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Implementation Strategies and Tools for Condition Based Maintenance at Nuclear Power Plants

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FOREWORD

There is now an acute need to optimize maintenance to improve both reliability and competitiveness of nuclear power plant operation. There is an increasing tendency to move from the preventive (time based) maintenance concept to one dependent on plant and component conditions.

In this context, various on-line and off-line condition monitoring and diagnostics, non-destructive inspection techniques and surveillance are used. Component selection for condition based maintenance, parameter selection for monitoring condition, evaluation of condition monitoring results are issues influencing the effectiveness of condition based maintenance. All these selections of components and parameters to be monitored, monitoring and diagnostics techniques to be used, acceptance criteria and trending for condition evaluation, and the economic aspect of predictive maintenance and condition monitoring should be incorporated into an integrated, effective condition based maintenance programme, which is part of the plant's overall maintenance optimization programme.

This publication collects and analyses proven condition based maintenance strategies and techniques (engineering and organizational) in Member States. It includes selected papers on maintenance optimization presented during its preparation.

This report was prepared under IAEA project on integrated NPP life cycle management including decommissioning. The main objective of an integrated life cycle management programme is to enable NPP's to compete, without compromising safety, successfully in the changing energy markets throughout their service life and to facilitate life extension and eventual decommissioning through improved engineering, technological, economic and managerial actions. The technical working group on NPP life management and other advisory groups nominated by the Member States provide recommendations on high priority needs of Member States in this area.

The IAEA wishes to thank all the participants for their valuable contributions. The IAEA officer responsible for this publication was H. Cheng of the Division of Nuclear Power.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. Background

The condition based maintenance (CBM) process requires technologies, people skills, and communication to integrate all available equipment condition data, such as: diagnostic and performance data; maintenance histories; operator logs; and design data, to make timely decisions about the maintenance requirements of major/critical equipment. This methodology is often regarded as having existed for many years, it is in fact a recently developed methodology that, has evolved over the past three decades from precursor maintenance methods. This is shown in Figure 1.

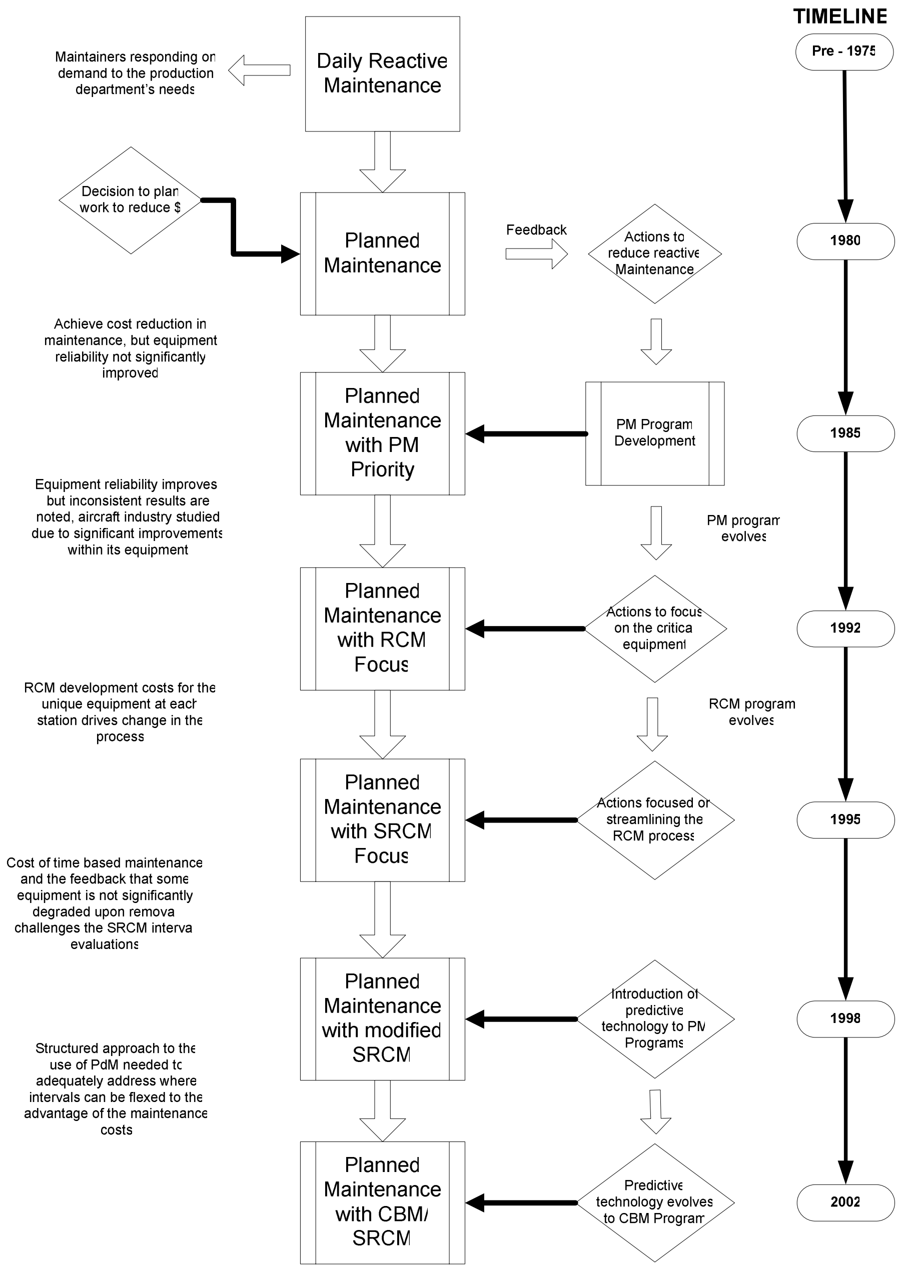


Fig. 1. Evolution of condition based maintenance.

Condition based maintenance assumes that all equipment will deteriorate and that partial or complete loss of function will occur. CBM monitors the condition or performance of plant equipment through various technologies. The data is collected, analysed, trended, and used to project equipment failures. Once the timing of equipment failure is known, action can be taken to prevent or delay failure. In this way, the reliability of the equipment can remain high.

Condition based maintenance uses various process parameters (e.g. pressure, temperature, vibration, flow) and material samples (e.g. oil and air) to monitor conditions. With these parameters and samples, condition based maintenance obtains indications of system and equipment health, performance, integrity (strength) and provides information for scheduling timely correction action.

As experience grows with the fundamentals of a strong condition based maintenance programme users can use proactive maintenance (PAM) concepts to make continuous improvements to the programme and to maintenance activities in general. Proactive maintenance is a concept for 'learning from experience' of maintenance work, preventive maintenance and condition based maintenance. This process involves utilization of direct feedback from maintenance personnel, through failure cause codes, equipment condition codes and work order completion remarks, to improve the effectiveness of the maintenance work. PAM also includes making appropriate adjustments to the maintenance task balance to eliminate failures or deficiencies in the future. Incidents that require root cause analysis are identified as part of the PAM process.

1.2. Maintenance and condition monitoring publications at the IAEA

IAEA Safety Standards Series No. NS-G-2.6 entitled Maintenance, Surveillance and In-service Inspection in Nuclear Power Plant recommends international actions, establishes conditions and procedures regarding the maintenance for meeting the safety requirements. That safety guide clearly recommends that a systematic approach be used in establishing a preventive maintenance programme and for optimization of the ongoing maintenance programme. Optimization strategies may include condition monitoring and diagnostics, reliability centered maintenance and streamlined RCM, risk informed maintenance, and others. In order to support NPPs in utilizing various strategies and tools on optimizing their maintenance programme, the IAEA has published a number of publications such as:

- Guidance for Optimizing Nuclear Power Plant Maintenance Programme, IAEA-TECDOC-1383, IAEA, Vienna (2003).
- Advances in Safety Related Maintenance, IAEA-TECDOC-1138, IAEA, Vienna (2000).
- Good Practices for Cost Effective Maintenance of Nuclear Power Plants, IAEA-TECDOC-928, IAEA, Vienna (1997).
- Safety Related Maintenance in the Framework of the Reliability Centered Maintenance Concept, IAEA-TECDOC-658, IAEA,Vienna (1992).

In addition, the IAEA organized a series of specialists meetings on:

- Monitoring and diagnostics systems to improve NPP reliability and safety, UK, 1996.
- NPP diagnostics – safety aspects and licensing, Slovenia, 1997.
- Condition monitoring and maintenance, France, 1998.
- NDT methods for monitoring degradation, Netherlands, 1999.
- Optimization of NPP maintenance Programmes, USA, 2001.

1.3. Optimization efforts of maintenance

Maintenance has a role in all aspects of the plant's organization. When reviewing the organization it is important not only to examine the processes, but also the management approach, work culture, skill set, motivation of the work force, and the effective use of the technologies. Any of these could be blocking forces that can prevent a successful transition. A carefully scripted plan for accomplishing a significant change in the organization is of the utmost importance; otherwise significant time will be required to gain acceptance afterwards and re-establish the lost confidence. The primary focus should be on optimization of plant maintenance and a programme to create a work environment that optimizes the use of resources, maintenance processes, employee skills and technology for the purpose of meeting the maintenance objectives. Additional discussion of the optimization process is provided in Section 3.

1.4. Structure

Section 1 introduces the background and related IAEA publications and Section 2 discusses the benefits of condition based maintenance. Section 3 lays out various maintenance strategies for optimization including conditional based maintenance. Then, Section 4 presents an implementation example for a condition based maintenance process. Section 5 elaborates many important condition monitoring techniques, such as vibration, thermography, tribology, acoustics and motor currents. Section 6 lists necessary elements and key performance indicators which a condition based maintenance reports shall describe. Section 7 discusses how a condition base maintenance programme shall be evaluated in terms of technology, organization and management, costs and benefits. Section 8 concludes the publication with a number of points of lessons learnt provided by the publication contributors during the consultancy meetings. In the appendices are selected technical papers on maintenance optimization presented during the technical meeting.

2. TARGETS AND BENEFITS OF CONDITION BASED MAINTENANCE

Condition based maintenance is not a substitute for the more traditional maintenance management methods. It is, however, a valuable addition to a comprehensive, total plant maintenance programme. Where traditional maintenance management programme rely on routine servicing of all machinery and fast response to unexpected failures, a condition based maintenance programme schedules specific maintenance tasks as they are actually required by plant equipment. It cannot totally eliminate the continued need for either or both of the traditional programmes, i.e. run-to-failure and preventive, predictive maintenance can reduce the number of unexpected failures and provide a more reliable scheduling tool for routine preventive maintenance tasks.

2.1. Benefits of condition based maintenance

Maintenance costs are a major part of the operating costs of all manufacturing or production plants. Depending on the specific industry, maintenance costs can represent between 10 and 40 per cent of the costs of goods produced. For example in food related industries, the average maintenance cost represents about 15 per cent of the cost of goods produced; while in iron and steel, pulp and paper and other heavy industries maintenance represents up to 40 per cent of the total production costs. Discounting the cost of fuel for nuclear units, most power production facilities in the United States of America also fall into the upper range of costs.

Recent surveys of maintenance management effectiveness in the US manufacturing industry indicate that one third, 33 cents out of every dollar, of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance. When the high percentage of operating cost attributed each year to maintenance of plant equipment and facilities is considered the impact on productivity of maintenance operation becomes obvious.

The main reason for this ineffective and/or inefficient management is the lack of factual data that quantifies the actual need for repair or maintenance of plant machinery, equipment and systems. Maintenance scheduling has been, and in many instances is predicted on statistical trend data or on the actual failure of plant equipment.

Until recently, middle and corporate level management have ignored the impact of maintenance on product quality, production costs and more importantly on bottom line profit. The general opinion has been that 'maintenance is a necessary evil' or 'nothing can be done to improve maintenance costs'. Perhaps these were true statements ten or twenty years ago when many of the diagnostic technologies were not fully developed.

However, the developments of microprocessor or computer based instrumentation that can be used to monitor the operating condition of plant equipment, machinery and systems have provided the means to manage the maintenance operation. They have provided the means to reduce or eliminate unnecessary repairs, prevent catastrophic machine failures and reduce the negative impact of the maintenance operation on the profitability of manufacturing and production plants.

2.2. Achieving maximum use of equipment

The premise of condition based maintenance is that regular monitoring of the actual mechanical condition of equipment trains and operating efficiency of process systems will ensure the maximum interval between repairs; minimize the number and cost of unscheduled outages created by machine-train failures and improve the overall availability of operating plants. Including condition based maintenance in a total plant management programme will provide the ability to optimize the availability of process machinery and greatly reduce the cost of maintenance. In reality, condition based maintenance is a condition-driven preventive maintenance programme.

Plants that have implemented successful condition based maintenance methods indicate substantial improvements in reliability, availability and operating costs. The successful programmes include a cross-section of industries and provide an overview of the types of improvements that can be expected. Major improvements can be achieved in: maintenance costs, unscheduled machine failures, repair downtime, spare parts inventory, and both direct and in-direct overtime premiums.

The addition of regular monitoring of the actual condition of process machinery and systems reduced the number of catastrophic, unexpected machine failures by an average of 55 per cent across the general industries. The comparison used the frequency of unexpected machine failures before implementing the condition based maintenance programme to the failure rate during the two year period following the addition of condition monitoring the programme. By avoiding catastrophic failures, much of the losses due to parts that are unrecoverable are also avoided.

Condition based maintenance has the ability to reduce the actual time required to repair or rebuild plant equipment. The improvement in mean-time-to-repair, MTTR, was created by the predictability of failures ahead of time that enabled the maintenance staff to plan each repair. The ability to predetermine the specific repair parts, tools and labor skills required provided the dramatic reduction in both repair time and costs.

The ability to predict machine train and equipment failures and the specific failure mode provided the means to reduce spare parts inventories. Rather than carrying repair parts in inventory, plants have sufficient lead-time to order repair or replacement parts as needed in many cases.

2.3. Prevention of catastrophic failures

Prevention of catastrophic failures and early detection of incipient machine and systems problems increased the useful operating life of plant machinery. A condition-based predictive maintenance programme prevents serious damage to machinery and other plant systems. This reduction in damage severity increases the operating life of plant equipment. Advanced notice of machine train and systems problems reduces the potential for destructive failure, which could cause personal injury or death. The determination can be based on catastrophic failures where personal injury would be most likely to occur, such as heater and extraction piping where erosion and flow accelerated corrosion have resulted in injuries and deaths.

A side benefit of condition based maintenance is the automatic ability to monitor the mean-time-between-failures, MTBF. This data provides the means to determine the most cost effective time to replace machinery rather than continue to absorb high maintenance costs. The MTBF of plant equipment is typically reduced each time a major repair or rebuild occurs. Condition based maintenance will automatically display the reduction of MTBF over the life of the machine. When the MTBF reaches the point that continued operation and maintenance costs exceed replacement cost, the machine should be replaced.

Several other benefits can be derived from a viable condition based maintenance management programme: verification of new equipment condition, verification of repairs and rebuild work and product quality improvement.

2.4. Condition based maintenance as a quality acceptance process

Condition based maintenance techniques can be used during site acceptance testing to determine the installed condition of machinery, equipment and plant systems. This provides the means to verify the purchased condition of new equipment or offsite rebuilt before acceptance. Problems detected before acceptance can be resolved while the vendor has reason (the invoice has not been paid), to correct any deficiencies. Many industries are now requiring that all new equipment include a reference vibration signature be provided with purchase. The reference signature is then compared with the baseline taken during site acceptance testing. Any abnormal deviation from the reference signature is grounds for rejection, without penalty of the new equipment. Under this agreement, the vendor is required to correct or replace the rejected equipment.

2.5. Outage work screening using condition based maintenance

Data acquired as part of a condition based maintenance programme can be used to schedule and plan plant outages. Many industries attempt to correct major problems or schedule preventive maintenance rebuilds during annual maintenance outages. Predictive data can provide the information required to plan the specific repairs and other activities during the outage.

The condition based maintenance data eliminated the need for many of the repairs that would normally have been included in the maintenance outage. The overall benefits of condition based maintenance management have proven to substantially improve the overall operation of both manufacturing and process plants. Typically, the benefits derived from using condition-based management have offset the capital equipment cost required to implement the programme within the first three months. Use of microprocessor-based predictive maintenance techniques has further reduced the annual operating cost of condition based maintenance methods so that any plant can achieve cost effective implementation of this type of maintenance management programme.

3. MAINTENANCE STRATEGIES

As stations evaluate their current maintenance and equipment reliability programmes they sometimes find the need to consider a complete restructuring of their processes and programmes to optimize the programme and meet their actual needs. When approaching these complex decisions, it is important to consider that maintenance affects all aspects of the plant's organization. Equipment reliability must be maintained in order to achieve generation goals, safety goals, and to reduce overall production costs from avoidance of catastrophic failures that require extensive downtime, labor, and parts to recover. Key to the strategy for improved equipment reliability is the condition based maintenance programme that aids in the maintenance response to degrading conditions, not just a time based and intrusive programme that could well introduce degraded conditions by "fixing what is not broken". This introduces the need to determine the conditions that actually drive the need to do some corrective maintenance by optimizing the programmes used by maintenance. Figure 2 reflects the concept of a total site equipment reliability strategy with the focal processes the support the programme.

3.1. Plant maintenance optimization

To optimize maintenance it is important not only to examine the maintenance processes, but also the management approach, work culture, skill set, motivation of the work force, and the effective use of the technologies. Therefore, plant maintenance optimization is a programme to create a work environment that optimizes the use of resources, maintenance processes, employee skills, and technology for the purpose of meeting the maintenance objectives. The PMO categories include:

- **Management and business culture** – Creating a positive work environment that promotes a learning organization optimizes plant maintenance. This is accomplished by: setting goals; providing strong leadership; promoting good communication; establishing an organization where individuals know their roles and responsibilities and are held accountable; and, providing the means to learn from the staff's experiences. Metrics are tracked for the purpose of understanding the areas where improvement opportunities exist and are corrected.

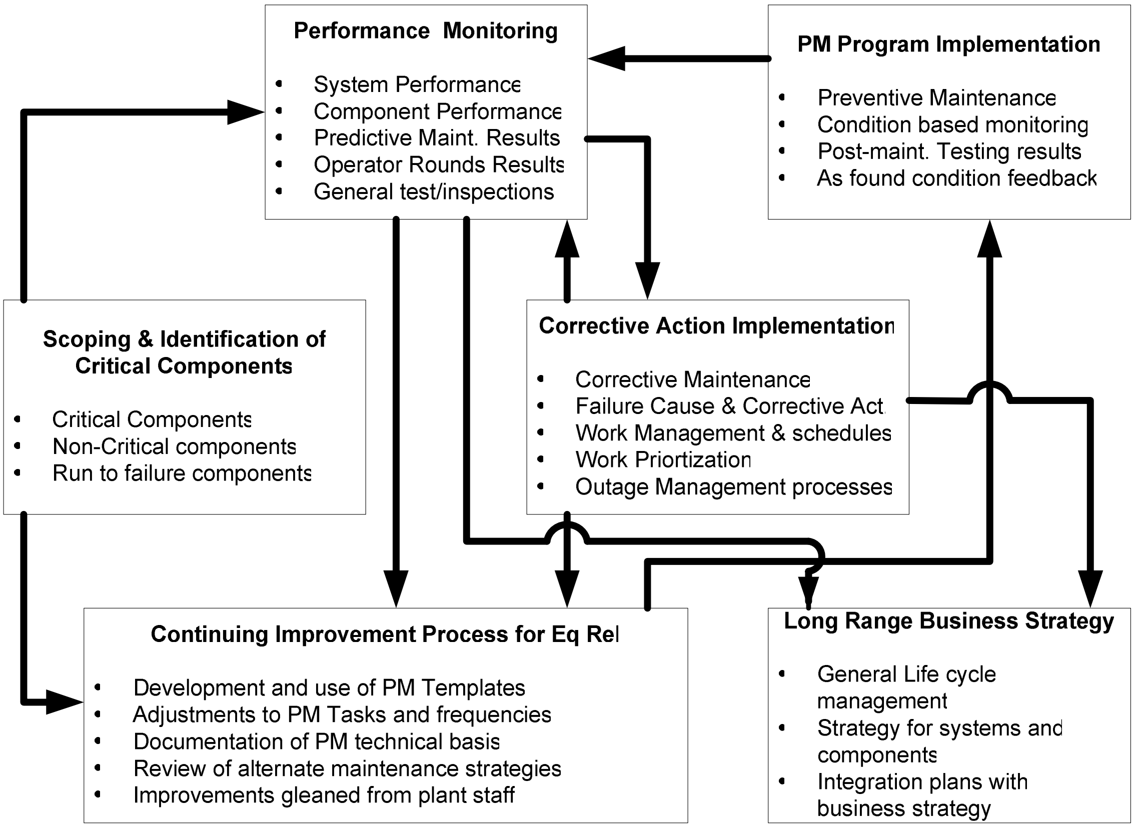


Fig. 2. Equipment Reliability Conceptual Programme.

- **Maintenance processes** – Using the industry's best maintenance practices to minimize the impact on production and to maximize the workforce utilization optimizes plant maintenance. This is accomplished by identifying work at the right time so it can be prioritized, planned, scheduled, and performed. Work is documented and reviewed to learn from the experience. These processes include day-to-day work, both planned and unplanned outage work and work resulting from proactive activities such as engineering projects.
- **People Skills/ Work Culture** - Plant maintenance is optimized by developing a highly motivated, qualified and skilled workforce, and a safe work environment. This is accomplished by providing an effective training and qualification programme, and by implementing a human performance initiative that stresses positive behaviors and values.
- **Technologies** – Plant maintenance is optimized by utilizing cost effective technologies that maximize maintenance process efficiencies, provides timely information on equipment condition, and captures the lessons learned. Integration technologies are incorporated that allow access to multiple plants and department data sources, and allow the findings, recommendations, and corrective actions to be shared. Examples of technology tools are the CMMS, Process Data (PI/PHD), enterprise-wide data sharing software, and a number of condition monitoring technologies and their supporting software.

Condition based maintenance programme (CBM) that consists of information on plant maintenance strategies, predictive maintenance applications, certification, and results reporting are best described in plant programme documents. Where companies own multiple plants there is value in having a corporate programme to ensure consistency throughout the company. Structured programmes are more predictable in their value output, easier to project budget needs, control expenditures on technology, and to ensure the workforce is well qualified.

Figure 3 shows the overall maintenance strategy including the supporting programmes. Broadly, the strategy consists of preventive and corrective maintenance programmes.

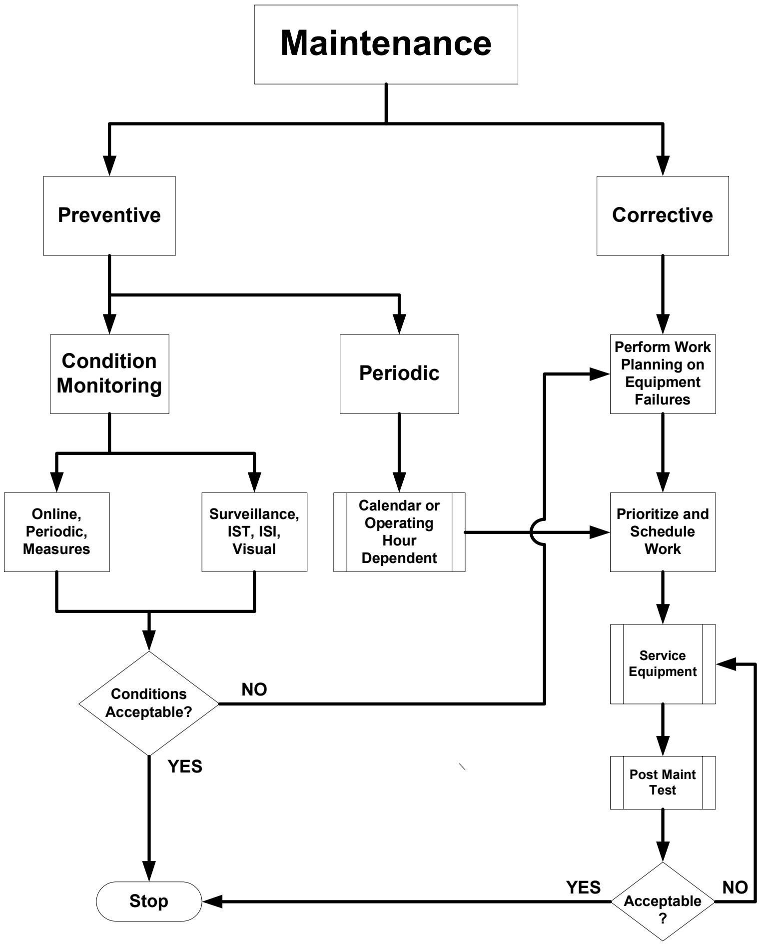


Fig. 3. Maintenance Strategy.

3.2. Corrective and preventive maintenance

Corrective maintenance can be divided into those items that require prompt attention and those that have been determined to be non-critical and can be repaired as needed. This approach has been used by industry for years and can be used to prioritize work activities.

Preventive maintenance includes periodic and condition based maintenance. Periodic maintenance may be done at calendar intervals, after a specified number of operating cycles, or a certain number of operating hours. These intervals are established based on manufacturers' recommendations, and utility and industry operating experience. The equipment population covered by preventive maintenance was established during the plant startup stage and is refined as experience accumulates. Generally, the equipment population covered, the associated maintenance tasks, and their frequency of performance were initially established without a systematic evaluation of the related factors such as:

- Importance of equipment failure to the overall plant function.
- Equipment duty cycles.
- Equipment redundancies.
- Effectiveness of the maintenance activities in preventing failures.
- Effectiveness of the maintenance activities in predicting failures.

The result was that there were too many maintenance tasks, high work backlogs, and equipment failures. As a result a reliability centered maintenance process has been attempted.

3.3. Reliability centered maintenance

Reliability-centered maintenance (RCM) is an engineering process (see Figure 4) used by some nuclear utilities and in other industries to optimize PM.

RCM may be defined as a process used to determine the maintenance requirements of any physical asset in its operating context. Briefly, it is a top-down approach that begins with establishing system boundaries and developing a critical equipment list. An equipment item is deemed to be critical if it performs a function or if its failure can affect functioning of equipment that ensures:

- Nuclear safety
- Prevention of release of radioactivity to the environment
- Personnel safety
- Continued power production

For each equipment item in that list, a failure modes and effects analysis (FMEA) is conducted to:

- Identify each failure mode and its probability of occurrence
- Evaluate the significance of each failure mode to the item performing its specified function

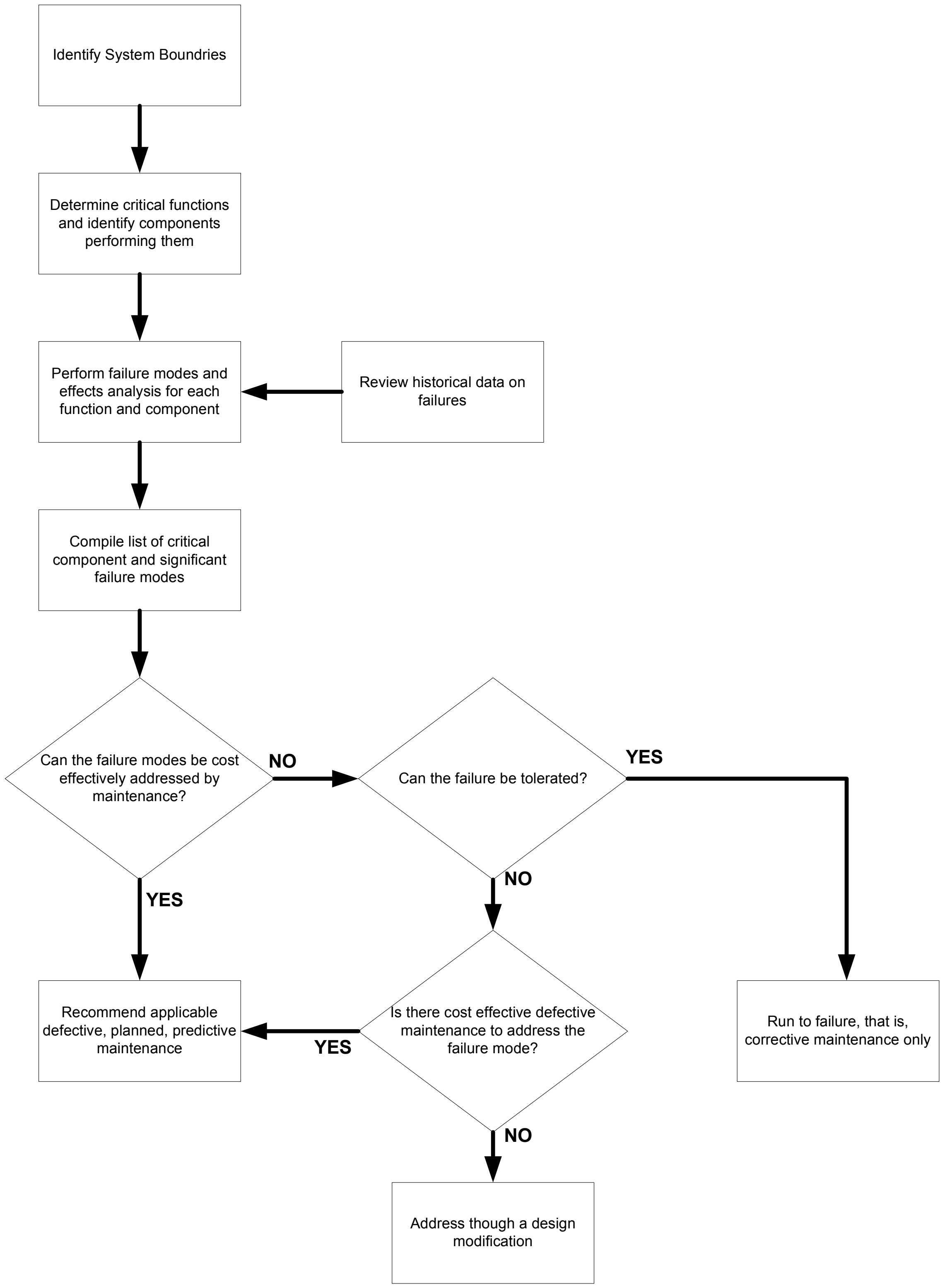


Fig. 4. Reliability Centered Maintenance Process Overview.

Functional failures are the only ones considered important in the failure modes and effects analysis, FMEA. The probability of occurrence of a failure mode is determined (usually on a qualitative basis) based on a review of equipment failure history. Failure history databases used include the Institute of Nuclear Power Operations (INPO) provided Equipment Performance Information eXchange or EPIX, formerly the Nuclear Plant Reliability Data Systems (NPRDS).

RCM recognizes that not every failure mode needs to be or can be addressed by a maintenance-based solution. If a maintenance action addressing a significant failure mode is not available or is not cost effective, and the failure cannot be tolerated, then a design modification is recommended. If the failure can be tolerated, then a run-to-failure strategy, that is, corrective maintenance is acceptable.

In the decision logic phase, the cost effectiveness of periodic maintenance and predictive technologies appropriate to address the failure mode of interest are evaluated. It is this part of the RCM process that ensures a balanced mix of periodic and condition based maintenance. It is presumed that an optimal balance between PM and CM is achieved through the rigorous process of establishing the critical equipment list. This presumption is true if the criteria for determining the criticality of an item are complete and if the criteria are applied objectively. In summary, RCM addresses two issues:

- Is the equipment important to the mission (that is, what is the effect of its failure on the mission)?
- What cost effective periodic and condition based maintenance can eliminate or significantly reduce the probability of occurrence of the failure modes that affect the functions important to the mission.

Over time, plants that have used RCM typically report significant reductions in periodic maintenance and increased use of condition based maintenance. This migration in process is a result of the limitations presented to operators of generating facilities. Limitations of RCM as a maintenance optimization tool include the following:

- It is a very costly and time-consuming process.
- Successful implementation requires highly trained engineering resources dedicated for an extended period.
- Maintenance of the RCM programme requires a minimum number of these highly trained resources to remain available as long as the process is used.
- It leaves room for subjectivity in the decision-making process regarding the type of maintenance that can be effective for a specific situation.
- It must be used as a living programme and not as a one-time engineering evaluation process.

To overcome some of these limitations of RCM, plants have implemented various modified or streamlined versions of RCM.

Plants that have implemented an optimized plant maintenance programme generally start with a study that defines their plant maintenance basis (PM Basis). A PM Basis is developed using the reliability centered maintenance (RCM) process or some streamlined version of an RCM. This type of study defines the critical equipment in the plant and the activity required around each piece of equipment to ensure good operability, availability, and optimum performance.

The result of the study is the PM Basis for each piece of equipment selected. The information can be lengthy; however, some studies consolidate this information into a spreadsheet format with the equipment listed, tasks required, and the frequency of tasks to be performed. If the operating plant has developed a PM Basis then the components, technologies, and frequency of activity have already been developed for each technology responsibility. Figure 5 represents a high level view of the PM/PdM/Condition Monitoring and Analysis Process.

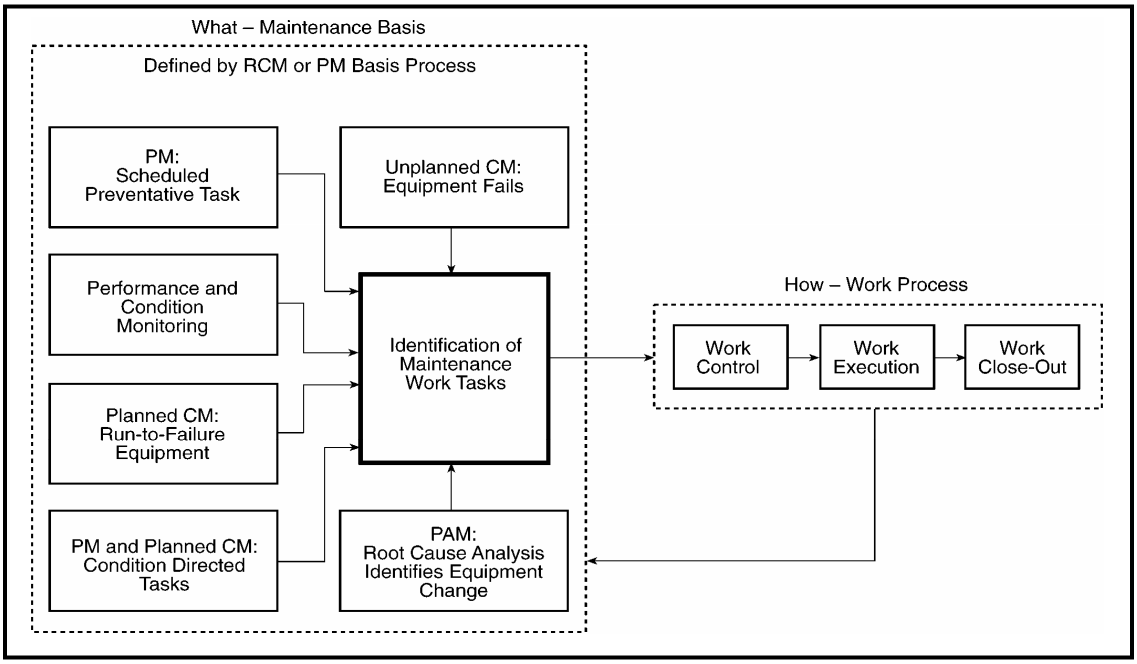


Fig. 5. PM/PdM/Condition Monitoring and Analysis Process.

3.4. Condition based maintenance

Condition based maintenance has been described as a process that requires technologies and people skills that integrates all available equipment condition indicators (diagnostic and performance data, operator logged data, maintenance histories, and design knowledge) to make timely decisions about maintenance requirements of important equipment. Condition based maintenance assumes that equipment failure modes will follow one or more of the classical degradation styles and that there is sufficient local knowledge of the equipment's historical performance to perform an extrapolation of its remaining life. This in itself is a form of prognostics based partially on science, and partially on elicited experience of the plant staff. These measurement techniques, observations, tests, and operator intuitions are what forms the plant's condition based maintenance programme.

The goal of condition based maintenance is to optimize reliability and availability by determining the need for maintenance activities based on equipment condition. Using "predictive techniques", technologies, condition monitoring, and observations can be used to project forward in an effort to establish the most probable time of failure and this act to enhance the ability of the plant to plan and act in a proactive manner. PdM/CBM assumes that equipment has indicators that can be monitored and analyzed to determine the need for condition directed maintenance activities. Condition based maintenance allows the lowest cost and most effective maintenance programme by determining the correct activity at the correct time.

In comparison, preventive maintenance assumes that operating time is the key factor in determining the probable condition of equipment. If there is not a close relationship between operating time and the need for maintenance, these preventive maintenance activities are often not needed and maintenance resources are wasted. Sometimes the equipment is in worse condition after maintenance is performed and will fail sooner than if nothing were done.

Condition based maintenance is accomplished by integrating all available data to predict impending failure of equipment as well as to avoid costly maintenance. This process depends to a large extent on the ability to recognize undesirable operating conditions as measured by diagnostic monitoring systems. The process also allows equipment to continue operating in an undesirable condition while it is being monitored until maintenance can be scheduled.

The primary objectives of an optimized maintenance strategy programme that include predictive and condition based maintenance are:

- Improve availability
    - Reduced forced outages
    - Improve reliability
- Enhance Equipment Life
    - Reduce wear from frequent rebuilding
    - Minimize potential for problems in disassembly and reassembly
    - Detect problems as they occur
- Save Maintenance Costs
    - Reduced repair costs
    - Reduced overtime
    - Reduced parts inventory requirements

Condition based maintenance refers to a set of tasks performed to detect incipient failures of equipment, to determine the maintenance actions required, and to restore equipment to its operable condition after detection of an incipient failure condition.

