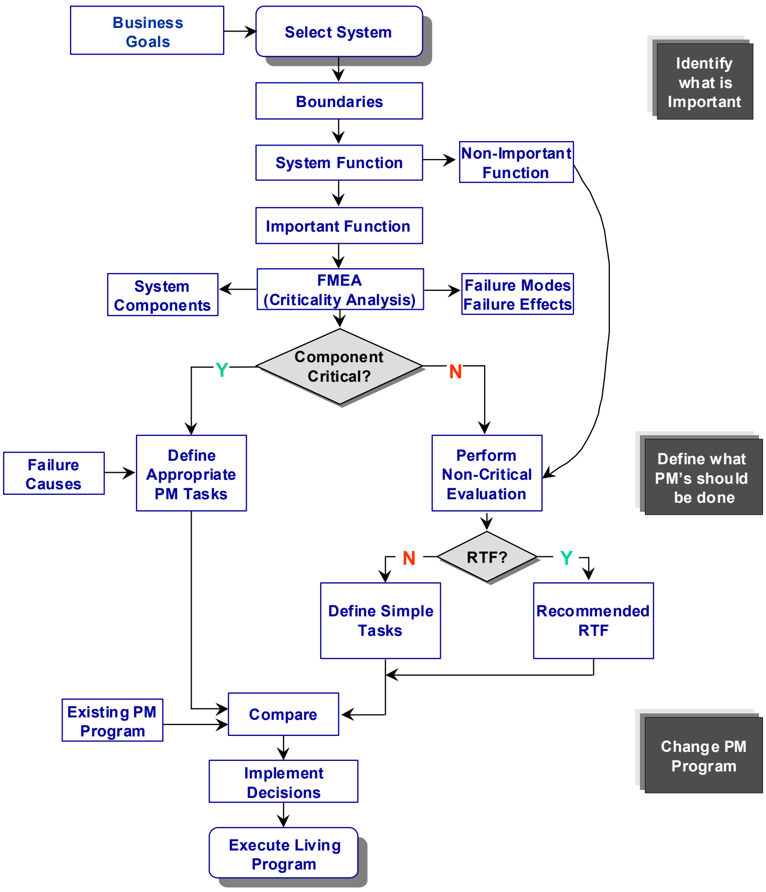


FIG. 1. The logic for the SRCM process.

The "Non-Critical Analysis" provides an evaluation using economic criteria for those components that were identified as functionally non-critical in the Critical Analysis. In the Non-Critical Analysis, several questions are used to determine the cost-effectiveness of providing some level of preventive maintenance versus allowing the component to run to failure. The questions used in the non-critical evaluation are as follows;

1. Is there a high repair/replacement cost if the component is run to failure or is there excessive corrective maintenance performed on this component?
2. Is there a simple cost-effective task that can be performed to prevent component degradation?
3. Can failure of this component induce other failures?
4. Is there an increased personnel or environmental hazard if the component is run to failure?
5. Is this component required to perform or in support of other recommended maintenance activities?

During the critical and non-critical analysis steps, corrective maintenance data from the plant is reviewed. Interviews are held with plant operations and maintenance personnel to obtain additional information regarding component performance and maintenance. This data appears in the analysis in the form of assumptions which are verified during the plant reviews of the analysis.

Plant reviews and interviews are also used to verify the classification of a component as critical or non-critical, the existence and performance of PMs, and the potential for design changes to reduce CM or PM or improve the ability to perform PM.

The comparison of the SRCM analysis results with the existing maintenance program is created by combining the tasks as they appear in the criticality analysis, the non-critical analysis and the existing maintenance program. For each component, the existing and recommended tasks are compared. A determination is made to:

- "Add" a new task from the critical or non-critical analysis when there is no existing task;
- "Retain", "Delete", or "Modify" the existing task based on the critical or non-critical analysis; and
- identify redundant existing tasks.

Implementation of changes takes into account a number of factors, including: 1) existing PM bases (code, insurance or regulatory requirements); 2) obtaining approval for changes to any required tasks, if determined to be cost-effective; and 3) prioritizing changes based on task frequency, impact on plant availability and reliability and the impact on maintenance cost reduction.

4.2. What does it take to conduct SRCM?

Performance of SRCM on any plant system entails a coordinated effort between plant personnel and the analyst. The plant personnel involved include craft, engineering, operations personnel, as well as those directly responsible for the project (Core Team).
In order to obtain the most thorough and accurate information about the system under analysis, the analyst must solicit input from these various organizations. For this to happen, the project lead/manager must coordinate schedules such that, for the most favorable impact on the project, the personnel most knowledgeable are available for analysis reviews (criticality, task selection and task comparison) and maintenance interviews. This can, at times, be a substantial investment of manpower into the SRCM analysis, therefore, it is vital that the reviews and interviews be conducted efficiently, without sacrificing quality for speed.

Typically, the core team make-up consists of personnel from engineering, operations, planning and maintenance (including supervisors, foremen and craft personnel). These personnel are empowered to make decisions and implement changes in the maintenance program (change existing PM tasks, add new tasks, purchase PdM technology/equipment, etc.). The core team will also know which personnel are "expert" on a particular system, and will ensure that these experts are available to participate in the analysis. Most often, the analyst will perform the analysis with predetermined steps identified as review points. Usually, these points are the criticality analysis, task selection and task comparison. The reviews are usually conducted by the analyst with the core team and any other personnel as appropriate. Quite often, the criticality analysis is reviewed by the analyst with only a representative from operations. This is acceptable, as criticality is a functional determination based on the effects of failure on the operation of the plant. However, the criticality review and determination should involve all members of the core team, as this will ensure that all members of the group understand the reasoning behind a component's criticality. Task selection and task comparison, however, require full core team participation in the reviews.

4.3. Project and work set up

The scope of work were to perform 7 SRCM analyses during a period of almost 7 months including training to analysts and participants.

4.4. Project organization

To run the pilot project an organization was put together.

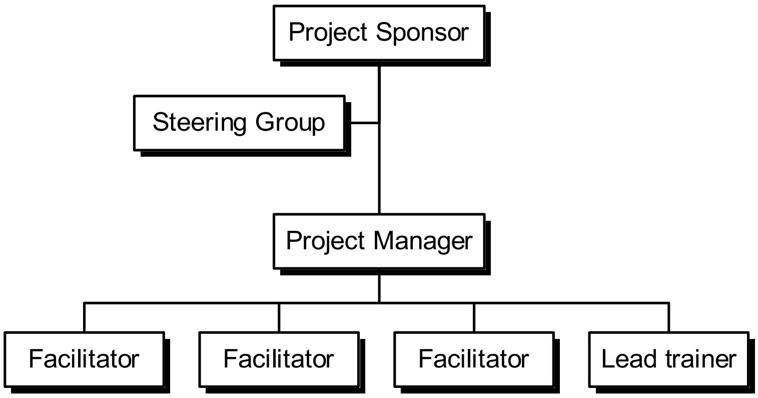
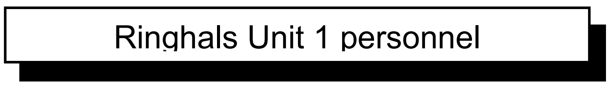


FIG 2. Pilot project organization.

The manager and the facilitators were working full time during the project. They also moved together to be able to exchange experiences, help each other, discuss problems, how the method works and so on.
The **lead trainer** was an experienced SRCM consultant from ERIN Engineering. The lead trainer supported the facilitators.



4.5. Analyzed systems

Ringhals unit 1 is a Boiling Water Reactor built by ASEA Atom and put into operation 1976. The following seven systems were analyzed;

- Containment spray system,
- Reactor main circulation system,
- Reactor water cleanup system,
- Main steam piping,
- Resudial heat removal,
- Condensate system,
- Electrical systems, this analysis included several systems including 20kV down to 500 V.

The systems were selected due to their functions, size and history. Maximizing the saving wasn't the goal.

4.6. Project set up

The project was divided into five phases;

1. Training and analysis of 1 system. The facilitators participated in a 3-day SRCM course and worked together in the analysis of the first system as a part of their training. The maintenance and operations personnel from unit 1 participated in a 1-day SRCM course.

2. Analysis of the next 3 systems were run in parallel, one system was analyzed per Facilitator.
3. Analysis of the final 3 systems were run in parallel, one system was analyzed per Facilitator.
4. Evaluation of analyses results, experiences and impressions from SRCM. The evaluation resulted in a cost/benefit report. The project manager and the facilitators in cooperation performed this work.
5. Finish. Dissolve the project and project organization, performed by the project manager.

4.7. Results from SRCM pilot project

The purpose of the pilot project was as mentioned earlier to verify all the advantages that were identified in the previous cost/benefit analysis and thereby gives Ringhals the opportunity to make the right decision about RCM. The cost/benefit analysis recommended Ringhals only to implement RCM if the soft benefits were considered valuable, the economical potential was not big enough.