Condition monitoring may consist of continuous monitoring (for example, on-line diagnostics used in digital instrumentation systems or turbine generator thrust bearing wear monitoring) using permanently installed instrumentation or activities performed at specified intervals to monitor, diagnose, or trend the functional condition of equipment. The results from this activity support an assessment of the current and future functional capability of the equipment monitored and a determination of the nature and schedule for required maintenance.

Although visual inspections can be very useful, modern condition monitoring generally involves the use of advanced technologies. Nuclear plants have been using condition based maintenance for major structures, systems, and components (SSCs) such as pressure boundary components, containment structure, main turbine generator, and reactor coolant pumps for several decades. Since the late 1980s, heightened focus on reducing operation and maintenance cost has led to a broader use of condition based maintenance for other equipment. The technologies now are combined with operator observations, routine log results, input from the corrective maintenance programme on equipment conditions, non-intrusive data monitoring, and other methods that allow cross reference of conditions to measurements so that a decision can be achieved that will be cost effective and ensure reliability of the component and its system.

When the probability of a failure mode is determined to be low or if a failure mode does not affect the equipment's capability to perform its specified function, then no specific maintenance to address that failure mode is required. For other failures, a logical or other analysis is conducted to determine if a cost effective maintenance technique is available that can eliminate or reduce their probability of occurrence. Typically, maintenance professionals have not until recently become involved in risk based evaluations, but current trends are now leading them into this science.

A general understanding of reliability and risk has long existed in the specialist field of probabilistic safety assessment (PSA), but these topics are not familiar to most maintenance professionals. A working knowledge of the meaning and usage of risk significance is becoming important to a wide range of nuclear power plant personnel. The industry and the regulators are currently using risk significance concepts in several initiatives to rationalize regulations and to direct plant resources more effectively. These applications will require plant personnel and regulators to have a fairly complete understanding of risk significance. The US-NRC pointed out the need for additional explanation and discussion of risk-significant measures and their applications in their review of comments on the final draft of EPRI TR-105396. As the regulations become more risk based in their methods of determining extent of control or allowance for variances, the industry must develop training and qualifications for the maintenance professionals.

4. IMPLEMENTATION EXAMPLE FOR A CONDITION BASED MAINTENANCE PROCESS

Do you listen when your equipment speaks to you, or do you wait and see what will happen? This is a question that we should be asking before any problems start. The industry through many organizations has established methods and standards for condition based maintenance monitoring. Organizations like EPRI have developed products to provide guidance and the industry itself has participated in the development of standards such as ISO 17359, Condition Monitoring and Diagnostics of Machines, General Guidelines, to establish consistency.

Maintenance within the industry is often built upon a long tradition of a hierarchy in the organizational structure with traditional roles in the decision making. Maintenance is built up around well proven (tried and tested) work routines which are in principle founded from the manufacturers' original recommendations. A traditional work method with a time-based maintenance interval, where the intervals are often founded from conservative recommendations from the manufacturer, but which afterwards have changed, based upon one's own operating experience with the equipment. New technology has enabled better controls and analysis and have been included with routine work, but often been included in already established time-based maintenance programmes at the various sites.

Today's problem does not lie in the knowledge that there is new technology or whether to use it in daily maintenance. Instead the difficulty often lies in letting go of the 'old' methods (tried and tested), being able to change to a new culture and breaking the traditional barriers. To change the way we look at maintenance and utilize the possibilities which the new technology and knowledge brings is the key to successful implementation of the predictive programmes.

For the nuclear industry to achieve the results from condition based maintenance we must be willing to dare to change the organization, responsibilities, established routines, and trust the surveillance-control, the newly adopted knowledge, and the newly developed competence for steering daily maintenance. Additionally, we must move resources from traditional maintenance role and focus them on developing the new surveillance-control, follow-up, and analysis processes.

4.1. Process for implementation of condition based maintenance

Conditions necessary for a successful implementation process are typically ones of culture change and change management. They require substantial efforts by all site personnel and management.

4.1.1. Commitment

The staff must have commitment to the process and its new technologies as well as their use. Staff has to trust the training and the technology. Management must have the commitment to procure adequate equipment and training for the Staff.

4.1.2. Participation

All groups must participate in the programme. The organization's support for condition based maintenance must be 100% to achieve success. Management has to reinforce this expectation.

4.1.3. Holistic approach

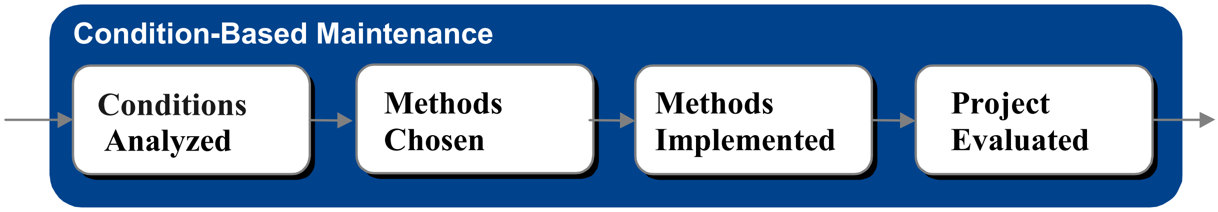
It applies to all systems throughout the plant. No exceptions.

4.1.4. Sustainability

The programme, its staff, its equipment has to be maintained through time to ensure the long term benefits of the process. As people move into and out of organizations, the needed resources must be available. This includes the management support and attitude to trust and maintain it.

4.2. Communication process for implementation of condition based maintenance

Site workers and management should be provided with the training and orientation on the process to ensure clear understanding so that support can be without question. The following is a suggested communication method used to educate one plant and to explain the basics of the processes. Starting with Figure 6 onward, these can be used to explain the process.



Conditions for implementation process:

- Commitment
- Participation
- Holistic approach
- Sustainability

Fig. 6. Condition-Based Maintenance Process.

Take each part of the thought process in Figure 6 and break it down into its basic parts so the entire organization will have a full understanding (see Figures 7–10).

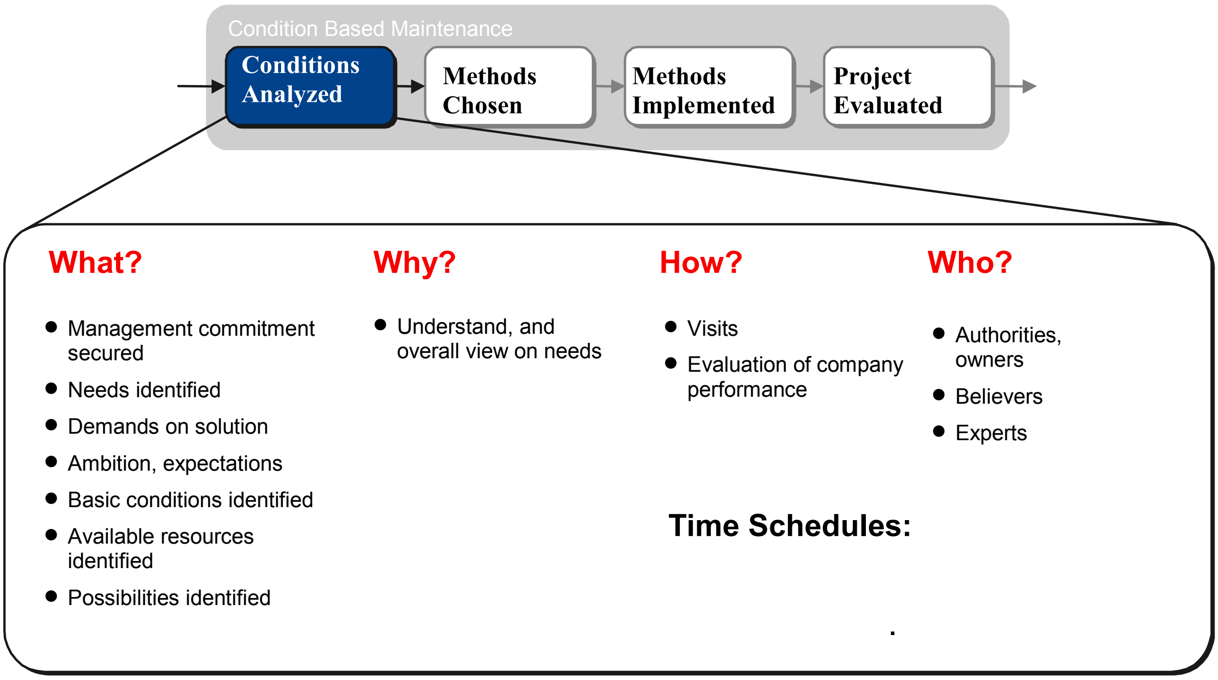


Fig. 7. Condition Analysis.

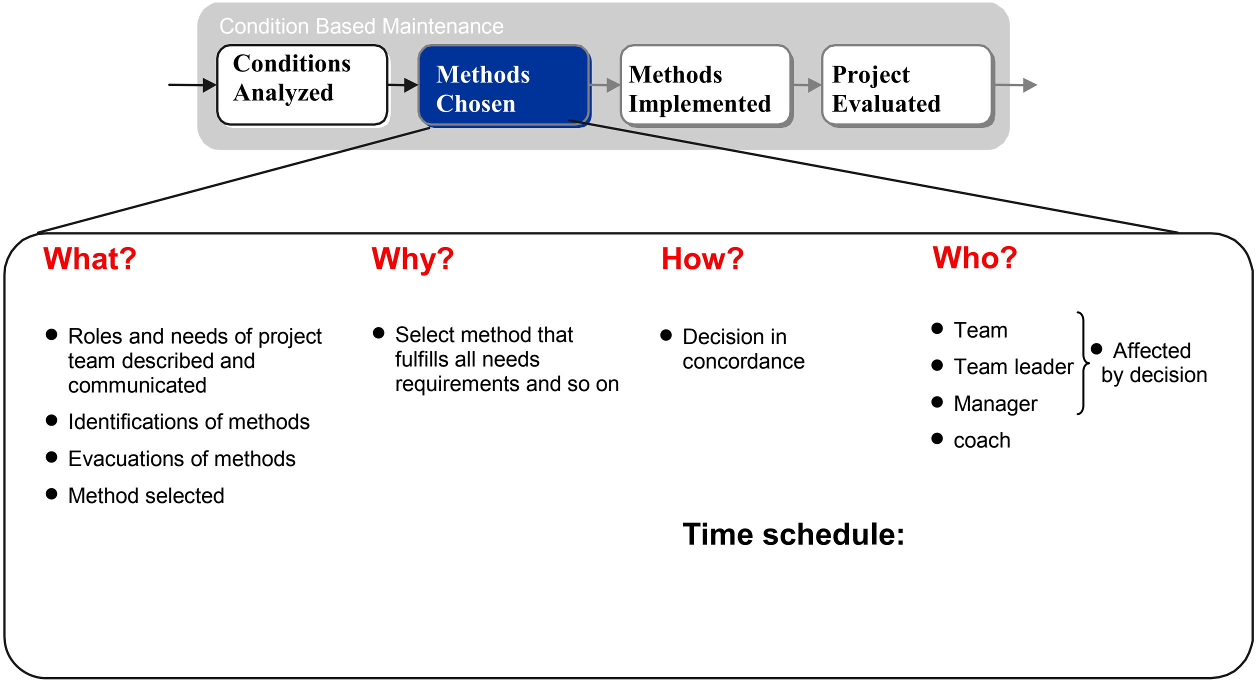


Fig. 8. Method Selection.

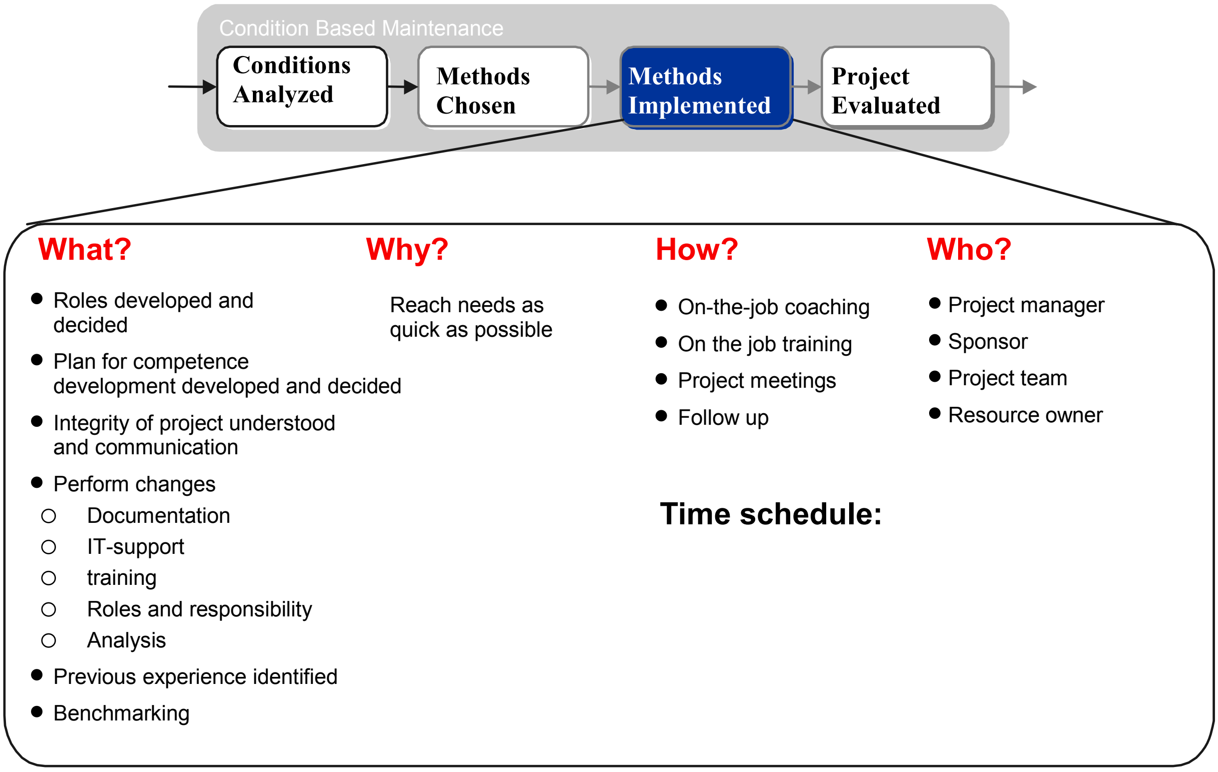


Fig. 9. Condition-Based Maintenance Implementation.

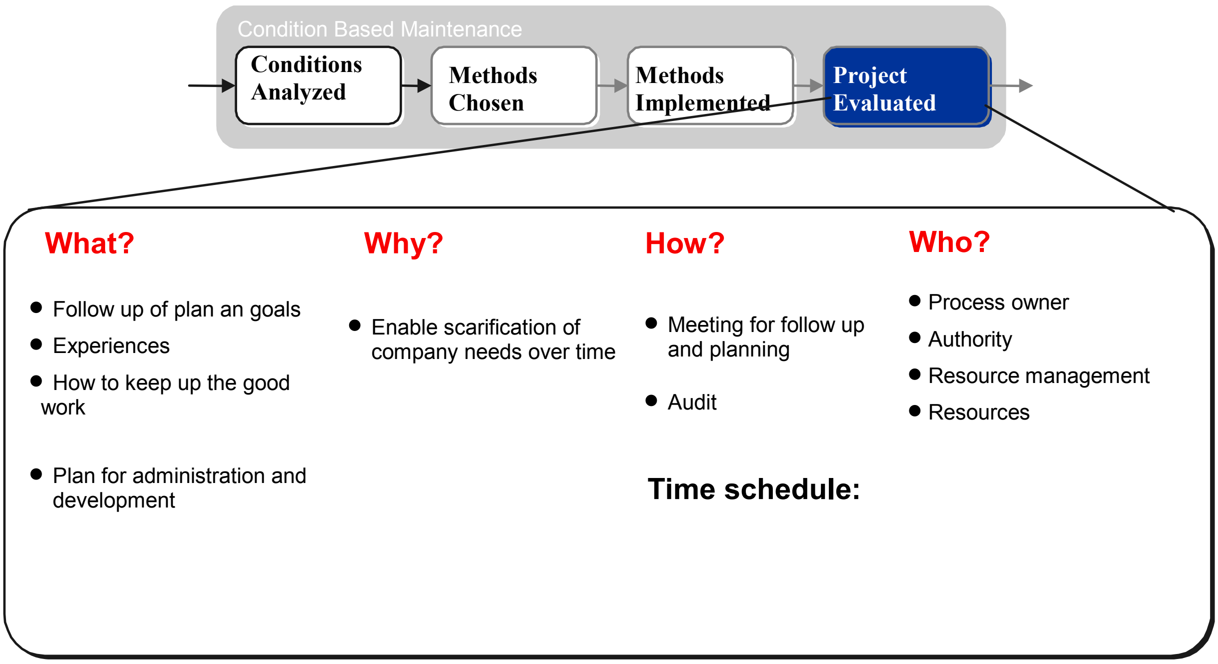


Fig. 10. Project Evaluation.

5. CONDITION MONITORING TECHNOLOGIES

This section deals with the most typical of the technologies that can be applied to most of the power plants' equipment with prompt results and payback. It is important to identify which machine condition monitoring technologies will be the most useful and cost effective in achieving your goals and objectives. Each technique is limited to specific types of machinery and is useful in identifying specific types of problems. Each technique also provides different short and long term economic benefits.

Short term economic benefits include identifying and troubleshooting problems such as misalignment, unbalance, deteriorating bearings, worn gears or couplings, lack of lubrication, oil deterioration or contamination, loose electrical connections, electrical shorting, or poor insulation. These benefits are the most easily quantifiable since they involve specific machines and the cost of actual repairs. These short term cost savings can be substantial, and are often used as the `hard evidence' to justify the initial investment in hardware, software, personnel and training.

The most significant economic benefits, however, come from long term changes or improvements in maintenance or operating practices. It is these structural changes in maintenance and operating standards and procedures that provide an opportunity to eliminate some types of problems or failures completely, rather than simply provide advance warning of their occurrence.

It is also important to understand that there are practical limitations to each of the machine condition monitoring techniques; and that, in spite of the high degree of technology often involved, there is a very important human element necessary for success.

Visual observation, listening and touching are perhaps the most common condition based maintenance techniques used in industry today. 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.

The value of observations is not limited to unmonitored equipment however, since sensory information may also be extremely valuable as a supplement to predictive data and analysis. It is recommended that both operations and maintenance personnel be trained observers, since that will provide the most complete and knowledgeable coverage of plant machinery.

A variety of technologies can and should be used as part of a comprehensive condition based maintenance programme. Since mechanical systems or machines account for the majority of plant equipment, vibration monitoring is generally the key component of most condition based maintenance programmes. However, vibration monitoring cannot provide all of the information that will be required for a successful condition based maintenance programme. This technique is limited to monitoring the mechanical condition and not other critical parameters required for maintaining reliability and efficiency of machinery. Therefore, a comprehensive condition based maintenance programme must include other monitoring and diagnostic techniques. These techniques include:

— Vibration monitoring.
— Acoustic analysis.
— Motor analysis technique.
— Motor operated valve testing.
— Thermography.
— Tribology.
— Process parameter monitoring.
— Visual inspections.
— Other nondestructive testing techniques.

This report will provide a description of the techniques that should be included in a full capabilities condition based maintenance programme for typical power plants.

5.1. Vibration monitoring

Vibration analysis detects repetitive motion of a surface on rotating or oscillating machines. The repetitive motion may be caused by unbalance, misalignment, resonance, electrical effects, rolling element bearing faults, or many other problems. The various vibration frequencies in a rotating machine are directly related to the geometry and the operating speed of the machine. By knowing the relationship between the frequencies and the types of defects, vibration analysts can determine the cause and severity of faults or problem conditions. The history of the machine and the previous degradation pattern is important in determining the current and future operating condition of the machine.

Vibration analysis monitors the following conditions on rotating machines:

- Cracks, pits, and roughness in rolling element bearing components.
- Unbalance of rotating machine parts.
- Shaft misalignment.
- Coupling problems.
- Bends, bows, and cracks in shafts.
- Excess sleeve bearing wear.
- Loose parts.
- Misaligned or damaged gear teeth.
- Deterioration caused by broken or missing parts.
- Deterioration caused by erosion and corrosion.
- Resonance of components.
- Electrical effects.

Machines are mounted so that the rotating shaft is horizontal or vertical with respect to the earth's surface. Gravity has more effect on vibration within horizontally mounted machines than it does on vertically mounted machines. Gravity forces on horizontal machines are perpendicular to the rotating axis and combine with rotating forces. A vertically mounted rotating shaft has the force of gravity acting in the same direction as the rotating axis. The rotating forces do not combine with gravity forces in a vertical machine.

Certain faults or problem conditions are more easily detected because of the type of machine or components the faults occur in. For example, rolling element bearings (ball or roller bearings) give more distinctive, earlier signs of wear than sleeve bearings do. Sleeve bearing lubricant films (oil or water) prevent parts from impacting, except in extreme situations. Rolling elements also have lubricant films (oil or grease). These films, however, may soften but do not eliminate the impact between components.

5.1.1. Vibration analysis correlation

Integrating oil and vibration analysis can yield early detection and trending of numerous equipment problems. Detecting the faults is the first step in the diagnostic process. Table 1 shows a comparison of the vibration and oil analysis detection capabilities for several machine conditions.

Thermography can also be used to verify vibration analysis on rotating equipment. Thermography can detect any overheating of bearings due to insufficient lubrication, misalignment, and other causes.

Table 1. Vibration and Oil Analysis Correlation

Equipment Condition	Oil Analysis	Vibration Analysis	Correlation
Oil lubricated anti-friction bearings	Strength	Strength	Oil analysis can detect an infant failure condition. Vibration analysis provides late failure state information.
Oil lubricated journal/thrust bearings	Strength	Mixed	Wear debris will generate in the oil prior to a rub or looseness condition.
Unbalance	N/A	Strength	Vibration analysis can detect unbalance. Oil analysis will eventually detect the effect of increased bearing load.
Water in oil	Strength	N/A	Oil analysis can detect water in oil. Vibration analysis is unlikely to detect this.
Greased bearings	Mixed	Strength	Some labs do not have adequate experience with grease analysis. Vibration analysis can detect greasing problems.
Greased motor operated valves	Mixed	Weak	It can be difficult to obtain a good grease sample and some labs do not have adequate experience with grease analysis. Vibration data is difficult to obtain when the valves are operating.
Shaft cracks	N/A	Strength	Vibration analysis is very effective in diagnosing a cracked shaft.
Gear wear	Strength	Strength	Oil analysis can predict the failure mode. Vibration analysis can predict which gear is worn.
Alignment	N/A	Strength	Vibration analysis can detect a misalignment condition. Oil analysis will eventually see the effect of increased load.
Lubricant condition	Strength	N/A	Oil analysis can determine inadequate lubrication.
Resonance	N/A	Strength	Vibration analysis can detect resonance. Oil analysis will eventually see the effect.
Root cause	Strength	Strength	Need oil and vibration analysis to work best.

5.1.2. Measuring vibration

There are five characteristics of rotating machine vibration:

- **Frequency** represents the repetition rate of a periodic event. It is usually expressed in cycles per minute (cpm) or cycles per second. There are 60 cpm in one Hertz (Hz.). Frequency can also be expressed in multiples of rotational speed (orders). Orders are commonly referred to as 1X speed for machine operating speed, 2X speed for twice operating speed, etc. For example, an 1800 rpm speed will have 1X speed equal to 1800 cpm or 30 Hz.

- **Displacement** is the amount of the up and down movement of a surface and is measured between the amplitude extremes (peak-to-peak). The corresponding frequency of the displacement must be known for analytical purposes. The unit of displacement measurement is typically in thousandths of an inch (mil) for the English system or microns for the metric system at a specific frequency. Displacement sensors provide a measure of the relative motion between the rotating part of the machine and the structure holding the sensor.

- **Velocity** in rotating systems is the change of the displacement per unit time of a surface as the machine vibrates. The unit of measurement is typically inches per second for the English system or millimeters/sec for the metric system. As the surface moves up and down, the velocity constantly varies. The most common unit of measure is the square root of the average (mean) of each instantaneous velocity squared or the root mean square (RMS). Some analysts measure velocity from zero to peak and that is called peak velocity. Velocity is not as dependent on frequency in the range of approximately 600 to 120,000 cpm (10 to 2,000 Hz). This frequency range is where the majority of component frequencies are found within common rotating machinery. Velocity is generally considered the vibration parameter of choice since its response is considered to be “flat” over a wide frequency range. For example, a machine experiencing a vibration level of 0.3 in/sec, peak (5.4 mm/sec, rms) would experience the same level of severity at 1000 rpm as it would at 10,000 rpm. This would not be the case with displacement or acceleration.

- **Acceleration** is the rate of change of velocity of the vibrating surface of the machine. Acceleration gives an indication of the dynamic forces generating the vibration. The unit of measure is inches per second squared (in/sec2) for the English system and millimeters/sec2 for the metric system. Analysts usually use a unit called g where 1.0g represents the earth’s gravity of 32.2-ft/sec2 a t seal level for the English system and 9.8 m/ sec2 for the metric system.

- **Phase angle** is a measurement of the timing relationship between two signals or between a specific vibration event and a keyphasor pulse. In single channel vibration analysis, this relationship is between the peak amplitude of the vibration signal and the firing of the tachometer. The time difference is then used to calculate the phase angle. The analyst uses phase when balancing a rotor to locate the heavy spot. Phase is also a useful tool to detect faults such as unbalance, misalignment, eccentricity, looseness, soft foot, bearing misalignment, resonance and other problem conditions. Phase measurements are very important when diagnosing and correcting machine unbalance. However, other machine faults such as misalignment and soft foot can also occur at 1 X rpm similar to unbalance. Therefore, understanding the phase relationships of unbalance, misalignment, eccentricity, and other machine faults can enhance the detection of the particular problem.

5.1.3. Vibration sensor overview

All vibration sensors or transducers convert the physical movement of the machine or structure that the sensor is placed on into an electric signal. This signal is a representation or signature of that machine and is stored in the vibration analyzer or data logger. Three different types of sensors are commonly used in a vibration monitoring programme. The proximity probe converts shaft displacement to mils or microns. The velocity pickup measures velocity and has an output in units of inches per second or mm/sec. The accelerometer measures acceleration and produces a signal in the unit of gs.

Proximity probe — The proximity probe or displacement probe is used to measure the distance between the probe tip and a target on the machine shaft. This is typically a permanently installed sensor and, due to the added expense of installation, usually only monitors critical plant equipment. The proximity probe operates by generating a flux field that is sensitive to the relative position of the shaft. As the shaft changes position with respect to the proximity probe, the flux field at the probe tip senses this change and produces an output that is proportional to that position change.

Proximity probes are valuable for monitoring shaft vibration. They are inexpensive, durable, not affected by lubricating oil, and possess a frequency response of up to 1000 Hz. A major disadvantage in the proximity probe is that it will respond to shaft scratches, other imperfections, and to variations in rotor eccentricity and shaft metallurgy. It may also respond to residual magnetism that may have been induced into the shaft.

The proximity probe monitors shaft motion relative to its mounting. If the probe is mounted inside a bearing, then the shaft motion is said to be relative to the bearing housing.

Advantages of displacement transducers include:

- Measures static displacement or gap using the DC portion of the signal
- Measures relative motion or vibration using the AC portion of the signal
- Operates over a wide frequency range approximately 0-1000 Hz or 60,000 cpm
- Inexpensive
- Small and lightweight
- Research and development is ongoing

Disadvantages of displacement transducers include:

- Requires a stable datum plane
- Requires an outside power supply
- Output affected by material
- Output affected by magnetic spots
- Dynamic signal rides on DC voltage
- Limited at high frequency
- Double differentiation to cross all vibration parameters
- Should be calibrated each time for the target material

Velocity probe or pickup — One of the earliest vibration sensors is the velocity sensor that is still widely used today. Its construction is simple and rugged. A velocity pickup consists of a coil or wire and a magnet in a non-conductive housing. As motion causes the magnet to move, it induces a flux in the coils that produces a signal that is proportional to the initial movement or vibration.

The advantages of velocity transducers are:

- Self-generating.
- Excellent signal-to-noise ratio.
- Rugged.

The disadvantages of velocity transducers are:

- Large and heavy.
- Limited frequency range.
- Limited temperature range.
- Some effect from magnetic fields.
- Output varies with measurement position.
- Relatively expensive.
- No research to improve design.

Accelerometer — The accelerometer is another type sensor that is commonly used for vibration monitoring. An accelerometer uses a piezo-electric crystal. In it simplest form, the piezo-electric crystal is placed between its base and a pre-determined amount of mass. As physical movement is applied to the sensor the mass squeezes and exerts pressure on the crystal, and this action produces an electrical signal. Accelerometers are very light with a linear response range that lends themselves to the tasks required in a periodic vibration monitoring programme. Another reason for its broad acceptance in this type of programme is because of its wide frequency response, normally 2 Hz to 10 kHz. For special applications, however, sensors are available that have a lower or higher frequency capability outside of this range. For example, accelerometers are available to monitor the lower frequencies of a 90-rpm motor, or the higher frequencies associated with rolling element bearing defects.

The advantages of accelerometers are:

- Small.
- Light weight.
- Relatively inexpensive.
- Wide frequency range.
- Research to improve.

The disadvantages of accelerometers are:

- High input impedance to charge amplifier.
- Limited signal-to-noise ratio.
- Requires outside power.
- High frequencies can saturate the sensor element.
- Double integration required to cross all vibration parameters.

The accelerometer is usually the vibration sensor of choice because it is lightweight, easy-to-use and has a wide frequency response. Most accelerometers include, internally, an integrated circuit preamplifier.

5.2. Thermography

Thermal measurement technology measures absolute or relative temperatures of key equipment parts or areas being monitored. Abnormal temperatures indicate developing problems. Temperature and thermal behavior of plant components are the most critical factors in the maintenance of plant equipment. For this reason, temperature is frequently considered the key to successful plant maintenance and is the most measured quantity. There are two types of equipment used in this technology, contact and non-contact. Contact methods of temperature measurement using thermometers and thermocouples are still commonly used for many applications. However, non-contact measurement using infrared sensors has become an increasingly desirable alternative over conventional methods.

5.2.1. Contact temperature measurement

Contact temperature measurement involves measuring the surface or interior temperature by sensing conducted heat energy. In the past, mercury or alcohol thermometers were used to measure temperature. They consisted of a liquid glass bulb reservoir leading to a long narrow tube. As the bulb was heated, the fluid expanded and began to fill the tube. Expansion of the liquid is proportional to the temperature. A temperature scale was marked along the tube. This allowed the temperature to be read by an observer.

Bimetallic thermometers operate on the principle of different thermal expansion of two metals. Two metal strips are connected at one end by solder or welding. As the strips are heated, they expand. All metals expand at different rates. The expansion difference can be translated by a mechanical linkage to turn an indicator needle. A temperature scale behind the needle allows an observer to read the temperature.

Resistance temperature detectors (also called thermistors) use sensors that are electrical conductors. When heated, the conductor’s electrical resistance changes. Analysts determine the temperature by measuring the resistance and knowing the resistance to temperature relationship.

A thermocouple also operates on electrical principles. Two different pieces of metal welded together at one end will produce a voltage proportional to the absolute temperature. The voltage produced is proportional to the heat sensed. Thermocouples provide very accurate temperature measurement in certain temperature ranges.

5.2.2. Non-contact thermal measurement

The four most commonly stated advantages of non-contact thermal infrared measurement over contact measurement are that it is:

- Non-intrusive.
- Remote.
- Faster than conventional methods.
- Provides a thermal distribution of the object surface.

Any one, or a combination of the following conditions, warrants the consideration of a non-contact sensor:

- **Target in motion** — When the target to be measured is moving, it is usually impractical to have a temperature sensor in contact with its surface. Bouncing, rolling, or friction can cause measurement errors and the sensor might interfere with the process.

- **Target electrically hot** — Current-conducting equipment and components present a hazard to personnel and instruments.

- **Target fragile** — When thin webs or delicate materials are measured, a contacting sensor can often damage the product.

- **Target very small** — The mass of a contacting sensor that is large with respect to the target being measured will usually conduct thermal energy away from the target surface, thus reducing the temperature and producing erroneous results.

- **Target remote** — If a target is very far away from, or inaccessible to, contacting sensors, infrared measurement is the only option.

- **Target temperature changing** — Infrared sensors are much faster than thermocouples. Infrared radiant energy travels from the target to the sensor at the speed of light. A rapidly changing temperature can be monitored by infrared sensors, with a millisecond response or faster.

- **Target destructive to thermocouples** — When the high mortality rate of thermocouples due to jarring, burning, or erosion becomes a serious factor, an infrared sensor is a more cost effective alternative.

- **Multiple measurements required** — When many points on a target need to be measured, it is usually more practical to re-aim an infrared sensor than it is to reposition a thermocouple or to deploy a great number of thermocouples. The fast response of the infrared sensor is important.

Some basic concepts for non-contact thermal measurement are:

— Electromagnetic spectrum.
— Infrared energy.
— Infrared thermography.
— Infrared image.
— Emissivity.
— Blackbody, graybody, and realbody.

Electromagnetic spectrum — It is known that infrared radiation is a form of electromagnetic radiation that is longer in wavelength than visible light. Other types of electromagnetic radiation include x-rays, ultraviolet rays, radio waves, etc. Electromagnetic radiation is categorized by wavelength or frequency. Broadcast radio stations are identified by their frequency, usually in kilohertz (kHz) or megahertz (MHz). Infrared detectors are categorized by their wavelength. The unit of measurement used is the micrometer, or micron. A system that can detect radiation in the 8 to 12 m band is usually called ‘long wave’. Alternately, one that detects radiation between 3 to 5 m is termed ‘shortwave’ (A 3 to 5 m system can also be classified as ‘midband,’ because there are systems that can detect radiation shorter than 3 m.).The visible part of the electromagnetic spectrum falls between 0.4 and 0.75 m. Different colours can be seen because they can be discriminated between different wavelengths.

Infrared energy — All objects emit infrared radiation as a function of their relative temperature. That means that all objects emit infrared radiation. Infrared energy is generated by the vibration and rotation of atoms and molecules. The higher the temperature of an object, the more that these nuclear particles are in motion and hence the more infrared energy that is emitted. This is the energy detected by infrared cameras. The cameras do not 'see' temperatures, they detect thermal radiation. Infrared energy is part of the electromagnetic spectrum and behaves similarly to visible light. It travels through space at the speed of light and can be reflected, refracted, absorbed, and emitted.

Infrared thermography (IRT) — Infrared thermography is based on measuring the distribution of radiant thermal energy (heat) emitted from a target surface and converting this to a surface temperature map or thermogram. The thermographer requires an understanding of heat, temperature, and the various types of heat transfer as an essential prerequisite in preparing to undertake a programme of IR thermography.

Infrared thermography is the technique of producing an image of invisible infrared light emitted by objects due to their thermal condition. The most typical type of thermography camera resembles a typical camcorder and produces a 'live' TV picture of heat radiation. More sophisticated cameras can actually measure the apparent temperatures of any object or surface in the image. The cameras can also produce colour images that make interpretation of thermal patterns easier. An image produced by an infrared camera is called a 'thermogram' or sometimes a 'thermograph'.

Infrared image — The IR camera captures the radiosity of the target that it is viewing. Radiosity is defined as the infrared energy coming from a target modulated by the intervening atmosphere. Radiosity consists of emitted, reflected and sometimes transmitted IR energy. An opaque target has a transmittance of zero. The colours on an IR image vary due to variations in radiosity. The radiosity of an opaque target can vary due to the target temperature, target emissivity and reflected radiant energy variations. This is an extremely important concept. Thermographers see targets exhibiting this emissivity contrast behaviour every day. It could be an insulated electric cable with a bare metal bolted connection. It could be a bare metal nameplate on a painted surface such as an oil-filled circuit breaker or load tap changer. It could be a piece of electrical tape placed by the thermographer on a bus bar to enable an accurate reading. For opaque objects, the emissivity and reflectivity are complementary. High emissivity means low reflectivity and vice versa.

Emissivity — Every target surface above absolute zero radiates energy in the infrared spectrum. The hotter the target, the more radiant infrared energy is emitted. Emissivity is a very important characteristic of a target surface and must be known in order to make accurate non-contact temperature measurements. Methods for estimating and measuring emissivity are discussed in industry literature. The emissivity setting that is needed to dial into the instrument can usually be estimated from available tables and charts. The proper setting needed to make the instrument produce the correct temperature reading can be learned experimentally by using samples of the actual target material. This more practical setting value is called effective emissivity.

Emissivity tables exist, but establishing the exact emissivity of a target is sometimes difficult. Emissivity was discussed above as a material surface property. However, it is more than a surface property. For example, the surface properties are continually changing. In addition, the shape of an object affects its emissivity. For semi-transparent materials the thickness will affect emissivity. Other factors affecting emissivity include viewing angle, wavelength, and temperature. The wavelength dependence of emissivity means that different IR cameras may get different values for the same object. And they would all be correct! It is recommended that the emissivity of key targets be measured under conditions they are likely to be monitored during routine surveys.

In general, dielectrics (electrically non-conducting materials) have relatively high emissivities, ranging from about 0.8 to 0.95, which includes painted metals. Unoxidized bare metals have emissivities below about 0.3 and should not be measured. Oxidized metals have emissivities ranging from about 0.5 to 0.9, and are considered the problematic category due to the large range of values. The degree of oxidation is a key ingredient to an object's emissivity. The higher the oxidation is, the higher the emissivity is.

For opaque objects, if the emissivity and the background (reflected) temperature are known, an IR camera with a temperature measurement feature can, in theory, give temperatures accurate to within a few percent. To get temperature, the IR camera must extract just the fraction of the radiosity due to the energy emitted by the target. Modern IR cameras are capable of doing this however, for emissivities below 0.5 the errors may be unacceptably large. They subtract the reflected component, and then scale the result by the target emissivity. The resulting value can then be compared to a calibration table and the temperature extracted.

Blackbody, graybody, and realbody — A blackbody is a perfect radiator because it has zero transmittance and zero reflectance. According to the emissivity equation, the emissivity of a blackbody is one. Blackbodies were first defined for visible light radiation. In visible light, something that doesn't reflect or transmit anything 'looks' black, hence the name.

A graybody has an emissivity less than one that is constant over the wavelength. A realbody has an emissivity that varies with wavelength. IR cameras sense infrared radiant energy over a waveband. To get temperature, they compare the results explained above with a calibration table generated using blackbody sources. The implicit assumption is that the target is a graybody. Most of the time this is true, or close enough to get meaningful results. For highly accurate measurements, the thermographer should understand the spectral (wavelength) nature of the target.

5.3. Tribology

A lubricant is a substance capable of reducing friction, heat, and wear when introduced as a film between solid surfaces. The secondary functions of a lubricant are to remove contaminants and protect the solid surfaces.

One of the basic technologies of condition based maintenance is lubricating oil analysis. The reason for this is that lube oil analysis is a very effective tool for providing early warning of potential equipment problems. The goals of oil monitoring and analysis are to ensure that the bearings are being properly lubricated. This occurs by monitoring the condition of both the lubricant and the internal surfaces that come in contact with the lubricant.

Some utilities maintain their own oil analysis laboratories and chemists. However, most utilities send the samples to a recognized laboratory. The outside laboratories normally produce a very comprehensive report, in a very short turn-around time, and at a modest cost. Lube oil sampling intervals should be based on operating history, operating time, oil condition, etc.

Rotating and reciprocating equipment typically have two different types of lubrication systems. The first is a pressurized lubrication system where oil is pumped from a reservoir through filters to each of the bearings, and then is returned to the reservoir. The bearings in this type of system are typically journal bearings. The second type of lubricating system typically encountered is an oil bath. In this application the bearings are partially or fully immersed in a bath of oil, and as the shaft and bearings rotate, they are lubricated. This type of system is very common for ball and roller bearing applications.

Wear is the inevitable consequence of surface contact between machine parts such as shafts, bearings, gears, and bushings. Equipment life expectancies, safety factors, performance ratings and maintenance recommendations are predicated on normally occurring wear. However, such factors as design complexity, unit size, intricate assembly configurations, and variations in operating conditions and environments can make maintenance or repair needs (ordinary or emergency) difficult to evaluate or detect without taking equipment out of service.

During normal equipment operation, there is a continuous process of particle generation and removal that occurs within a lube oil system. This process is dependent on many factors:

- Equipment load.
- Machine speed.
- Operating temperature.
- Type of lubricant and additive package.
- Bearing design.
- Type of filtration.
- Environmental conditions.

As lubricant and machine conditions degrade, the physical properties of the oil and wear/contaminant levels will change. By monitoring and trending these changes over time, and establishing useful limits for acceptable operation, lubricant and equipment problems can be quickly identified and resolved. A key element in determining the root cause of oil-related problems, is the ability to classify the types of wear and contaminants present (both chemical and particulate) and their potential source(s). This requires an understanding of chemical properties of the lubricants being used, the metallurgy of the internal components within the bearing reservoir, and the sources of contamination that can enter the system.

Wear and contamination can be classified in four different categories:

Internally generated wear / contamination — Internally generated wear/contamination can be a combination of ferrous and non-ferrous particles that are generated from bearings, slinger rings, seals, and other internal components that come in contact with the lubricant. In forced oil systems, oil pump wear, filter debris, and particulates from system piping/reservoirs may also be present. The particles generated from internal components can be caused by abrasive wear from metal particles and other contaminants circulating in the system, metal surface fatigue, loss of film thickness/strength, and other fault conditions. In order to determine what is wearing, how severe the condition is, and what corrective actions may be required, information regarding the amount, size, and types of particles is required. Typical elements monitored to assess the amount of internal wear present include: iron, copper, tin lead, aluminum, chromium, silver nickel, titanium, and antimony.

Particles generated from internal component wear and external contamination is inherently abrasive to the metal surfaces they come in contact with. They may also chemically interact with the oil itself, causing the formation of insoluble acids. These acids will corrode metal surfaces, deplete additives, and accelerate the chemical breakdown the lubricant.

From a diagnostic perspective, the size of the particles is an important factor in determining what wear mechanisms will occur and the effects that these particles will have as they circulate within the lubrication system. Smaller particles (less than 15 microns) typically pass through the bearing clearances and contact areas, cutting away at the metal surfaces they come in contact with. This results in the damage to the metal surfaces, fatigue, and the generation of new particles that will be introduced into the system.

In some cases these particles may also imbed themselves in the metal surfaces. This creates a surface anomaly that acts as a cutting tool against the opposing bearing surface. Larger particles (greater than 15 microns) will wear machine surfaces in a similar fashion, or they may break into smaller particles. In either case, the amount of internal component wear will increase, accelerating the amount of abrasive particles and contaminants that are in the system.

- **External contamination** — Contamination from airborne particulates (dirt, coal dust, organics), process fluids (Freon, acids), and other external processes are another source of contamination that can affect lubricant and machine condition. These contaminants typically enter lube oil systems from the outside environment through breathers, fill/vent plugs, access covers, and other entry pathways. Typical parameters monitored to assess the amount of external contamination present include Fourier transform – infrared spectroscopy, and elemental levels of silicon, sodium, boron, and potassium.

- **Moisture/water** — One of most common and damaging sources of contamination is water/moisture. Even at low levels, the presence of water will corrode metal surfaces (i.e. rusting), increase oxidation, and reduce the oil film strength (which can lead to increased wear). There are a variety of sources where water can come from (cooler leaks, seal leaks, condensation), and pathways into the lube oil system (through breathers, access covers, vents, and other openings).

Depending on the type and severity of the problem, water may exist in three different states: free water, emulsified water, dissolved water. It is important to understand where the source of ingression is and the type(s) of water present, so that adequate corrective actions can be taken to eliminate the problem and restore water concentration levels to acceptable standards.

Water is one of the most harmful contaminants that can affect lubrication systems since it degrades both lubricant and machine condition. At low concentrations, the presence of water will increase the rate of oxidation, and deplete additives through the process of hydrolysis. As conditions worsen, insoluble acids are created that cause corrosion of the metal surfaces, pitting, bearing fatigue, and the generation of abrasive rust particles. The rust particles accelerate machine wear. The acids also breakdown the chemical properties of the lubricant. This leads to the formation of sludge and varnish. Under extreme conditions, large amounts of water can lower viscosity and reduce film thickness, to the point where metal-to-metal contact may occur. The end result is inadequate lubrication and reduced bearing life.

- **Byproducts from the chemical breakdown of lubricants** — Most industrial lubricants specified for use in bearing applications are formulated and manufactured with high quality base stocks and additive packages. The additive packages are designed to withstand chemical breakdown during normal operation.

As lubricants age and oxidation occurs, additive levels are depleted and eventually insoluble acids and oxides are created. As the amount of insoluble acids accumulates, the viscosity will increase, causing greater fluid friction and an increase in operating temperatures. These higher temperatures will increase the rate of oxidation and the chemical breakdown of the lubricant. This process is accelerated under abnormal conditions such as high operating temperatures, water contamination, air entrainment, and excessive machine wear.

Under extreme conditions, lacquering may occur as oxidation deposits harden and adhere to metal surfaces. In forced oil systems, where the lubricant may act as a hydraulic medium, the accumulation of sludge deposits can also cause slow and erratic control.

Typical parameters that are monitored to assess the chemical breakdown of lubricants and oxidation include:

- Fourier transform - infrared spectroscopy.
- Total acid number (TAN).
- Elemental levels of zinc, phosphorous, barium, calcium, magnesium, and molybdenum.

Lube oil analysis plays a significant role in assessing contamination levels and managing the condition of the lubricant and machine components. By establishing target levels for lubricant properties, contamination, and machine wear, and measuring actual equipment performance against these limits, abnormal conditions can be quickly identified and resolved before internal component damage occurs. Controlling contamination is a key element in maintaining lube oil system cleanliness and reducing internal component wear.

There are two distinct but related areas of concern associated with machinery lubrication: The condition of the lubricant and the condition of the surface lubricated. Both are determined from representative fluid samples obtained in the lubrication system flow path. Analysts look at the amount, makeup, shape, size, and other characteristics of wear particles and solid contaminants in the lubricants. This yields important information concerning the internal machine condition. With experience and historical information it is possible to project degradation rates and estimate the time until machine failure.

There are many tests for lubricant quality, wear analysis and wear particle analysis. The most commonly used tests are:

- Lubricant quality – Cleanliness (precipitants/solids), color/appearance, fuel soot/nitration/oxidation/organic contamination by infrared spectroscopy, particle counting, total acid/base number/pH, viscosity, and water content.
- Wear or contamination analysis – Spectrometric analysis.
- Wear particle analysis - Ferrography, micropatch.

Table 2 summarizes the common tests employed for lubricant quality, wear analysis and wear particle analysis.

Synthetic lubricants — Synthetic lubricants are man-made lubricants whose base oils are chemical products manufactured or "synthesized" to provide properties not available in Group I and some Group II mineral-oil-based products. Although the synthetics represent less than one percent of the total lubricant inventory, they are available for and are used in many applications. Table 3 shows the various classes of synthetic base oils and the finished products in which they are used.

Table 2. Lubricant Testing for Quality

Lubricant Test	Object of Test	Indication	When Used
Cleanliness	Any solids in oil	Potential for or actual wear of lubricated parts	Routinely (monthly) and after start-up following major repairs.
Color/ Appearance	Hazy or darkened appearance	Presence of water or particulates. Deterioration of oil through oxidation when sudden change occurs	Routinely (monthly)
Infrared Spectrography	Organic (non-metal) contaminants/fuel dilution/fuel soot, acidic nitrates contamination, and oil oxidation in diesel engines. Degraded grease compared to new grease. Additive concentration.	Potential for reduced lubricant effectiveness and increased wear, lacquer, and other deposits, metal corrosion, and reduced oil life due to oxidation inhibitor additive depletion. Lubricant or additive deterioration.	Routinely (quarterly for emergency diesels) Annually or every refueling outage for greases.
Particle Counting	Solids in oil used in systems such as turbine control and hydraulics	Potential for causing binding or orifice clogging and wear in close tolerance systems (turbine control systems)	Routinely (monthly)
Total Acid/ Base Number/ pH	Deviation from new oil quality	Oil constituent oxidation/ deterioration/reduced protection ability. Ability to neutralize acid contaminants. Verification that proper oil has been used after change.	Routinely (monthly)
Viscosity	Resistance to flow, reduction in oil film strength (ability to prevent unwanted metal-to-metal contact)	Presence of fluid contaminants (water, fuel, solvents). Verification that proper oil has been used after change and for thermal breakdown of oil or oxidation	Routinely (monthly) and after oil change
Water Content	Presence of free water in system	Potential for reduced lubricating quality of total fluid, rusting of metal parts and oxidation of lubricant constituents such as additives.	Routinely (monthly) and when water leakage into lubricant is suspected
Note: Anti-rust protection, remaining oil life, foaming, and flash point tests are not done routinely. They should be considered as on-condition tests for troubleshooting backed by annual or biennial testing.			
Spectrometric Analysis	Concentration of small metal wear particles, additives, and contaminants	Possible wear, presence of contaminants, additive depletion	Routinely (monthly)
Ferrography	Size, concentration, shape of wear particles of any size (up to ~ 250 microns)	Machine condition/wear mode/probable cause	Screening test used routinely. More detailed analysis done *on-condition* indicated by test
Micropatch	Solid contaminants and wear particles of any size present in the oil sample taken.	Presence or absence of wear. When present, the nature of the wear occurring. Nature of large contaminant particles.	Routinely (monthly) or when wear suspected

Table 3. Synthetic Base Oils1 and Their Application

	Engine Oils		**Industrial Oils**	**Greases**	**Fire Resistant Oils**	**Relative Cost2**
Synthetic Oils	**Combustion Turbine**	**Other**				
Poly (alpha-olefins) (PAOs)		X	X3	X3		4-8
Diesters	X			X4		5-7
Polyolesters	X					10-14
Phosphate Esters					X5	10
Polyethers (Polyglycols)			X			6-8
Silicones (Siloxanes)7			X6	X6		30-100
Perfluoropolyethers				X	X	80-800
Polyphenylethers			X	X		100+
Chlorofluorocarbons					X	100+

Footnotes:

1. In the field of metalworking/cutting fluids, water-based fluids are sometimes called "synthetic."
2. Approximate cost multiplier relative to most common mineral oil.
3. Mobil SHC series, Mobilgrease 28.
4. Beacon 325 (Exxon).
5. Fyrquel (Akzonobel), etc.
6. Dow Corning; GE.
7. Including halogenated species.

The poly (alpha-olefins) (PAOs - Group IV) are the most widely used synthetic base oils in industrial and automotive lubricants. However, the differences between them and the new highly refined (hydrocracked) mineral oil base stocks (Group III) are becoming blurred as shown in Table 4. Because of this, the marketplace is likely to see fewer PAO-based products in the future. The hydrocracked base oils cost half as much as the PAOs and their properties are often similar.

Table 4. Comparative Properties of PAO Synthetic Base Oil and Various Mineral Base Oils

	Mineral Oils Group I*	**Mineral Oils Group II***	**Mineral Oils Group III***	**PAO API Group IV***
Viscosity, 40°C, cSt	32	44	39	32
Viscosity, 100°C, cSt	5.3	6.6	7.0	6.0
Viscosity Index	95	102	135	136
Pour Point, °C	-15	-15	-20	-66
Flash Point, °C	210	230	240	246
Fire Point, °C	240	—	—	272
Evaporation Loss, Wt% (6.5 Hr. at 204°C)	16	—	—	4
Aniline Point, °C (ASTM D 611)	108	115	127	127

* American Petroleum Institute (API) base stock classification

The good low temperature properties of the PAOs are reflected in the viscosities, viscosity index, and pour point. They are matched, except for the last, by the Group III mineral base oil. The lower volatility for a given viscosity shows up in higher fire point and lower evaporation loss. The aniline point is a measure of solvency – the lower the number, the higher the solvency. Here the PAO and Group II and III oils are inferior to the normal, or Group I, mineral oil. That is, if sludge is formed, it will precipitate out later with a Group I-based product. However, the sludge, which is oxidized material, might not form so readily with the synthetic oil- or Group II- or III based product. This is because the Group II, III, and IV oils generally give a higher degree of oxidation resistance with a given amount of antioxidant.

Improved performance with synthetic oil-based lubricants comes with an increased price tag. Such costs make it hard to justify the use of synthetic-based products unless the application demands their superior properties. For example, if equipment needing lubrication is used in subzero weather, it is worth the added cost reliably to start or operate the frigid apparatus with a PAO-based oil. The cost, of course, is only half as much if a Group III based product can be used. In another example, if fire-resistant oil is needed, then the additional cost is justified. But if these properties are not required, there is no need to use expensive synthetic products. The vast majority of the nuclear power plant lubrication requirements can be met with high quality mineral oil-based products.

The area of oil analysis is covered in the following sections:

- Lubricant quality.
- Particle contamination.
- Wear particle analysis.
- Oil sampling.
- Correlation of technologies.
- Laboratory reports.
- On-site oil testing.

5.3.1. Lubricant quality

Contamination is a leading cause of machinery damage and reduction in the oil's ability to properly perform. By controlling contamination, the life of the lubricant and machine can be extended greatly. Like any good maintenance practice, the earlier a problem is detected, the cheaper it is going to be to correct. After implementing a few good maintenance practices to control contamination, the rewards can be seen almost instantaneously.

There are many possibly sources of contamination with any oil reservoir. New oil is one of the most important areas to consider as a source of potential contamination. When we think of something as being new, we typically think of it as being fresh and clean. Although new oil has not normally been considered as a likely source of contamination, new lube oils are often contaminated.

Contamination of new lubricants can happen in a variety of ways. The oil itself may be dirty upon receipt from the supplier. The oil may be dirty as it leaves the refinery or contamination can be introduced during the transportation process. Most end-users do not ask their vendors what type of cleanliness levels they will be receiving and most vendors do not automatically provide this information.

Storage of the oil on-site also can be a source of contamination. Many times the containers of new oil are stored in an area and manner that can introduce contamination. Exposing the new oil to extreme weather conditions or unclean environments can easily introduce water contamination or airborne dust and debris. Transporting the fluid from the storage area to the equipment also may introduce a variety of contaminants.

The equipment itself can contribute to sources of contamination. Vents, breathers, filters and seals all offer an avenue of contamination. Vents that are open provide a passage for airborne particles or water. Breathers and filters that are not effectively controlling particles or moisture allow them to enter the system. Similarly, seals that are damaged or not working properly also allow particles or water to enter units.

The environment can also be a contributing factor for introduction of contamination. Whenever it rains or if the equipment is washed down during a cleaning process, the opportunity for water to be introduced into the equipment increases.

Additionally, units that contain fuel, glycol or coolant all have the potential to be contaminated with these products. Improper or defective equipment can cause these products to enter systems. Furthermore, systems with poor combustion may also introduce excessive soot levels.

Contamination of any kind can have an adverse effect once it enters a system. Contamination can affect the equipment itself in addition to the oil that is lubricating the equipment.

Particles can increase the rate of wear and oxidation and reduce the effectiveness of the additives in the oil.

Water increases wear, promotes rust and oxidation, and weakens the lubricant's ability to perform.

Fuel contamination causes lubricants to thin, dilutes additives, increases wear, and creates a fire hazard.

Glycol contamination increases wear, corrosion, and oxidation.

Soot increases viscosity, reduces the additive's ability to perform and promotes varnish and sludge.

After identifying sources of potential contamination, procedures can be implemented that help avoid the risk of the contamination. Controlling the risk of contamination will help extend the life of the equipment and lubricant. It may be that the lubricant arriving from the supplier does not meet your cleanliness requirements. This can be corrected by requiring the supplier to provide you with cleaner oil or by filtering the oil before it is introduced into the equipment.

On-site storage facilities may need to be re-evaluated. All new oil should be stored in a clean, controlled environment. Additionally, all storage containers should be clearly marked. Containers used to transport the oil to the equipment should be clean and used for only one lubricant.

Vents, breathers, filters and seals should all be checked for their effectiveness in keeping contaminants out of the equipment. Equipment that does not have breathers and filters should be evaluated. Breathers can be installed in place of the vents and installation of filters can add extra protection.

5.3.2. Particle contamination

Break-in wear, normal wear, and abnormal wear are the three phases of wear that exist in equipment. Break-in wear occurs during the start-up stages of a new component. This phase typically generates significant wear metal debris that will be removed during the first couple of oil changes. Normal wear occurs after the break-in wear stage. During this stage the component becomes more stabilized. Wear metals will increase with equipment usage and decrease when makeup oil is added or oil changes occur. Abnormal wear occurs as a result of some form of lubricant, machinery, or maintenance problem. During this stage the wear metals increase significantly.

By using oil analysis on a routine basis, a base line for each piece of equipment can be established. As the oil analysis data deviates from the established base line, abnormal wear modes can be identified. Once abnormal wear modes are identified corrective action can be planned.

Implementation of an oil analysis programme with analyses consistent with the goals of the condition based maintenance programme will significantly reduce maintenance costs and improve plant reliability and safety. Lubricant analysis for the purpose of machinery conditioning monitoring is at its best with a significant amount of historical data. It is important to establish a base line for each piece of equipment. Certain analytical results may change with lube oxidation and degradation due to normal use. The major changes occur due to contamination from environmental factors and machinery wear debris. The analytical costs of a properly implemented programme should be covered by the extension of the lubricant change interval. Increased reliability, availability, and the prevention of unanticipated failures and downtime are added benefits.

All machines generate wear. The key to understanding whether or not a machine is operating properly is to analyze the wear particles being generated from the lubricated surfaces, and correlate this data to the physical condition of the internal components. The wear particles exist as a separate phase in the oil, and are often not uniformly distributed throughout the system. As a result, extreme care must be taken in selecting the locations to sample, and in the actual steps taken in obtaining the sample.

During normal operation of lubrication systems, particles are continually generated and removed from the oil. The particles being generated typically come from the bearings, slingers, shafts, reservoir housings and/or piping, and other internal components that come in contact with the oil. Particles are continually being removed from the oil due to filtration, settling, adhering to the reservoir sides and/or lube oil piping, etc. An equilibrium level is achieved based on the amount of particle generation and removal occurring in the system. It is this equilibrium rate (i.e., wear particle concentration) that should be trended over time to monitor and diagnose internal problems.

The wear particle concentration achieved once a machine has reached equilibrium has two main constituents. One is the amount of small wear and contamination present in the system. These small wear particles (typically less than 5 microns in size) tend to stay suspended in the lube oil and often pass through most filters if present. As a result, they are generally distributed evenly throughout the lube oil reservoir /system and tend to increase over time. However, the larger particles being generated in the lube oil reservoir/system are typically not distributed uniformly due to their tendency to settle out or adhere to the bearing reservoir and piping. These larger wear particles provide the most valuable information regarding the present condition of the internal components since they typically indicate an abnormal wear condition. As a result, the location and method of sampling must be carefully selected to ensure a representative sample of both small and large wear and contamination can be obtained.

The equilibrium rate (i.e. wear particle concentration) of particle generation and removal is affected by oil changes. In order to ensure that an oil change is effective, the bearing reservoir should be thoroughly cleaned and flushed with an approved, commercially available solvent before installing the new lubricant. Proper flushing will ensure that all of the unwanted contaminants and wear particles are removed, and new sample data taken after oil changes are not tainted with particulate from the previous lubricant installed.

Following an oil change, the amount of particle generation will increase, causing the amount of particle removal to increase until an equilibrium rate is achieved. The time it takes a machine to reach its equilibrium level depends on the type of machine, the filtration system installed if applicable, and the type of flow and circulation within the lube oil system. In most cases, an equilibrium wear particle concentration will be achieved within a couple of hours, but could take up to a couple of days. It is recommended that an oil sample be taken shortly after an oil change to re-establish baseline data, and to ensure that the proper oil was installed.

The quantitative testing of wear particles is to trend the concentrations to identify the onset of abnormal wear. The qualitative testing of wear particles is the particle identification by microscopic analysis to predict source, cause, and scope of wear (i.e. wear mode and severity).

Particles can be classified as:

Ferrous – magnetic, paramagnetic, Fe, Fe2O3, Fe3O4, stainless

Non-ferrous – copper alloys, aluminum, babbitted metals, zinc, chrome, etc.

Contaminant – fluids, dust, dirt, external process, manufacturing debris, filter material, friction polymers, organic matter.

5.3.3. Wear particle analysis

Ferrography is a technique that provides microscopic examination and analysis of wear particles separated from all type of fluids. Developed in the mid 1970's as a condition based maintenance technique, it was initially used to magnetically precipitate ferrous wear particles from lubricating oils.

This technique was used successfully to monitor the condition of military aircraft engines, gearboxes, and transmissions. That success has prompted the development of other applications, including modification of the method to precipitate non-magnetic particles from lubricants, quantifying wear particles on a glass substrate (ferrogram) and the refinement of our grease solvent used in heavy industry today.

Ferrography is also a method of evaluating machine wear condition by examination and evaluation of particles separated from used lubricant samples (oil or grease). The particles are separated by flowing the sample slowly through a high gradient magnetic field, using magnetic force to trap the ferrous debris and gravity to capture the non-ferrous debris. Following the lubricant, a solvent fixer is used to remove residual lubricant from the slide substrate, leaving just the wear debris on the substrate.

A high-magnification bichromatic microscope is used to identify and examine the particles remaining on the substrate. Particles caused by specific wear modes have distinctive characteristics that reveal the wear mechanism(s) that formed them. Analysts can classify wear particles by size, shape, concentration, and metallurgy. Various types of particulate contamination can also be identified. The analyst can then assess the machine's wear condition and make appropriate recommendations.

5.3.4. Oil sampling

Many plants get involved in routine oil sampling and analysis to help reduce the costs associated with maintaining lubrication systems. The most significant costs involve periodic oil changes based on a time schedule as recommended by the equipment specific manufacturer. Recommended oil change frequencies can range from weekly to yearly depending on the equipment, its operating environment, the duty cycle of the equipment, and many other factors. To help reduce and possibly eliminate the need to perform time-based oil changes, a well-designed oil sampling and analysis programme can help.

One of the biggest concerns in implementing an oil analysis programme is to determine which equipment should be sampled. For larger systems (greater than 10-15 gallons), it is usually more cost effective to establish a condition based oil change programme, rather than a time-based one. For smaller reservoirs (less than 10 gallons), there may or may not be a financial benefit from performing oil analysis versus oil changes. A lot of determination on whether or not to sample smaller reservoirs depends on the criticality of the equipment, and the resultant effects on production or operation, if the equipment or lubrication fails in service.

The usefulness of wear particle analysis results depends on how accurate the oil samples are representative of the oil. The most difficult problem encountered in implementing a ferrography programme is procedural control of the oil sampling. Special consideration must be given to location, sampling method, and frequency. While adherence to the following recommendations will not guarantee the securing of representative samples, failure to comply with some or all of them will usually result in the collection of samples that do not represent actual oil conditions.

5.3.5. Correlation of technologies

Table 5 shows a correlation of lubricant and wear particle analysis with other technologies.

Table 5. Correlation of Lubricant and Wear Particle Analysis with Other Technologies

Technology	Correlative Method	Indication	When Used
Vibration	Time sequence	Wear particle build up precedes significant vibration increase in most instances.	Routinely (monthly)
Thermal analysis	Time coincident	With major wear particle production (near end of bearing life) occurs as the bearings fail	When bearing degradation is suspected
Advance filtration/debris analysis	Time sequence/ coincident	Major bearing damage has occurred when significant amounts of material appear in the lubricating system filters.	Routinely with each filter cleaning or change

Each of these tests may be performed independent of the other tests. The test results should be routinely correlated by an analyst for the systems being monitored.

5.3.6. Laboratory reports

The key to interpreting oil analysis reports is to establish baseline levels for all parameters, and trend the values over time to identify any significant changes. Usually, each oil sample has two reports, one for lubricant condition and one for equipment condition.

Because oil analysis is looking at equipment condition on a microscopic level, it often identifies problems earlier in a failure mode than vibration analysis does. Oil analysis also provides an indication on certain failure modes that will rarely be identified with other technologies (i.e., the presence of water, incorrect viscosity, and oxidation/chemical breakdown). It is recommended that a routine testing programme be used in a comprehensive CBM programme.

A typical lab report for one oil sample has over fifty different data values from the various tests that are performed. Understanding and making information from this data can be quite difficult. All data should be thoroughly reviewed before filing away test reports.

Do not limit the review to only the “Critical” reports. There could be some “Marginal” reports that need attention, and possibly some “Normal” reports that were improperly classified. In all cases, data should be trended over time to effectively understand the operating condition of each machine.

5.3.7. On site oil testing

In-shop, in-house, and bench-top are all terms associated with on-site oil analysis. Mini-lab oil analysis is most often accomplished by condition based maintenance personnel in conjunction with their vibration analysis duties.

Several thousand plant maintenance departments have decided to perform at least a portion of their oil analysis on site. The amount of lab analysis depends on capabilities of the mini-lab. Here are some of the reasons to perform on-site oil analysis:

- Ownership and control of the analysis.
- Immediate results.
- Immediate retest when needed.
- Analysis is done by the people who know the most about these machines.
- Electronic data with no transfer.
- More frequent testing.
- Test lubricants before using.

The on-site mini-lab that performs industrial oil analysis should have the following:

- Quantitative WDA (e.g., Ferrous Density).
- Qualitative WDA (e.g., Analytical Ferrography or Analytical WDA).
- Particle counting.
- Water measurement such as crackle or time-resolved dielectric.
- Oil chemistry measurement such as dielectric or voltametric or TAN/TBN test kits.
- 40 C viscosity.
- Expert system in software.
- Electronic import and export to and from labs.

5.4. Acoustic analysis

Acoustic emission is defined as the science that deals with the generation, transmission, reception and effects of sound. It is the detectable structural or air-borne sound that can manifest itself as a signal on mechanical objects, the pressure waves associated with leaking vapors or gasses, or the humming of electrical equipment. Acoustics technology includes frequencies as low as 2 Hz and as high as the mega-Hertz range. Through a process of filtering, frequency band passing, and sensor selection, the potential uses for acoustic testing to diagnose equipment condition and operability is virtually unlimited.

Acoustic work can be performed in either the non-contact or in the contact mode. In either case, it involves the analysis of wave shapes and signal patterns, and the intensity of the signals that can indicate severity.

Because acoustic monitors can filter background noise, they are more sensitive to small leaks than the human ear, and can detect low-level abnormal noises earlier than conventional techniques. They can also be used to identify the exact location of an anomaly.

Acoustic systems can be simple portable devices that can detect anomalies, either structural or airborne. They provide a digital indication of the sound intensity level and can locate the source of the sound. If it is necessary to know the wave shape and the frequency content of the signal, a more sophisticated portable waveform analyzer type is needed. When it is necessary to monitor critical equipment on a continuous basis, the sensors are permanently attached to the equipment and the signals are transmitted to an on-line acoustic monitoring system.

Most machines emit consistent sound patterns under normal operating conditions. These sonic signatures can be defined and recognized; and changes in these signatures can be identified as components begin to wear or deteriorate. This enables technicians to identify and locate bearing deterioration, compressed air or hydraulic fluid leaks, vacuum leaks, steam trap leaks and tank leaks.

Evaluation of long term ultrasonic analysis trends can identify poor maintenance practices such as improper bearing installation or lubrication, poor steam trap maintenance, and improper hydraulic seal or gasket installation. Long term ultrasonic analysis can also identify machines that are being operated beyond their original design limitations, inadequately designed machines, or consistently poor quality replacement parts.

Ultrasounds are defined as sound waves that have frequency levels above 20 kHz; higher than what the unaided human ear can normally hear. Airborne ultrasound operates in the lower ultrasonic spectrum of 20 kHz to 100 kHz. Airborne ultrasounds are easily blocked by small objects, and they will not penetrate solid surfaces (though they will go through cracks). Since airborne ultrasound radiates in a straight line, its source can be relatively easy to locate. Though they do not travel a great distance, airborne ultrasounds can be readily differentiated from audible plant noise.

A compressed gas or fluid forced through a small opening creates turbulence with strong ultrasonic components on the downstream side of the opening. While most of the audible sounds of a pressure leak may be masked by ambient noise, the ultrasound will still be detectable with a scanning ultrasound device. Therefore, when the PM technician scans the side of a pressure vessel, a leak will produce a definite increase in ultrasound volume. Scanning is most effective when the ultrasonic instrument is close to the surface being inspected; however, it can also be done at a distance by increasing the sensitivity setting. This is particularly useful when the pressurized gas is dangerous, or when the technician must inspect overhead pipes or locations that are not readily accessible.

Vacuum leaks produce turbulence similar to pressure leaks; however, the ultrasound is generated within the system. Some of the sound escapes through the opening, though the amplitude is much lower than that of a pressure leak. This is not a problem, since the instrument can be placed closer to the vacuum leak or the sensitivity can be increased.

Poorly seated valves can also be detected. When the technician touches the contact probe to the body of a leaking valve, the sound of dripping or squirting fluid will be heard in the earphones (the noise from a leaking valve will be more evident on the downstream side of the valve).

Ultrasonic detection instruments can also be used for bearing condition monitoring. The ultrasonic detector is generally a hand-held device that can be conveniently taken into the field. The instrument often looks like a pistol, weighs 0,5-1 kg, and can be used in confined places. The technician "hears" the ultrasound after it has been modified and processed into the audible range, and determines the intensity by observing a meter on the instrument.

Monitoring machinery on a periodic basis (once a month or once a quarter) can provide a more subtle indication of seal or packing wear, steam trap contamination or deterioration, or cracks in tanks or piping. This allows personnel to project acceptable performance into the foreseeable future. Advance notice of problems means that they can be repaired during normal shutdowns, rather than have a catastrophic failure cause unscheduled down time. Since problems are detected when they are minor, they are often less expensive to repair.

Long term ultrasonic analysis can identify improper maintenance practices, including poor seal or packing installation, improper steam trap maintenance, poor welding or pressure vessel maintenance. Long term trends can also identify improper operating conditions, such as running equipment beyond design specifications. They can be used to compare similar equipment from different manufacturers to determine if there are design benefits that will be reflected in increased service life; and they can identify consistently poor quality replacement parts.

Ultrasonic analysis is one of the less complex and less expensive predictive techniques. Its simplicity is directly related to the size and ease of use of handheld detectors, and the relatively straightforward presentation of measurement data on meters or digital readouts. The cost of the equipment is moderate, as is the amount of training required for its use. The technique is limited to applications which produce measurable ultrasounds: hydraulic, compressed air, steam or vacuum systems.

Because of its broad frequency spectrum, acoustics is further defined into two ranges, the sonic range and the ultrasonic range, and their applications are as follows:

- Sonic range – (0Hz – 20kHz) – The sonic range includes all frequencies in the hearing range of humans. Sonic range includes all frequencies used in mechanical vibration analysis and low frequency leak detection (2Hz – 20kHz)

- Ultrasonic range – (20 kHz – 1MHz) - Ultrasonic frequencies are used in cavitation detection, acoustic emission, high frequency leak detection, corona and partial discharge detection.

Each of these frequency ranges makes use of contact and non-contact transducers, such as microphones, accelerometers, and high frequency resonant transducers.

This section is divided into acoustic leak detection and acoustic crack detection.

5.4.1. Acoustic leak detection

When applying acoustics for condition monitoring and fault detection, it is advisable to select the frequency band that is anticipated, and to filter out all other unwanted background noises. The following provides some guidance for selecting the sonic bands:

— 100 Hz to 20 kHz – General fault detection
— 1.0 Hz to 20 Hz – Leak detection that eliminates low frequency background noises
— 3.0 Hz to 20 kHz – Leak detection that eliminates additional background noise

The following intensities are provided for guidance:

— Less than 0.1g = small or no leak
— Greater than 0.1g and less than 3g = medium leak (scheduled repair)
— Greater than 3g = large leak (immediate repair)

Acoustic monitoring devices have been applied in several different areas. They include leak detection for feedwater heaters, valve internals, valve externals, and boiler tubes.

Feedwater heater tube leaks are commonly detected by changes in heater water level, flow rate, or water chemistry. Because of the large total fluid volume, all of these methods require large leaks in order for the change to be noticeable, and it may be hours or days before the leak is discovered. Such a delay in the tube leak detection can reduce plant efficiency through thermal efficiency losses. If the leak remains undetected even for a short period of time, impingement of the escaping feedwater can damage adjacent tubes, further increasing repair time and expense.

Determining which heater in the train is leaking can also be a difficult task. Not only is there a delay in detecting the leak, but in some cases the wrong feedwater is taken off line, adding to an already inefficient situation. When a feedwater leak is detected early, it is possible that the leaking heater can be taken of-line for repair while the other heaters remain in service. This avoids a complete shutdown and minimizes the performance efficiency degradation.

In a feedwater leak detection system, sensors are mounted at various locations on the heaters. When a hole develops in a heater tube, the fluid flowing through the orifice generates acoustic pressure waves. These waves are detected by the sensors and converted to electrical signals. Leaks are annunciated by alarm lights and contacts for remote alarm indication. An analog output from the signal processing unit is available to provide an indication of the acoustic level on any auxiliary peripheral device such as a data analysis computer, control room recorder, or distributed control system. The system can provide trending, alarm, and graphics capabilities that are used by the technician in predicting feedwater heater tube failure.

In a boiler tube leak detection system, steam escaping through a hole in a boiler tube generates a broadband noise that peaks in the range of 1 to 5 kHz. High temperature sensors, mounted onto waveguides that couple the acoustic pressure waves in the boiler to the sensor, are installed in locations of the boiler that have had a history of failures.

Acoustic pressure waves generated in the boiler from a tube leak are detected by the sensors and converted to an electrical signal. The signal from the sensors near the leak increases proportionately with the size of the leak. The increase in signal level is monitored on a trend plot until the level exceeds a preset alarm point. The relative magnitude of the various sensor readings allows approximation of the leak location. More information on boiler tube leak detection systems is found in Appendix A.4 of this guide.

Acoustic detection of valve leaks can be performed either with permanently installed or portable devices. Fluid flow through the valve will provide a signature of acoustic activity. When the valve is closed, the acoustic level should drop to zero taking background noise levels into account. This would indicate that the valve has seated and no leak is present. Should a leak be detected, the valve would b scheduled for maintenance action.

Acoustic leak detection applications include:

- Feedwater heater tube leaks
- Valve internal leaks in liquid systems
- Valves and fittings external leaks in high pressure air systems
- Boiler tube leaks

Table 6 shows a correlation of leak detection with other technologies.

Table 6. Correlation of Valve Leak Detection with Other Technologies

Technology	Correlation Method	Indication	When Used
Thermal analysis	Time coincident	Abnormal temperature coincident with acoustic signals indicating internal leak of fluid or gas	On condition of suspected leak, especially in systems with many potential leak points
Non-intrusive flow	Time coincident	Flow downstream of shut valve giving acoustic indication of internal leakage	On condition of suspected leak and many choices of valves to open for repair
Visual inspection	Time sequence	Visual indication of valve disks or seal damage sufficient to cause internal leakage	Use for confirmation before valve disassembly. Use after removal for correlation between acoustic signal and visually observed degree of leak causing damage.

5.4.2. Acoustic emission crack detection

Acoustic emission is defined as the transient elastic waves that are generated by the rapid release of energy. It is the sound resulting from a crack developing in solid material. As this extremely small, low-level sound propagates through the material, it can be picked up by highly sensitive piezoelectric or strain gauge sensors. The advantage of acoustic emission is that very early crack growth can be detected well before a highly stressed component may fail.

Acoustic emission technology is intended to provide analysts with early indication of the onset of degraded strength in metal components such as pressure vessels. By trending the acoustic emission event occurrence, analysts can track and project the progression of grain structure breakdown. With this information, the plant can remove the metal component from service before total loss of function occurs.