The pilot project showed that Ringhals had done their homework. Analyzing of plant systems with SRCM showed that almost all benefits were there and some new ones;

- Reduction of man-hours (manh) for planned maintenance: –16%. 1 system's results reduced man-hour equals 63% of the total saving when spareparts and other services are included.
- As an average were 260 manh used in total to perform one system analysis. This was about 20-60 manh less than calculated.
- Pay off time for performed analyses is average 2,2 years. This is based on the reduction of maintenance and the average use of manh to perform the analysis.
- "Center of gravity has moved". SRCM divides components in two groups, critical and non critical. Critical components are those who could have non-tolerable failure effects. The pilot project has shown that the new maintenance program in some cases considers other components important than before. This means that maintenance resources at a higher degree are spent on the right components than earlier. This benefit was bigger than expected.
- Reviewing and analyzing of plant systems in a group were all disciplines were gathered resulted in "findings". These are failures in documentation, operations, tests that not verify functions and a lot more. Ringhals found more of these than anticipated. These findings are a product of discussions and cooperation between diciplines.

5. NEEDS BEYOND SRCM – WORK MANAGEMENT

5.1. Over all maintenance process

The SRCM™ program requires commitment by all levels of management as well as dedicated resources. It also requires several 'infrastructure' processes and programs to fully utilize and effectively achieve the maximum results from the program. Key maintenance management programs that should be in place are: maintenance program change control, planning and scheduling; root cause failure analysis (RCFA); computerized maintenance management system (CMMS); operator rounds/logs; engineering performance testing; predictive maintenance (PdM); post maintenance testing (PMT); and condition monitoring (CM). All of these programs are required to some level of implementation to truly obtain maximum value from the SRCM results. Integration of the SRCM results in how the plant performs the work should occur in order to effect and maintain the bases and decisions made during the initial SRCM analyses

The results from an SRCM analysis include the addition of new PM tasks or the deletion, modification, or retention of existing tasks. For the tasks to be retained, no effort is required for implementation other than ensuring the tasks are packaged and planned appropriately. For new tasks, determining whether it is for a critical component or not and the type of PM task (e.g., condition monitoring, operator rounds, PdM, time-directed, or testing task) is necessary to understand the importance and effort required for implementation. In fact, these recommendations tend to be the most time consuming, particularly when the recommendation is for a new PdM activity. For modification or deletion of current tasks, the activity is merely updating the task frequency or deleting the task from the CMMS. Task information contained in the CMMS may include specific direction to the maintenance crafts on what maintenance actions are required as well as what maintenance history information is needed. Emphasis is placed on **what** actions are required not on **how** to perform the actions.

Full implementation is achieved when an executable PM program is contained within the CMMS or other appropriate programs such as operator rounds, test procedures, etc. using the SRCM analyses as its bases. This will in-turn require updating the SRCM analyses when changes of the maintenance program are required. The living program is designed to manage the change to the SRCM analyses.

5.2. Living Program

Following the implementation of SRCM™ results into a power plant's CMMS and their subsequent use in changing the plant's maintenance program, a maintenance program change control (living program) capability is put in place. The purpose of the living program is to ensure that the maintenance basis developed and executed by utilizing the SRCM process is continuously improved. In addition, it ensures that a means of controlling and modifying the maintenance basis is in existence.

The objectives of the living program are to 1) ensure that design changes and operation changes are reflected in the PM program, 2) ensure that new maintenance technologies are optimally used by the PM program, 3) track maintenance experience to confirm that the bases for the recommendations remain valid and that they are still effective, and 4) keep current the SRCM decision basis.

A living program procedure defining responsibility for the program, detailing the program elements, and specifying the schedule for reviews and updates has been developed and utilized.

The living program must have a complete listing of the system analyses, PM recommendations, and status of PM task implementation.

Elements of the living program include:

1. Completing timely PM change request reviews for components with SRCM evaluations.
2. Reviewing plant modifications
3. Reviewing SRCM and PM program effectiveness by monitoring and trending maintenance history

Periodically reviewing predictive maintenance capabilities, and assisting maintenance personnel with optimizing application of new technologies.

Administratively, the living program will require that no changes to the maintenance program (e.g., time-directed, condition-directed, and performance testing tasks) can be made unless the potential change has been reviewed and considered against the current basis (analysis). This will ensure the analysis will always reflect the actual program. Procedures will be developed that will manage the program and provide guidance on how to implement the program. The procedures will cover:

1. Evaluation of need for PM change recommendations
2. Development of PM change recommendations
3. Program revisions and tracking
4. Program effectiveness
5. Periodic reviews

Requested changes will follow a process similar to the process shown in Figure 3.

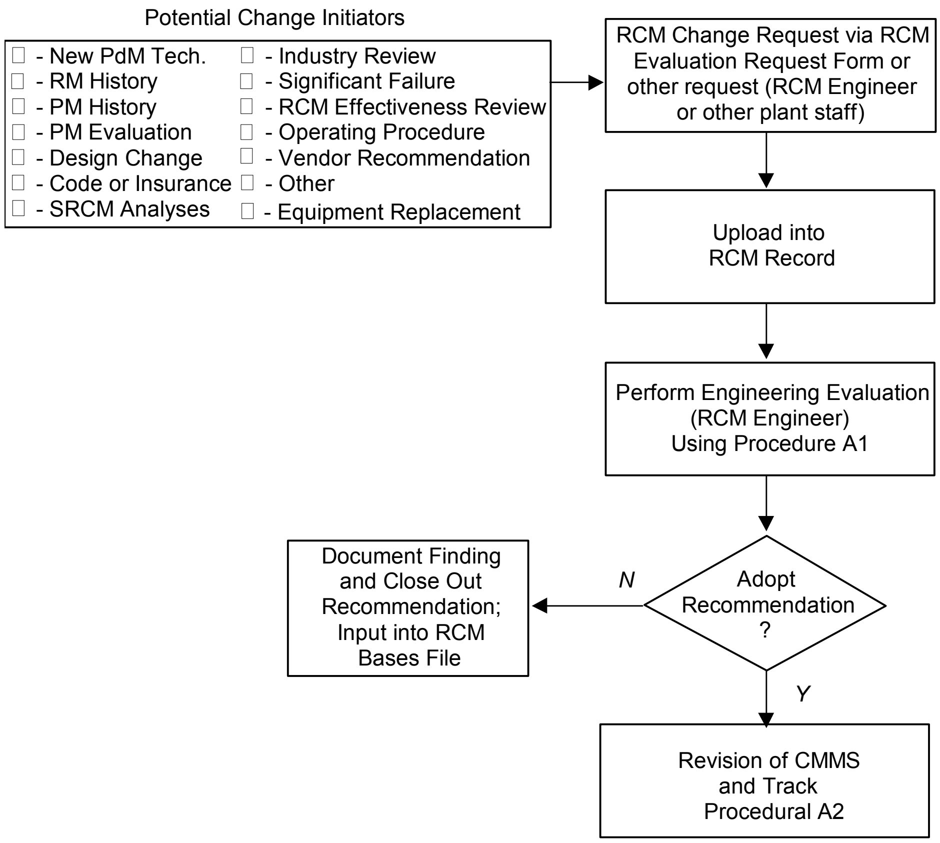


FIG. 3. RCM Recommendation flow process.

Annex 9

THE CANDU EXPERIENCE WITH RELIABILITY CENTRED MAINTENANCE AND PLANT LIFE MANAGEMENT

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Abstract. After operating successfully for more than half their design life, CANDU® reactors are now engaging in Plant Life Management (PLiM) activities with the view of not only life attainment, but also life extension. For several years, Atomic Energy of Canada Ltd. (AECL) has been working with these CANDU utilities on a comprehensive and integrated CANDU PLiM program that will see existing CANDU plants successfully through their design life and beyond. For the CANDU 6 plants, AECL is working to assist in implementing the elements of the PLiM program. In-depth assessments of critical systems, structures, and components (CSSCs) are being carried out and the recommendations are being implemented. At one CANDU station (Point Lepreau) these efforts are being applied in concert with more broadly applied system and component condition assessments to provide important inputs to the overall plant requirements for life extension. Other CANDU owners are considering following this path. In order to assure high capacity factors to the end of design life and after the plants are refurbished, there is a major effort on system maintenance optimization integrated within the PLiM Progam. This system maintenance optimization program, utilizing Reliability Centered Maintenance (RCM) analysis of critical systems, is now moving into its implementation phase. As part of this effort, AECL is developing strategies that highlight the synergy of the resulting maintenance and monitoring optimization and the goal of managing plant life. This paper gives background on the AECL CANDU 6 PLiM initiatives, with a focus on the issues currently being addressed to implement the outcomes of the RCM assessments into the current plant surveillance, inspection, and maintenance programs. Also described is the current philosophy for integrating the maintenance and monitoring assessments into the overall PLiM program.

1. INTRODUCTION

Plant life management and performance improvement starts with the design function, where allowances are built into the design requirements and specifications for key components, structures and systems. To define these allowances, the designer needs to be aware of how the system will age and by what means the system can be monitored and maintained in anticipation of the expected aging. This knowledge is in turn reflected in the commissioning phase of the plant where system performance is benchmarked. During the operational period, the utilities carry this monitoring and maintenance strategy forward through comprehensive and adaptive programs that provide for attainment of performance goals and improvements in inspection, surveillance, and performance/safety analysis methodologies. The knowledge gained in every phase of the plant operation is in turn reflected in the new reactor designs. This is the vision for an evolving PLiM program for the entire life of the plant.