Acoustic emission technology has been successively used on the following equipment:

- Reactor vessels and related piping
- Control rod housings
- Main steam lines
- Transformers
- Fossil high energy piping

Micro-granular material, such as steel, put under tension or compression beyond its yield point, breaks and tears along grain boundaries (inter-granular cracking). This can happen in pressure vessels, structural supports and high-energy piping. Acoustic emission monitors for micro cracks in heavy metal components and specifically, the growth of cracks. The breakdown in plant component’s metal crystalline structures can lead to equipment failure in extreme cases.

Acoustic emission sensors have been very effective when applied to reactor vessels and related piping for the early determination of developing cracks. In these applications, the sensors are monitored continuously during all levels of plant operations. Other applications include monitoring the integrity of control rod housings and main steam lines.

Acoustic emission monitors use many acoustic pickup transducers to detect the energy bursts caused by the inter-granular cracking and other sources. The equipment sends these signals to a computer console for signal conditioning, measuring, and comparison of arrival time. Arrival time comparison locates the signal source.

Different acoustic emission equipment versions present the data in several ways. Most show the acoustic events per second, cumulative total events over time, change in count rate, or some combination of these three ways. Analysts can then trend this data.

Table 7 shows a correlation of acoustic emission with other technologies.

Table 7. Correlation of Acoustic Emission with Other Technologies

Technology	Correlation Method	Indication	When Used
Ultrasonic imaging	Time sequence	Cracking in heavy metal weld joints	In conjunction with code requirements for periodic (10 year) inspection or after a rise in acoustic emission events in a specific region indicates cracks may be developing.
Dynamic radiography	Time sequence	Cracking in heavy metal weld joints	In conjunction with code requirements for periodic (10 year) inspection or after a rise in acoustic emission events in a specific region indicates cracks may be developing.
Stress/strain measurement	Time coincident	High levels on strain gauges or distortion indicated by other methods.	When monitoring for pressure vessel or heavy section weld deterioration during hydro testing or other high stress event.

Acoustic emission sensing techniques can be particularly useful for monitoring of in-service power transformers. A major concern of transformer failure is focused on the partial discharge associated with the degradation of insulation inside the transformer. This insulation breakdown causes electrical arcing that deteriorates the oil insulation factor and, if continued, produces highly explosive gases.

Each partial discharge propagates to the tank wall. These stress waves are similar in character to stress waves propagated in solids during crack formation, and generate acoustic emission signals that contain an appreciable amount of energy in the 150 kHz frequency range. These signals can readily be differentiated from other signals emanating from the transformer.

By taking into account the intensity of the acoustic emission signal, the approximate location of the emitting source, and estimated the level of activity involved, it is often possible to estimate the severity of the problem and make a reasonable assessment of its cause.

The detection of acoustic emissions from partial discharge events in transformers is established and instrumentation is available for this detection. However, acoustic emissions from transformers have been detected in the absence of partial discharge. It has been shown that these signals are produced as a result of the inception of bubbles.

The operating transformers can generate acoustic emissions for a variety of reasons. These can be categorized into heating sources, electrical sources, and background noises.

Partial discharge inside a transformer produces acoustic emissions. There are other sources that can produce acoustic emissions prior to the actual occurrence of partial discharge in the transformer. Some of these are:

- Localized heating in oil or paper can sometimes acoustic emissions
- Paper tracking or carbonization produces acoustic emission signals

- Energy released during hydrogen gas evolution by partial discharge either from heating or implosion
- From cavitation, nitrogen is released from solution and generates acoustic emissions.

These mechanisms produce acoustic emission that is directly related to a breakdown in the transformer. There are other mechanisms that have been observed that will generate acoustic emission activity that is not directly related to a problem in the unit. Some of these are:

- Environmental sources due to the impact of rain, snow, ice, or dust against the transformer
- When there are areas or pockets of turbulent oil flow within the unit, acoustic emission can be generated
- Acoustic emissions are observed during pump flow with colder oil. It is believed that these emissions are caused by static discharge and not associated with gassing.
- Oil pyrolysis (chemical change as a result of heat) and core winding irregularities produce acoustic emissions.

Data filtering techniques allow separation of the relevant and non-relevant acoustic emission data. There are several filtering schemes that are used for different situations. Also, by making use of the newer digital signal processing techniques, the accuracy and speed of analysis has improved. Testing transformers in situ can produce a large amount of data if the transformer is acoustically active. The speed and accuracy of data analysis is critical.

There are several different sources of acoustic emission that can be detected within a transformer. They can be classified as burst emissions and continuous emissions.

5.5. Motor analysis techniques

Monitoring electric motor condition inevitably involves determining the extent of electrical insulation deterioration and failure. Traditional insulation tests have concentrated on the ground wall, with a common test being insulation resistance. Less attention is paid to turn-to-turn or phase-to-phase insulation, yet there is evidence that deterioration of this thin film is also a major cause of motor failures.

5.5.1. Electrical surge comparison

Surge comparison testing can be used to identify turn-to-turn and phase-to-phase insulation deterioration, as well as a reversal or open circuit in the connection of one or more coils or coil groups. It has been used for years as a quality control test in motor manufacturing plants, and development of portable test instruments now allows this testing to be conducted on a troubleshooting and condition based maintenance basis.

Looseness, motion and wear of insulation develop as a result of stresses applied to the motor windings in service. Stresses include: differential thermal stress, different coefficients of expansion, varnish weakening at high temperature, and magnetic force due to winding currents. Thin insulation is least able to sustain this wear; and as a result, turn-to-turn and phase-to-phase shorting often occur prior to deterioration of ground wall insulation.

The surge comparison test can identify excessive wear by applying a transient surge at inherently high frequency to two separate but equal parts of a winding. The resulting voltage waveforms reflected from each part are displayed on an oscilloscope. If both windings are identical, each waveform will be exactly superimposed on each other, so that a single trace will appear on the screen. If, however, one of the two winding segments contains a short circuit, or a reversed or open coil, the waveforms will be visibly different.

Once a problem is detected, it is necessary to determine which of the segments it is located in. This can be done by comparing each segment to a third segment, and noting which combination produces the same waveform deflections. Generally, shorted or missing turns will cause fairly small differences in waveform amplitude. Misconnections such as coil reversal or interphase shorts tend to cause large differences or irregularities in waveform shape. An experienced test operator can therefore gauge the type and severity of the fault.

With the surge comparison method it is often possible to determine the voltage at which turn-to-turn or phase-to-phase conduction begins. If this shorting is near operating voltage, then the motor has a serious insulation fault and should be replaced as soon as possible. If shorting is not detected up to twice operating voltage plus 1000 V, the winding is considered good and the motor can be returned to service.

Unlike other predictive techniques, surge comparison produces no numbers which must be plotted or trended to identify a problem. Like a high-potential test, this is simply a pass/fail procedure. Spot checking can be cost effective for critical or expensive electrical motors; however, it may also be effective for less critical or balance of plant equipment.

Additional information can be obtained by monitoring electric motors on a periodic basis, for example once every 3-6 months. Over time, surge comparison testing can provide a more subtle indication of insulation deterioration; allowing personnel to project acceptable electric motor performance into the future. This advance notice means that developing problems can be identified and repaired during normal shutdowns, rather than allowing a machine failure to cause unscheduled downtime.

Long term surge comparison analysis and trending can be used to identify improper motor repair practices, either in-house or at a repair shop. In that regard, surge testing can be an effective quality assurance test prior to acceptance of motors that have just been repaired. Long term surge comparison data trends can also be used to identify improper operating conditions, such as continually running equipment beyond design specifications. The trended information can be used to compare similar equipment from different manufacturers, to determine if there are design benefits or flaws that can provide increased service life, improved operating performance, or reduced maintenance costs.

Surge comparison testing is a moderately complex and expensive condition based maintenance technique. The test instrument, though very versatile, is moderately expensive, and it requires a trained and experienced operator for the most effective results. Although often used on stator windings of either induction or synchronous machines, the test is equally useful on dc armatures or synchronous field poles. Most surge comparison test equipment is also capable of performing high-potential tests.

The primary short term economic benefits from this testing do not come from reducing the number of electric motor failures; but rather from identifying problems early enough so that maintenance can be efficiently planned and scheduled. These benefits can be substantial, with some companies paying for the investment in less than a year by identifying one or two critical electric motor problems.

Attempts have been made to correlate more closely the conduction voltage to useful life remaining, but these correlations are complicated by differences in stresses on insulation during motor operation. For example, a motor which cycles frequently and/or starts under heavy load will not run long with even slightly deteriorated insulation; while a motor that starts infrequently and is lightly loaded can operate with a high level of insulation deterioration.

Surge comparison testing cannot evaluate one coil by itself; since it is a comparison test, it requires careful repetition to determine the location and severity of an observed fault. Still, surge comparison is a very useful and cost effective technique to identify turn-to-turn and phase-to-phase insulation deterioration, and reversal or open circuit in the connection of one or more coils or coil groups.

5.5.2. Motor current signature analysis

Motor current signature analysis (MCSA) provides a non-intrusive method for detecting mechanical and electrical problems in motor driven rotating equipment. The basis for MCSA is that an electric motor driving a mechanical load acts as an efficient, continuously available transducer. The motor senses mechanical load variations and converts them into electric current variations that are transmitted along the motor power cables. These current variations, though very small in relation to the average current drawn by the motor, can be monitored and recorded at a convenient location away from the operating equipment. Analysis of these variations can provide an indication of machine condition, which may be trended over time to provide an early warning of machine deterioration or process alteration.

MCSA has found application within a broad range of plant machinery. Motor current signals can be obtained remotely, typically at a motor control center. The signals are obtained non-intrusively with a single split jaw current probe placed on one of the power leads. Because no electrical connections need to be made or broken, the hazard of electrical shock is minimized. The resulting raw signal is amplified, filtered and further processed to obtain a measurement of the instantaneous load variations within the drive-train and ultimate load.

A comparison of motor current and mechanical vibration signatures obtained simultaneously from a motor operated valve provide similarities and distinctions. Both spectra contain frequency peaks corresponding to the motor speed, worm gear tooth meshing, and its harmonics; though the amplitude relationships are different.

One distinction is that there is a strong spectral component in the motor current signature that is defined as the slip frequency. This signal is a general characteristic of AC induction motors and reflects the rate at which the spinning armature continually falls behind the rotating electrical field generated by the motor's field windings (no such peak appears on DC motor signatures). Since this motor slip frequency component is electrical rather than mechanical in origin, it has no vibration counterpart and it is not present in the vibration spectrum.

Information can also be obtained by monitoring machinery once a month or once a quarter. Periodic motor current signature analysis can provide a more subtle indication of bearing, packing, coupling or gear wear; allowing personnel to project acceptable machine performance into the future. This advance notice of developing problems means that they can be repaired during normal machine shutdowns, rather than allowing a failure to cause unscheduled down time. Since problems are detected when they are relatively minor, they are usually less expensive to repair.

Long term motor current signature analysis can be used to identify improper maintenance or repair practices. These can include improper seal/packing installation, improper bearing or gear installation, inaccurate shaft alignment or imprecise rotor balancing. This information can be of particular importance in reducing recurring machine problems.

Long term trends can also be used to identify improper operating conditions, such as continually running equipment beyond design specifications. They can be used to compare similar equipment from different manufacturers to determine if there are any inherent design flaws or benefits that can be reflected in increased service life.

Motor current signature analysis is one of the moderately complex and expensive predictive techniques. The complexity stems in large part from the relatively subjective nature of interpreting the spectra, and the limited number of industry-wide historical or comparative spectra available for specific applications.

In the last several years the technique has been simplified and this has improved the technique from a data collection and analysis standpoint, and significantly increased the amount of practical field experience. The technique is particularly useful due to its non-intrusive nature. Measurements can be taken without the need to make or break electrical connections, and shut down or open up machinery. This eliminates equipment downtime for inspection, and improves personnel safety. In addition, since readings can be taken remotely, the technique can be more conveniently and safely performed on large, high speed, or otherwise hazardous machines.

5.6. Motor operated valve testing

The purpose of MOV performance testing is to confirm that the setup and operation of an MOV is within acceptable limits. The acceptance criteria for MCC based performance testing may be derived from the baseline test data.

Once the acceptance criteria have been established, static performance test results are used to periodically evaluate actual MOV performance against the established acceptance criteria. Periodic static performance testing is not intended to re-affirm the acceptance criteria, but simply the existence of acceptable margin.

Each of the MCC-based technologies start with measurement of supply current, supply voltage and switch actuation times at the MCC. These signals are combined electronically or in software to create meaningful measurement parameters.

Several approaches with regards to application of the measurement parameter are discussed below.

5.6.1. MPM equivalent thrust methodology

The EQT methodology uses motor power data acquired at the MCC and a thrust trace acquired at the valve to determine the thrust at torque switch trip for certain MOVs. There are no limitations placed on the amount of time that may have lapsed since the baseline thrust test and subsequent MCC tests.

The EQT methodology takes advantage of the rigid mechanical MOV system, the relatively constant speed of the MOV motor under running load conditions (i.e. packing load) and the repeatable nature of the motor's torque versus speed relationship in order to quantify the thrust at torque switch trip for periodic performance testing. The thrust trace is analyzed in order to determine the amount of time between the point indicating hard seat contact and rapid loading begins and the torque switch trip point where the motor is de-energized.

The corresponding thrust/time relationship is established as well as the fixed running load (packing load) prior to hard seat contact. At a later date, motor power data acquired at the MCC is analyzed in order to determine the amount of time between hard seat contact and the torque switch trip point. The thrust/time relationship that was established during the thrust test plus the fixed running load from the thrust test is used to determine a new thrust at torque switch trip value.

The MPM EQT software generates an equivalent thrust signature that can be overlaid with the baseline data. Since the power data is often cyclic, it is smoothed with a fourth order polynomial and the median value is used to create the EQT signature.

In order to maintain EQT methodology accuracy, the thrust load rate during seating must remain relatively constant over time.

The EQT methodology has only been validated for Limitorque SMB rising stem actuators with AC motors that are torque switch controlled in the closed direction. Therefore the accuracy statement and validation only apply to close direction total thrust at torque switch trip values for these actuators.

Although EQT results are not validated for other applications, motor performance data can still be obtained and trended on these actuators from the MCC.

The identification of hard seat contact is a critical issue when using the EQT methodology. If hard seat contact is not or cannot be properly identified, it can affect the accuracy of the thrust determined by the EQT methodology. Use of concurrent power data obtained during the thrust test helps the analyst in identification of signature features necessary for proper rapid loading begin placement.

5.6.2. MC^2 motor torque

The MC^2 System includes a software algorithm that calculates motor output torque from input motor power, motor current and other nameplate and motor curve data. The motor torque model makes adjustments for inertial effects, stray load losses, and I2R losses.

Two different motor torque analysis methods have been developed and validated for periodic static performance testing of MOVs.

Motor Torque Methodology

The motor torque method employs the time based motor torque history that was generated from motor electrical data acquired during an MCC based test. The motor torque data is used with the Limitorque design performance equations to calculate actuator torque and thrust.

Based on the Limitorque sizing and selection procedures, the relationship between stem thrust and motor torque is best described by the following equations:

Actuator Torque = Motor Torque X Ratio X Efficiency* (1)

Thrust = Actuator Torque/Stem Factor

or

Thrust = Motor Torque X Ratio X (Efficiency/Stem Factor)

* Efficiency is inclusive of application factor

The MC^2 motor torque data can be converted to actuator torque using a representative actuator efficiency value. The resulting actuator torque can be converted to thrust by dividing actuator torque by a representative stem factor. Under certain conditions it is also appropriate to combine efficiency and stem factor data as one term when assessing MOV performance margin.

Site specific actuator efficiency and stem factor data should be used. When site specific information is not available the test equipment OEM recommends use of pullout efficiency and application factor when converting motor torque to actuator torque.

The Correlation Methodology

The correlation method requires a simultaneous MCC and at-the-valve test. Data from this test is used to create a linear curve fit relationship between motor torque and actuator output torque and/or stem thrust. A representative correlation coefficient is developed. The correlation coefficient is mathematically equal to the product of gear ratio, actuator efficiency and stem factor. These correlation coefficients can be applied to subsequent motor torque signature sets to generate correlated stem thrust and actuator output torque signatures.

The correlation coefficient should be adjusted to account for expected degradation over time.

The MC^2 motor torque accuracy has not been validated for all motors used on Limitorque actuators. The motor torque method is currently limited to Reliance AC motors up to and including 60 ft-lb. The estimated motor torque data can still be created given the proper inputs for motors that are not included in the motor torque validation. However certain restrictions are placed on use of motor torque data for non-validated motors. This data can be used for trending purposes and in the correlation method. The correlation method has been validated for all Limitorque SMB, SB and SBD actuators with AC motors.

The motor torque method requires knowledge of actuator efficiency and stem factor history in order to produce reliable results. The correlation method requires an initial, parallel, at-the-valve and MCC test in order to establish the overall relationship between motor torque and actuator output thrust. Both methods must assume degradation of stem factor and actuator efficiency to properly assess actuator output torque and/or thrust.

5.6.3. NEET method

NEET (Non-invasive Evaluation of Electric Torque) method calculates electric output torque of three phase induction motors. NEET method is developed on the basis of several assumptions. First, the stator windings are assumed to be sinusoidally wound so is to couple only to the fundamental-space-harmonic component of air-gap flux. Second, the self-inductances of the rotor are assumed not to vary with rotor angular position. Finally, linear magnetics are assumed.

Under these assumptions, the air-gap torque produced by a two-phase induction motor that can be transformed from the three-phase induction motor is given by:

$$T_E = P(\lambda_{s\alpha} i_{s\beta} - \lambda_{s\beta} i_{s\alpha}) \qquad (2)$$

where $\lambda_{s\alpha}$ and $\lambda_{s\beta}$ are the flux linkages of the two stator phases $i_{s\alpha}$ and $i_{s\beta}$ are the currents of the two stator phases and P is number of pole pairs. The currents $i_{s\alpha}$ and $i_{s\beta}$ can be directly measured at the stator terminals. The flux linkages can also be determined from terminal measurements. For a two-phase machine,

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = R_s \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \lambda_{s\alpha} \\ \lambda_{s\beta} \end{bmatrix} \qquad (3)$$

where $v_{s\alpha}$ and $v_{s\alpha}$ are the two stator voltages and $R_{s\alpha}$ is the stator phase resistance. Thus, the motor torque is expressed only in terms of stator variables that can be measured in the MCC.

5.6.4. NEST method

The NEST method calculates the stem thrust based on the motor torque and the stem displacement. The motor torque can be estimated by NEET method as described in the previous section and the stem displacement can be obtained using the motor speed and the dimensions of the moving components.

The NEST method is developed on the basis of a major assumption: the rigidity of an MOV does not change with time. This means that the increasing rate of torque with respect to the stem displacement during the valve seating does not change. If it is assumed that the rigidity does not change and there is no degradation, the slope of torque with respect to the stem displacement during the valve seating of both baseline case and later case coincide each other. However, it is worthwhile to recognize that the rate of change in the stem thrust with respect to time does change even though the rigidity does not change since the motor speed which is related to the stem displacement may change due to degradation of the motor.

Based on the assumption, the efficiency of the transmission mechanism can be estimated. As the efficiency of the transmission mechanism degrades, more motor torque is needed in the stroke. Therefore the slope of the motor torque signature increases, which gives us a good indication of the change of efficiency. Once the efficiency is obtained based on that of baseline condition, the stem thrust can be calculated using the motor torque and the efficiency as shown in Eq.(1).

Additionally, the NEST method considers the inertia effect of moving parts after the motor is de-energized. Therefore, it estimates the stem thrust for the entire opening and closing stroke including the thrust increase due to the inertia.

5.7. Other techniques

Numerous other non-destructive techniques can be used to identify incipient problems in plant equipment or systems. Therefore, these techniques are used as the means of confirming failure modes identified by the condition based maintenance techniques identified in this chapter. Other techniques that can support condition based maintenance include acoustic emissions, eddy-current, magnetic particle, residual stress and most of the traditional non-destructive methods. If you need specific information on the techniques that are available, the American Society of Non-destructive Testing (ANST) has published a complete set of handbooks that provide a comprehensive database for most non-destructive testing techniques.

5.7.1. Coil current monitoring system

As one of other techniques, the on-line coil current monitoring system (CCMS) for the magnetic jack type control rod driving system (CRDS) is introduced for the effective and predictive maintenance of CRDS. All coil currents of selected CRDSs are monitored and acquired automatically at high speed sampling rate depending on the CRDS movement. The acquired coil current data is automatically analyzed to check the timing sequence of CEDM (control element driving mechanism) motion, coil current amplitude and pattern mismatch of waveform. The various analytical results and diagnosis information of abnormal conditions are provided on MMI displays. For a more precise analysis, the CCMS provides various data manipulation tools of noise filtering, data comparison and database generation for automatic fault detection. The CCMS has shown that it is very useful to diagnosis quickly and exactly the status of many control components of the CEDM and CEDMCS (Control Element Driving Mechanism Control System) such as CEDM coils, hall effect current sensor, timing control cards, voltage adjustment cards and Silicon Controlled Rectifier (SCR). If enough coil current data are accumulated historically, the degradation trends of CEDM coil, hall effect current sensor, voltage adjustment card and SCR can be predicted more exactly. Abnormal or degraded control components identified by the CCMS can be calibrated or replaced before their failure which may cause a severe problem.

6. RESULTS REPORTING

The purpose of a condition based maintenance programme is to communicate information about the condition of the machinery under surveillance. The condition based maintenance report should include only information that helps the reader to clearly understand the results of the condition monitoring efforts. The report should include:

- An equipment status report including operating availability and component availability
- A priority work list including work pending, work in progress and work completed
- Status definitions for satisfactory, marginal and critical
- A summary of the operating status of each component to include fully operational, marginal, critical, and inoperable
- Individual equipment status reports for equipment that is marginal or worse

The report serves two primary functions:

- It provides a valuable source of information for plant maintenance, operations, and engineering.
- It continually shows the impact of condition based maintenance on the plant to upper management. This line of communication justifies the programme and allows for continued management support.

The reporting period is determined by the needs of the plant but should be prepared at least annually. It is important to note that the report should not contain any raw data collected from a diagnostic system. It should be concise and clear.

The following elements should be included in a condition based maintenance periodic report:

- **Management summary** - Provide a synopsis that highlight the activities performed during the reporting period. When possible, use photographs of actual plant conditions that illustrate successes.
- **Equipment performance** - Provide a list of equipment that condition based maintenance indicates is in an abnormal condition and has been placed on an alert or watch list. A windows format and supporting documentation could be used to identify equipment condition. Also indicate in this section those pieces of equipment that have been removed from the alert or watch list.
- **Information sharing** – Provide a section to be used by condition based maintenance personnel to explain various aspects of the programme or to share examples where assistance has been provided to other station departments.
- **Cost-benefit** – Provide cost savings that are attributed to condition based maintenance activities. Consider costs that were avoided because equipment replacement, maintenance labour hours, and purchase of replacement power were not needed.
- **Continuous improvement and operating experience** – Provide discussions on new technologies and training received by condition based maintenance personnel. This section could also be used to document any internal or external examples of operating experience factored into the condition based maintenance programme.

Other components of reporting results are developing a watch list and programme metrics.

6.1. Watch list

Components included on the equipment watch list exhibit conditions that warrant additional attention. These conditions may range from the earliest subtle stages of degradation that do not warrant corrective maintenance, to advanced final stages of degradation that warrant immediate maintenance. Any of the three predictive maintenance disciplines (vibration analysis, thermography, and oil analysis) may be used in this determination.

Components may be removed from the watch list when their condition no longer warrants increased attention. Removal may occur as a result of maintenance, changes in operating condition, or condition re-evaluation.

6.2. Programme metrics

All nuclear plants have extensive goals and metrics to indicate effectiveness of plant programmes and processes and to measure progress toward desired improvements. These metrics do not always relate to the effectiveness and progress of the CBM programme itself. Therefore, it is useful to have a clearly defined set of performance measures that specifically relate to the CBM process.

CBM programmes are judged with performance indicators that reflect performance and trends. A best practice set of metrics is as follows:

1. Four important cost areas:
   a. Equipment reliability and unit availability
   b. Operations and maintenance costs
   c. Capital expenditures
   d. Thermal unit performance

2. Maintenance task balances among unplanned CM (corrective maintenance) tasks that are totally reactive, planned CM on run-to-failure equipment, repetitive PM tasks, and condition directed tasks that are planned CM or PM tasks initiated as a result of decisions from the CBM process. Planned CM is defined as situations where equipment has been predetermined as run-to-failure or condition monitoring has detected degradation of the equipment and allowed time for proper planning and optimum scheduling of the task.

3. Return on investment for CBM activities.

4. Effectiveness in implementing the CBM process.

An example of a condition based maintenance programme metrics is provided by TXU's Comanche Peak Steam Electric Station is shown in Table 8.

7. CBM PROGRAMME ASSESSMENT

The core technologies of oil and grease analysis, vibration monitoring, and thermography are used to varying degrees at most nuclear power sites. The CBM self assessment programme provides guidelines for determining the effectiveness that the technologies are being employed and identifies opportunities for improvement. Additional CBM technologies that are used within the CBM programme, that are used by other groups within the plant, or that are not used but are expected to be cost effective, are included unless specifically excluded from the assessment.

Interaction between the CBM group and other stakeholders is evaluated to determine where interfaces exist and how information is being exchanged. The effectiveness of the information exchange and corresponding use of data is evaluated. Areas for enhancement are identified.
For nuclear plant applications, the assessment is structured around 14 focus areas. These 14 areas have been found to completely and effectively address the entire scope of the CBM process. These 14 areas are listed in Table 9 and described below:

Table 8. Examples of PdM Key Performance Indicators

Performance Parameter	Indicator	Target
Data Collection	Number of delinquent data collection PMs	0
	Number of surveillance tests repeated due to errant vibration data	0
	Percentage data collection of total PdM components – Motor Analysis Programme	100%
	Percentage data collection of available PdM components – Motor Analysis Programme	100%
	Percentage data collection of total PdM components – Thermography Programme	95%
	Percentage data collection of available PdM components – Thermography Programme	98%
	Percentage data collection of total PdM components – Vibration Programme	95%
	Percentage data collection of available PdM components – Vibration Programme	98%
Data Analysis	Number of occurrences of unidentified equipment degradation within PdM scope	0
	Lube Oil Sample Backlog	80% ≤ 2 weeks 0% > 4 weeks
Equipment Reliability	Percentage of undetected failures of PdM scope components	<1.0%

Table 9. Fourteen CBM Assessment Areas

1. PM Task Technical Basis
2. Technology Application
3. Process Flow Definition
4. Programme Leadership and Coordination
5. Organization, Roles, and Responsibilities
6. Information Management and Communication
7. Equipment Condition Assessment and Decision Making
8. Training and Qualifications
9. CBM Work Prioritization and Scheduling
10. Work Closeout and Maintenance Feedback
11. Goals and Performance Metrics
12. Calculation of Cost-Benefits and Return on Investment
13. Customer Satisfaction
14. Continuous Improvement

7.1. PM task technical basis

Condition monitoring data collection tasks should be considered as a vital part of an integrated PM programme for plant equipment. Such tasks are generally preferable to repetitive PM or surveillance tasks. This situation is true when the condition monitoring task is applicable and can cost effectively prevent failures or predict the timing of necessary refurbishment. Also, when the surveillance requires operation or intrusive activity on equipment. As such, they should have scope and intervals determined to be appropriate considering the functional criticality, service environment, and duty cycle of the equipment.

The determination of applicability and frequency of equipment condition-indicating technologies should be in accordance with industry PM technical basis guidelines. Certainly, the CBM tasks should not be done in addition to other tasks that protect against the same degradation mechanisms. CBM tasks should be optimized and justified together with other PM and monitoring for the same equipment. The process should be documented.

Some assessment interview questions are:

- Are personnel comfortable extending intrusive PM task intervals based upon condition monitoring activities?
- Do deferrals receive the correct approval?
- Are the scope and frequency of CBM tasks documented in the PM technical basis?

- Does the basis consider criticality, duty cycle, and operating environment?
- Is a continuous or periodic process in place for updating the maintenance basis with learning from condition monitoring?
- Is a process in place to use condition data to extend intervals of intrusive PM tasks?
- Are CBM task frequencies based upon providing early detection of equipment degradation?
- Is CBM considered an effective corrective action for maintenance rule failures or goal setting for the maintenance rule?
- Is there a documented technical basis that describes the failure modes and degradation mechanisms addressed by the PM tasks?

7.2. Technology application

The CBM technologies are at the heart of the CBM process. Standard technologies should be in widespread use and competently applied. Hardware should be state of the art and in good condition. Procedures and guidelines should exist. Mechanisms should be in place to identify and evaluate new technologies for application to the CBM programme. The following are considered best practice criteria:

7.2.1. Oil and grease analysis

- Condition data from oil analysis can be used to monitor not only the quality of the lubricating oil but to make judgments regarding the condition of equipment. New oil reference samples are used for comparison and alert/alarm level determination and adjustment.
- Lubricating oil is changed only when analysis shows degradation of lubricant properties or accumulated wear particles (normal wear).
- Oil analysis sample taps are utilized to increase programme consistency, repeatability of samples, and lower labor costs.
- Sample locations are selected based on system design.
- Analysis results from labs are transmitted to the customer in 24–48 hours. The results are electronically mailed to the site with trending data through the use of common software supplied by the laboratory.
- The analysis testing package is tailored to the type of equipment being monitored, including items such as large particle analysis, where applicable.
- Oil filtering equipment is used, where applicable, to further increase oil change intervals.
- The manufacturer nominally ± 10% determines viscosity limits.
- Baseline comparison levels are determined by new oil sample analysis.
- Large particle wear analysis is used to monitor equipment condition.
- Alarm and alert levels are established using ISO and ANSI standards as a basis.

7.2.2. Vibration monitoring

- Vibration data are trended for subtle anomalies and integrated with other condition-based information.
- Periodic reports are prepared for all equipment monitored by the programme.

- Initially, all reports are routed to a CBM coordinator. Problem condition reports are routed to the equipment owner (system/component engineer) and to the CBM coordinator.
- The CBM vibration technology owner is responsible for coordinating data, assigning problem severity, initiating action, coordinating post maintenance follow-up testing, documentation distribution, and case closure.
- Coordination of vibration monitoring data and lube oil analysis data is important. One technology serves as an important backup to the other. With careful coordination, significant increases in value will result.
- Alarm and alert levels are established using ISO and ANSI standards as a basis.
- Equipment history is used to tighten alarm and alert levels to achieve optimum equipment performance and life.
- Vibration data are integrated with other condition data to assess equipment condition.
- Vibration baseline values are established in post-maintenance tests.
- Post-maintenance baseline values are taken for major components.

7.2.3. Infrared thermography

- Pre-survey meetings are held with equipment owners and operations to ensure information exchange about subtle equipment anomalies.
- Post-survey meetings are held with equipment owners and operations to ensure that information about each survey is conveyed in a timely manner.
- A database programme is used to maintain route lists of equipment to be inspected, maintain baseline images, and generate reports.
- Inspection reports are prepared after each survey and conveyed to the appropriate groups.
- Follow-up actions are taken with maintenance to gather information regarding the as-found condition of equipment that was identified in the report as exhibiting thermal anomalies.

7.2.4. Electric motor predictive maintenance

- Periodic electrical tests are performed on all critical motors, in addition to routine vibration, lube oil, thermography surveys, and insulation resistance testing.
- EMPM data are gathered and integrated. Data should include off-line meggars and high pot testing. Parameters recommended for trending include motor starts/stops (if available), amps, winding temperatures (if available), and run time hours. Periodic diagnostics applied during equipment operation include:
    - Motor current
    - Vibration
    - Thermography
    - Oil analysis
- Motor maintenance traceability is maintained both in-house and at vendor facilities.
- EMPM reports are prepared on a periodic basis.

7.2.5. Ultrasonic and acoustic leak detection

- Ultrasonic and acoustic leak detection technology owners should perform surveys on critical plant valving, compressed air and gas systems, and other applicable equipment.
- Survey routes are established and performed with input from the plant CBM coordinator, engineering, and maintenance personnel.
- Acoustic leak detection data are integrated with infrared thermography and other CBM data.
- Reports are prepared after each survey and distributed to the appropriate work groups.

7.2.6. Example assessment interview questions are:

- Are equipment owners knowledgeable of CBM technology applications, and do they have reference materials for baseline-prescribed tasks?
- Is condition data history stored and trended on important equipment?
- Are baseline data available for comparison?
- Is analysis of new data timely and comprehensive—including complementary technologies?
- Does a controlled maintenance basis maintain updates, changes, and applications of condition monitoring tasks?
- Are alert and alarm conditions established for important equipment—are ISO or ANSI standards referenced or utilized?
- Are alert levels tightened based upon data history?
- Are equipment data collection points marked/specified for consistency, repeatability, and ease of collection?
- Is data collection equipment tested/calibrated on a periodic basis?
- Are data from operator rounds included as condition data and part of the process?

7.2.7. Process flow definition

The CBM process includes not only the CBM group, but also its interfaces with engineering, maintenance, operations, and work planning and control groups. These interfaces are equally important to the effectiveness of CBM as the technologies themselves. The process should be well defined and well understood by those performing the work. In addition, the processes should be documented and supported by procedures and guidelines.

The best practice is that procedures, guidelines, and flow charts depicting key activities, information flows, and roles of plant personnel in the CBM process are available. Further, the process is well understood and internalized by programme participants. Charts serve as shorthand for how the plant CBM process operates.

Some assessment interview questions are:

- Is a programme/process manual that describes goals, roles, responsibilities, and process flow available and understood by those participating in the process?

- Are guidelines or procedures for technology applications utilized? Are topics such as equipment operating instructions, data storage and reporting processes, alarm and alert levels detailed?
- Is a process flow chart available that summarizes the process or shows the flow of information and decision making? Does the flow depict actual conditions and do participants understand it?
- Are programme scope limitations and boundaries defined?

7.3. Programme leadership and coordination

Individuals should be identifiable as CBM technology owners and as CBM coordinators responsible for knowing equipment condition and performance. These individuals should be visibly applying and promoting the CBM process. Management support for the CBM process should be visible.

CBM is generally not regulatory driven. Therefore, it must be management driven. Both enhanced implementations of CBM technologies and enhanced utilization of the results by other plant organizations will not occur if the plant staff does not perceive that CBM has a high importance to plant management.

Also, reliance on CBM for decision making is perceived as higher risk. This perception of high risk, without an incentive to assume that risk, results in a staff unmotivated to advance the use of CBM.

The best practice is that the maintenance strategy is well understood and can be articulated by management. Symbolic acts are planned and orchestrated by management in order to model and legitimize desired behaviors and to accelerate new programmes in their development. There is a CBM supervisor or coordinator who promotes the use and integration of CBM.
Some assessment interview questions are:

- Is station management knowledgeable and supportive of the role of the CBM process?
- Does an entity—CBM coordinator, work group, department, or supervisor—have ownership of the CBM process to ensure continued growth and development?
- Is there a process and/or person responsible for coordinating action on early indications of equipment trouble?
- Are adequate resources (training and equipment) provided to personnel both for technology applications and plant processes to work?

7.4. Organization, roles, and responsibilities

Roles and accountabilities in the execution of the CBM process should be well defined and clear of any ambiguity. Individuals should be aware of and should support these roles. Evidence should exist that responsibilities are being carried out as defined. There should be real accountability for these responsibilities.

CBM programmes reside in various organizations at different plants. They can be part of system engineering, support engineering, maintenance, or maintenance engineering. Different technologies can be within different groups, even when these technologies must be integrated for complete condition assessment of a single piece of equipment.

There can be a CBM coordinator over several technologies or the technology experts can have no formal coordination. Data collection can be performed by various operations personnel, by a small group of dedicated technicians, or by the technology engineers. Finally, the equipment owners can be responsible for analysis of CBM data and action determination or the primary responsibility for analysis can lie with the CBM technology owner.

Each of these and other decisions about organization and responsibility can influence the effectiveness of CBM. Roles and accountabilities in the execution of the CBM process should be well defined and clear of any ambiguity. Individuals should be aware of and should support these roles. Evidence should exist that responsibilities are being carried out as defined. There should be real accountability for these responsibilities.

A best practice is that the quality and consistency of CBM data collection are assured by the training and assignment of conscientious technicians. Responsibilities of the CBM technology engineers do not preclude having adequate time for quality and timely analyses. The CBM engineers are confident that the CBM analyses are properly considered in corrective action decisions. Plant equipment owners are identified and sponsored by the respective management to own and sponsor maintenance decisions. An optimum level of coordination between CBM and condition monitoring activities is taking place, preferably by a CBM coordinator.

Some assessment interview questions are:

- Is there a document that succinctly defines roles and responsibilities of personnel?
- Are roles and responsibilities clearly understood?
- Are roles, behaviors, and general expectations for equipment and technology owners established, monitored, and corrected?
- Are equipment owners and technology owners clear about the responsibilities they have?
- Does the CBM function report appropriately in the organization? Is it given attention and access to management support and collaboration with groups having complementary responsibilities?
- Are individuals held accountable for poor results from lapses in responsibility?

7.5. Information management and communication

Condition monitoring information should be efficiently entered into databases. Condition information should be accessible in a timely and integrated manner with effective user interfaces. Information relating to the suitability of the equipment for continued operation should be effectively communicated to equipment owners and operating personnel. Also, varying levels of awareness of CBM programme activities, goals, roles and responsibilities, and results should be effectively communicated to the appropriate plant and support personnel.

The very heart of a CBM programme is taking data on equipment condition, turning the data into new and useful information, and taking appropriate action on the new information. Figure 11 illustrates the process.