This vision of a PLiM program helps to shape the scope and focus the elements of the program. It is also important to capture any salient features of the topic of interest. In the world of maintenance, there are two distinct but interrelated perspectives. The first perspective is from the component itself. The performance parameters, aging mechanisms, associated potential monitoring tools, and typical maintenance strategies are all usually related directly to a component. In many cases, components are treated as commodities. Motorized ball valves, for instance, may all be treated in a similar fashion.

The second perspective is that of the component as part of a system. The failure effects of a component, and in some cases the cause of the failure, are better understood from a system or most importantly from a plant or owner's perspective. Moreover, the ability to monitor a component can be significantly enhanced using various system performance indicators. Finally, the criticality of a component can only be understood within the context of the system.

The development of a comprehensive CANDU PLiM program began in earnest in 1994. With consideration of the vision and with the system versus component perspective, the program embarked on several areas of PLiM applications in partnership with CANDU utilities. The CANDU PLiM program is now reaching maturity, and an integrated program is being followed, which includes the following key components:

I. Systems Maintenance Optimization
II. Components and Structures Aging Management, to ensure degradation mechanisms are understood and steps taken to mitigate them.
III. Obsolescence Mitigation to identify or in some cases, to reverse-engineer replacement components and spare parts that meet the original design bases and qualification standards.
IV. Integrated Safety and Performance Assessment
V. Technology Watch, Research and Development, and Operational Experience Monitoring to anticipate new emerging issues as early as possible.

In addition to management of the physical plant, the CANDU PLiM program also recognizes the importance of managing the configuration control of the plant, its management and personnel, and the business, regulatory, and public impact as the station ages.

Some CANDU plants are now at the stage where they are looking beyond life attainment, and considering life extension. To further support this effort, system and component condition assessments covering a significant proportion of the plant have been carried out.

Experience has been gained in the different elements of the CANDU PLiM program. The following sections will discuss this experience from the component and structures aging management, the system maintenance optimization (using Reliability Centred Maintenance techniques), and in particular the implementation of the assessment outcomes to the plant programs that address aging.

2. COMPONENT AND STRUCTURES AGING MANAGEMENT

Once a component is defined as critical to plant goals, the component becomes a candidate for a focused life assessment study. The methodology that is followed is similar to approaches used internationally but tailored to the specific technologies and operational experience of CANDU components. Major steps of the process include:

- Identification and description of the structure/component and the associated sub-components;
- Review of design documentation, specifications, and related data including the review of safety analysis to identify safety related constraints;
- Review of manufacturing and installation data including the methods of repair and replacement;
- Review of CANDU operational experience as well as the Canadian and international experience;
- Identification of degradation mechanisms and evaluation of these mechanisms on its life attainment and life extension;

The output from a typical study is a component based health prognosis, along with a set of recommendations to assure long life. These recommendations may include:

- Requirements for additional data collection and record keeping,
- Changes to maintenance and inspection programs,
- Changes to operating conditions,
- Modifications or early replacements,
- Further research and development activities to develop techniques to better assess the impacts of aging, and
- Recommended schedule for updating of the assessment.

These recommendations are then incorporated into the plant life attainment or plant life extension programs as appropriate. In certain cases, as agreed with the utilities, a detailed plan with cost and schedule estimates to implement the recommendations is generated.

Two CANDU 6 utilities have now started detailed planning of a plant extended operation program for their plants. A key part of the life extension program is to utilize the outcomes of the PLiM assessments and implementation in enhancing current plant programs for extended operation. These studies are used in concert with more broadly based condition assessment studies. For instance, the life assessment work on the concrete containment has led to an enhanced inspection and monitoring program at Point Lepreau. With knowledge from the containment condition assessment program at the decommissioned Gentilly 1 plant, AECL developed the detailed containment aging management program (including the monitoring instrumentation) for extended operation.

Concrete containment is an example of how a comprehensive PLiM program is used to provide important inputs to the surveillance, maintenance, and operations programs to achieve the utility's targets for safety, reliability, and production capacity during its extended life. The AECL/utility PLiM program interaction over the last few years has provided the utilities with in-depth assessments and promising life prognosis for the key critical components, structures, and systems in the plant. These outcomes have been important inputs into utility decisions to embark upon a detailed CANDU plant extended operation program.

3. MAINTENANCE OPTIMIZATION

System based maintenance optimization is performed utilizing Reliability Centered Maintenance (RCM) techniques, as adapted to the CANDU PLiM program. The approach to RCM selected for the CANDU PLiM program makes use of a streamlined RCM tool. This tool ensures a structured analysis is carried out following the principles of RCM. The process streams components into categories of critical and non-critical as an outcome of the Functions and Functional Failure Analysis (FFA), and the subsequent Failure Modes and Effects Analysis (FMEA). The analysis is further aided by using templates that contain information regarding components, failure modes, and suggested maintenance tasks and frequencies. A task selection process is applied based upon the outcomes of the FMEA analysis.

The RCM process has been organized into 22 specific steps, which cover the 8 basic elements shown in figure 1, excluding the implementation step. The analysis is carried out by AECL analysts, which constitutes a third party application, as described in Reference 2. Plant staff are typically involved in the process through a System Engineer and a representative from the Reliability Group. Component specialists and maintenance experts are involved as available.

To foster ownership of the RCM analysis by the plant as a whole, a specific person in the plant takes ownership of the RCM process, encouraging all the involved parties throughout the analysis and implementation phases. To aid in creating "buy-in" amongst the different groups, the RCM process makes use of the appropriate plant representatives throughout the process. This enhances the ownership of the ultimate result by all parties.

The RCM process employed in the CANDU PLiM program has been further adapted to encourage "buy-in" during the analysis, and to put the foundation blocks in place to further foster this "buy-in" during implementation. For example, the process itself uses several detailed review sessions to ensure that the plant participants gain a significant ownership of the resulting analysis.

A second adaptation is to gain acceptance from the various groups within the plant by using the templates as a documented form of agreement on overall maintenance strategies from a component basis. The templates are then applied within the system context to shape the overall system based maintenance program. When translated back to the component programs, the program specialist is presented with requirements shaped by the previous agreement on the templates.

It is also important to gain credibility with the component specialists, which can be accomplished by ensuring that the RCM application brings new and useful information to the plant. With this intent, AECL is aggressively working to enhance the templates and ensure that they represent the state of the art for each application. In this way, the RCM process can be shown to have a valuable contribution, which has a well documented basis.

Acceptance of the RCM results by system and program specialists is important, but effectiveness may be limited if the plant management are not actively supporting the initiative. Hence, a number of measures are taken to obtain general managerial support within the plant organization, in order to facilitate timely implementation. For instance, specific presentations on the overall RCM process and benefits are made, tailored to plant management. Also, management are routinely invited to the "kick off" session for work on new systems, where the RCM process is explained through a shortened training session.

The efforts described above focus on gaining ownership of the RCM process by the plant through participation at many different levels. A second strategy is to ensure that the value of the resulting study is well understood. A RCM study provides a significant amount of information, resulting in a detailed, well documented, system based maintenance program. However, the level of detail of the analysis and its results is rather onerous to assimilate, making general understanding of the overall coherent strategy underlying the results more difficult to grasp.

To address this complexity of the RCM results, a special step has been added to the usual RCM process. This is the comparison of the existing and proposed maintenance program (as shown in Figure 1). This provides a detailed assessment of the proposed changes. Following this, a further adaptation has been added to ease plant implementation. To complement the comparison, the resulting maintenance program is packaged to present the maintenance strategy in a format that conveys the overall strategy more clearly. These outcomes are also packaged into groupings that suit the plant organization. A more complete description is in Reference 1.

The RCM analysis will usually result in a more significant focus on condition based maintenance. To convey this information more clearly, a surveillance matrix is developed. The matrix relates the system functions and functional failures to the various aging mechanisms, then to the surveillance activities, and ultimately to the required condition based maintenance for components. This activity combined with the task packaging and task comparison serve to aid the plant personnel in understanding what is required in the implementation phase and what the result will be.

An example of a typical result from a RCM study is the results for the equipment airlock (EAL), personnel airlock (PAL) and containment sealing door (CSD) systems. Greater detail of the results is presented in Reference 1. The study recommendations result in a significant reduction in the frequency and number of required maintenance operations, leading to an overall reduction in cost, while focusing on the maintenance that is critical to the system. For example, it is expected that the recommended program will result in fewer door seal replacements, hence less maintenance effort and also making the airlock itself more available in support of other maintenance activities.

From this and other analysis work, it has been concluded that the methodology is sound. The recommended changes will ensure that system performance does not deteriorate as the plant enters the second half of its design life. Redundant equipment down time for maintenance will also be minimized.

4. IMPLEMENTATION OF THE ASSESSMENT OUTCOMES

With the significant progress on the PLiM assessments, effort is now underway on implementation of the outcomes from the assessments into plant programs.

Effective plant practices in monitoring, surveillance, maintenance, and operations are the primary means of managing aging. From the experience to date, the PLiM program will modify and enhance, but not likely replace, existing plant programs that address aging. However, a successful PLiM program will provide assurance that current plant programs are modified to be effective in managing aging. This requires a structured and managed approach to the implementation process. The overall objective is to optimize plant programs for aging management, both for the remaining design life period and for the plant extended operation to come.

An example is the development of an implementation strategy for the streamlined RCM studies. This strategy is discussed in the following sections.

5. DEFINING THE IMPLEMENTATION STRATEGY

To aid in defining the implementation process for the RCM studies, it is useful to identify the inputs and outcomes of the process. The RCM study represents one key input. A second input is the existing plant organization and how that organization manages the current maintenance and monitoring programs. The primary outcome of the process will be a revised maintenance program. This revised program is herein called the “system based adaptive maintenance program” (SAMP). In a SAMP, RCM outcomes are reviewed and implemented into a maintenance strategy that is “adapted” as required to improve maintenance and monitoring effectiveness.

A key requirement of the SAMP is that the process provide for the systematic disposition and incorporation of the RCM outcomes into the current plant programs. Further, the current programs will be adapted such that the revised maintenance and monitoring programs are managed as an integrated, system based adaptive maintenance program, which is derived from the RCM analysis. This is an important consideration since a SAMP process that recognizes the results of a RCM study is needed to take full advantage of the full scope of what the RCM study provides. Therefore, in order that the implementation process can be properly defined, the required structure of the SAMP must be defined first.

6. THE SYSTEM BASED ADAPTIVE MAINTENANCE PROGRAM (SAMP)

A proposed SAMP is presented in figure 2. This figure shows two primary cycles that are both used to review and update the overall maintenance program. The first is the maintenance cycle, which includes all routine tasks that are carried out through a time based program, or on a demand basis. This cycle is primarily focused on components, although some system based monitoring is also included, such as chemistry monitoring. The maintenance cycle includes monitoring type tasks in support of the condition based surveillance requirements, time based maintenance activities, corrective maintenance activities, and the relevant reporting activities.

The second cycle is the system health monitoring cycle. This typically involves the "system health monitoring plan" (SHMP), which covers the collection and trending of all surveillance parameters and the generation of the resulting actions. An important activity is the gathering of all relevant system based performance data used for review of the maintenance program.

7. SAMP PROCESS CONSIDERATIONS

There are three considerations for the SAMP process shown in figure 2. The first is that the SAMP encompasses inspection, surveillance, and traditional maintenance activities. Hence, "maintenance" in this context is more than just the corrective or upgrading activities in traditional use of the word. The RCM process defines the significant interrelationships that exist between the inspection, surveillance, and traditional maintenance activities, and hence it facilitates an integrated set of plant activities that together result in a system based maintenance program optimized for the important functions of the system.

Using this broader definition of "maintenance", the resulting SAMP is required to reflect these interrelationships by ensuring that all the related plant programs are managed and updated from the system performance perspective. This is provided by using the RCM based FMEA and task selection as a focal point for periodic review (Box 4).

The final consideration is that the process requires the interaction of several different groups within the plant structure. Not only is there an overall system maintenance perspective to consider but there is also interrelationships between system specialists, component program specialists, the reliability group, and the groups that provide support to these areas.

In summary, plant maintenance must be understood to include the surveillance and inspection activities. A successful SAMP will ensure that the management of the process reflects this perspective. Finally, the plant personnel need to be aware of the resulting interrelationships to ensure that the process works well. Figure 2 is a simplified flow chart that shows the overall SAMP process, the various interrelationships of the groups, and means by which the RCM study is introduced into the process.

"ADAPTING" THE MAINTENANCE PROGRAM

Within the SAMP, adaptation is handled through the central review process. This review process is composed of the "maintenance program periodic review" (Box 4), which is followed by the "review and implementation of updated programs" (Box 5).

In addition to providing a documented review and disposition process, the SAMP also requires a formal feedback process to ensure that the appropriate information is used in the periodic review. This is accomplished by defining the appropriate flow of information, and ensuring that the SHMP report captures the relevant information prior to the periodic review.

8. MAINTENANCE PROGRAM PERIODIC REVIEW

The "maintenance program periodic review" (Box 4) is triggered by the system health monitoring cycle (Box 8), particularly the SHMP report. This report gives a compilation of all relevant information from the system perspective, including feedback from the Reliability group on maintenance performance.

The scope of the periodic review is to reconsider the details of the system maintenance database (SMD). This database is derived from the RCM study and represents the documented "maintenance" program as discussed later in the paper. The SMD information is available in a form that lends itself to updating on a periodic basis and includes both FMEA and task selection information. For the periodic review, the system's component performance in the past period and experience in execution of the surveillance and periodic maintenance activities is considered as it applies to the SMD. Additional information may also be added to the process (Box 5), such as:

- New safety or regulatory requirements or concerns
- New or improved methods or strategies based upon field experience
- External information regarding system condition such as life assessments and condition assessments
- New concerns arising from change in system operational constraints
- Identification of new maintenance or predictive maintenance technology
- Identification of new approaches identified from external sources

From consideration of all this data, the SMD would likely be updated.

This periodic review of the SMD would be usually limited to a smaller review group, with input from others as required. This could be considered a shortened version of the RCM analysis, with a very focused target scope.

9. REVIEW AND IMPLEMENTATION OF UPDATED PROGRAMS

The changes defined in the periodic review process are then reviewed by a larger group, which will include representatives from the various affected component program groups. The scope for this review (Box 6) is to ensure the updates defined in the periodic review are acceptable to the groups who must implement them, and then develop an appropriate implementation strategy. The specific actions agreed for implementation will then be carried out under the component program update (Box 9), or the SHMP update (Box 7). These actions are important, as this is where system based requirements are translated into component based actions.

The update of periodic maintenance tasks can be dealt with through established standard processes associated with preventive maintenance tasks (PM). Some key areas to be addressed relate to the proper documentation of the flow of information. Specific requirements for documentation need to be identified to ensure that the appropriate information is tracked for reporting to the various groups (surveillance or reliability for example). The entire process, its auditability, and overall value relies on providing adequate documentation to the appropriate users. Success of condition based activities is dependent upon this flow of information.

Surveillance tasks must be incorporated into the SHMP. It is noted that as the SAMP moves toward more condition based maintenance, the amount of monitoring information becomes large and tools used may need to be updated to facilitate trending by those concerned and to reap the advantages of condition based programs.

10. ESTABLISHING THE SYSTEM MAINTENANCE DATABASE

The preceding sections discuss the system based adaptive maintenance program, special considerations, and how the maintenance program is adapted. The focal point of the program is the review and update of the SMD. To initiate an SAMP for a system requires that a SMD be established which is based upon the RCM study for the system. Referring to Box 3, the RCM analysis requires a process of plant staff review and acceptance. The level of review is dependent on the process used to arrive at the RCM result. The outcome of the review will be a series of dispositions, assignments, and schedules that need to be tracked. The purpose of this activity is to translate the initial RCM database into the SMD to be used as part of the SAMP.

11. REVIEWING THE INITIAL RCM DERIVED PROGRAM

The revised program that results from the RCM study requires review and acceptance, such that each result from the study is systematically dispositioned. Several groups may be impacted, and each group needs to become part of the process to generate a sense of ownership. At this stage, there is an additional focus on finalizing the FMEA and task selection basis for use as part of the SAMP.

A review of the impact on system reliability is carried out by the reliability group for safety related systems – Box 2, since the changes in the maintenance program frequencies, or increasing the number of condition based activities may impact on the predicted system reliability. Hence, the reliability group assesses when revised task frequencies are simply not possible, when the change may need to be phased in over time, or when the temporary reduction in the predicted reliability can be justified with a view to seeing improved reliability once some history is developed with the revised maintenance strategy. The results of the reliability assessment are then incorporated into the SMD for tracking and future periodic review.

The RCM analysis may indicate a change to component programs as it provides specific system information for individual components based directly on importance to system functions. This information is helpful in optimizing the component programs but the overall SAMP must be capable of tracking these system specific requirements of individual components. This important part of the process represents the translation from the system based requirements to the component based actions.

For example, motorized valves can be categorized according to basic criteria such as size and criticality. The system information will reflect the specific failure modes of interest resulting in a further refinement within each generic category, besides providing system based criticality information. In this example certain tests may not be required, although the valve is considered critical, simply because the failure mode captured by the test is not critical for the valve in the context of its system. Tracking this individuality requires additional capabilities to smoothly carry out the component program.

A second impact on component programs is the identification of new technology. The RCM analysis may suggest improved methods of diagnosis not yet employed by the current component program. The decision to adopt the new technology requires evaluation and likely an economic and safety improvement assessment will need to be carried out. The ultimate dispositions need to be documented and incorporated into the SMD where changes are required, or where additional useful information is available.

Finally, the RCM study may identify areas where design changes are required. Again, the plant needs to assess criticality, assign responsibility, and determine a time frame. The recommended change will certainly need to be further evaluated to demonstrate the necessity of the effort.