Gathering the data, performing analysis, integrating data from multiple technologies, and specifying action are new activities for many organizations. PM and CBM programme coordinators, CBM technologists, system engineers, component engineers, maintenance planners, and maintenance rule personnel all need access to records of condition data and history of action taken. Processes must be put in place to make this task manageable for plant personnel. Information relating to the suitability of the equipment for continued operation should be effectively communicated to equipment owners and operating personnel. Also, varying levels of awareness of CBM programme activities, goals, roles and responsibilities, and results should be effectively communicated to the appropriate plant and support personnel.

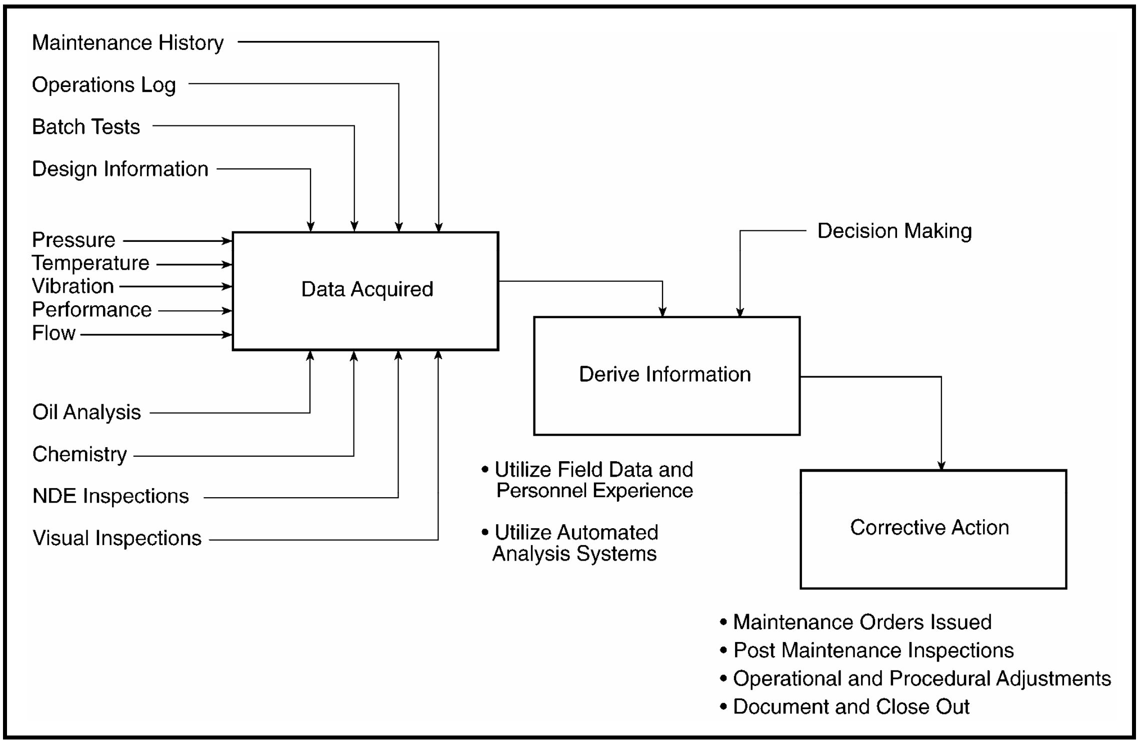


Fig. 11. Information Flow for CBM Condition Monitoring.

A best practice is that information integration tools are used to make data collection, monitoring, and analysis available on a broader basis for plant-wide decision making. The software has the capability to be updated by analysts, accept recommended actions, and is accessible to various users to provide an overall assessment of current condition of the critical plant equipment. Systems are capable of accepting common, one-time entry of information on costs, physical descriptions, and identifications that can be permanently stored in the database and easily retrieved for future reference. Actions are recorded and case histories maintained.

Some interview questions are:

— Are all parameters of condition monitoring listed or available for high priority equipment?
— Is summary information of technology/process/parameter monitoring that reflects status of data evaluation available?
— Is summary information, reporting equipment on the CBM watch list and actions in progress, available and reported to management?

— Is action—as a result of equipment anomaly indications—assigned, coordinated, and tracked?
— Is equipment condition data stored centrally and easily available to all personnel with need?
— Is data integration from multiple technologies performed?

7.6. Equipment condition assessment and decision making

Condition monitoring data should be trended and analyzed. Trained analysts should use analysis software where appropriate. There should be a process in place to generate and distribute equipment condition reports including a technology-integrated status of anomalies for equipment owners to review.

It should be clear who is making decisions to act, based on indications of equipment condition. Such decisions should be made in a timely manner among personnel taking and analyzing data, owners of equipment, and personnel responsible for assigning, planning, and performing maintenance tasks. There should be a strong working relationship and trust among these personnel.

Best practice plants have controls in place to consistently collect high quality data on schedule, for all relevant equipment, for all CBM technologies. Also, best practice plants create an equipment condition report with all condition indicators for each important piece of equipment. The report clearly identifies degraded conditions or adverse trends. The report is distributed to all work groups. The plant corrective action programme is used to document deficiencies discovered during CBM activities.

Equipment and technology owners function "as one" in the process of monitoring equipment condition. People in both roles rely heavily on the knowledge of the other and are clear about the responsibilities and accountabilities for each. A CBM programme coordinator with regular reports, updates, and meeting processes facilitates interaction. All sources of condition data are utilized, not just vibration, oil analysis, and thermography. Decisions to take corrective action based on CBM data and analysis appropriately involve the equipment and technology owners.

Some assessment interview questions are:

— Are CBM data collected on schedule and of a consistently high quality?
— Is data collection frequency and consistency adequate to establish a baseline condition?
— Are the data trended to detect undesirable degradation?
— Are there appropriate alert and alarm levels?
— Are data reviewed and analyzed in a timely manner?
— Is condition monitoring data reported in an integrated report for all technologies by component?
— Are anomalies and indications of degraded condition clearly presented?
— Are operations personnel notified of degraded performance in a timely manner?
— Is it clear who makes decisions about equipment from condition data and it is understood in the organization? Is there an "owner" of the equipment? Do they take responsibility?

- Is all available information on a component available and utilized prior to decision making?
- Are operations, maintenance, technical, and other involved groups consulted? Do they have input prior to maintenance decisions being made?
- Are decisions made in a timely manner?
- Is it clear who the owner(s) of CBM technologies are and whom you go to for action when needed?
- Is it clear who is responsible for expert analysis of equipment condition data?
- Are decisions timely?
- Are decisions trusted?

7.7. Training and qualifications

The ultimate value of CBM technology applications relies on the quality of the data collected, the analysis of the data, and the interpretation of the analysis. Although there is a lack of industry-wide requirements for training and certification for each of these activities, an adequate level of training and demonstrated skill is necessary for success. Technologists should be experienced, well qualified, and properly trained to perform CBM process tasks. Other persons who use the technology and its results should have adequate understanding of CBM technologies and the meaning of the results that may be reported to them. Management should support certification of personnel in CBM technologies. Critical activities should require formal certification.

A best practice is that the plant staff has received CBM programme level-of-awareness training. Technology owners are certified to Level II or higher for their areas of responsibility. Equipment owners have had technology overview training on CBM technologies. CBM technicians are Level I certified in areas of technical responsibility.

Some assessment interview questions are:

- Are personnel performing analysis of CBM data trained in the use of predictive technologies—Level I, II, or III certifications?
- Are CBM personnel knowledgeable of plant equipment and failure mechanisms?
- Are CBM data collection tasks standardized and simplified so that completion of tasks is not dependent on a limited number of personnel?
- Are all end users of CBM generally aware of the process?

7.8. CBM work prioritization and scheduling

Condition monitoring data collection tasks and collection routes should be well defined, planned, and performed on schedule. CBM data collection and analysis are most often not formally controlled by the maintenance work management system. However, they must be performed at the proper intervals and times to establish adequate baseline values and trends. The plant must be diligent to acquire data from equipment that is often inaccessible. Also, corrective actions resulting from CBM analyses must be scheduled and performed in a timely manner to prevent degraded performance or failure.

The effective use of CBM data and analyses is first manifest by the timely and accurate identification of work and generation of a work order whenever a single CBM data point, a trend of a single parameter, or an integrated consideration of several condition parameters on a component justifies a corrective action. This assessment area examines whether this work identification has been successful at the plant. It also examines whether the formal work process assures continued success. It examines whether, independent of the formal process, there are impediments to this process caused by work culture, organizational inefficiencies, poor information systems, work loads, or other factors.

A best practice is that the CBM monitoring tasks are scheduled and performed on schedule. Schedules are not vulnerable to the availability or workload of a single individual. The work management process is effective at planning and scheduling PMs and CMs called for by the CBM programme. There is a formal, timely, and effective process for work orders to be written based upon CBM data and analysis. Maintenance interfaces with CBM personnel or otherwise understands the CBM basis for a work order prior to work execution when necessary.

Some assessment interview questions are:

- Are CBM tasks scheduled and executed on a regular and consistent basis?
- Are CBM tasks scheduled with a due date and grace period?
- Are CBM tasks outside of grace reprioritized and rescheduled with review and approved by equipment owners?
- Are efficient data collection routes established to maximize productivity of data collectors?
- Are post-maintenance testing/operability checks utilizing CBM technology routine and appropriate? Is a process in place to identify requirements for this?

7.9. Work closeout and maintenance feedback

Closeout of PM tasks, corrective maintenance (CM) tasks, or other corrective actions that result from the CBM process are a necessary element of the CBM process. Timely and thorough closeout not only ensures that the immediate action is correct but also provides information for the continuous improvement element of the CBM process described later. Closeout activities should include documenting as-found conditions and feedback of information to programme, technology, and equipment owners.

A best practice is that the as-found information is recorded in a useful fashion by craft personnel and validated by maintenance supervision. Parts are saved and made available for examination after repairs. Technology owners, equipment owners, and PM programme owners all review the as-found information for desirable CBM changes.

Some assessment interview questions are:

- Are causal data from equipment failures fed back into the condition monitoring plan for equipment?
- Are as-found conditions documented per procedure or work instructions?
- Are craft/technician comments solicited at close out of work orders? Are comments reviewed and acted upon by equipment owners, PM, CBM, and Maintenance Rule coordinators?

— Are unexpected indications of equipment degradation acted upon in a timely manner and tracked through resolution?

7.10. Goals and performance metrics

Goals and performance metrics should be in place, well developed, and designed to link CBM activities and the CBM group to the optimizing of plant maintenance and operations. Stakeholders should be aware of metrics and their relationship to CBM objectives. Metrics should be used for optimization.

All nuclear plants have extensive goals and metrics to indicate effectiveness of plant programmes and processes and to measure progress toward desired improvements. These metrics do not always relate to the effectiveness and progress of the CBM programme itself. Therefore, it is useful to have a clearly defined set of performance measures that specifically relate to the CBM process.

A best practice is that the CBM programmes are judged with performance indicators that reflect performance and trends in:

- The following four important cost areas:
- Equipment reliability and unit availability
- Operations and maintenance costs
- Capital expenditures
- Thermal unit performance
- Maintenance task balances among unplanned CM tasks that are totally reactive, planned CM on run-to-failure equipment, repetitive PM tasks, and condition directed tasks that are planned CM or PM tasks initiated as a result of decisions from the CBM process. Planned CM is defined as situations where equipment has been predetermined as run-to-failure or condition monitoring has detected degradation of the equipment and allowed time for proper planning and optimum scheduling of the task.
- Return on investment for CBM activities.
- Effectiveness in implementing the CBM process.

Some assessment interview questions are:

- Are there formal or informal goals and/or performance indicators associated with condition based maintenance? If so, what are they?
- Do the goals and performance indicators relate to the operating performance of the plant? Guide the programme? If so, how? Examples:
  - X power reductions from material condition
  - X unplanned equipment failures
  - X equipment condition “action reports”
- Do the goals/PIs reflect continued development of the CBM process/programme?
- Are there data on how maintenance tasks are changing from reactive to planned?
- Are there data on equipment reliability/availability?
- Are overall/cumulative vibration levels tracked and trended?
- Are the data periodically reviewed with appropriate members of plant staff?

7.11. Calculation of cost-benefits and return on investment

The results of the CBM programme should be tracked. Case histories, cost-benefits, and contributions to plant performance should be documented, publicized, and used to justify current use and growth of CBM. Management should understand and support the value of these activities. Budget for CBM activities should be clearly identified and should reflect the actual and potential return on investment of the process.

Project experience demonstrates that initiating and maintaining a record of CBM programme savings, cost avoidance, and calculating an ongoing return on investment is necessary for the following reasons:

- Making the costs and savings of the programme public knowledge in the organization keeps plant personnel focused on the CBM activities that contribute value. It drives advancement and improvement of the programme. As the programme becomes successful in reducing costs and improving material condition, personnel react positively and seek to contribute more.

- When other priorities confront an organization, decisions are often made to reduce, limit, or suspend resources devoted to CBM activities in lieu of higher value activities. The view of CBM being an optional part of maintenance strategy without a clear payback to the plant is minimized over time as the financial benefits become widely known and understood.

- The plant is making an investment in the CBM programme and management should expect to see the return to the business.

Also, the budget for CBM activities should be clearly identified and should reflect the actual and potential return on investment of the process.

A best practice is that the return on investment is calculated, well publicized in the organization, and reviewed formally by plant management approximately annually. CBM costs are easily retrieved from plant information systems.

Some interview questions are:

- Are "avoided costs" tracked and publicized?
- Are reduced periodicity or elimination of PM tasks captured and cost savings calculated? Is the information publicized?
- Is the cost of the CBM process captured, annualized, and publicized through a return on investment calculation?
- Are plant personnel aware of the return on investment (ROI) of the CBM programme?
- Are ROI data credible to plant management?
- Are ROI data used by plant management to make decisions relating to CBM programme funding?

7.12. Customer satisfaction

The entire CBM process should support the cost effective and reliable operation of the plant. Persons with specific responsibilities for achieving these operational and cost objectives—management, operations, system and equipment owners—should use and value the CBM process. These end users should be viewed as customers.

Generally, CBM is a service that supports various end-users including operations, maintenance, and system engineering among others. These end-users can be viewed as customers whose satisfaction is a measure of the effectiveness and future support of CBM services. In assessing customer satisfaction, it is necessary to determine if customer expectations are realistic, if the CBM staff understands them and if these expectations are being met.

A best practice is that the CBM staff perceives operations, maintenance, and system engineering as customers and they strive to achieve satisfied customers. Both suppliers and customers understand the expectations, strive to achieve quality service, and value the relationship.

Some assessment interview questions are:

- Does the CBM staff recognize operations, maintenance, and system engineers as customers?
- Can customers state their expectations and are they realistic?
- Does the CBM staff know the current level of customer satisfaction?
- Do CBM staff and customers communicate opportunities to improve the CBM services?
- Are there any serious shortcomings in the way the CBM services are provided to customers?

7.13. Continuous improvement

The CBM process should have feedback and assessment elements to ensure that it continuously or periodically changes in response to plant experience, industry experience, and new technology. Changes in the process to reduce tasks or substitute for PM tasks, improve thermal performance, increase equipment reliability and availability, or prevent costly failures should be identified.

The CBM process is a dynamic area because predictive technology continues to evolve. As it evolves, it becomes more effective at preventing failures and managing the life-cycle cost of equipment. Therefore, continuous improvement is a necessary element of a successful programme. The CBM process should have feedback and assessment elements to ensure that it continually or periodically changes in response to plant experience, industry experience, and new technology. Changes in the process to reduce tasks or substitute for PM tasks, improve thermal performance, increase equipment reliability and availability, or present costly failures should be identified.

A best practice is that the best CBM processes have several formal programmes to assure continuous improvement. These include:

- Self-assessments and performance indicator reviews on a regular basis
- Feedback of plant and industry maintenance and failure experience
- Review of equipment failures to determine if a CBM task could have been used to detect failure
- Investigation of new technologies and new applications of technologies
- Interview Questions:
- Is there a periodic self-assessment process for CBM?
- What are the mechanisms to feedback failure experience to CBM task improvements?
- What are the mechanisms to feedback as-found conditions from PM and CBM tasks to consider CBM task improvements?
- What are the mechanisms to identify recurring problems for root cause consideration?
- How is new technology or new applications identified and evaluated?
- Is operating experience from other plants used to evaluate CBM effectiveness?
- Are cost-benefit and return on investment calculations used to identify CBM changes?
- Is the use of the corrective action programme an integral part of the CBM process?

7.14. Individual technology assessments

7.14.1. Infrared thermography testing assessment

Providing a comprehensive IRT programme requires a defined approach that is designed to meet specific IRT goals. These IRT goals should be driven by the specific plant goals such as availability, equivalent forced outage rate (EFOR), performance (heat rate), etc. Over time, these goals may change due to the operating mode of the plant, as well as technology advancements that may allow for new applications not previously possible. Therefore, it is important to continuously monitor a programme's direction to ensure that it is current with existing plant goals and the technological advancements.

Over the years several methods to monitor a plant's current condition for various programmes, as compared to the industry's best practices have been developed. This method was first started to gauge the effectiveness of a condition based maintenance (CBM) programme. The success of the CBM model has inspired new models to include plant maintenance optimization (PMO) and several technology models (vibration, IRT, lube oil, and motor monitoring). Each model uses industry experts to define the categories and sub-categories to determine what activity is required to achieve a best practice or 'World Class' ranking. The results are tabulated and displayed in the form of a 'spider chart'. The spider chart's best practice grade is considered 'world class' and is numerically graded as an eight (8) for each of the respective categories.

Using the spider chart concept can be used to monitor a comprehensive IRT programme. This chart helps define the requirements of a good IRT programme as determined by the industry experts. Therefore, whether a novice or expert, the spider chart provides a means to continuously evaluate the IRT programme by identifying the strengths and weaknesses and provides guidelines for continuous improvement. These key IRT categories, their subcategories, and samples of their ratings are listed in detail in Tables 10-16.

Table 10. Key Element Owner Category

Key Element: IRT Technology Owner	***Point Value***
Full Time – adequate time to support expectations	2.00
High School Education	0.50
College, Trade School, or Other	0.50
Level I Certification	1.00
Level II Certification	1.00
Level III Certification	1.00
Safety Training	1.00
Continued Education (conferences, Users Group, writes technical papers, etc.)	1.00
IRT Technology Owner - Roles and Responsibilities defined and understood	2.00
Total	*10.00*

Table 11. Key Element Equipment Category

Key Element: IRT Equipment	***Point Value***
Has use of camera that is adequate to perform job effectively and is available as needed	1.00
Has report generation software with capabilities of producing: • Equipment List • Severity Guidelines • Equipment Status (i.e. In or Out of Service) • Exception Page	1.00 1.00 1.00 1.00
Has access to computer, as needed, to produce report, view images, etc.	1.00
Has means to archive report/images effectively	1.00
Effective camera operation techniques utilized	1.00
Access to visual camera, as needed	0.50
Has and follows Corporate Standards	1.00
Follows suggested Camera Calibrations Frequency	0.50
Total	*10.00*

Table 12. Key Element Application Category

Key Element: Applications	*Point Value*
Initial IRT programme (just starting)	1.00
Other Plant disciplines involved with and support IRT programme (i.e. performance engineering, operations, maintenance, etc.)	1.00
Effective use with the following applications:	
• Electrical	1.00
• Rotating/Mechanical Equipment	1.00
• Performance	1.00
• Switchyard	1.00
• Other advanced applications	1.00
Appropriate selection methodology for equipment list and route development	1.00
Effective follow-up (post-maintenance testing, PAM, etc.)	1.00
Field survey periodicity maintained	1.00
Reviews previous reports to ensure previously OOS equipment is In Service for next field survey	1.00
Total	*10.00*

Table 13. Key Element Analysis Category

Key Element: Analysis	*Point Value*
Understands "Basic Severity Guidelines" for all applications	2.00
Performs IR diagnosis adequately	2.00
Effective Analysis Process	1.00
Ability/wiliness to influence maintenance decisions	1.00
Confers with other plant personnel and utilizes other condition indicators to better determine components condition	1.00
Transfers component condition to appropriate plant personnel effectively	1.00
Uses experience to assist in evaluating a condition on a 'component' and how it will effect plant production	2.00
Total	*10.00*

Table 14. Key Element Documentation Category

Key Element: Documentation/Communication	***Point Value***
Documented programme procedures and guidelines (i.e. TAD, MAG)	1.00
E&CI Matrix developed and used	1.00
Generates report with: • Equipment List • Severity Guidelines • Images • Recommendations • Equipment Status (i.e. In or Out of Service)	 1.00 1.00 1.00 1.00 1.00
Maintains records to provide component history to assist with continued programme improvement process (PAM, etc.)	1.00
Updates Condition Status Report or other communication mechanisms regularly	2.00
Total	*10.00*

Table 15. Key Element Metrics Category

Key Element: Metrics	***Point Value***
IRT programme cost calculated	2.00
Performs Cost Benefit Analysis effectively	2.00
Metrics selected to identify programme effectiveness	2.00
Performs Return On Investment (ROI) calculations effectively	2.00
IRT programme Metrics are tracked effectively	2.00
Total	*10.00*

Table 16. Key Element Improvements Category

Key Element: Continuous Improvement	*Point Value*
Root Cause Analysis is performed effectively on appropriate components	2.00
E&CI Matrix is maintained	1.00
Additional applications are added effectively	1.00
Programme is evaluated effectively for enhancements (i.e. Self Assessment)	1.00
Attends conferences and user group meetings	1.00
Takes advanced technology training	1.00
Continuous Maintenance Department feedback	2.00
Use of Industry Operating Experiences	1.00
Total	*10.00*

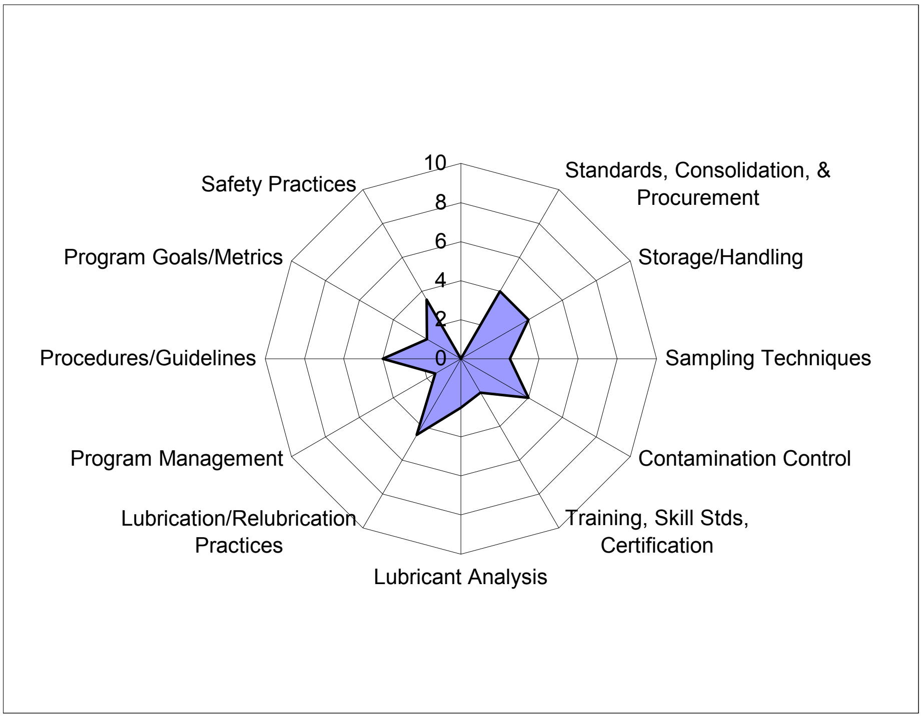


Fig. 12. Lube Oil Management Spider Chart.

7.14.2. Lubrication assessment

A lubrication assessment includes current practices in defined key areas that are assessed and compared to industry best practices. Programmatic aspects such as training, procedures, and defined roles and responsibilities are addressed to assure good programme management. The findings are graphically depicted in a spider chart as shown in Figure 12 to illustrate how the existing programme compares to industry best practice thresholds. The key areas are:

- **Standards, consolidation, and procurement.** Technical standards applying to all aspects of lubricant procurement and use are reviewed and evaluated for effectiveness. Also, the number of different types of lubricant should be kept reasonable for QA purposes.

- **Storage, handling, and contamination control.** Practical aspects of storage, housekeeping, and dispensing of lubricants are covered to clearly show the savings that can be realized from lubricant availability, and the avoidance of using contaminated lubricants that can cause equipment damage.

- **Sampling techniques**. Sampling techniques are reviewed to assure representative samples are collected. Sample location, collection methods, guidelines, training, and proper use of sampling containers are evaluated.

- **Containment control.** All too often lubricants are stored in areas that invite water or dirt. The care taken to protect against these and other contaminants will be well rewarded.

- **Training, skill standards, and certification**. A lubrication programme requires properly skilled individuals to ensure the effectiveness of the programme. Training methods, skill standards, and certification issues are addressed.

- **Lubrication analysis**. Specific equipment test slates are properly identified for each piece of equipment that is monitored. Samples must be analyzed and the test results properly evaluated. Appropriate targets and limits are established.

- **Lubrication/Re-Lubrication practices**. All too often lubricants are improperly applied resulting in more harm than good. Adequate training and the way of lubrication guidelines overcome common problems.

- **Programme management.** Good programme management requires both technical knowledge and good communication skills applied by a dedicated individual or group of individuals. Clearly defines roles and responsibilities coupled with focused goals, metrics, and measures assures customer satisfaction.

- **Procedures/guidelines**. Procedures and guidelines assure proper and consistent application of many of the programme elements.

- **Programme goals/metrics.** It is important that a programme have distinct goals and metrics in place to measure those goals. Example goals are cleanliness levels, inventory reduction, and elimination of oil change-out PM tasks.

- **Safety practices.** Safety is always a key factor that must be considered in any programme. MSDS sheets must be available, oil leaks must be properly contained, and precautions must be taken to assure there are not health risks associated with improper handling of lubricants.

- **Continuous improvement**. Programme improvement is obtained through the use of continuous self-assessments and the adjustment of programme goals. As cleanliness levels, inventory reductions, and other targets are reached, more aggressive targets can be set. A pro-active thinking organization will have a clear understanding of customer expectations and will always raise the bar on their performance.

7.14.3. Vibration

The vibration analysis assessment is being developed by the EPRI Nuclear Power division/TEAM (Technology for Equipment Assessment and Maintenance).

The following information is preliminary for the final Vibration Assessment. The spider chart for the vibration assessment would be similar to that shown in Figure 12.

The proposed key elements are listed below with brief descriptions:

- **Procedures/guidelines** - Procedures and guidelines will be reviewed to determine how the Vibration Monitoring Programme is implemented and interfaces with other plant functions and documents such as ASME Code, PM's, IST, maintenance rule, and other corporate documents.

- **Machine equipment selection -** A formal review of ASME and balance of plant machine selection shall be conducted to determine what machines should be in the vibration programme. Techniques used to determine equipment selected to be included in the Vibration programme shall be reviewed. Examples include PM Basis, FMEA Modeling, and RCM.

- **Database** - If databases are constructed properly, machinery problems can be identified early without time consuming detailed analysis. Databases should be constructed using formal guidelines as they relate to machinery failures. Database maintenance/optimization in the form of adjustments to parameters and alarm limit sets should be performed routinely.

- **Data collection -** Data collection sampling should be based on formal procedures for proper fault identification. Trending, proper collection techniques, recording process parameters, and increase and decrease sampling rates should all be a part of the data collection process.

- **Data analysis and reporting -** To improve accuracy and speed up analysis and reporting, data should be run through exception reports and only data in exception should be analyzed. Along with spectral analysis techniques, data analysis should include time waveform analysis, trends, fault frequency information, past history, visual inspections, and process information.

- **Special testing -** Special testing capabilities such as Phase analysis, filtered and non-filtered orbits, impact resonance testing, run up and coast down resonance testing (Bode & Nyquist plots), off-route data collection, special time waveform analysis, high frequency envelope detection, and diesel diagnostics will be evaluated.

- **Balancing** - Balancing capabilities such as single plane/multi-plane influence coefficient balancing (field & shop) will be evaluated.

- **Training** - A vibration programme requires properly skilled individuals to ensure the effectiveness of the programme. Training methods, skill standards, and certification issues will be evaluated.

- **Monitoring equipment -** Monitoring equipment should include walk around diagnostic equipment, on-line monitoring systems, and special testing equipment. Systems should have capabilities to interrogate data and alarm when faults occur.

- **Programme goals/metrics -** It is important that a programme have distinct goals and metrics in place to measure those goals. Example goals include reduction in plant trips, early detection of faults, elimination of unnecessary PM tasks, and extended component life.

- **Programme management -** Good programme management requires both technical knowledge and good communication skills applied by a dedicated individual or group of individuals. Clearly defined roles and responsibilities coupled with focused goals, metrics, and measures will assure customer satisfaction.

- **Continuous improvement** - The use of continuous self-assessments and the adjustment of programme goals will improve the programme. A proactive thinking organization will have a clear understanding of customer expectations and will always raise the bar on their performance.

8. CONCLUDING REMARKS

The CBM programmes depend upon the ability of the staff to assimilate the information into useable trends and combine seemingly unrelated technology outputs into sensible story boards that help to define how the equipment is performing. Within the subtleties, will be those infrequent findings that make the process worthwhile by preventing generation losses and helping to plan for controlled overhauls of critical equipment.

The CBM staff faces many challenges within the technologies. Their management must also face the task of developing their next generation of reviewers who will need the knowledge of time and experience to carry on the current team's activities. Training is a key task that must be completed in a timely manner. Association with vendors and industry groups is also a strengthening process that helps to educate the staff. It's the role of management to carry the programme foreword with support, understanding, and interaction with the organization.

Condition based maintenance (CBM) assumes that all equipment will deteriorate and partial or complete loss of function will occur. CBM monitors the condition or performance of plant equipment through various technologies. The data is obtained, analyzed, trended, and used to predict equipment failures. When equipment failure timing is known, then actions can occur to prevent or delay failure. In this way, the reliability of the equipment can remain high.

Condition based maintenance uses various sensors (e.g., pressure, temperature, vibration, flow) and fluid (e.g., oil and air) samples. With these sensors and samples, condition based maintenance obtains indications of system and equipment health, performance, integrity (strength) and provides information for scheduling timely correction action.

8.1. Considerations and limitations of condition based maintenance

Considerations and limitations canvassed from the industry participants during the development of the report are provided as insight to temper the expectations and enhance the development process for condition based maintenance programmes:

(1) The overall value of CBM is reduced or limited when overhauls still have to occur because of license/regulation, or other reasons that don't allow full extensions as designated by analysis

(2) As the plant operating conditions change, it makes it hard to compare the readings and the data scatter will be more difficult to trend.

(3) Condition monitoring and condition based maintenance may not easily achieve the confidence of maintenance, due to culture, management buy-in, or regulatory resistance.

(4) There needs to be a good balance between training of CBM technicians, good equipment for monitoring, knowledge of the equipment being monitored, and plant historical performance.

(5) Interpretation of the monitoring technology needs to be carefully and accurately performed to achieve confidence by the plant.

(6) There needs to be a clear set of expectations developed for the programme from the outset, focus on meeting the expectations. One important issues that needs to be understood, the purpose of taking data must have output related to corrective actions on the equipment.

(7) Monitoring must be integrated into the analysis then into the action to correct the anomalies.

(8) Culture change is necessary due to newly ascribed risk of approach toward degraded (not failure of) equipment.

(9) Management of resources to support CBM while transitioning from a PM based maintenance.

(10) Be aware of false indications and manage them so as not to discredit the programme.

(11) The CBM programme is not an all inclusive programme and must be balanced with other maintenance processes.

(12) The use of the IAEA TECDOC should be carefully approached to understand it is not replacing the maintenance function, but is enhancing it.

(13) Prior to initiating efforts on CBM, a full set of FME, failure modes and effects, should be completed to make it more focused on the types of tools that will be needed.

(14) The guideline should be reviewed and discussed within the management team prior to use as a development guide in the plant. The management team will have to be supportive of the programme through its own knowledge of what it is and what it is not.

(15) OSART would use the guideline to enhance their review.

(16) When implementing the CBM processes, the programme should be procedural zed to ensure it's properly being used and does not have risk that has not been considered.

(17) Explain why CBM is not a relaxation of safety.

(18) When implementing a CBM programme at the site, should anticipate finding a problem developing and need to predetermine who you're going to handle it.

(19) Programme is intended to be an adaptive programme that will be continuing to improve its process and predictive capabilities.

(20) All groups support the CBM process as noted in item 20 above, teamwork is a must.

(21) Team work is a requirement for the programme to be successful.

(22) Data from the programme should be widely accessible.

(23) Feedback is important to make the programme flexible, but feedback on the feedback is more important to encourage ensuring the plant's staff feels their input is important.

(24) Although data management is very important, keep it simple so that it takes little time to get it instituted.

(25) Take care to understand that CBM may require more calibration of installed equipment that was previously not required. Extra workload.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Standards Series No. NS-G-2.6, Maintenance, Surveillance and In-service Inspection in Nuclear Power Plant, IAEA, Vienna (2002).

[2] KANG, S., PARK, S., CHAI, J., "Verification of the operability of safety-related motor-operated valves", The Nuclear Engineer Vol. 44; Number 6, Nov./Dec. (2003).

[3] ELECTRIC POWER RESEARCH INSTITUTE, Improving Maintenance Effectiveness Guidelines: An Evaluation of Plant Preventive and Predictive Maintenance Activities- TR-107042, Palo Alto, CA, USA (1996).

[4] ELECTRIC POWER RESEARCH INSTITUTE, Predictive Maintenance Self Assessment Guidelines for Nuclear Power Plants - TR-1001032, Palo Alto, CA, USA (2000).

[5] ELECTRIC POWER RESEARCH INSTITUTE, Predictive Maintenance Guidelines - TR-103374-01, Palo Alto, CA, USA (1994).

[6] ELECTRIC POWER RESEARCH INSTITUTE, Predictive Maintenance Primer - NP-7205s, Palo Alto, CA, USA (1991).

[7] ELECTRIC POWER RESEARCH INSTITUTE, Predictive Maintenance Primer Revision 1 - 1007350, Palo Alto, CA, USA (2003).

[8] ELECTRIC POWER RESEARCH INSTITUTE, Electric Motor Predictive Maintenance Programme - TR- 108773-V2, Palo Alto, CA, USA (1999).

[9] ELECTRIC POWER RESEARCH INSTITUTE, Electric Motor Predictive & Preventive Maintenance Guide - NP-7502. R-1, Palo Alto, CA, USA (19920.

[10] ELECTRIC POWER RESEARCH INSTITUTE, Electric Motor Predictive Maintenance Tools and Practice - AP-101840-V3P3, R-1, Palo Alto, CA, USA (1995).

[11] ELECTRIC POWER RESEARCH INSTITUTE, Lube Oil Monitoring - TB-113351, Palo Alto, CA, USA (1999).

[12] ELECTRIC POWER RESEARCH INSTITUTE, Maintaining Lube Oil System Cleanliness in Motor Bearing Applications - 1004001, Palo Alto, CA, USA (2001).

[13] ELECTRIC POWER RESEARCH INSTITUTE, Lubrication Guide: Revision 3 - 1003085, Palo Alto, CA, USA (2001).

[14] ELECTRIC POWER RESEARCH INSTITUTE, Infrared Thermography Instruments - AP-101840-V2P15, Palo Alto, CA, USA (1993).

[15] ELECTRIC POWER RESEARCH INSTITUTE, Infrared Thermography Anomalies Manual Revision 2001 - 1004628, Palo Alto, CA, USA (2001).

[16] ELECTRIC POWER RESEARCH INSTITUTE, Infrared Thermography Guide Revision 3 - 1006534, Palo Alto, CA, USA (2002).

[17] ELECTRIC POWER RESEARCH INSTITUTE, Guideline for Developing and Managing an Infrared Thermography (IRT) Programme - 1004019, Palo Alto, CA, USA (2001).

[18] ELECTRIC POWER RESEARCH INSTITUTE, Infrared Thermography - 1004547, Palo Alto, CA, USA (2001).

[19] ELECTRIC POWER RESEARCH INSTITUTE, Level of Awareness Training - 1004621, Palo Alto, CA, USA (2002).

[20] GOODMAN, M., "Ultrasonic Tips on Monitored Bearings for Proper Lubrication and Wear", EPRI Predictive Maintenance Users Group Meeting, EPRI, Palo Alto, CA, USA, October (2002).

[21] UE SYSTEMS, Technology Overview: Ultrasonic Detection, Internet web site: http://www.uesystems.com.

GLOSSARY

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.

Time based maintenance:

Form of preventive maintenance consisting of intrusive inspections, servicing, parts replacement at predetermined intervals of calendar time, or operating time.

Planned maintenance:

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

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.

Predictive (Prognosis of condition based) maintenance:

Form of condition based maintenance used to monitor, diagnose, or prognose a SSC's future conditions; resulting in adjustments to the 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.

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
CRDS	Control rod driving system
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
RCM	Reliability centered maintenance
SSC	System, structure and component

ANNEX I. NUCLEAR POWER PLANT MAINTENANCE OPTIMIZATION WITHIN SENUF, A RECENT EUROPEAN COMMON INITIATIVE

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Abstract

While providing scientific and technical support to TAcis and Phare nuclear safety programmes a large amount of knowledge related to Russian design reactor systems has accumulated and led to the creation of a new network concerning Nuclear Safety in Central and Eastern Europe called “Safety of Eastern European type Nuclear Facilities” (SENUF). SENUF contributes to bring together all stakeholders of TACIS and PHARE: beneficiaries, end users, eastern and western nuclear industries, and thus, to favor fruitful technical exchanges and feedback of experience. At present the main focus of SENUF is the nuclear power plant maintenance as substantial element of plant operational safety as well as life management. A Working Group has been established on plant maintenance. One of its major tasks in 2004 was to prepare a status report on advanced strategies to optimize maintenance. Optimization projects have an interface with the plant’s overall life management programme. Today, almost all plants involved in SENUF network have an explicit policy to extend their service life, thus, component ageing management, modernization and refurbishment actions became much more important. A database is also under development, which intends to help sharing the available knowledge and specific equipment and tools. The paper presents SENUF and reports on the status of the ongoing tasks within the working group on Maintenance, as well as on perspectives for the future.