12. TRACKING DISPOSITION OF INDIVIDUAL TASKS

The reviews discussed above, will result in assignments, dispositions, and a basis for each decision. It is expected that there will be a significant list of actions required to implement the RCM study results. There is a need to track this process for two reasons. First the size and complexity of the effort requires tracking. Second, like the RCM analysis itself, the documentation of the dispositions and each individual basis for the disposition provide an auditable trail, which can be revisited to evaluate the effectiveness of the process at a later date. Moreover, the documented results become part of the system information, which provides valuable background for newly assigned staff in the future.

The list of specific activities resulting from the dispositioning process will require scheduling. The scheduling will require that the tasks be prioritized. The criticality assessment from the RCM study will aid in prioritizing. Further, a means is likely required to monitor the implementation process. The tools used by AECL provide this capability as a natural extension of the RCM analysis.

13. THE SYSTEM MAINTENANCE DATABASE

The review of the revised program (Box 3) may result in updates to the FMEA and task selection databases. The culmination of this review and disposition effort must be reflected in the final FMEA and task selection to create the updated "system maintenance database" (SMD). Reviewing and updating this database constitutes the focal point of the overall SAMP (Periodic Review Box 4). As with the periodic SAMP updates, the majority of the detailed tasks required to implement the new SMD are carried out under the component program update (Box 9), or the SHMP update (Box 7).

Several logistical items must also be dealt with in regard to the SMD. The responsibility for the updating and maintenance of the database must be assigned. The timing of the review process needs to be established (eg. annually). Finally, procedures need to be put in place that provide detail on who participates in the review, the scope of the review, the inputs to the review, the outputs, and the documentation requirements.

14. IMPLEMENTATION CHRONOLOGY

The process description given above assumes that a RCM analysis is completed for the system under consideration. The SAMP process assumes that there is information available on which to create the focus for updating. The process also assumes that a SHMP or equivalent exists. The reality is that the RCM analysis is being completed on a system by system basis, focusing on selected critical systems, which is not exhaustive of the plant systems.

Ideally, all plant systems would be treated the same way, but this is not necessarily the case because the application of RCM analysis itself is chronological, and second the plant systems as whole may be treated in phases. Therefore the SAMP process must be flexible to accommodate different states of completion of RCM analysis and implementation. The process must also acknowledge that each system will have different level of detail available.

Several actions can be taken to ensure the program can handle these variables. The first approach is to apply the current RCM program on all plant systems. A variation of this approach is to accept less rigorous applications on selected systems. This could involve a simplified expert panel approach. Plant management needs to assess the desired level of uniformity to be applied across the plant systems.

To address the need for flexibility in the SAMP process, it is acknowledged that the plants are generally tracking maintenance history and react to maintenance related problems or incorporate new technology. Current approaches largely rely on component programs to handle problems. This current capability can be enhanced, as discussed earlier, by having the plant personnel involved in reviewing the templates used for the RCM analysis. If the generic programs identified in the templates are applied on the remaining systems that are not RCM analysed, then there will be a consistent base program across the plant. This does not necessarily change the current plant generic component programs, which already are designed with the intent of ensuring consistency throughout the plant. The difference is that systems with a SMD have information that further refines the component program application. Further, the SAMP updates may include updates that affect component generic programs. These updates in turn can be translated to systems without a SMD to review.

The conclusion is that the preceding process outlined for updating the SAMP can be of benefit to those systems without a formal SMD. For instance, these systems can be influenced by the systematic effort of those systems that are using the SAMP process, as this process will ultimately influence the generic component programs. Conversely, updates to generic component programs need to be included and acknowledged in the periodic reviews of the SMDs. In essence, those systems without a SMD will not have such reviews, but changes can still be controlled indirectly through the updating elements of related SAMPs.

15. RCM AND PLIM

System maintenance optimization, using RCM techniques, has been included as a vital part of the overall CANDU PLiM program. This approach is justified when one considers that effective plant practices in monitoring, surveillance, maintenance, and operations are the primary means of managing aging. This is seen in the proposed Adaptive Maintenance Program in figure 2. While other PLiM activities such as Life Assessments can be viewed as having a one time impact, an enhanced value is obtained when these studies are also considered for improvements when updating the applicable SAMP. It is ultimately the SAMP that then provides the structure required to effectively implement and manage the long term impact of PLiM activities at the plant.

16. CONCLUSIONS

A comprehensive and integrated plant life management (PLiM) program has been developed. The program is helping CANDU reactor owners to achieve goals for safe, economic and reliable life attainment and to preserve the option for extended operation.

The AECL/utility PLiM program interaction has provided the utilities with in-depth assessments and promising life prognosis for the key critical components, structures and systems in the plant. Moreover, safety related systems are being analysed using a streamlined RCM process that is identifying efficient and cost effective system based maintenance and monitoring. Overall, the PLiM program has matured to the point where the focus is now on effective implementation of the analysis results.

Defining the implementation process for maintenance optimization studies requires understanding the implications of adopting an "System based Adaptive Maintenance Program" approach to maintenance. A SAMP process has been proposed, from which several implications have been identified. These are:

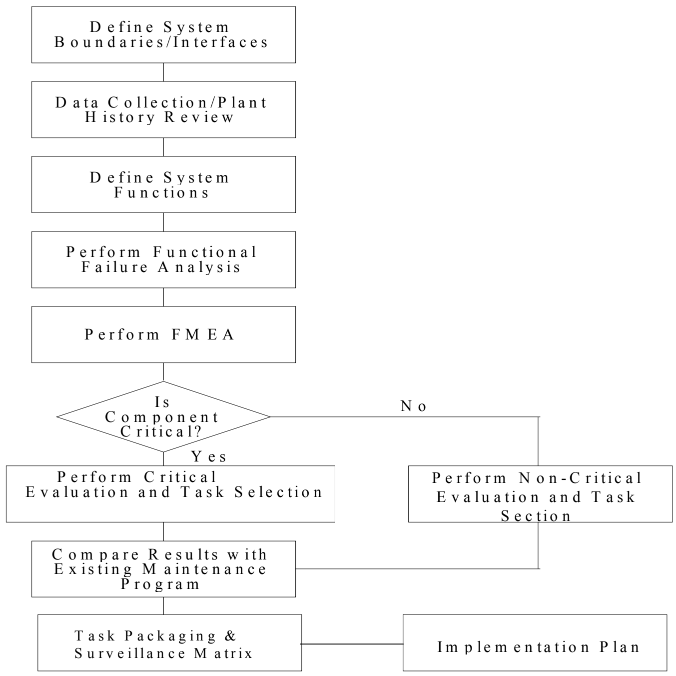

FIG. 1. The Systematic Approach to Maintenance Process.

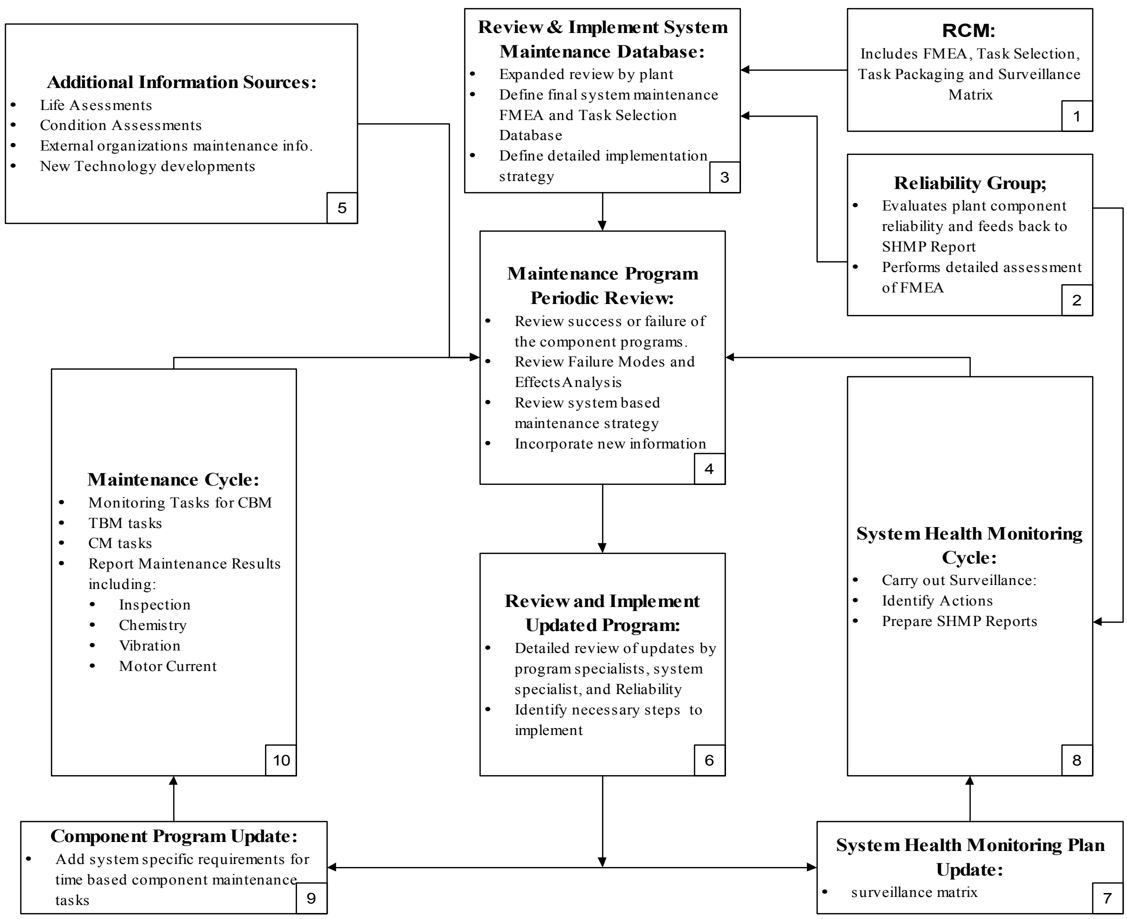

FIG. 2. Process diagram for the system based adaptive maintenance program (SAMP).

1. Plant maintenance must be understood to include the surveillance and inspection activities. Any successful SAMP will ensure that the management of the process reflects this perspective. Finally, the plant personnel need to be aware of the resulting interrelationships to ensure that the process works well.
2. A “system maintenance database” must be established through a detailed review of the RCM analysis. The review and updating of the SMD constitutes the new focal point of the SAMP process.
3. The definition of the required information content and flow is a key requirement for the process to be effective.
4. The SAMP process is required to accommodate systems not having a formal RCM analysis.

The proposed SAMP also demonstrates the synergy of other PLiM program components with the RCM assessments. In considering the implementation of the RCM study, it is recognized that the “maintenance” programs of the station are the primary means of managing aging. The outcomes of the various PLiM program components all ultimately enhance the plant programs to improve management of aging to attain the plant design life and beyond.

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Annex 10

COMSY SOFTWARE ASSISTS PLIM & PLEX ACTIVITIES

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Abstract. The COMSY software has been developed to provide a tool for the ageing and plant life management (PLIM) of systems and components in power plants. It is designed to support plant life extension (PLEX) activities and innovative maintenance management methods. The objective is the economical and safe operation of power plants over their design lifetime - and beyond. One of the primary requirements for an efficient application of lifetime and extension strategies is the capability to perform lifetime predictions and to indicate when a system or a component has reached the end of its effective lifetime. The lifetime prediction capability requires an understanding of how the relevant ageing and damage mechanisms work and the accessibility of data required for lifetime analysis, which are: system design and geometry, material properties, the history of thermal-hydraulic and water chemical operation conditions, stress conditions and results from non-destructive testing. The software utilizes a virtual power plant data model to manage these parameters. It integrates powerful analysis functions and comprehensive material libraries. Based on these plant data, the program conducts a condition-oriented lifetime analysis for various damage mechanisms which may occur in power plants (e.g. strain-induced cracking, material fatigue, flow-accelerated corrosion, cavitation erosion, droplet impingement erosion). The resulting service life prediction is validated and optimized through the performance of a small number of examinations at priority locations. This systematic process ensures the generation of a quantifiable database which is continually kept up to date with information related to the technical as-is status of the plant. On the basis of reliable and damage-relevant predictions, maintenance management and plant availability can be optimized. This capability is particularly useful for the service life extension of systems and components. The efficiency of this software based strategy was already confirmed by field experience in various power plants.

1. INTRODUCTION

The COMSY software has been developed to provide a tool for the ageing and plant life management (PLIM) of systems and components in power plants. It is designed to support plant life extension (PLEX) activities and innovative maintenance management methods. The objective is the safe and economical operation of power plants over their entire lifetime.

The purpose of a systematic ageing and plant life management program is to allow the lifetime of plant components to be planned, and to indicate when a component has reached the end of its effective lifetime before it fails. Another important function of such a strategy is to increase the availability of power plants and to enable implementation of a targeted maintenance strategy in terms of its economic and technical effect.

Implementation of software tools for plant life management requires the existence of detailed information concerning the design and operating conditions as well as the components as-is state. Based on this information a prediction of the components remaining life can be performed, provided that the relevant degradation mechanism has been understood. Advanced software programs provide such predictions for a number of degradation mechanisms at reasonable cost across all systems.

2. THE COMSY CONCEPT

Framatome ANP GmbH (formerly Siemens/KWU) developed the **COMSY** software system (*C*ondition *O*riented ageing and Plant Life *M*onitoring *Sy*stem) as a tool for ageing and plant life management of mechanical components in power plants. This knowledge-based program system allows the overall lifetime of mechanical components to be tracked. The concept is based on comprehensive integration of advanced analysis tools with powerful databases.

The goal of the software system, to provide cost-oriented tracking of overall service life, promises the following economic advantages to the plant operator:

- Transparent display of the design and manufacturing data, as well as the continually updated as-is condition of the plant,
- Concentration of examination and maintenance activities in relevant system areas,
- Assessment of the effects of refitting work prior to its performance through the use of simulation calculations.

The COMSY software system acquires, manages and evaluates component and operating parameters relevant to service life. Plant data pertaining to individual vessel elements, piping elements and systems are stored in a “virtual power plant data model”. Based on these plant data, the program conducts a condition-oriented lifetime analysis for various degradation mechanisms which may occur in power plants (strain-induced cracking, material fatigue, erosion corrosion, cavitation erosion, droplet impingement erosion). This process is supported via an intelligent user interface, powerful analysis functions (stress analysis, thermal-hydraulic and flow analysis functions, water chemistry cycle analysis), comprehensive material libraries (e.g. material data catalog, database of material acceptance values), and a module for management and evaluation of examination results.

The concept is based on comprehensive experience gained in the use of the predecessor software tools WATHEC & DASY in conducting analyses of weak points for flow-induced forms of corrosion over a period of more than ten years.

In the following the ageing management strategy implemented in COMSY (**Closed Loop Process**) is described in more detail including the relevant subitems

- **Cost effective plant diagnosis** with so called **rough** and **detailed analysis**,
- Modeling of **lifetime prediction** and
- **Software tools** supporting the analysis.

3. CLOSED LOOP PROCESS

Service life prediction is the key function of a software system for ageing and plant life management. On this basis can maintenance management and plant availability be optimized and the service life of components be extended. An efficient service life management program builds on these degradation predictions, which are validated and optimized through the performance of a minimized number of examinations at critical points.

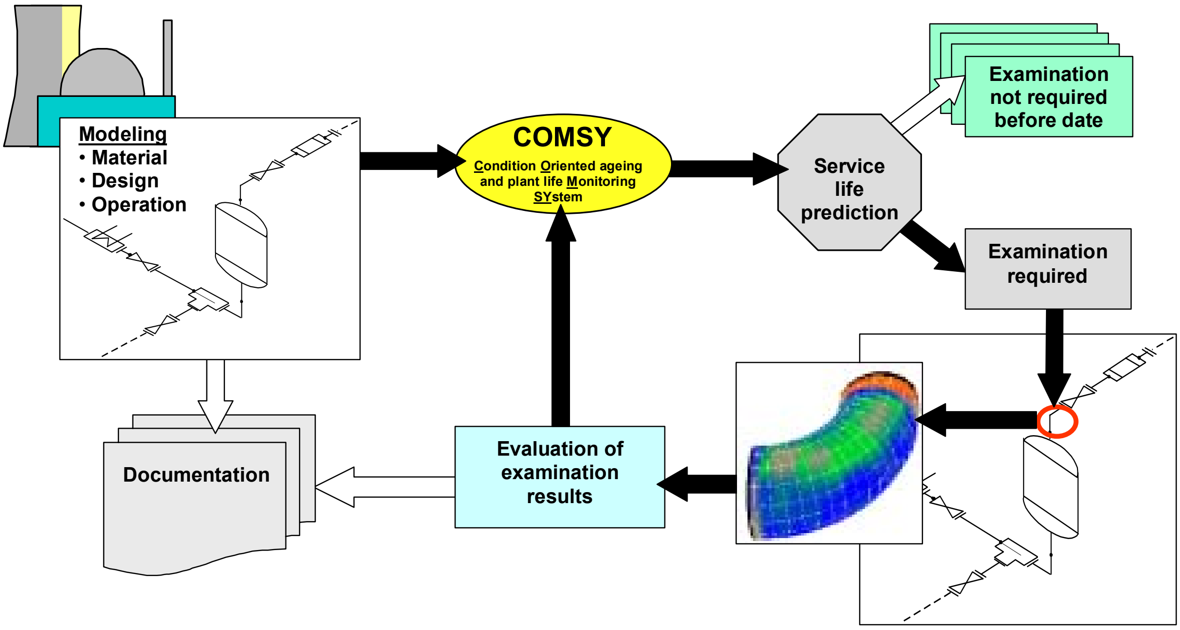

FIG. 1. The closed loop process for PLIM.