1. INTRODUCTION

In the past decade significant changes have occurred in the power industry: privatization and market deregulation have led to a competition among plants and generation technologies. This situation increasingly enforces plant managers and maintenance managers to reduce their operational and maintenance budget and, sometimes, also the number of their staff, to increase plant availability while continuously meeting the more and more rigorous safety requirements. Since building of new nuclear power plants (NPPs) is not in the agenda, the focus from new reactors has been placed on long-term safe operation of the existing nuclear power units. Life management became an independent, multi-disciplinary activity covering engineering and economic aspects of safety and plant availability. Goal of the life management can either be to ensure NPP operation until the end of design life or to operate the plant beyond its design life.

Maintenance in the broad sense used to include service, overhaul, repair, replacement, calibration, surveillance and in-service inspection (ISI). In the framework of life management all functions necessary for safe and reliable power production must be kept on a long-term basis. Structural integrity assessment of passive components is supported mainly by means of ISI and functional integrity insurance of active components by maintenance in its conventional sense and by surveillance. Thus maintenance is one of the key areas of NPP life management. It has to be noted that, due to evolution of technologies and changes in approaches, the traditionally separate activities like operational surveillance and maintenance tend to merge together, which may also have an impact on the horizontal cooperation of the plant operations and maintenance departments.

2. MAINTENANCE OPTIMISATION

2.1. General Aspects

A systematic activity to analyze and evaluate the effectiveness of an existing maintenance programme, and to carry out modifications on it, in order to eliminate or decrease imbalance between maintenance requirements (legislative, technical, economic, etc.) and resources used (staff, spare parts, tools, facilities, collective doses, etc.), called maintenance optimization, is going on in many utilities or NPPs. This process can lead to maintenance related decisions at various levels, i.e. related to the entire maintenance strategy, the organization of maintenance including the question of outsourcing, the selection of maintenance actions for individual components and the decisions on replacement of major components or even modernization of whole systems. Scheme of the maintenance optimization process is shown in Figure 1. Among 'Requirements', which in fact are the drivers, can appear life management or, explicitly, the NPP service life extension. See more details in [1].

Once the owner of a utility or an NPP decides about systematic life management actions, fields like maintenance or in-service inspection will play a significant role in these activities. Monitoring ageing of both non-replaceable and replaceable components, modernizations of components or even whole systems, replacement of parts or entire components, refurbishment (e.g. reactor pressure vessel annealing) become much more important. Maintenance receives a new perspective: the planned works (Preventive Maintenance, PM, basis) have to be carried in harmony with modernization and replacement/refurbishment operations. All these things are mainly concentrated on the planned outage periods and thus maintenance (and outage) optimization will become a high priority issue.

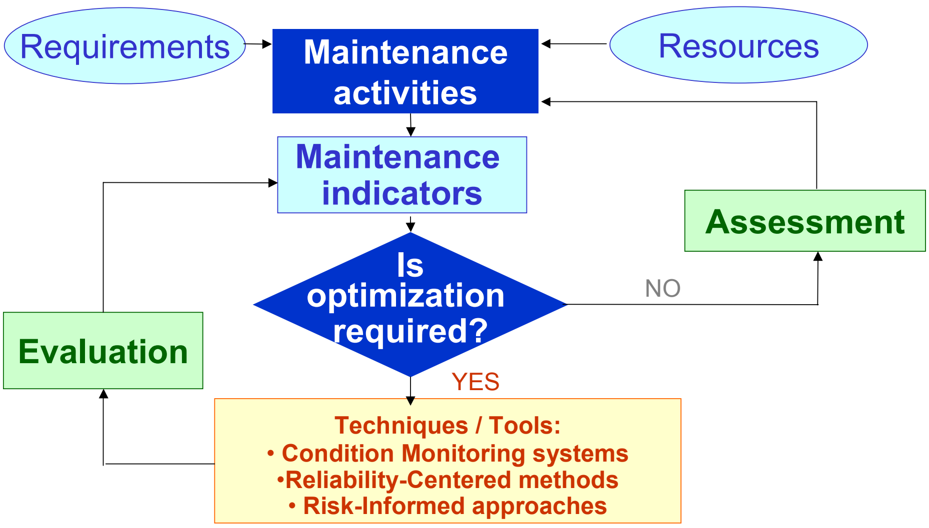

Fig. 1. Process of the maintenance optimization.

As part of the evolution in maintenance approaches, risk-informed solutions have been offered to move away from the mostly time-based predictive maintenance (PM) practice to strategies based on component condition, i.e. Predictive maintenance (PdM) and associated risk. Condition based maintenance (CBM), Reliability centered maintenance (RCM), as well as risk-informed ISI and maintenance can help to improve plant safety and reliability and to optimize resources by ensuring that maintenance is focused on critical components.

The main difference between the risk-informed methodologies and the condition-based maintenance is that while the latter one is looking for the actual degradation (even in its early stage), the risk-informed approach concentrates on the degradation mechanism Therefore, the monitoring, inspection and maintenance efforts need to combine the relevance of the component in terms of safety or availability with the probability of occurrence of defects relevant for safety or availability.

The principles are illustrated in Figure 2. The optimized situation occurs when the test, inspection and monitoring requirements are adjusted with the reliability models of the component, providing for an appropriate link between root causes and corresponding damages [2, 3].

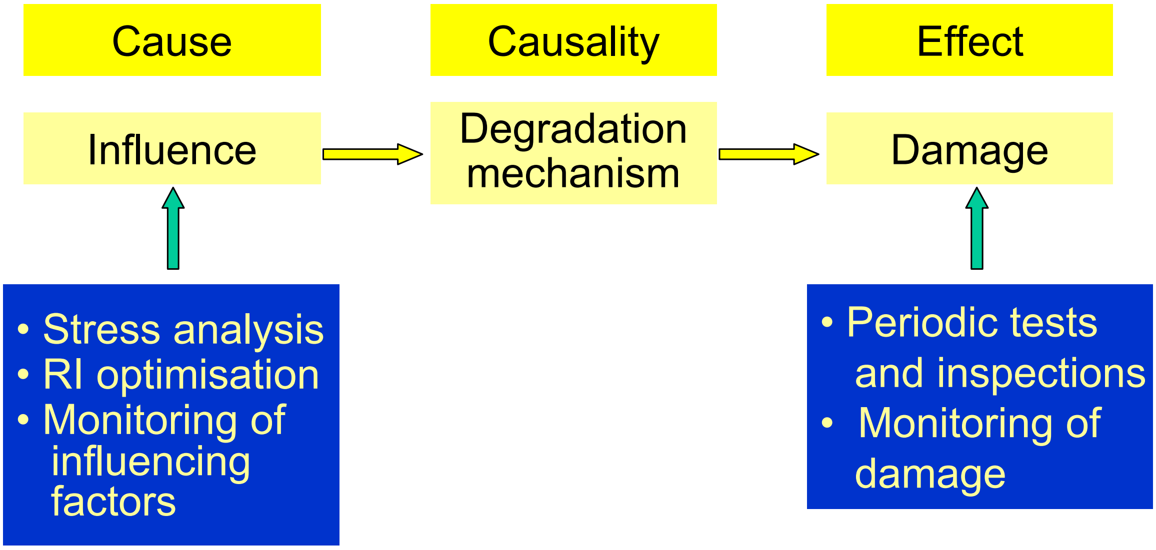

Fig. 2. Principles of Risk-Informed Approaches.

2.2. Current maintenance optimization activities in the countries of CIS and CEEC

Although to different extent, the countries of the former Soviet Union, known as Commonwealth of Independent States (CIS) and the Central and Eastern European Countries (CEEC), have gone through an economic transition and have still been facing with its consequences. Most of these countries operate Russian-type NPPs: primarily VVERs and RBMKs the safety of which is under permanent debate (VVER = Light-Water-Cooled, Water-Moderated Power Reactor, RBMK = Light-Water-Cooled, Graphite-Moderated reactor). Only Slovenia and Romania have other than Russian design reactor in operation, i.e. a Westinghouse type PWR (Pressurized Light-Water-Cooled and Moderated Reactor) and a CANDU type PHWR (Pressurized Heavy-Water-Cooled and Moderated Reactor), respectively. Due to the transition economy, the plants in CIS and CEEC need to put more effort to cope with difficulties related to the entire situation described in the introduction.

The challenges, NPPs in CIS and CEEC are facing today, do not really differ from those the Western plants are facing. These basically are the following:

- Safe and reliable plant operation;
- Outage duration reduction;
- Reduction of maintenance costs, in general.

To meet these challenges the enhancement of maintenance performance and, in some cases, a complex optimization of the maintenance programme are taking place.

In Cernavoda NPP (Romania), a Maintenance Enhancement Project is under progress, which is based on the EPRI recommendations and methodology [4]. The cost effective streamlined version of the methodology covers the following:

- Identification of key components of critical systems and creation of a database;
- Composition of equipment/component groups by type and technical characteristics;
- Expert panel for each type of equipment/component for reviewing PM tasks and intervals;
- Summary of the expert panel recommendations;
- Review of the maintenance procedures accordingly.

The EPRI based approach to optimizing maintenance programme has been used in Krško NPP (Slovenia), too. There, all the systems' functions have been analyzed according to their safety as well as production significance (critical and non-critical equipment/components), and the corresponding maintenance actions were defined accordingly. Also predictive maintenance group with multi-disciplinary teams as equipment "owners" has been established. For assessing maintenance effectiveness, Maintenance Rule is followed [5, 6].

The objectives of the maintenance optimization project currently under implementation in Dukovany NPP (Czech Republic) have included the following:

- Introduction of a differentiated approach to maintenance based on component significance;
- Increased use of PdM at the expense of time-based PM one;
- Change from Preventive (PM) to Corrective Maintenance (CM) in case of functionally and economically 'insignificant' equipment/components;
- Optimization of PM cycles and extent;
- Involvement of operations staff in maintaining and monitoring equipment technical condition.

Bohunice NPP (Slovakia) has implemented a comprehensive safety improvement programme at Unit 3 and 4 to increase a safety level in accordance with the latest safety requirements issued by the Slovak Nuclear Regulatory Authority. This programme, except of safety improvement measures also involves an extensive re-qualification programme which focuses on equipment in safety related systems, and which is placed in the containment or in the areas where harsh environmental conditions may be expected.

Diagnostics tools and In-service inspections methods have been widely implemented at the plant so that to provide for inspection of material integrity, diagnostic of mechanical components, including assessment of its material degradation.

Bohunice NPP has commenced implementation of a systematic programme on lifetime management of selected equipment to develop preconditions for extension of the service life to 40 years in compliance with the national energy policy. The plant's maintenance department commenced a pilot programme on RCM by application of systematic method to address the choice between corrective and preventive maintenance. This programme focuses on specific equipment such as emergency diesel generators.

In Mochovce NPP (Slovakia), recently commissioned Unit 1 and 2 maintenance engineers have been trained to prepare potential future RCM applications.

The Kozloduy NPP (Bulgaria) has also a safety enhancement and service life optimization programme for the units 5 and 6. The goal of this programme is to operate the units 15 to 20 years beyond their design life. One of the fundamental part of this programme is a 10-year maintenance plan, which is based on a long-term strategy concerning original design components like reactor pressure vessels, main coolant pumps, steam generators, turbine and electric generators, and the most important electric and I&C systems (e.g. reactor protection system). This plan defines priorities, and co-ordinates the maintenance activities. Another important part of the programme is provided by systematic monitoring and analyzing the status of technological systems carried out by operations, maintenance and engineering department staff. A specific ageing management programme was developed and is being implemented by an expert group under the leadership of the operations department during outages. Based on the assessment and evaluation of I&C system reliability and related ageing research, some systems or typical components were selected as a subject of replacement.

Hungary's Paks NPP has decided to follow the American way of license renewal for preparing its own life management strategy. It was identified that the following four major areas have to be managed successfully in the technical justification of the long-term operation:

- Reconstitution of design basis information;
- Implementation of a new regulation for monitoring of maintenance effectiveness, similar to the 10 CFR 50.65 see [5];
- Completion of environmental qualification for electrical and I&C equipment;
- Improvement of the current ageing management programme.

A complementary measure consists in the optimization of the existing ISI programme as well, in which both, inspection qualification and risk-informed ISI, play important role. Qualification of ISI systems according to the European methodology [7] has been a regulatory requirement and became routine task in most of the Countries in question. Risk-informed ISI is still in less advanced stage; however, pilot studies are under implementation in some plants. It has to be noted that the aforementioned tasks do need serious considerations even in case of operating the plant "only" until the design life.

In some plants, the maintenance optimization projects have a clear interface with the plant's overall life management programme. Today, almost all plants in the region have established a policy to extend their service life. Thus, component ageing management, modernization and refurbishment actions became much more important. Since carrying out of plant modifications, including cyclic replacement of obsolete I&C components or in extreme case a steam generator replacement, is a permanent task, it can provide a solid work load to maintenance departments. Also these big reconstructions are completed during outage periods and, sometimes even, are incorporated into a normal outage schedule (e.g. steam generator replacement in Krško NPP, reactor protection system refurbishment in Paks NPP).

3. SENUF

3.1. Objectives

During providing scientific and technical support to TAcis and Phare nuclear safety programmes a large amount of knowledge related to Russian design reactor systems has accumulated and led to creation of a horizontal and integrated project concerning nuclear safety in Central and Eastern Europe. The project called “Safety of Eastern European Type Nuclear Facilities” (SENUF) has linked to the JRC Institute for Energy’s existing nuclear safety related SAFELIFE action. The SENUF objectives are to facilitate:

- The harmonization of safety cultures between the Candidate Countries, new Members States and the European Union,
- The understanding of needs to improve the nuclear safety in Candidate Countries and new Members States,
- The dissemination of JRC Institute for Energy nuclear safety institutional activities to Candidate Countries.

SENUF is a new forum promoting safety of Eastern European type (mainly Russian designed) nuclear facilities by providing communication between Eastern European operators in Candidate Countries themselves and relations with major operators from Western Europe. It contributes to bring together all stakeholders of TACIS and PHARE: beneficiaries, end users, Eastern and Western nuclear industries, and thus, to favor fruitful technical exchanges and feedback of experience.

At present the main focus of SENUF is the nuclear power plant maintenance as substantial element of plant operational safety. A specific Working Group has been established on NPP maintenance and to date ten institutions (mainly utilities or NPPs) from Western as well as Central and Eastern Europe have signed agreement with JRC Institute for Energy to collaborate. Negotiations are still continuing to involve further institutions. Major tasks of the Working Group on NPP Maintenance in 2004 focus on the following topics:

- Analysis of the existing maintenance concepts and practices as well as optimization strategies e.g. condition based, reliability centered, risk informed maintenance and, based on this, preparation of a status report on advanced strategies to optimize plant maintenance;
- Setting up and operation of a database on advanced and specific equipment, tools, materials and processes to provide maintenance managers and engineers with adequate information in order to help them selecting the most appropriate and cost efficient solution.

3.2. Advanced Strategies to Optimize Maintenance

As it was described in the previous chapter, each Utility and/or NPP faces with more and more rigorous safety requirements and thus increasingly relies on maintenance. At the same time, ageing management using new technologies and advanced information management can contribute to high plant availability as well as potential license renewal that help to utilize shrinking resources allocated to maintenance. This tendency underlines the need for a continuous improvement and optimization in the maintenance programme. This need led to establish the task to prepare a status report advanced strategies to optimize NPP maintenance with the following objectives:

- To collect and analyze the existing strategies on NPP maintenance optimization, i.e. Predictive Maintenance based on monitoring component conditions, Reliability Centered Maintenance and Risk-informed approaches in the NPPs of the collaborating parties;
- To identify differences and commonalities in the Western and Eastern European practice.

To be able to achieve these objectives, a comparison has been carried out covering all important aspects of NPP maintenance in plants or utilities of the collaborating institutes. These are:

- Maintenance management (maintenance departments standards, company and maintenance objectives, priorities, performance monitoring, self-evaluation, regulatory control);
- Types of maintenance and their ratio to each other (concept of type selection, predictive methods implemented);
- Attention for components/equipment problems (failure database, maintenance history, root cause analysis, equipment "ownership");
- Long-term focus (outage planning, partnership, life management aspects, ageing management);
- Maintenance personnel competence (training programme, training records, contractors' training);
- Effective work management (procedures, scheduling, coordination, post-maintenance testing, temporary modifications);
- Spare part policy (procurement system, obsolescence of equipment, perenniality of suppliers);
- Maintenance optimization (basic motivation of maintenance optimization, way of optimization, its organizational aspects, cost/benefit analysis, lessons learned).

Implementation of the task is in progress. A preliminary analysis of the collected data was going on just recently, and highlights of the findings are summarized here. 53 nuclear power units in 7 countries are involved in the benchmark (32 PWRs including 24 VVERs, 17 LWGRs, 2 BWRs, 1 FBR and 1 PHWR).

Concerning maintenance management it seems that sound management practices exist in all plants. Maintenance objectives (indicators), criteria, necessary procedures and feed back (including operational experience) are in place. Also state-of-art assessment techniques are used to assess maintenance effectiveness. Additional data and further analyses seem to be needed in the area of maintenance activities prioritization, specific maintenance performance indicators (amongst which risk-informed ones), and approaches to improve human performance reliability.

Amongst the types of maintenance, the leading concept is the time-based Predictive Maintenance (PM); while the Corrective Maintenance (CM) has its role too. Introduction of Predictive Maintenance (PdM) is in initial stage; the used prediction techniques are very similar. The PM/CM ratio varies between 95/5 to 50/50. The PM work bank is primarily based on the manufacturer's recommendations but component history and engineering judgment play a role as well.

Analyzing the long-range focus approaches, it can be seen that prioritization of investments are mainly carried out taking into consideration safety, reliability and production (power upgrade) aspects. In some plants regulatory requirements may affect long-term investments. The long term outage planning varies in a broad spectrum. A significant part of the plants applies a 10-year planning cycle but some plants do not forecast more than one or two years. The importance of long-lasting partnership with original manufacturers is quite visible. The return rate of contractor workers from outage to outage is 50 to 70 %.

Training of maintenance personnel becomes solid part of the entire training programme and covers all relevant area. Within types of training setting the On-The-Job (OJT) training is the most widely used. Using Systematic Approach to Training (SAT) as methodology was reported too. In most cases, training of contractor personnel belongs to the plants' responsibilities.

Within maintenance optimization, the Reliability Centered Maintenance (RCM) plays the leading role. Its streamlined version is introduced or under pilot operation in almost all countries or plants. Amongst the optimization goals, safety aspects are put on the first place, following by component reliability (plant availability) and maintenance cost reduction aspects.

During the preliminary analysis of the results of an inquiry launched among the SENUF members, we have identified some lack of information as well as inconsistency in the information, which are to be compensated and clarified or eliminated during finalization of the corresponding State-of-the-Art report.

3.3. Database on Advanced and Specific Equipment, Tools, Materials, Products and Technological Processes

Due to extreme radiation conditions, technical complexity and/or novelty, maintenance and associated actions in nuclear power plants may require individually tailored approaches and treatments to achieve, both, a proper technical solutions and economic viability. Advanced (remotely controlled) or specially designed manufactured equipment or tools, specific materials, products and technological processes need to be provided and put into operation. These equipment and tools are usually costly. Information about the existence, the main parameters of such equipment and the experience of their usage can be valuable for others, facing similar problems. The objective of the database on advanced and special equipment, tools, materials, products and technological processes is to provide maintenance managers and engineers with adequate information on the subject in order to help them selecting the most appropriate and cost efficient solution.

The target users are engineers and managers in the Utilities/NPPs of SENUF collaborating parties, responsible for planning, execution and supervision of maintenance and maintenance related activities like repair, replacement, modification, decontamination, diagnostics, calibration, testing, etc. Also persons involved in outage planning and management, in safety as well as in engineering support departments can take benefit from the database.

The database intends to cover the advanced and/or special (state-of-art, costly, unique) equipment, tools, materials and technological processes, which have been used at the nuclear power plants of the collaborating parties. They are being included in the database, only if they cannot easily be purchased and are special ones. Plant types currently covered are VVER-440/1000, RBMK-1000/1500, CANDU-600, and other PWRs (Westinghouse, Siemens/KWU, GE design in particular).

The database structure has been developed and a demonstration with some sample data to SENUF partners was done recently. The database will be accessible through INTERNET and restricted to SENUF partners. JRC/IE is entitled to be its operator. A pilot version shall be made available by the end of 2004 to SENUF members for data collection and implementation. The preliminary home page is shown on Figure 3.

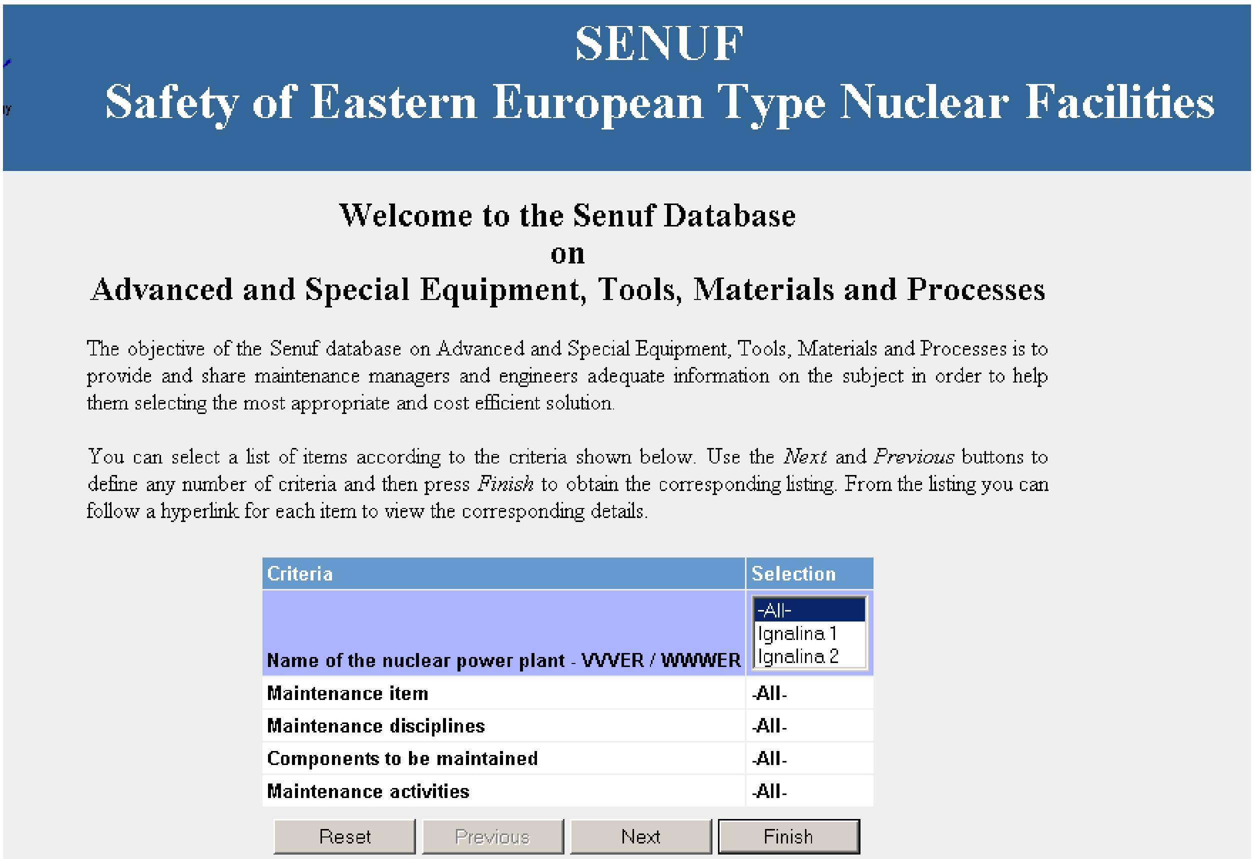

Fig. 3. Preliminary home page of the pilot SENUF database on "Advanced and specific equipment, tools, materials, products and technological processes".

The database hierarchy will include various levels. Among those the most relevant are detailed hereafter:

- Maintenance items (Technological Processes, Tools & Equipment, Materials & Products);
- Maintenance discipline (Mechanical, Electrical, I&C including Monitoring and Alarm Systems, Control, Diagnostics and Structures)
- Components to be maintained (Reactor component [Vessel, Internals, Assemblies, CRDM…], Fuel handling equipment, Primary Pipeline [Main Coolant Line and connected], Secondary Pipeline [Steam/Feed lines and connected], Steam Generators,

Pumps, Valves, Heat exchangers, Turbines, Unit generators, Electric motors, Transformers, Diesel generators, Electrical batteries, I&C equipment, Vessels [Tanks and Accumulators], Ventilation Systems [ducts, dampers, fans…], Cables [power, I&C, control, others…], Cranes and other lifting machines, Structures and Structural components)

- Maintenance activities (Control and Test, Replacement, Modification, Repair, Calibration, Monitoring/Diagnostics, Decontamination, Cleaning, Lubrication, Training)

- Parameters (main technical parameters, pictures/drawings if applicable, origin of design/manufacturing, date of purchase, date of commissioning/installation, name of NPP, where it was commissioned/installed, frequency of usage, experience feedback, contact person at the utility/plant).

The database shall be English and Russian (the first pilot will be prepared in English).

4. IMMEDIATE ACTIONS BY THE GOVERNMENT AND LICENSEES

The recently established SENUF Working Group on Nuclear Power Plant Maintenance is a new forum to promote safety of Eastern European nuclear plants. Results and experience of the 2004 activities will certainly contribute to appropriate technology transfer among the members, which is crucial to underpinning common safety standards for NPPs in the enlarged Europe and further, including Candidate Countries as well as Ukraine and the Russian Federation.

The first two tasks of the work plan (Status of implementation of advanced maintenance optimization strategies among the members / development of a database on Advanced and Specific Equipment, Tools, Materials, Products and Technological Processes) are well advanced and shall be completed by mid-2005.

For 2005, the work plan also includes activities on Reliability-Centered Maintenance and Risk-Informed approaches on maintenance optimization. The plan is to call specialists together for exchanging knowledge and experience with the objective to identify appropriate tasks for the future. Co-operation with the IAEA is anticipated in that phase.

Today, SENUF has ten (10) active members contributing to the Working Group on Nuclear Power Plant Maintenance. Further extension of the number of members is expected in the near future.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for Optimizing Nuclear Power Plant Maintenance Programmes, IAEA TECDOC-1383, IAEA, Vienna (2003).

[2] Hüttner, Ch., Holzer W. and Kauer R.: Optimization of monitoring, in-service inspection and maintenance with risk informed methodologies. In: Proc. 26. MPA-Seminar, Stuttgart (2000).

[3] Jovanovič, A.: Risk-based inspection and maintenance in power and process plants in Europe. Nuclear Engineering and Design, 2003, vol. 226, pp. 165-182.

[4] Preventive Maintenance Basis. Project Overview Report Update. TR-106857 R-1, EPRI, Palo Alto (1998).
[5] Code of Federal Regulations 10 CFR Part 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants", Office of the Federal Register National Archives and Records Administration, U. S. Government Printing Office, Washington DC (1998).
[6] Monitoring the Effectiveness of Maintenance at Nuclear Power Plants. US NRC Regulatory Guide 1.160, Revision 2 (1997).
[7] European methodology for qualification of non-destructive tests, second issue. EUR 17299 EN (1997).

ANNEX II. TECHNIQUE ON PREDICTIVE MAINTENANCE FOR MAGNETIC JACK TYPE CONTROL ROD DRIVING SYSTEM

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Abstract

Currently, maintaining a high level of availability and reliability in Nuclear Power Plant (NPP) operation is one of the most important issues. In this point of view, the nuclear power generation industry is experiencing an increased awareness and emphasis on the benefits of predictive maintenance because the condition based predictive maintenance can enhance the operability and reliability of the plant and reduce possibility of unwanted reactor trips. KOPEC has developed the on-line Coil Current Monitoring System (CCMS) for the effective and predictive maintenance of the magnetic jack type Control Rod Driving System (CRDS) of the Korean Standard Nuclear Power Plants (KSNPs). The CRDS of KSNP is composed of 73 Control Element Drive Mechanisms (CEDMs) and CEDM Control System(CEDMCS). The CCMS is capable of monitoring all coil current traces of up to 8 CEDMs at the same time. All coil currents of selected CEDMs are monitored and acquired automatically at high speed sampling rate depending on the CEDM movement. The acquired coil current data is automatically analyzed to check the timing sequence of CEDM motion, coil current amplitude and pattern mismatch of waveform. The various analytical results and diagnosis information of abnormal conditions are provided on MMI displays. For a more precise analysis, the CCMS provides various data manipulation tools of noise filtering, data comparison and database generation for automatic fault detection. The CCMS has been supplied to six KSNP units and mainly used for the predictive maintenance of the CEDM and CEDMCS during plant overhaul period. The CCMS has shown that it is very useful to diagnosis quickly and exactly the status of many control components of the CEDM and CEDMCS such as CEDM coils, hall effect current sensor, timing control cards, voltage adjustment cards and Silicon Controlled Rectifier (SCR). If enough coil current data are accumulated historically, the degradation trends of CEDM coil, hall effect current sensor, voltage adjustment card and SCR can be predicted. Abnormal or degraded control components identified by the CCMS can be calibrated or replaced before their failure which may cause a severe problem. Therefore, the condition based maintenance using the CCMS has been demonstrated to be effective in enhanceing the operability and reliability of the CEDM and CEDMCS, and reduceing possibility of unwanted reactor trips.

1. INTRODUCTION

The condition based maintenance technology through on-line monitoring for the predictive maintenance of equipment is becoming one of the most important issues to reduce the time, cost and manpower required for system maintenance in NPPs, which enhances the plant operability and reliability. The Control Element Drive Mechanism Control System CEDMCS) controls the Control Element Assembly (CEA) to maintain the balance between the reactor and turbine powers in KSNP. It provides the motive power and the holding power for the operation of the CEDMs with a magnetic jacking device and, thus, controls the withdrawal and insertion, rate and duration of CEA. The magnetic jack type CEDM is an electromechanical device that uses induced magnetic fields to operate a mechanism for moving a CEA. In KSNP, seventy three (73) CEDMs are utilized, and each CEDM consists of four coils; Upper Lift (UL) coil, Upper Gripper (UG) coil, Low Lift (LL) coil and Low Gripper(LG) coil. It was reported that the failures or abnormal conditions of the CEDM and CEDMCS components resulted in plant abnormal conditions such as an inability of reactor power control, rod slippage and reactor trip. Table 1 shows the CRDS failures occurred at 14 pressurized water reactor nuclear power plants operating in Korea. Listed failures resulted in reactor trip and average reactor shutdown time per failure came up to approximately 25 hours.

Table 1. Control Rod Driving System Failure Experiences with Korean NPPs (as of 2002)

Reactor Trip Causes	No. of Occurrence	Total Down Time (hrs)	Average Down Time (hrs)
Power Connector Damage	3	266	89
Fuse Clearing	5	173	35
Diode Failure	2	39	20
Control Circuit Failure	7	106	15
Communication Failure	3	27	9
Human Error	3	16	5
Loss of Control Power Supply	1	6	6
EMI and Etc	3	31	10
CEDM Malfunction	1	unknown	unknown
Total	28	664	25

Although the current CEDMCS incorporates some failure detection capabilities, it is difficult to determine the root cause of a malfunction and, hence, unable to take a corrective action to eliminate the trouble in a timely manner. Generally, the CEDM coil current trace provides an important clue for fault diagnosis because it implies information regarding the malfunctions of the CEDMCS and the mechanical parts of the CEDM. In order to evaluate the system performance and to facilitate the predictive maintenance of the CEDM and CEDMCS, a separate digital recorder has been used for the acquisition of coil current data, and then analytical evaluation is visually done and judged by site personnel. This method takes time for both data collection of coil current and fault analysis along with complicated processes. Moreover, the site personnel must have enough experience and special knowledge needed for the analysis of coil current waveform, and the establishment of an efficient maintenance procedure is not easy due to the difficulty in the systematic management of the acquired data.

Hence, the development of the CCMS has been initiated due to the necessity of the on-line health monitoring of the CEDM and CEDMCS. For this development, the expected fault signals are identified through a review of past operation experience data from the CEDM and CEDMCS failures, literature survey and operator interviews. Also, some of fault signals are generated using the CEDM coil current wave simulator developed by KOPEC since the historical data of component failures in the CEDM and CEDMCS are not sufficient to derive all kinds of failures. Based on both real faulty signals and the extracted signal features from the CEDM coil current waveform, automatic fault detection algorithms are developed.

2. DEVELOPMENT APPROACH

Failure modes and abnormal conditions of the CEDM and CEDMCS need to be identified and evaluated for checking the system integrity. This section provides the approach used to define failure modes through the review of overall function of the CEDMCS. Accordingly, detection methods and analysis methodology of the CEDM and CEDMCS failures or abnormal conditions were reviewed for failure diagnosis, establishment of functional requirements and fault detection algorithms.

2.1. Overview of CEDMCS Function

The overall block diagram of the CEDMCS shown in Figure 1 is used to identify what kinds of failure modes could cause system malfunctions following component failures of the CEDMCS. The motive power for CEDMs is supplied from redundant motor generator sets at 240 Vac 3 phase. The CEDMCS cabinets house many logic control cards and power control cards to convert AC power to DC power which is supplied to CEDM coils. The Zero Cross Detection(ZCD) card generates the synchronizing pulse when the phase voltage crosses zero point. The phase synchronization card provides the pulses to control the high and low CEDM coil voltages for the firing of the SCRs. The coil driver actuation card selects the SCR firing pulses based on Automatic CEDM Timing Module (ACTM) control commands. Three SCRs, one per each phase, are used to control the three phase voltage to each coil. The withdrawal or insertion of the CEA is accomplished by the linear motion of a magnetic motor of CEDM as a result of applying DC voltage to the CEDM coils. The CEDM control command for withdrawal, insertion and holding is provided to the ACTM, and then the ACTM generates the programmed timing pulses used to control the high, low and off time of the four coils of a CEDM.

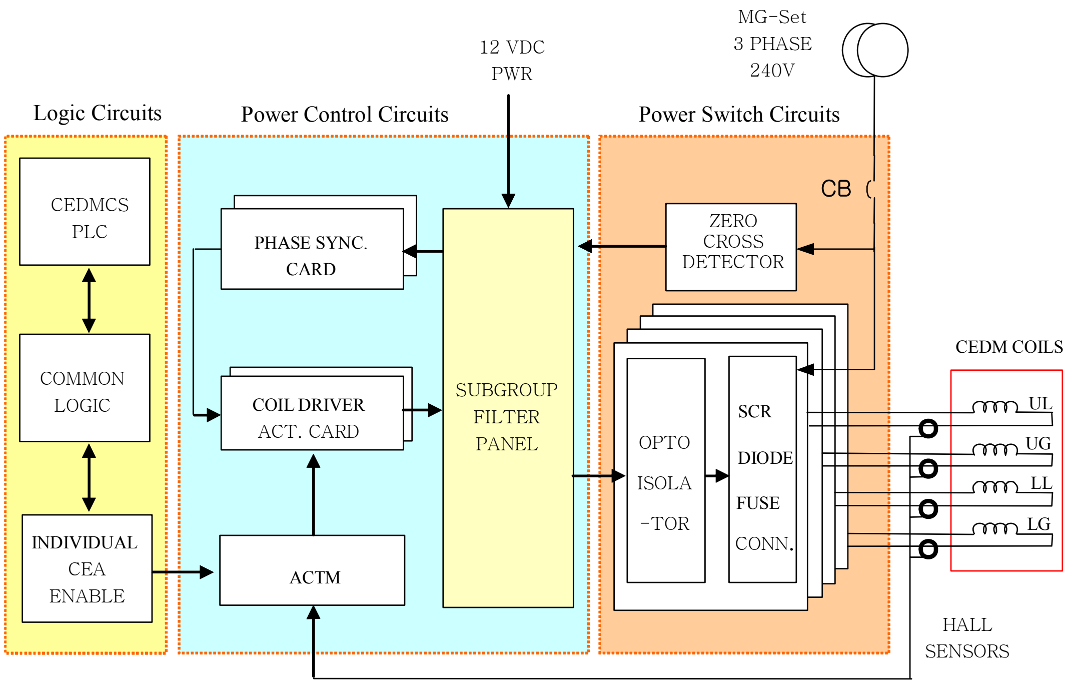

Fig. 1. Overall block diagram of CEDMCS

The ACTM monitors the coil currents by hall effect sensors to verify CEDM mechanical actions during CEA movement and takes corrective actions for inadequate holding current in gripper. The proper operation of the CEDM and CEDMCS can be verified using the information such as coil current peak value, engagement time, existence of mechanical action, engagement current, inadequate holding current, decay time and dropout delay time [1]. As the CEDM continuously moves in the normal operation, the same type of coil waveform is repeated with 1.5sec period. The CEA moves to 3/4 inches per each step.

2.2. Failure Modes Review and Extraction of Signal Features

Failure modes were reviewed to produce a database to identify fault conditions and to develop fault detection methods. Through the failure modes and the effect analysis for the CEDM and

CEDMCS, the structural and functional system hierarchies were decomposed [2]. It was concluded that the CEDMCS could cause those failures in terms of system failure modes and specific component failures. It was identified that the major failure modes of the systems are CEDM coil damage and CEA holding failure and motion failure. Table 2 indicates a summary of the identification of failure modes of the CEDM and CEDMCS. It should be defined what kinds of signals could be used to detect abnormal signals on-line. There are several sensor signals available such as CEDM coil current, voltage, CEA position, cycle time, and total travel steps.