Based on the predicted service life, components can then be prioritized for examination programs and condition-oriented inspection plans can be prepared, as shown in Fig. 1. The results of component examinations are fed back into the program system, and are used for further optimization of service life predictions over the life cycle of the component. Overall, this systematic, closed-loop process enables up-to-date maintenance of a database with quantifiable information relative to the technical as-is status of the plant.

Based on a known type of degradation and a validated rate of degradation progression, suitable remedies and preventive measures can be implemented in order to extend the service life of components. Experience over many years has shown that a maintenance management program based on reliable service life predictions enables costs to be minimized and plant availability to be increased.

4. COST EFFECTIVE PLANT DIAGNOSIS

In order to determine the areas of the plant affected by the ageing and degradation mechanisms in question, a first cost-effective step is the performance of a so-called **rough analysis** (Fig. 2). During the rough analysis process the heat balance diagram of the water/steam cycle in the power plant is modeled using graphical tools, and the system parameters are specified for each system area. This model establishes the basic data structure of the virtual power plant, and allows an analysis of the water chemistry cycle to be performed based on the thermal-hydraulic parameters. Taking into consideration the materials used in each case, the system areas are then examined with respect to the potential risk posed by degradation mechanisms. The results indicate which power plant systems have a limited service life based on their design and operating parameters. The rough analysis process guarantees an economically and technically useful application strategy. Based on rough analysis priorities, the program provides for staggered, condition-oriented generation of a data model in annual cycles.
Systems which are definitively not at risk as indicated by the rough analysis need not be examined in future analyses.

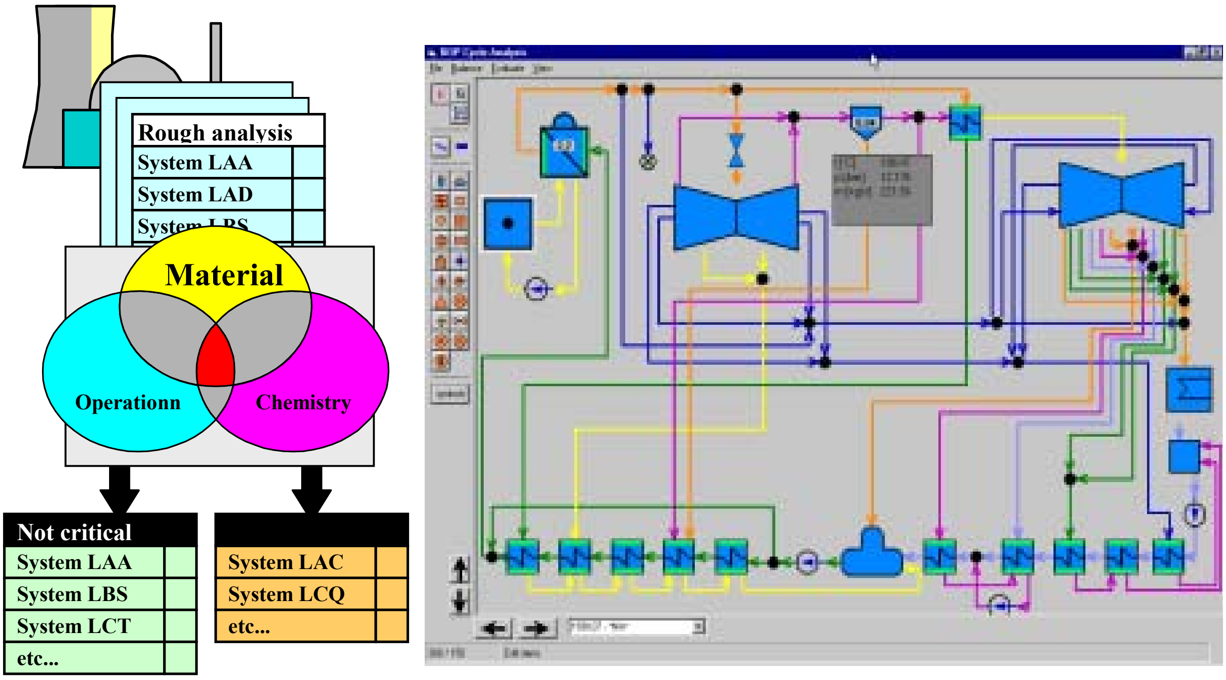

FIG. 2. Rough Analysis using COMSY.

In system areas in which the occurrence of a degradation mechanism is a possibility, the existing risk must be examined by means of a so-called **detailed analysis**, including a service life prediction for each component. This second step, which is based on the information used in the performance of the rough analysis, requires additional information about the relevant component or system parts in question and physical and chemical parameters for the implemented degradation models.

5. LIFETIME PREDICTION

The service life of mechanical components is limited by ageing and wear mechanisms – in particular corrosion and fatigue. In order to assess the service life of a component, the following questions must be asked:

- Which degradation mechanisms are relevant to the material under its intended conditions of use?
- What rate of component degradation progression is to be expected under those conditions?
- Which limiting condition caused by the progression of the degradation places a restriction on the service life of the component?

The properties of the material, the ambient water-chemistry and thermal-hydraulic conditions, and the mechanical load on the component must be evaluated in order to assess the type of corrosion to be expected as well as the rate of degradation progression.

The limit on the service life of the component is reached, for example, when

- the maximum allowable stress in the pressure-retaining boundary is reached,
- the maximum allowable utilization factor is reached with respect to material fatigue,
- the toughness of the material drops below the required values.

6. LIFETIME PREDICTION MODELS

The preparation of degradation models presumes a detailed understanding of the type of degradation concerned as well as the functional interactions of the relevant parameters which influence the rate of degradation progression. Studies and degradation analyses have been conducted in this area for some 25 years in the Framatome ANP laboratories in Erlangen, Germany. The experience gained from these activities has been compiled in analytical and semi-empirical corrosion models for each degradation mechanism. To date, degradation models have been elaborated for the following types of corrosion: strain-induced corrosion cracking, material fatigue, erosion corrosion, droplet impingement corrosion and cavitation erosion. A degradation model for stress corrosion cracking is currently under development.

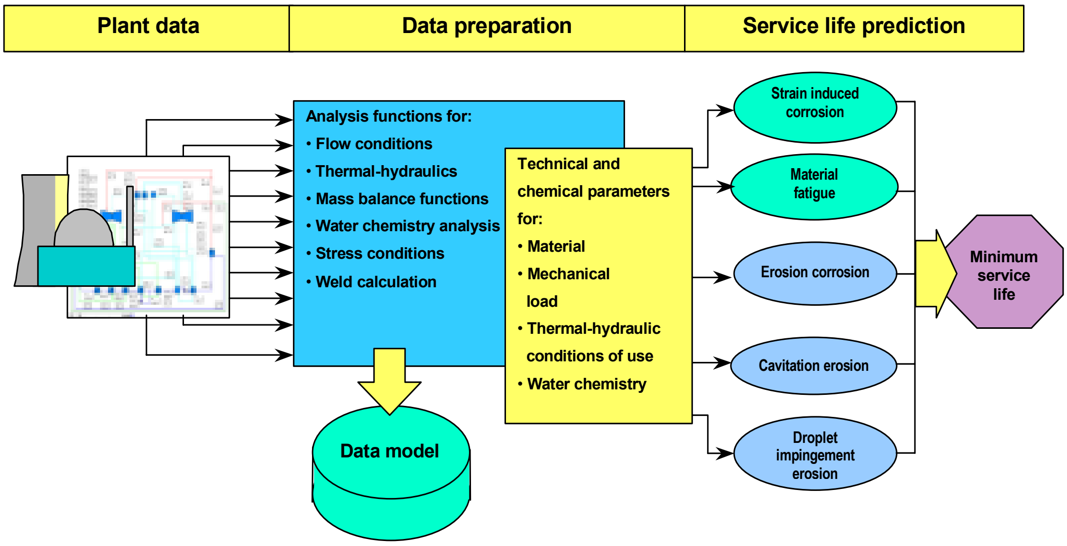

FIG. 3. Data conditioning for lifetime prediction.

The corrosion models used to make analytical service life predictions require the use of a number of physical and chemical parameters which cannot always be taken directly from the plant documentation. In order to enable economical application of service life predictions despite this limitation, COMSY includes appropriate analysis functions for pre-processing corrosion-relevant parameters based on the available documentation, see Fig. 3.

The rate of degradation progression is determined for the relevant degradation mechanism in each case using these degradation models, whereby a corresponding safety factor is used to allow for expected uncertainties. The calculated rate of degradation progression and the strength boundary conditions calculated for the component are used by COMSY to determine the minimum service life.

7. "CALIBRATION" OF LIFETIME PREDICTIONS

The COMSY software system acquires and assesses measurement results from nondestructive component examinations and visual inspections. The examination and inspection results are linked to the examined component for documentation of its as-is condition at that specific time in the operating history of the plant, and are integrated into the so called virtual power plant data model, see Fig. 4.

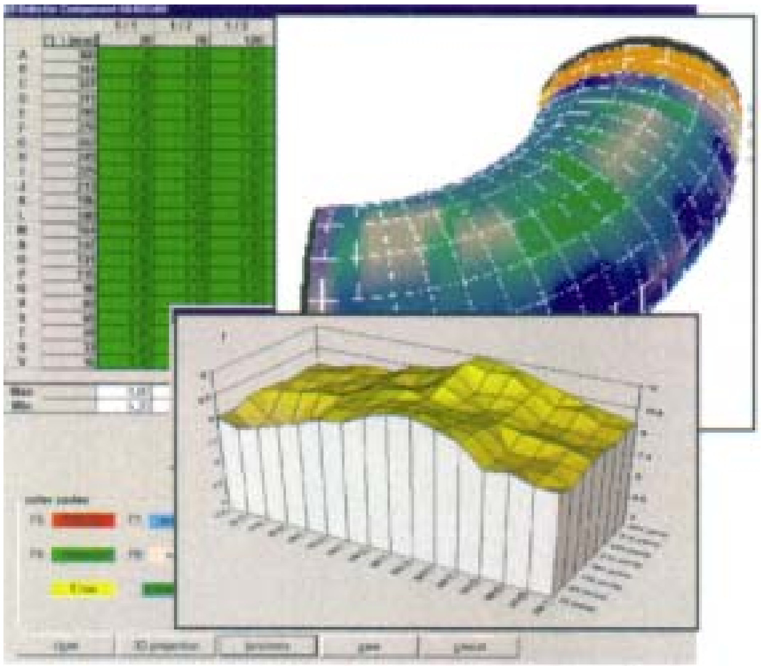

FIG. 4. Evaluation of component examinations.

The evaluation of component examinations is supported by interactive analysis functions which greatly simplify the geometry-dependent evaluation of measurement results, among other things. A calibration function supports the comparison of the as-measured condition with the predicted progression of the degradation, while making allowance for measurement tolerances. The results of this comparison are used in order to improve the accuracy of future service life predictions.

This process ensures that experience gained from evaluation of examination data will be fed back into the performance of analytical service life predictions. Examination data resulting from in-service inspections are thus consistently used in the preparation of a reliable database which is kept continually up to date. This process increases the informational value of the examination results, and makes it possible to prepare a transparent description of the as-is condition of components and systems, the quality of which will continue to increase with every year the process is in use.

8. EXAMPLE FOR LIFETIME PREDICTION

In the course of using COMSY for a boiling water reactor, it was determined following the performance of a rough analysis that the service life of the feedwater system is limited by three potential degradation mechanisms: erosion corrosion, strain-induced corrosion cracking and material fatigue. Using the service life predictions determined by the program, the subsequent revision of the program was used to perform examinations of specific welds, piping elements and vessel nozzles. The results of these examinations showed a high degree of correlation with the calculated degree of degradation, including conservative margins. In the next step, examination results and predictions were correlated to enable an even more precise determination of weak points in subsequent major inspections, and thus long-term maintenance planning capability.

Software Tools

Power Plant Data Model

A systematic program for aging and plant life management requires an overall view of the power plant, because individual components cannot be viewed in isolation when attempting to predict the remaining service life of the plant.

The information used in making such a determination must on the one hand be stored in a component-specific manner (e.g. geometry, material, examination results, material acceptance data, etc.), but on the other hand must be valid across components (design criteria, thermal-hydraulic and water chemistry conditions of use) and across systems (flow rates, availability times). This is achieved by using a "virtual power plant data model" which enables user-driven assignment of parameters to various hierarchies. A significant characteristic of the data model is the determination of the conditions of use and component states as a function of time in service.

Component Model

The program processes components such as piping or vessel elements individually. If a piping element is to be generated in COMSY for a specific piping run, for example, the user selects the corresponding system area and selects the component type from a list of predefined component symbols. The operator selects the desired diameter, wall thickness and material from the integrated, standardized libraries. Subsequently the program generates a component data sheet. Using integrated analysis tools, it calculates the conditions of use which apply to the component in question based on existing thermal-hydraulic and water-chemistry data such as flow geometry, degree of turbulence, pH and oxygen concentration of the fluid. In a next step, the program calculates the strength conditions of the component for the given design criteria – in accordance with ASME, for example – and enters this information on the component data sheet. A plausibility routine checks the design of the component for compliance with applicable standards, and indicates any input errors. The completed component data sheet can then be used as the basis for further parameters relevant to ageing which can be supplemented as required over the life cycle of the component. These parameters can be defined in greater detail, if required. Subsequently the automatic generation of service life predictions for each component is provided.

As-Built Material Data Library

Knowledge of specific material properties of component is indispensable in the detailed evaluation of specific degradation mechanisms (e.g. stress corrosion cracking). For this purpose, COMSY can rely on an "as-built" database which includes the material acceptance documentation prepared at the time the material or component was manufactured, for example. This database (see Fig. 5) contains the following information:

- Material-relevant information on components about the manufacturing process (e.g. manufacturer, semi-finished product form dimensions, heat treatment steps).
- Manufacturing and acceptance data regarding chemical analysis and mechanical characteristics (strength, toughness) for base material heats, welds, weld overlay cladding and buttering, as well as for production weld test coupons and welding material batches.

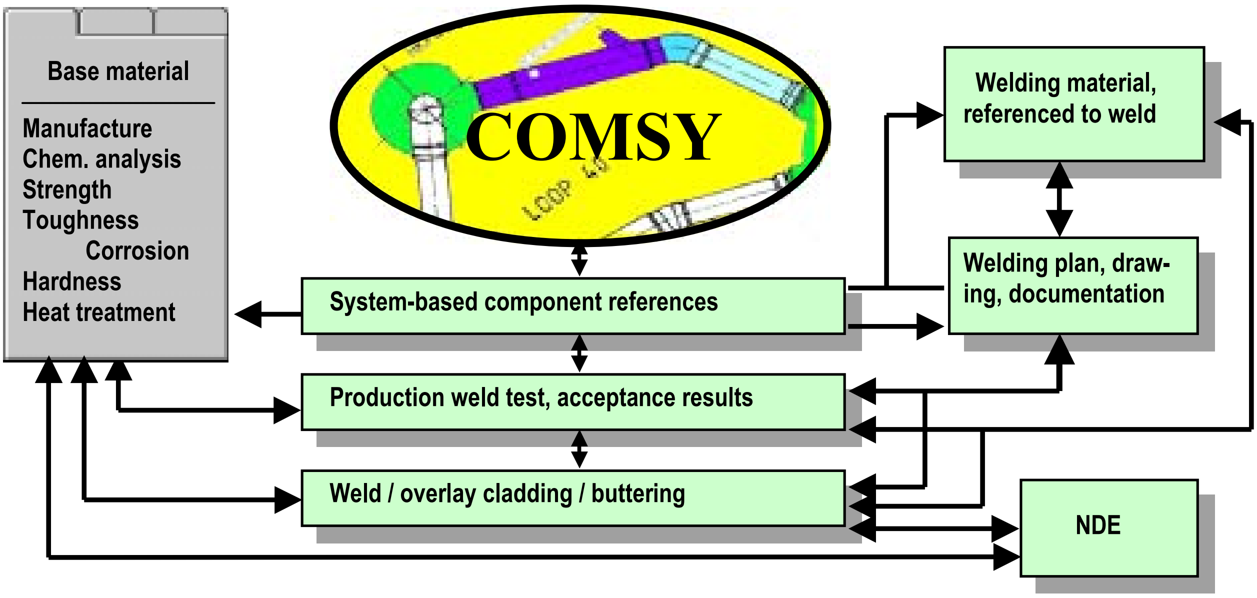

FIG. 5. Detailed material acceptance information.

If a corresponding record exists, COMSY uses the "as-built" material properties of the component in assessing the degradation mechanisms. In this process, complex data associations allow the retrieval of material properties as well as the identification of other components made from the same heat.

In addition to material acceptance procedures, details concerning examination results such as examination records and pictures taken during visual inspections can be accessed for the component in question. The component data sheet also makes it possible to access static documents – drawings, parts lists, reports and acceptance certificates which exist as files – also in power-plant-specific documentation systems. Moreover, the software system enables the use and/or integration of information extracted from existing databases.

9. CONCLUSIONS

Systematic aging and plant life management is becoming more and more important internationally in order to ensure efficient power plant operation in spite of continued ageing. One of the primary requirements for efficient application of such a program is the provision of all necessary data, i.e. information about the as-built condition and the as-is condition in a structure which allows the computation of service life predictions.

In this regard the COMSY software system makes a knowledge-based program system available which integrates advanced analysis tools and comprehensive material libraries with a "virtual power plant data model." It enables the condition-oriented service life evaluation of vessels, piping systems and complete plants with respect to relevant degradation mechanisms. The results of component examinations are fed back into the program system, and are used for further status evaluation over the life cycle of power plant systems. Overall, this systematic process ensures the creation of a quantifiable database which is continually kept up to date with information relative to the technical as-is status of the plant. On the basis of reliable and degradation-relevant predictions, maintenance management and plant availability can be optimized and the service life of costly systems and components extended.

Practical application in various power plants within and outside Germany have confirmed that systematic plant life management makes good economic sense, and that the process can be greatly streamlined through software support.

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