Table 2. Failure Mode Analysis of the CEDM and CEDMCS

Failure Mode	Causes	Detection Method
CEDM coil damage	- ZCD card - Opto-isolation card - Coil drive card - Phase sync. card - ACTM - Filter panel - Power supply	- Current level and trend - Gripper transfer - Waveform comparison
CEA holding failure	- Power Switch - ZCD card - Bad ground - Power supply - Phase sync. card	- Current level - Waveform - Gripper transfer - Drop rod contact - Glitch
Electrical motion failure	- Current sensor - SCR mis-firing - ACTM - Phase missing - Opto-isolation card - Coil drive card - Phase sync. card - Power supply	- Position deviation - Change of cycle time - Restep - Waveform comparison
Mechanical motion failure	- Friction increase due to slow latch and magnet	- Glitch occurrence time - Dropout time increase - Change of cycle time - Waveform comparison
	- Misalignment - Moving parts broken	- Early glitch - Slow sequence - Change of cycle time - Waveform comparison - Position deviation - Drop rod contact
	- CEDM coil degradation	- CEDM coil current level - Waveform comparison - Ripple
Safety scram failure	- Stuck latch - Stuck latch magnet - Stuck CEA or ESA	- No glitch and no bump - Change of cycle time - Restep - Waveform comparison

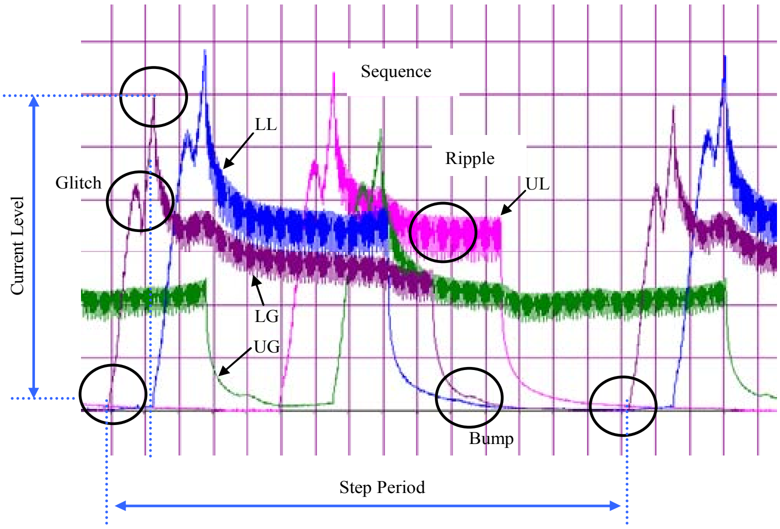

Fig. 2. Typical CEDM coil current waveform and signal features

The expected faulty signals are identified through the review of the past operating experience data from the CEDM and CEDMCS failures, literature search and operator interviews. Based on the identified faulty signals, a failure mode database is constructed and updated on newly identified faulty signals.

Figure 2 represents the typical CEDM coil current waveform and signal features. The reduction in current after glitch engagement is due to the closure of the armature gap, and then the current builds up again until CEDMCS ACTM commands a low voltage. Disengagement is shown in the current decay with a small bump. Various signal features, shown in Figure 2, are extracted from coil current waveform for the application of the CCMS

3. DEVELOPMENT OF THE COIL CURRENT MONITORING SYTEMS FOR THE CRDS

This section describes the design requirements, system configuration, diagnostic detection methodology, MMI displays and site test results of the CCMS.

3.1. Establishment of Design Requirements

It is utility requirement to implement the CCMS, without modification of the current CEDMCS, which can provide the on-line health monitoring of all 73 CEDMs by adding hardware components only in the future. Due to the limitation of the installation space, the CCMS hardware is currently designed to support up to 8 CEDMs at a time. Because it is designed as a network-based system, it can be easily expanded to cover all 73 CEDMs.

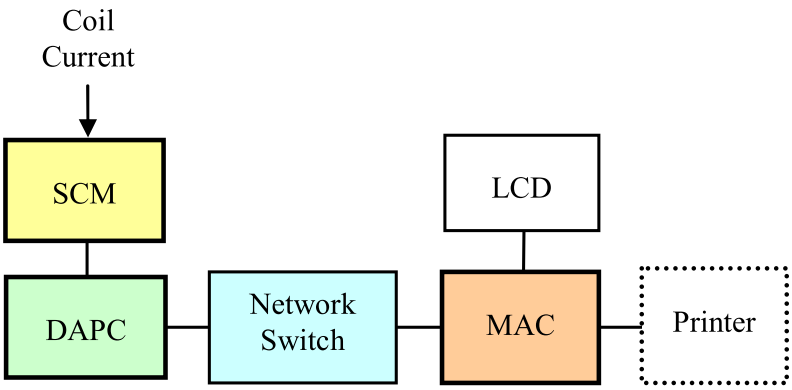

Fig. 3. CCMS hardware configuration.

3.2. System Configuration

Figure 3 shows the CCMS hardware configuration that consists of Signal Conditioning Module (SCM), Data Acquisition and Processing Computer (DAPC), Monitoring and Analysis Computer(MAC) and supporting equipment such as network device and printer.

The SCM acquires coil current data from each of four coils through a CEDM coil current monitor connector on the front panel of the CEDMCS cabinet. The coil current signals are processed by the amplification, isolation and low pass filtering circuits. The electrical isolation between the CCMS and CEDMCS cabinets is provided by the SCM. The coil current within 0 to 25 A range is measured by shunt resisters and/or hall effect current sensors, and normally includes 180 Hz noise signal derived from 3 phases power source.

The DAPC, which receives the data from the SCM, processes digital conversion of the coil current data, temporary data storage, data processing and data transmission. The data communication between the DAPC and the MAC is carried out through network.

The MAC conducts the automatic analysis, diagnosis, storage, display, and printing of the data transmitted from the DAPC. In addition, network device is composed of network hub switches for connection between the DAPC and the SCM and additional data acquisition modules for future use.

The application program for data acquisition runs in the DAPC following the commands from the MAC. All acquisition data are continuously stored in the temporary buffer and converted to engineering value. After checking the validity of input signal and self-diagnostic test, the data and message are transmitted to the MAC. The system places itself automatically into standby mode on a power failure and initiates an automatic restart upon power restoration. This program supports three acquisition modes: Standby, Monitoring and Continuous.

The application program for monitoring and analysis enables the MAC to perform the overall system operation, and it sends the control value and set points to the DAPC. The MAC program interlocks with the DAPC, and saves the acquisition data, alarm signals, and automatically analyzes data from the DAPC. Also it conducts automatic or manual analyses, display, alarming, and logging.

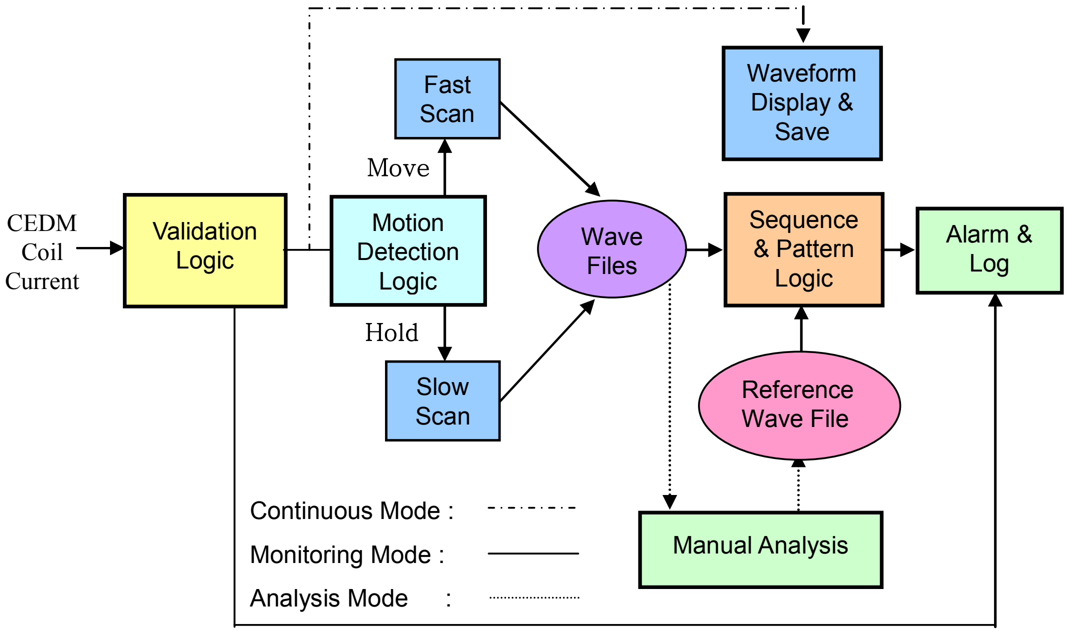

Fig. 4. CCMS software operation flow.

3.3. Diagnosis Detection Methodology

Figure 4 shows the software operation flow for data acquisition and automatic analysis. The system is designed to provide the ability to perform automatic fault detection and diagnosis. The fault detection and diagnosis algorithms are intended to detect discrepancies or change of operating characteristics and to monitor the system conditions so that the coil current waveform is automatically analyzed by checking CEDM timing sequence, CEA motion or non-motion, coil current level, and pattern mismatch of waveform.

The motion detection logic detects the CEDM motion and non-motion, the change status of characteristic parameters from the coil waveform and the distinction between the reference signal and the acquired signal using both the historical data and simulated fault data.

The motion sequence check logic verifies abnormal conditions by examining the withdrawal and insertion sequence waveforms, which are processed by the average filtering. After the CEA motion is successfully verified by the motion sequence check, the pattern mismatch logic is performed in order to check CEDM glitch and timing during rod motion. This logic calculates the accumulated error value between reference waveform and the acquired waveform at every sampling point. If the total error value is higher than the set point, it generates an alarm.

3.4. Man-Machine Interface

The system MMI provides a user friendly environment to easily maneuver the graphic displays. It is also designed to provide a user with the ability to support functions such as archive and recall of historical data, logs and the set points entry. The CCMS has five operation modes; Standby, Setup, Monitoring, Continuous, and Analysis modes. Figure 5 shows the overall configuration with the monitoring mode display which patterns 73 CEDMs in a table format based on CEDM group and subgroup so that a user can monitor all system status at a glance.

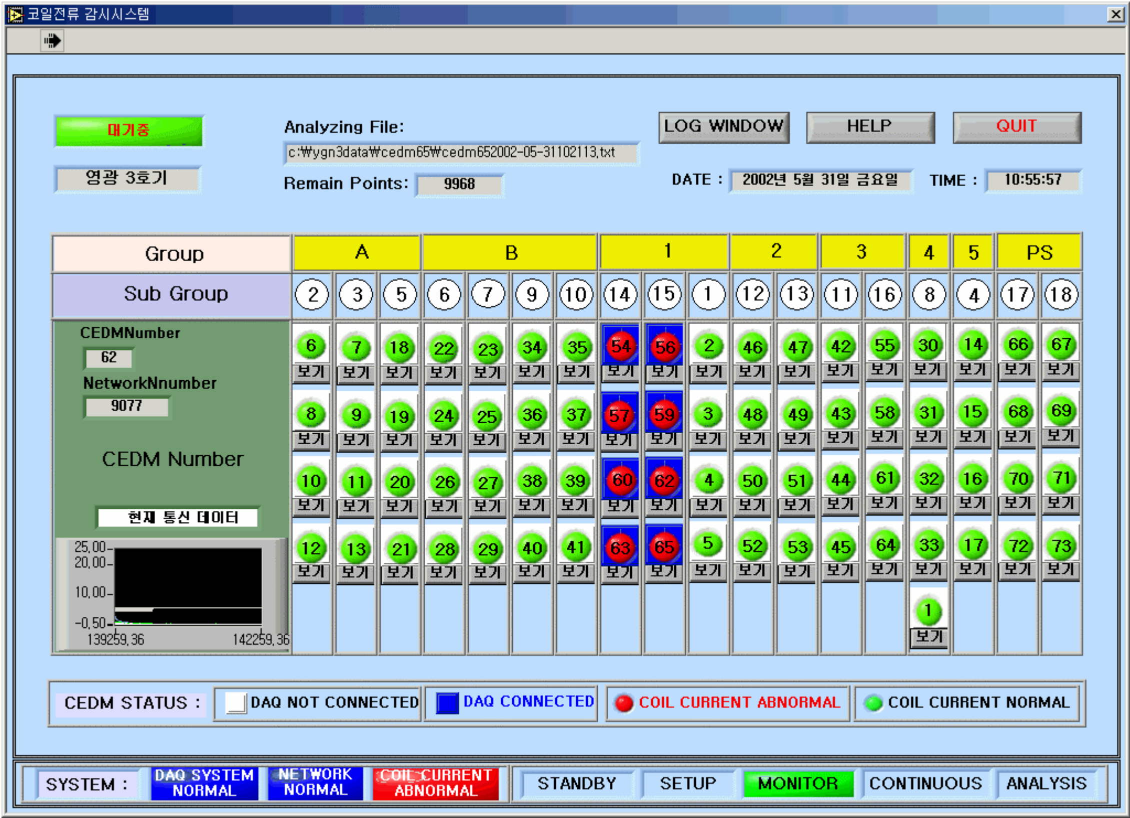

Fig. 5. CCMS MMI display in the monitoring mode

The normal and abnormal states of each CEDM, system status such as DAPC connection and network are monitored. If an abnormal status of each CEDM occurs, the color of respective CEDM changes and detail information pops up for diagnosis.

The analysis mode is utilized to detect and identify faults by a precise observation and manual analysis of coil current characteristics. It supports useful means such as overlap, scroll, zoom, data edit, move, print and extraction of input signal. User can also define the extraction of abnormal signals that will be used as a reference database.

3.5. Test Results

The system functions such as isolation, noise reduction, data acquisition, alarm, log and automatic diagnosis were tested using CEDM load simulator during CEDMCS pre-operational test in one of KSNPs. The first site test was successfully completed and the second site test was conducted to validate on-line monitoring capabilities of CCMS during the plant overhaul period.

Figure 6 shows examples of abnormal coil waveforms. Case 1 shows an abnormal coil current due to a missing phase of SCR. It indicates that voltage supplied to UL coil contains noise signal and is below the normal value. Three SCRs, one per each phase, are used to control three-phase voltage to each coil. A missing phase would be reflected by a 120 Hz ripple. As compared to UG coil signal, the UL coil current decreases at the point where one SCR is not fired and, then recovers at the time when the other two SCRs are fired.

In comparison with normal waveform in the Case 2, the sluggish glitch of the abnormal UL coil signal occurs at a lower current level and is less sharp and wider than normal current and ripple. UL engagement time was also delayed by 260 ms, which resulted in a delay of the cycle time.

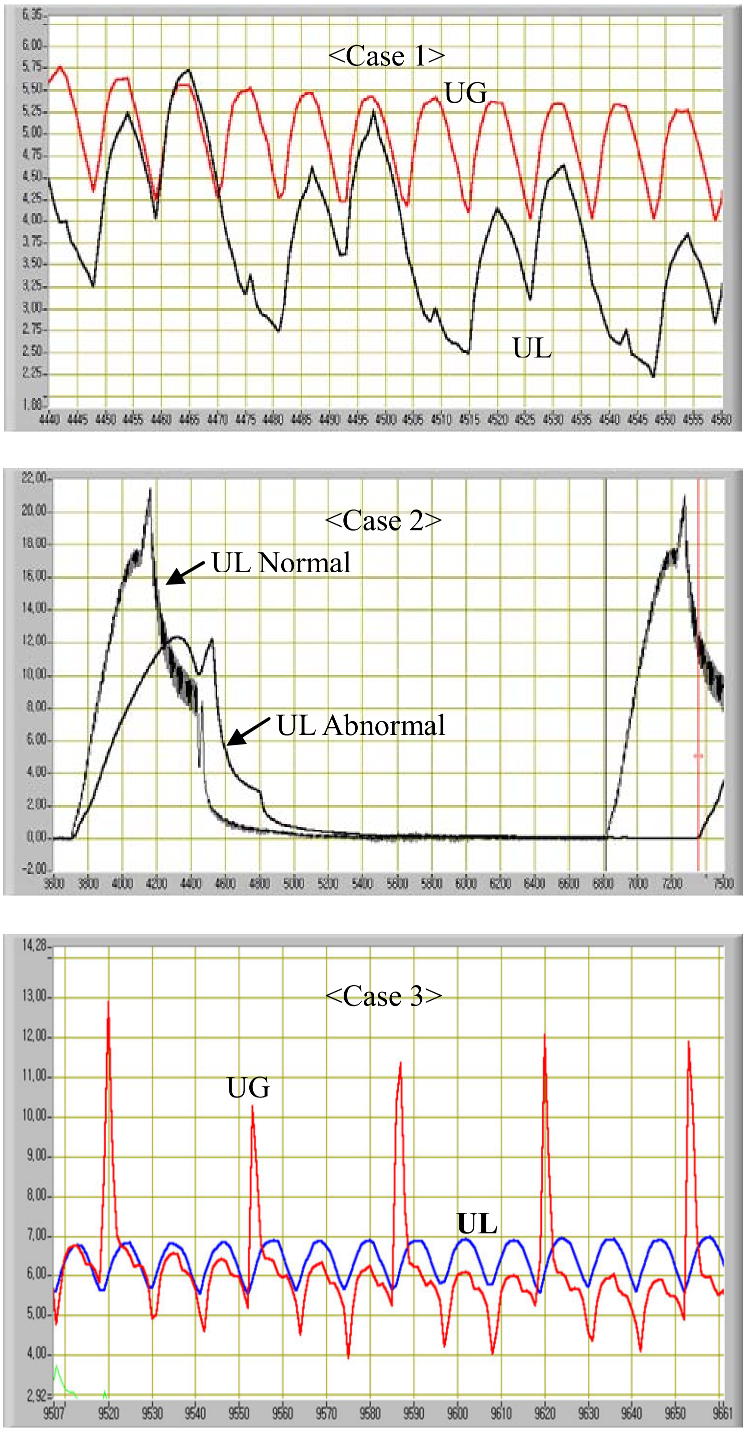

Fig. 6. Examples of abnormal waveforms

Case 3 shows the UG coil current with periodic pulse noise signals at the frequency of 60 Hz which results from insulation degradation between power devices and heat dissipation plate.

Through the laboratory and site tests, all functions and performance of the CCMS has been verified. All CEDM current data were automatically stored in the hard disk via the network, then analyzed, indicated, and logged properly.

Fig. 7. Front view of the CCMS

After a successful site tests, the developed system shown in Figure 7 has been supplied to several KSNPs and used mainly during plant overhaul period. The CCMS has shown that it is very useful to diagnosis quickly and exactly the status of many control components of CRDS such as CEDM coils, hall effect current sensor, timing control cards, voltage adjustment cards and Silicon Controlled Rectifier (SCR). Once enough coil current data are accumulated historically, the degradation trends of the CEDM coil, hall effect current sensor, voltage adjustment card and SCR can be predicted. Abnormal or degraded control components identified by the CCMS can be calibrated or replaced before their failure which may cause a severe problem.

3.6. Further Study on the Intelligent Predictive Maintenance

Based on the operating experiences of the current CCMS, KOPEC has a plan to perform the further study on "development of the advanced intelligent predictive maintenance technology". The intelligent predictive maintenance technology requires various technologies such as smart sensor design, signal processing for data reduction and feature extraction, virtual machine modeling, simulation, integrity diagnosis and expert system. These advanced technologies could be applicable to new CRDS of the next generation NPPs in the form of built-in style with covering all CEDMs. Even though the development is focused on the CRDS application, this intelligent predictive maintenance system concept can be generalized through an additional study since the methodology could be applied to other systems and components, and also could be expanded to the plant wide level.

Another development plan is to expand the application of the CCMS to the different types of nuclear power plants such as Westinghouse and Framatome NPPs. These plants also use magnetic jack type CRDS, but their control systems are somewhat different with KSNP. The CCMS can be easily applicable to these plants if some parts of the CCMS are properly modified.

4. CONCLUSIONS

KOPEC has developed the CCMS for the effective and predictive maintenance of the CEDM and CEDMCS. This system provides data acquisition of the CEDM coil current waveform, automatic and manual analysis, alarm, and the systematic data storage and management. Site test and practical application demonstrated that the CCMS performs its intended functions successfully. The developed system has been supplied to six KSNP units and mainly used during plant overhaul period. Once enough coil current data are accumulated historically, the degradation trends of the CEDM coil, hall effect current sensor, voltage adjustment card and SCR can be predicted. Abnormal or degraded control components identified by the CCMS can be calibrated or replaced before their failure, which will contribute in improving the availability, reliability, and safety of NPPs by preventing unexpected reactor trips.

REFERENCES

[1] H.S. Yim, H.P. Hong, H.H. Han, J.M. Koo and H.B. Kim, "Development of the Predictive Maintenance Methodology", Proc. of KIII of Summer Annual Conference, p.2058, Korean Institute of Electrical Engineers, Cheju, Republic of Korea (2002).

[2] E. GROVE and W. GUNTER, Aging Assessment of the Combustion Engineering and Babcock & Wilcox Control Rod Drives, page (7-3), Brookhaven National Lab., NY, USA (1993).

[3] J.M. Koo, H.S. Yim, H.P. Hong, Y.B. Kim and H.B. Kim, "Development of the Coil Current Monitoring System for Control Element Drive Mechanism Control System", Proceeding of ICAPP 2003, paper 3280, Cordoba, Spain (2003).

ANNEX III. IMPLEMENTATION OF CONDITION MONITORING TECHNIQUES TO IMPROVE VALVE RELIABILITY AND PERFORMANCE

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Abstract

Innovations in technology have provided for the development and use of sophisticated diagnostic systems for monitoring plant equipment such as motor-operated valves, pneumatic control valves, check valves and motors. This capability has in a sense allowed us to revise our plant maintenance philosophy concerning valves and motors in nuclear power plants from time-based maintenance practices to condition based maintenance (CBM). In the establishment of a predictive maintenance philosophy, the equipment's operability, working environment and risk significance are taken into consideration in determining the frequency of testing as well as the need for maintenance. The activities of several international nuclear organizations have kept pace with the technology and have initiated process improvements necessary to maximize the technical and economic benefits of condition based maintenance. This paper discusses adoption of valve and motor condition monitoring in the nuclear power industry, relevant documentation and research in this field, and recent efforts to combine risk assessment with condition monitoring strategies to achieve the highest level of reliability and safety without significantly affecting operation and maintenance cost.

1. INTRODUCTION

The practice of condition monitoring or Condition-based Maintenance (CBM) has been around for quite some time in nuclear valve maintenance programmes. The early test systems were first introduced in the 1980's to address motor operated valve (MOV) operability concerns in the US stemming from incidents at Three Mile Island and Davis Besse Nuclear Plants. Investigations into these incidents revealed that existing preventive maintenance practices were inadequate in addressing the operability, or safety function operation of MOVs. In accordance with US Nuclear Regulatory requirements, US utilities were forced to develop valve testing programmes to address MOV operability concerns.

Although this testing approach is more aptly termed "performance testing" versus "condition monitoring", it played a major role in the introduction of diagnostics to the valve maintenance programme. Over the past twenty years, valve diagnostic technology and CBM have evolved to encompass a larger scope of application. In addition to MOV testing programmes, utilities today are also focusing on the adoption of similar condition monitoring programmes for air operated valves (AOV) and check valves. In contrast to the complex safety-related MOV testing programmes practiced today, there is no significant regulation requiring the use of such technology for AOVs or check valves. However, utilities have recognized the benefits of valve diagnostics to be as follows:

- Troubleshooting valve and actuator issues
- Ensuring proper switch settings
- Monitoring adverse trends in valve performance (aging and degradation)
- Determine required maintenance and overhaul frequencies

It is evident that valve diagnostics play an integral role in valve preventive maintenance. This paper discusses some relevant information in regards to specific regulatory information, test programme development, testing technology application, and CBM test evaluation.

2. MOTOR OPERATED VALVE CONDITION MONITORING

2.1. Background1

Following the accident at Three Mile Island the Electric Power Research Institute (EPRI) conducted a PORV block valve test programme at Duke Power Company's Marshall Steam Station. The test programme was originally proposed in NUREG 0737 (TMI Action Plan), as an additional means of reducing the number of challenges to the emergency core cooling system and the safety valves during plant operation. This test programme represents the earliest known use of strain measuring equipment to record valve performance. During the EPRI testing, three of seven motor-operated block valves selected for the programme failed to fully close under conditions that simulated the actual block valve service environment. The ultimate conclusion of this testing was that components of the valve-actuator sizing and selection process were non-conservative.

On June 9, 1985, one of the more significant nuclear power plant events in which motor-operated valves (MOVs) played a major role occurred at the Davis Besse Nuclear Plant. Both auxiliary feedwater containment isolation valves failed to reopen after inadvertent closure. The subsequent transient resulted in both steam generators boiling dry due to the loss of auxiliary feedwater. The failures were attributed to improper torque and torque bypass switch settings for certain critical MOVs (i.e. maintenance/programmatic degradations).

To this point the maintenance philosophy across the nuclear industry was focused on scheduled preventive maintenance activities and periodic overhauls. In fact, overhaul projects were thought to be the sure method of correcting all MOV performance issues. However, these events revealed that flaws in the engineering and maintenance approach for existing valves produced a high probability of common mode failure due to generic issues that could not be corrected by simple preventive maintenance or overhaul. The primary concern was the ease at which misadjustment of control switches during installation, start-up activities or routine maintenance could render the MOV inoperable under design basis conditions. Even more alarming was the fact that indications or "symptoms" of a problem could not be uncovered during the stroke time testing required by the ASME code and the plant's license.

As a result of the Davis Besse event, and other significant events, the NRC issued IE Bulletin 85-03, Motor Operated Valve Common Mode Failures during Plant Transients due to Improper Switch Settings. The bulletin required nuclear power plant licensees to develop and implement programmes to ensure that switch settings on certain safety-related motor operated valves were set and maintained correctly to accommodate the maximum design basis loading during both normal and abnormal events within the plants design basis.

As more MOV issues unfolded, the NRC took steps to extend the scope of 85-03 to cover all safety-related MOVs. Generic Letter 89-10, Safety-Related Motor-Operated Valve Testing and Surveillance, was issued in June of 1989. In response, industry organizations such as

[1] "Improvements in Valve Reliability Due to Implementation of Effective Condition Monitoring Programs", Stan Hale, CRANE Nuclear, International Conference on Nuclear Engineering, 04/20/03

INPO, NUMARC (now NEI), EPRI, ASME and others initiated efforts to help improve the industry-wide knowledge and understanding of how MOVs operate.

During the public workshops on GL 89-10, NRC reviewed the MOV issue and discussed research results that indicated a larger generic issue with methods used to establish thrust requirements for rising stem gate valves. As part of the resolution of Generic Issue 87, Failure of HPCI Steam Line without Isolation, researchers at the Idaho National Engineering and Environmental Laboratory (INEEL) performed full flow isolation tests to evaluate the ability of certain motor-operated gate valves to close under blow down conditions. The results of these tests supported the contention from the EPRI/Marshall testing that the generic model for calculating valve thrust requirements for gate valves may not always be conservative.

In addition to the findings relating to thrust calculations, the INEEL researchers and participating test equipment suppliers discovered that MOV output capability changed between static and dynamic test conditions. The phenomena termed “load sensitive behavior” or “rate-of-loading” is the difference in the output thrust of an MOV between static and dynamic conditions (usually lower under dynamic conditions).

Based on the INEEL research and an accumulation of related plant events, the NRC suggested in GL 89-10 that MOVs be tested at or near design basis differential pressure for the purpose of demonstrating operability. The NRC suggested this approach because a validated method of calculating thrust requirements was not available, and it was not clear how all of the various phenomena affecting MOV performance could be addressed through a static testing programme.

In September of 1996 the NRC requested in Generic Letter 96-05, Periodic Verification of the Design Basis Capability of Safety-Related Motor-Operated Valves, that nuclear plant owners establish programmes or modify existing MOV programmes to periodically verify that safety-related MOVs can perform their intended safety functions. In effect, GL 96-05 requests that MOVs continue to receive the same high level of care and attention established during 89-10 programme efforts.

The primary concern at this point is the potential for degradation to increase the design basis performance requirements and/or decrease the MOV’s output capability in excess of what was verified or assumed in the GL 89-10 margin analysis. The final analysis reveals that the 85-03 and 89-10 work played a key role in the potential adoption of CBM and risk-based maintenance strategies. As a result of this work nuclear plant owners have high confidence in the installed equipment, have verified the field setup and have a basis and means by which to evaluate future condition. With the newfound knowledge and tools in hand, informed condition based decisions can be employed to prioritize the maintenance schedule and address GL 96-05 concerns. Seventeen years after the first regulatory initiative on MOVs, nuclear power plants continue to adjust MOV programmes to gain the highest possible level of safety at the right cost and impact on operations.

2.2. Motor Operated Valve Testing Process

The key components to establishing an effect MOV Condition Monitoring Programme that satisfies USNRC GL 89-10 are as follows:

- Verify Design Requirements
- Update/Review Sizing and Setup Requirements
- Verify Setup & Mechanical Condition through Testing
- Establish margin over design basis requirements
- Maintain and Verify margin throughout the life of the plant

The first step in the test process is to determine the set point requirements for the MOV to be tested. In safety related condition monitoring programmes, these requirements are focused on the output force of the MOV. The design basis thrust calculation for the valve is most commonly used as the thrust requirement with the valve or actuator weak link utilized as the maximum force value. These values are then adjusted for uncertainty. Uncertainty variables include measurement error as well as actuator repeatability effects and aging as listed below:

- Actuator Repeatability
- Rate-of-Loading (Load Sensitive Behaviour)
- Test Equipment Uncertainty
- Expected Degradation Over Time
- Stem Lubrication
- Valve Factor
- Spring pack Relaxation

Once these uncertainty adjusted set points have been determined, the MOV is tested and utilizing various types of sensors the following parameters are measured:

Primary Parameters	Optional Parameters
Stem thrust	Vibration through FFT of power or motor current
Motor current	Upstream and downstream line pressure
Limit and torque switch set points	Motor voltage (AC/DC)
Secondary Parameters	Power factor
Actuator torque	Motor torque
Stem movement	Actuator efficiency
Motor power (AC/DC)	Correlated thrust and torque (MCC method)
Stem Factor/stem friction	Compensator deflection
Spring pack movement	Spring pack force

Upon collecting information from the various parameters measured, the test engineer will then ensure that the limit switches and torque switches are set properly in order to achieve the appropriate amount of force required to close or open the valve under design basis flow conditions (ensure positive margin). The engineer will also review the test data to ensure that no anomalous conditions exist.

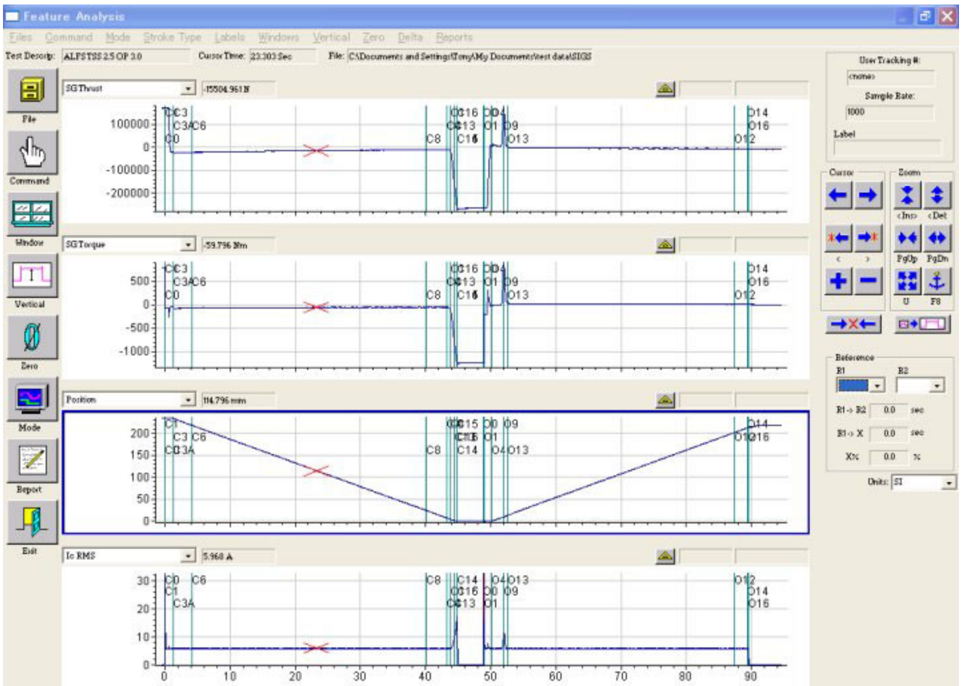

Fig. 1. MOV Test Data: Full Stroke from Open to Close to Open

2.3. MOV Test Programme Development

Once positive margin has been achieved in the initial baseline test, the periodic test frequency is determined considering the amount of margin that exists and the safety significance of the valve. This area is left up to the user to determine, however, significant documentation exists to provide guidance on both risk ranking and margin assessment.

The Joint Owners Group (JOG) MOV programme has recommended a blend of risk ranking and margin utilizing 3 levels of each. High-risk valves with low margin are tested more frequently than lower risk valves with higher margin. Risk is classified by the core damage frequency (CDF) contribution in the event of MOV failure. Equally, risk ranking in accordance with ASME OMN-3 also addresses the same valves that are contributors to an increased CDF. However, OMN-3 identifies only two levels of risk and sets the requirement for only testing high safety significant component (HSSC) MOVs in accordance with OMN-I. For low safety significant (LSSC) MOVs, the requirements for in-service testing are minimal.

Risk ranking is a critical part of determining the periodic condition monitoring frequency for a given MOV. However, there is no regulation requiring any particular method of assessing risk. One plant in Central Europe defined their assessment through their existing probabilistic risk assessment (PRA) ranking procedures for safety related systems. Their matrix is as follows:

PRA	**Low Margin**	**Medium Margin**	**High Margin**
High Risk	1	2	3
Medium Risk	2	4	6
Low Risk	3	6	6
Low-Low Risk	4	6	6

Fig. 2. Example Periodic Test Frequency by Refueling Cycle

There are a variety of different approaches, technology, and methods for condition monitoring of motor operated valves. In fact, utilities today are further developing their programmes to combine IST and GL89-10 testing requirements utilizing advanced Motor Control Center (MCC) test technology. This MCC-based provides a method of evaluating the condition of the actuator and valve through both qualitative and quantitative methods allowing users to take credit for GL 96-05 test during regular online quarterly IST valve strokes.

3. AIR OPERATED VALVE CONDITION MONITORING

3.1. Background

Air Operated Valve Condition Monitoring has a slightly different history than MOV testing. Air Operated Valve test technology has also been around for quite sometime, however, the primary focus was never on safety function operation. Control valves play a critical role in nuclear power applications. Inefficient control valves can create numerous problems concerning process efficiency, namely heat loss.

Through various studies and research, several significant control valve issues were found at various facilities as summarized below:

- Physical condition of many installed AOVs is poor
- Maintenance procedures are not effective
- The current set-up of "control" AOVs may not be optimal (affecting plant efficiency and thermal performance).
- Spring adjustment on fail-to-close AOVs may be inadequate (affects safety function)
- Packing configuration control and adjustment
- Contaminated air supply (USNRC Generic Letter 88-17)

In addition, potential issues that could prompt the USNRC to issue Generic Letter regulation were noted as follows:

- Actuator Sizing and Selection (INPO Letter)
- Potential diaphragm area issues (USNRC Information Notice 96-68)
- Validated Calculational Approaches
- Thrust Requirements- Different valve designs, existing data limited
- Actuator Capability-Internal friction (piston, seals, spring) stem packing (USNRC Information Notice 88-94), valve internals

Knowledge of these issues prompted the USNRC to prepare a study of various preventative maintenance programmes throughout the US. Their findings were published in NUREG 1275, Volume 13, Evaluation of Air-Operated Valves at US Light Water Reactors and its companion document prepared by INEEL NUREG/CR-6654, A Study of Air-Operated Valves in US Nuclear Power Plants. This study included plants that both had and had not incorporated condition monitoring in their preventive maintenance programme. The USNRC's recommendation in NUREG 1275 suggests that utilizes should incorporate CBM technology in their programmes.

In addition, it was determined that some control valves also had dual function as an isolation valve in accordance with site operating procedures. It was determined that these valves should be evaluated based upon their ability to also provide a safety function operation in the event of a design basis accident scenario. The JOG developed guidance on developing such a programme for AOVs taking a very similar approach to what was developed for MOVs.

3.2. Air Operated Valve Test Process

As mentioned in the previous section, the main purpose of AOV or control valve testing is to ensure the efficient handling of the process. Our primary concern in this regard is:

- Identify leaking valves
- Troubleshoot problem control valves
- Verify proper calibration
- Identify degraded valve performance
- High friction (packing loads)
- Mechanical binding
- Valve stem misalignment
- Seating problems
- Design issues

Considering the application of these control valves versus the motor operated valves, the performance characteristics that need to be monitored differ. AOV test technology today takes control of the AOV and through the control signal input, drives the control valve through a series of tests. These tests vary from simple ramp tests, to step sensitivity and response, to dead band, to frequency response tests.

Depending upon the required function of the valve the specific types of test will be selected. While the test system sends the input signal to the control valve, it also monitors such parameters as I/P pressure, supply pressure, diaphragm pressure, stem movement and even stem thrust. Once the test system completes the test profile and stores the data, very specific control functions and performance parameters are then calculated based on this data as well as the database inputs/characteristics of the valve and depicted in both graphical and tabular form as seen below:

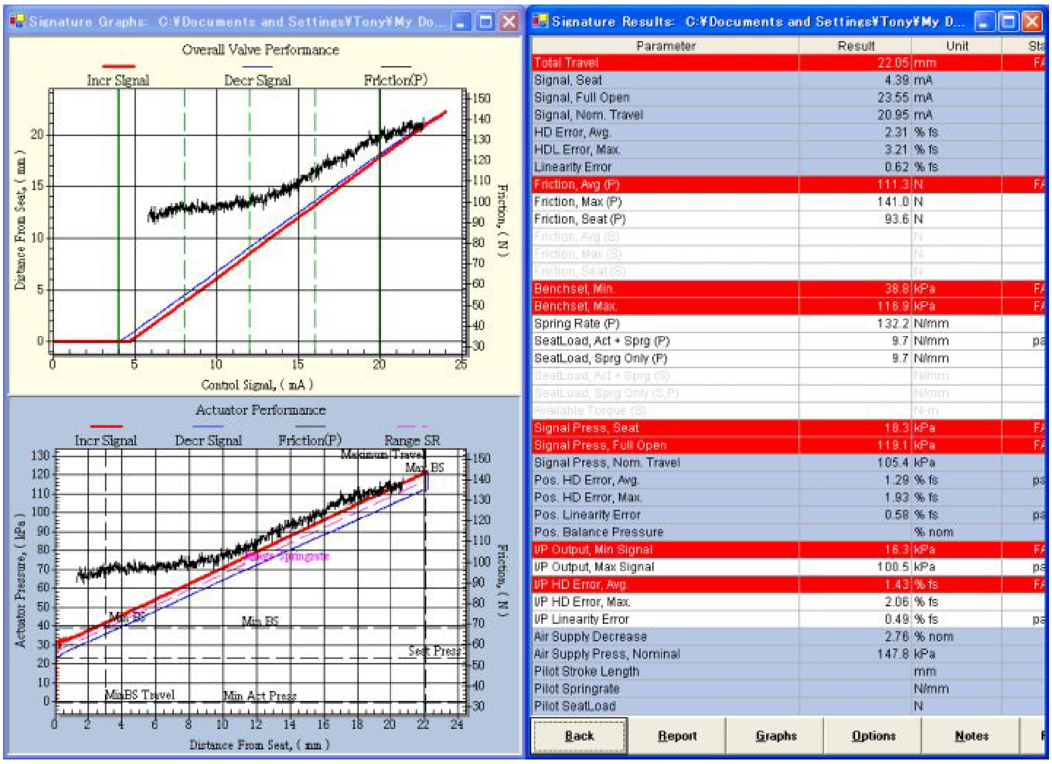

Fig. 3. AOV Baseline Test: Fisher Diaphragm Control Valve

Of course different types of test profiles will provide the user with different parameters. The engineer will need to first determine the type of valve that is being tested and based on the function and requirements, determine the types of tests that need to be performed. The following flowchart shows a typical process by which the user should evaluate and test an AOV with a true controlling function.

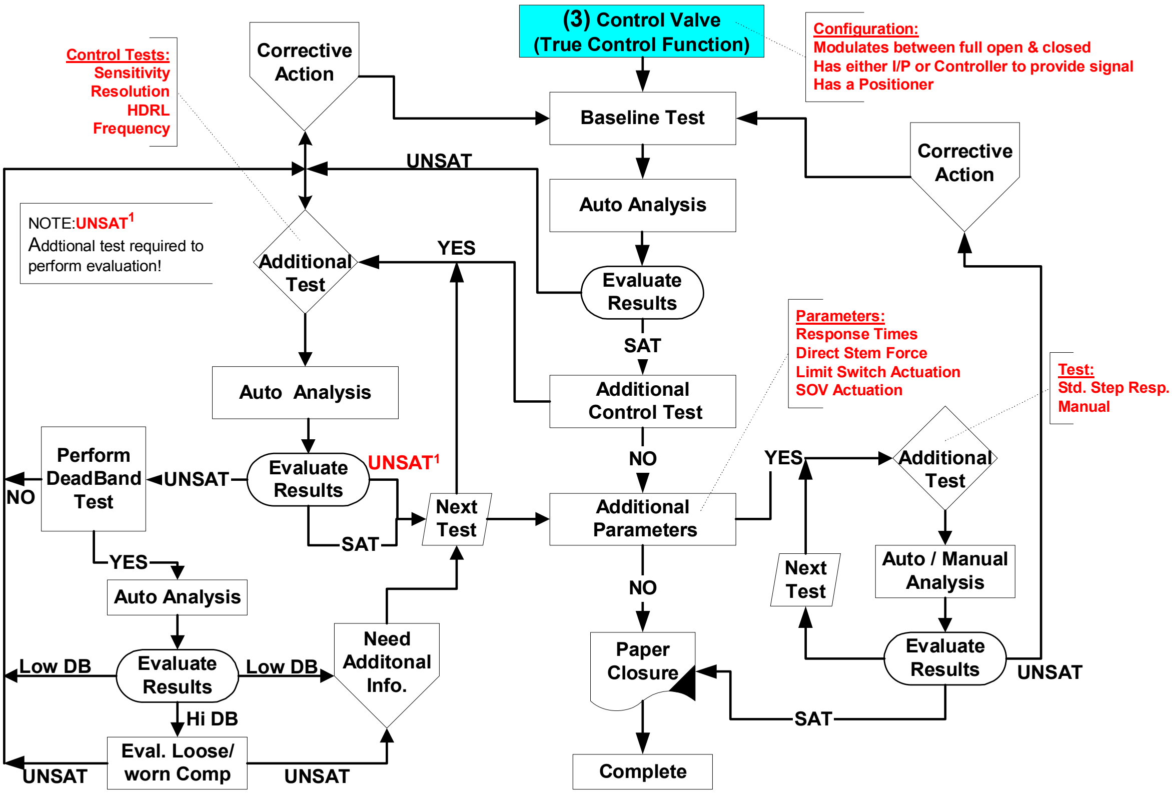

Fig. 4. Air Operated Valve Test with true controlling function

3.3. Air Operated Valve Test Programme Development

At present there is no industry accepted methodology for determining the frequency of testing for control valves. As these valves are tested to ensure optimum operation versus safety, it is usually left to the individual utilities to determine the appropriate frequency for each control valve. This frequency is usually determined based on the importance of the controlling function and the maintenance history for the AOV.

For those AOVs that provide a safety function, they are tested and evaluated against thrust requirements much the same way that MOVs are. According to these same thrust requirements, these valves need to be tested using accurate thrust sensors, and margin is evaluated against these requirements. According to the JOG guidance, these valves should be tested on a periodic frequency determined from a margin versus risk evaluation just as MOVs.

4. CHECK VALVE CONDITION MONITORING

4.1. Background

Check valves are located in throughout safety and non-safety-related system in a nuclear power plant. The check valve is designed to control the direction of fluid flow in a pipe. Check valves differ considerably in their construction and operation from other types of valves in that they are passive, and are activated internally by the flow of the medium they regulate. Check valves permit flow in only one direction. If the flow stops or reverses direction, the check valve closes to prevents back flow. As soon as the flow in the line is re-established, the check valve opens and flow is resumed in the proper direction as before. The five (5) most common check valve types are listed below:

- Swing check
- Tilting disc (TDC) check
- Piston or Lift check valves
- Duo disc
- Nozzle check valves

These components are susceptible to failure generally associated with either improper application or wear of internal parts. Failure of one of these valves during plant operation or in some cases, under cold shutdown conditions, could significantly affect plant safety. Failure can also result in costly and time consuming maintenance. Operating conditions that cause the valve disc and hinge arm to oscillate (flutter) can lead to accelerated wear eventually causing early failure. A major cause of check valve failure has been excessive wear of the hinge pin, hinge pin bushings, and disc stud. In addition, excessive oscillations can cause “disc tapping” at the backstop or seat which has lead to fracture of the disc nut or possibly damage to the seat.

Early detection of conditions that accelerate wear in check valves and cause their eventual failure is critical to an effective predictive maintenance programme for check valves. This need was noted in the release of SOER 86-03. This SOER sited a lack of proper methods to determine check valve condition assessment. Conditions that affect proper operation of check valves include excessive disc flutter and undesirable internal impacting. This SOER inclusive of other findings eventually prompted the USNRC to issue Generic Letter 89-04 requiring full stroke exercising of check valves under flow or through manual, visual inspection.

Through non-intrusive check valve diagnostics, it was determined that these conditions can be identified and trended to ensure proper scheduling of maintenance activities. Non-intrusive check valve diagnostics can also be employed to satisfy the requirements of ASME Code 10, Section XI for "full stroke exercise" without disassembly and inspection. In NUREG 1482, the USNRC accepted the use of non-intrusive testing as a means to satisfy the requirements of GL 89-04 and ASME Section 11. Later, NUREG 1482 and ASME OM 22, Condition Monitoring Exercise, provided an approach to establishing a comprehensive condition monitoring programme inclusive of flow testing, non intrusive testing, and visual inspection.

4.2. Check Valve Test Process

Non Intrusive Testing (NIT) is performed to eliminate the unnecessary disassembly of check valves for regulatory required periodic inspection. Depending on the type, size, and application of the check valve, a variety of different test equipment and test methods can be used to perform such a test effectively. A check valve can be tested under the following conditions:

- Normal flow: condition monitoring of the disc movement under normal flow conditions
- Transient (valve stroke): provides visual verification to satisfy full stroke exercise requirements
- Closed (leak detection): trend changes in

The main tools for Check Valve condition monitoring utilize three main technologies to effectively see and hear movement inside the check valve non-intrusively. These technologies are as follows:

- look technology = Ultrasonics and Eddy Current
    - Eddy Current: detects visual movement (limited to stainless steel)
    - Ultrasonic: highly accurate disc position and movement (limited to fluid media)
- listen technology = Acoustic Emissions
    - Utilized to verify impacts inside the valve
    - Additional frequency spectrum analyses reveals additional valve abnormalities

Based upon the technologies available, there are some cases in which not all technologies can be used. However, the use of at least two technologies together provides confident trending of check valve performance and should be required. For example, in accordance with ASME stroke test requirements, only eddy current and acoustics are required. However, in performance of condition monitoring in accordance with GL 89-04, ultrasonics and acoustics would be used under normal flow conditions to monitor the disc oscillations.

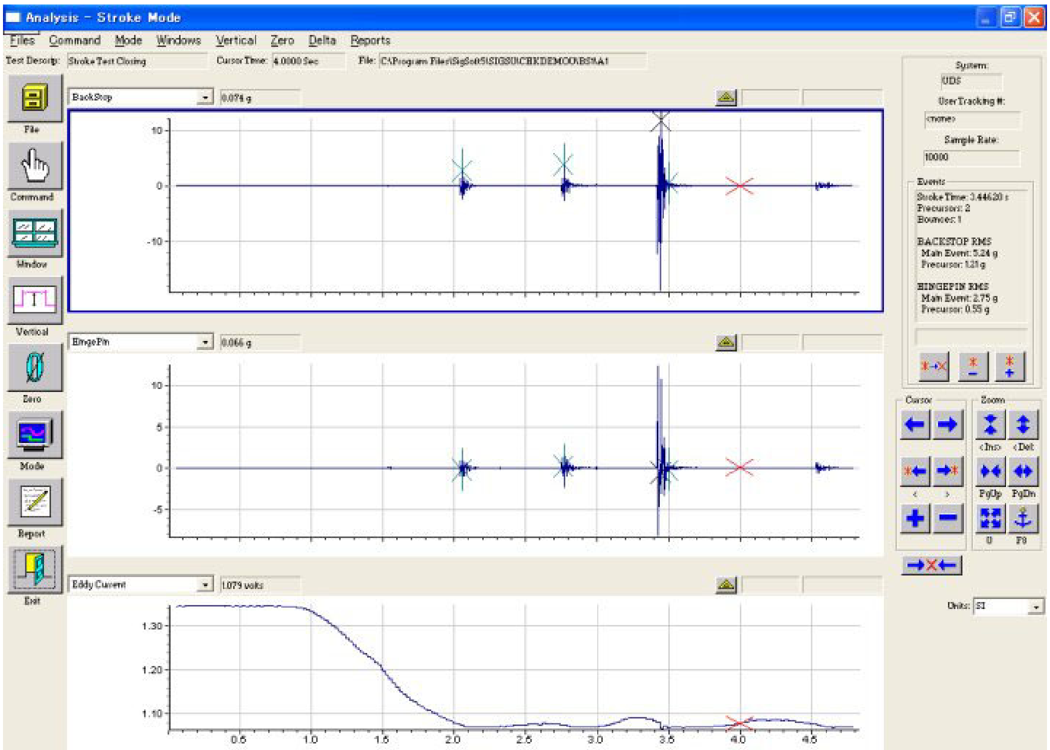

Fig. 5. Check Valve Stroke Test with Acoustic and Eddy Current

Generally, check valves are tested close to the end of the refuel cycle when systems are being tested and started up. The equipment utilizes probes that are attached to the check valve by using threaded mounting studs. These studs can be tack welded or glued onto the side of the valve permanently making installation on subsequent condition monitoring tests quick and easy.

4.3. Check Valve Test Programme Development and Evaluation

In the past, utilities incorporated a periodic disassembly and inspection programme to address stroke exercise requirements and condition assessment for check valves. As stated earlier, NUREG 1482 and ASME OM22 provide guidance in establishing a CBM programme for check valves in critical safety systems. Safety injection check valves are the primary issue. These are check valves are required to open to deliver coolant to the reactor in case of a low pressure accident. These valves are required to be tested to satisfy ASME Section XI and plant Technical Specifications. Other primary systems to consider are residual heat removal (RHR), and Chemical Volume and Control (CVCS).

On the secondary side, most systems that operate to support normal plant operation and see continued service are good candidates for the predictive maintenance aspect of the equipment. This allows for an accurate determination of which check valves really need attention and prevents disassembly for no good reason. Many US utilities are using this aspect more and more with good results. Some systems where this methodology is applied in the US are Component Cooling, Main Feedwater, Condensate, Condensate Booster, and Auxiliary Feedwater. There are others that vary from site to site but any system that contains check valves that are a concern can be tested.

NUREG 1482 suggests the most appropriate method of setting the sampling frequency is through grouping check valves by type, size, and application. GL 89-04 provides guidance in establishing these groups. Based on the grouping, the utility should incorporate a test matrix inclusive of blend of flow testing (FT) and non-intrusive testing (NIT). The following sample table from NUREG 1482 provides us with an example:

Refuelling Cycle	Train 1 Valve	Train 2 Valve	Train 3 Valve	Train 4 Valve
1	FT/NIT	FT/NIT	FT/NIT	FT/NIT
2	FT/NIT	FT	FT	FT
3	FT	FT/NIT	FT	FT
4	FT	FT	FT/NIT	FT
5	FT	FT	FT	FT/NIT

Fig. 6. NUREG 1482 Sample Test Matrix

According to this test matrix one valve from each group should be tested during each cycle. The remaining valves in the group are exercised during a flow test. If problems are discovered in a check valve, the remaining valves in the group are required to be tested by NIT methods as well.

5. CONCLUSIONS

The nuclear industry today faces many critical issues that affect its very existence. Key issues that face many utilities today in highly developed nuclear countries are deregulation and plant licensing. In response to these issues, utilities have countered with cost reduction measures and more extensive condition monitoring programmes to assess operating conditions. These measures have resulted in reduced refuel outage durations, increased condition monitoring activities, online maintenance and CBM, and extended operating cycles.

Valve and condition monitoring technology has played a key role in both cost reduction measures and improved monitoring activities. The advanced technology we can find available today can be used to:

- Increase equipment and personnel safety
- Increase plant efficiency
- Reduce refuel outage maintenance activities
- Reduce unplanned maintenance activities

Considering these advantages and the issues that the nuclear industry is facing today, we can easily see the advantage of such technology. As technology evolves, nuclear power utilities should share in the benefits that these technologies offer and implementing a comprehensive maintenance programme that incorporates a blend of risk informed condition monitoring into their existing overhaul and inspection programme.

ANNEX IV. CONDITION BASED MAINTENANCE EXPERIENCE IN THE EDF'S NUCLEAR POWER PLANTS

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Abstract

As a nuclear operator, the purpose of EDF's maintenance policy is to guarantee the operation of its installations, in compliance with safety requirements and in the best conditions for production of a safe and clean kWh, at a competitive price for its customers. Within this context, one of the day to day aims is to ensure that each maintenance activity is correctly carried out, in terms of both its definition and its timing. In 1995, operational implementation of an initial level of optimization of systematic preventive maintenance enabled EDF to obtain conclusive results in terms of cost reductions, while increasing equipment reliability and therefore the availability and safety of the plant.

1. INTRODUCTION

The maintenance strategy in recent years has been to continue with deployment of this maintenance optimisation approach, while using levers, such as condition-based maintenance methods or, in certain particular cases, condition-based maintenance using pilot equipment items.

After recalling the various possible maintenance practices, this article describes the contribution of condition-based maintenance, in which an interpretation of supervision information enables customised maintenance work to be done only when it is relevant. This predictive maintenance approach can also be accompanied by inspection of pilot equipment items as part of the defence in depth process.

Examples drawn from EDF's experience illustrate the main domains linked to these notions as well as the contribution in terms of reliability and cost.

2. MAINTENANCE-RELATED ISSUES

Industrial equipment is disturbed by malfunctions which may affect production costs, availability and safety of installations, quality of products and services, and safety of people and environment. Maintenance works out actions to limit the effects of these disturbances and thus make it possible to achieve required performance. It compares company objectives with the results shown by experience.

In the case of nuclear power plants which refuel during unit outages, most maintenance actions must fit in with the requirements of the calendar of these outage periods, as dictated by fuel requirements. The methods and techniques used make it possible to construct strategies which assist the people responsible for maintenance in their decisions within the overall scope of these constraints.

In order to optimize the maintenance of their equipment, process industries have generally turned towards the Reliability Centred Maintenance (RCM) method. This method makes use of equipment breakdown, basic component failure analysis and reliability data to determine the risks of equipment malfunction and to identify the factors according to which it is efficient to take action to reduce these risks.

This is the position of Electricité de France (EDF) which launched an RCM project in 1990. Since then, this method has become widespread and has been adapted to the nuclear power plants. It is now part of EDF technical maintenance policy.

EDF's maintenance policy comprises three key pillars:

- Maintain dependability at a level required for all reactor operating phases,
- Boost the competitiveness of the nuclear kWh
- Prepare for the future, by maintaining the production tool, enabling a service life of at least 40 years to be envisaged for the nuclear unit fleet.

The constant search for optimization is the basis of the maintenance policy that EDF has been implementing on its nuclear fleet from the outset. It is applied to the maintenance programmes with three major absolutes:

- Give priority to safety, if there is any conflict between safety demands and economic needs,
- For each item and system, guarantee that it is able to perform its duties,
- Permanently seek to optimize preventive maintenance.

In all the cases, it is a matter of implementing a rational maintenance approach for controlling the consequences of equipment failures in the installation. The method makes it possible to ascertain the equipment on which preventive actions are necessary, what sort of actions to be effected and when they need to be carried out.

Beyond their role for scheduling routine maintenance, these studies also make it possible to rethink the maintenance carried out, and highlight requirements, costs and potential savings. It is often noticed that they lead to a reduction in the frequency of intrusive interventions, even to dispensing with them, and to less costly in-service monitoring tasks being introduced into the programmes, these enabling the trend of degradation to be monitored. These studies therefore often result in the setting up or the development of condition-based maintenance techniques associated in specific cases with inspection of sampled equipment.

Monitoring reliability data is a means of permanently questioning the pertinence of our maintenance options, whether with respect to definition or frequency. Monitoring equipment and system unavailability (duration, number), in particular as specified in the General Operating Rules, keeps the operator EDF permanently informed of its maintenance policy's conformity with safety requirements. Internal experience feedback within the EDF nuclear fleet, from manufacturers and at an international level, also contributes to this analysis.

3. CHOICES OF DIFFERENT MAINTENANCE STRATEGIES

3.1. Definition of the different types of maintenance

Whereas it is easy to agree on the general breakdown of maintenance into different types of activities (Figure 1), different interpretations are sometimes encountered when attempting to classify the interventions more precisely. This paragraph shows the definitions we use here.

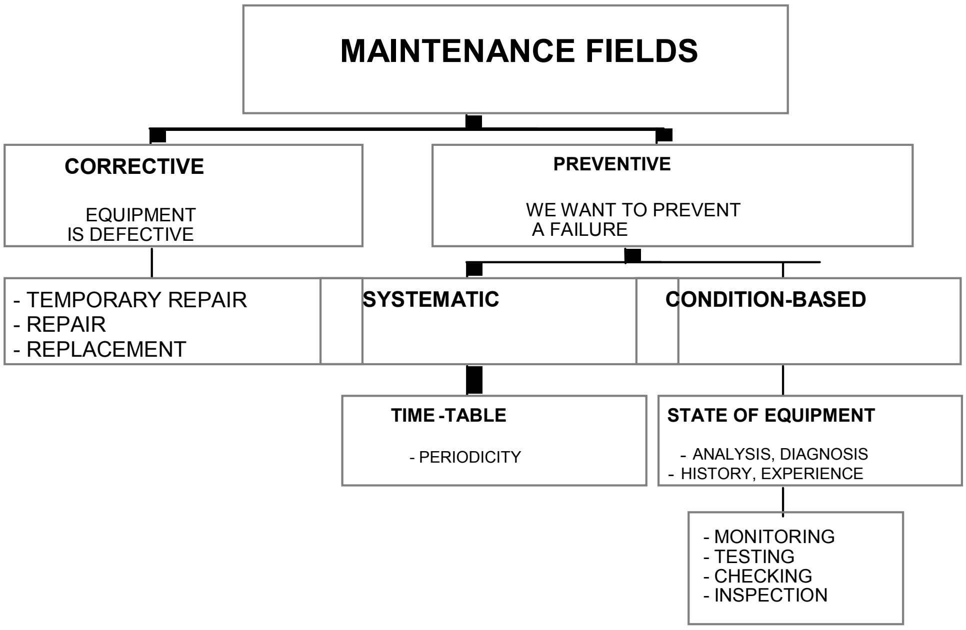


Fig. 1. Different types of maintenance

European standard EN13306, which has recently replaced terminology standards of European countries, has changed certain definitions, in particular including the following:

- Predetermined maintenance: Preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation.

- Condition-based maintenance: Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions.

  Note: Performance and parameter monitoring may be scheduled, on request or continuous.

- Scheduled maintenance: Preventive maintenance carried out in accordance with an established time schedule or established number of units of use.

These definitions make it possible, amongst other things, to clearly distinguish "scheduled maintenance" and "predetermined maintenance". A classification of the maintenance tasks can be drawn up on the basis of the representation in Figure 2.

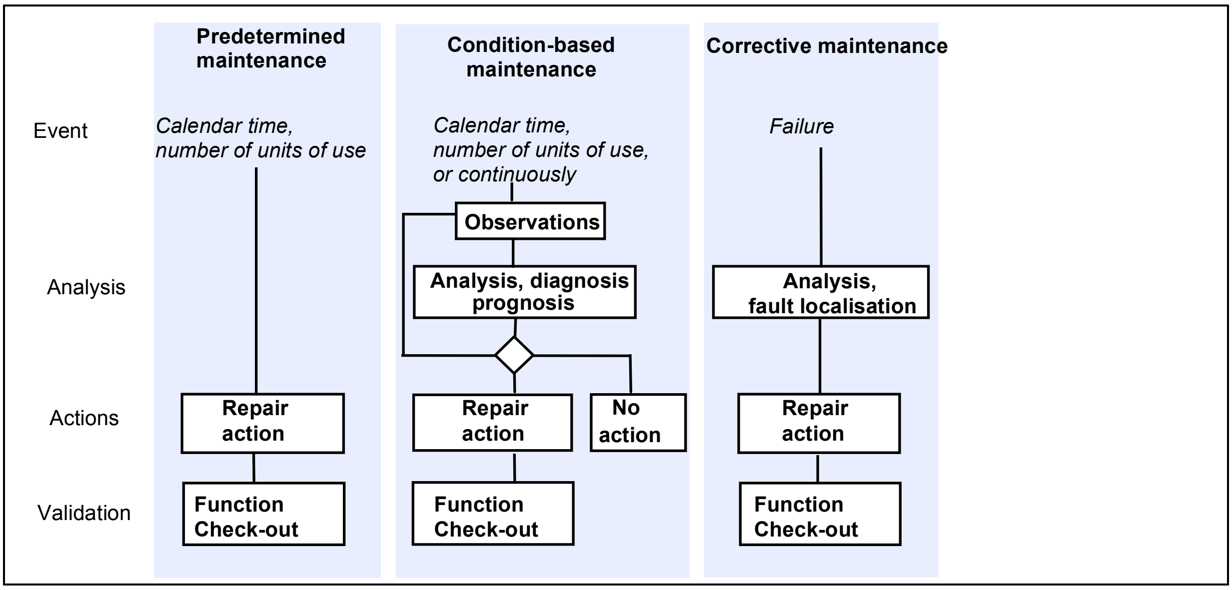


Fig. 2. Comparison of the different types of maintenance

3.2. Identification of a number of characteristic maintenance tasks

This paragraph describes certain task according to the different types of maintenance.

3.2.1. Predetermined maintenance

For the main part, predetermined maintenance is based on tasks involving the predetermined replacement of components and on the servicing tasks on the equipment or its environment.

The purpose of the predetermined replacement of components is to reduce the failure rate in the equipment and, so to speak, to «rejuvenate» it. It generally requires the equipment to be shut down and dismantled, and therefore leads to unavailability and can be expensive. These tasks are all the more efficient since the operating life of the components or materials replaced is accurately known. So this avoids pointless observation of the trend in the degradation and makes it possible to intervene at the right time. If, on the other hand, the operating life fluctuates or is not accurately known, there is a risk, if the predetermined replacement time is too long, of running into a breakdown nevertheless or, conversely, if the period is too short, of unnecessarily discarding parts in good condition.

Lubrication is almost always a predetermined operation which consists of topping up oil or lubricant. Strictly speaking, it does not involve a replacement. Lubrication does not have the effect of rejuvenating the equipment; on the other hand, it does preserve it against excessively early degradation. It may therefore be said that it serves to control the trend in the failure rate. Routine servicing (removal of dust, re-clamping of connections, blow-downs, etc.) shares the same objective, which is why we classify it within the same type of generally simple and inexpensive tasks.

3.2.2. Condition based maintenance

As shown in figures 2 and 3, the key points of condition-based maintenance are the recording of observations, the analysis of these and the decision taken following this analysis.

An initial category of tasks concerns the recording of observations. This involves inspections, monitoring, checks, etc.

By inspection is meant simple operations consisting in examining an item of equipment without dismantling it. These tasks, in particular the ones done during the rounds, are generally carried out by the operating team.

The purpose of monitoring and inspection is to detect degradation in such a way as to be able to undertake condition-based operations to bring the equipment into line. They are generally carried out when the equipment is in-service. Consequently, they do not affect production. They may be carried out during operation or when tests are being conducted. Naturally, they only have an effect on the failure rate of the equipment when they lead to repairs. Otherwise they only serve to increase confidence in an item of equipment. The inspections of pilot equipment items chosen from amongst the most heavily stressed items are also a means of revealing hidden faults.

Monitoring implies good knowledge of the equipment degradation modes (OMF studies) and consequently the faults likely to occur and the measurement and assessment means for monitoring them. In Nuclear Power Plants, this monitoring is conducted by EDF by following the trend data produced by the operation and maintenance professional sectors.

The checks or overhauls constitute another category of preventive maintenance tasks. Generally, they require the equipment to be out of action to be able to carry out the dismantling operations. They are often costly tasks. The purpose of the overhauls is also to reveal degradation likely to give rise to faults. As a result of the dismantling operations, they often lead to parts being replaced.

The compliance tests constitute a separate category amongst the preventive maintenance tasks. In fact, they are only worthwhile on equipment whose functions are on standby (in particular, the protection devices). They may then do away with any uncertainties there may be concerning the capacity of the equipment to fulfil its functions. These tasks enable hidden faults to be revealed and to ensure that the equipment is capable of fulfilling its functions. Their main significance is in revealing the possible unavailability of standby equipment. Finally, the overload tests which make it possible to establish that there are margins beyond the nominal operating conditions, will also be classified within this category of tasks. As a result, it may be considered that they only apply to standby functions since they are not required under normal working beyond their nominal point.

It is this breakdown which is used in the RCM method. It is, however, necessary to state clearly here that what is frequently understood by "condition-based maintenance" is in fact no more than the set of non-intrusive tasks known as "monitoring" to the exclusion of the checking tasks and the tests requiring the equipment to be rendered unavailable. This meaning of the word will be used in the remainder of this paper.

Condition based maintenance method using pilot equipment items:

In some cases, an installation comprises a number of similar - even identical - items, operated in a comparable way, so that it is in principle possible to draw conclusions applicable to all equipment in the similar equipment family considered from the checks conducted on only some of the equipment in the family. This method, which makes the maintenance work to be done on the whole family dependent on the inspection results available for these items known as pilot equipment, is called pilot equipment condition-based maintenance. The application of this method to nuclear power plants is illustrated in chapter 5.

Diagnosis and prognosis:

Monitoring and inspections provide information on the state of an item of equipment. From this information, the operator must undertake an analysis aimed at replying to two questions:

- is the equipment the source of degradation and, if so, which ones?
- given the current condition of the equipment, is it likely to change and in particular by when must I absolutely schedule maintenance in order to prevent a failure?

The first question summarises the issue of diagnosis, the second, that of prognosis.

These activities generally require analysis and interpretation of available information. They are based on feedback and on the expertise of equipment specialists. Such expertise may be based on knowledge of the degradation mechanisms and their consequences on behaviour, on keen understanding of the operation of the equipment making it possible to identify malfunctions, on a modelling of its structure.

The condition-based maintenance diagnosis is made on the basis of **monitoring the evolution** of parameters and of **periodic health check-ups** on the equipment. It is a means of identifying anomalies with an assessment of their seriousness, in order to perform maintenance at the right time and anticipate problems. As shown in the example in figure 4, the equipment health check-up covers all the components involved in the working of the equipment.

Diagnosis is a stage common to corrective maintenance and condition-based maintenance in order to identify components to be repaired and actions to be undertaken, in the event of degradation or failure. Prognosis is specific to condition-based maintenance; it is used to plan as efficiently as possible which operations to undertake. Through such diagnosis and prognosis activities, monitoring contributes to condition-based maintenance. A characterisation can therefore be seen in what may be expected from monitoring within this framework: it must offer information, which can be interpreted in terms of diagnosis and prognosis; it must also make it possible to highlight degradation and failures as early as possible.

The prognosis may be an estimate at a given moment of the time to failure of an item. To make a prognosis, we use experience feedback data. This enables us to determine the moment at which the maintenance thresholds will be reached.

In the case of complex equipment likely to be affected by different degradation modes at different rates, the prognosis can also involve the production of various scenarios for the changing health of the equipment considered, which can be combined with various maintenance strategies prepared in advance in order to minimise the risks of unavailability. Chapter 7 will illustrate an application of this Diagnosis/Prognosis approach to the case of generators.

In both cases, the resulting maintenance choices may range from increased monitoring to the decision to take immediate or deferred action.

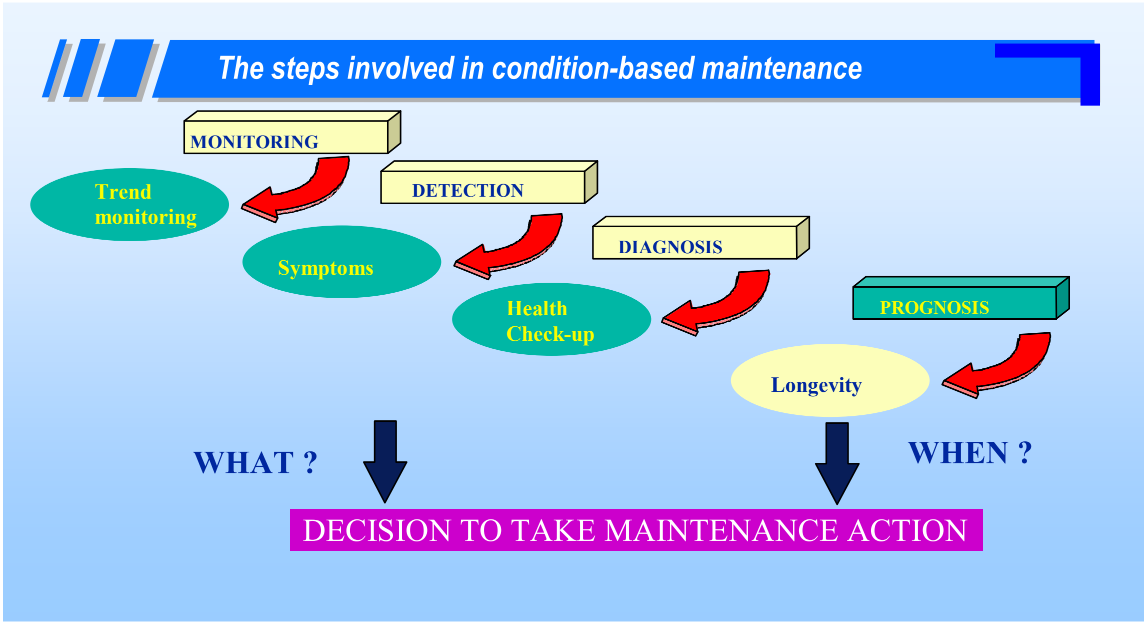


Fig. 3. The steps involved in condition based maintenance

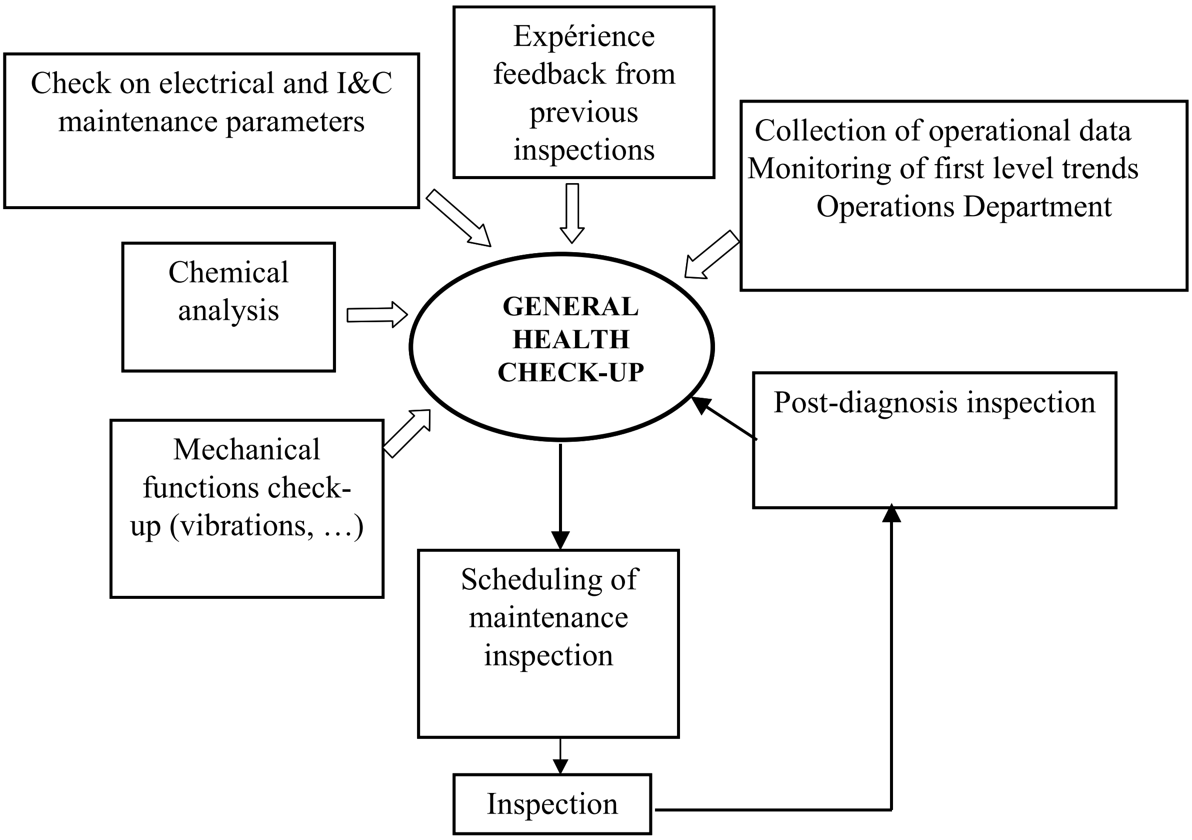


Fig. 4. Health check-up used for generator CBM

4. APPLICATION OF CONDITION BASED MAINTENANCE AT EDF

4.1. State-of-the-art in monitoring and the diagnosis support facility for the main components at EDF

EDF has long sought to improve the availability and safety of its generation installations. To do this, it has used monitoring techniques on its equipment: vibration monitoring of the turbo-generator sets, monitoring of flame-boilers, etc. The start of the French nuclear programme in the 1970s strengthened this approach. EDF then researched and developed monitoring systems for the early detection of anomalies and the diagnosis support facility for faults in the main components of its reactors.

Today, EDF uses the main existing monitoring techniques and applies these techniques to most of the equipment in the nuclear power plants. Table 1 shows the monitoring techniques used for the main components.

Table 1: Monitoring techniques used

	Leak detection	Vibratory monitoring	Acoustic monitoring	Acoustic emission	Chemical monitoring	Electrical measurements	Infrared thermography	Diagnosis support facility
Primary PWR circuit	X	X	X	X				X
PWR steam generators	X							
Heat exchangers	X				X			
Valves	X			X		X	X	X
Turbo-generator sets		X			X	X		X
Auxiliary rotating machines		X						X
Reactor Coolant Pumps		X			X			X
Generation transformers				X	X		X	
Piping	X							
Generators		X				X		X
Back-up diesel engine		X						X

It should be remembered that the main measurement techniques used to detect leaks in the monitoring systems are acoustic measurements (overhead acoustics, acoustic emission), temperature measurements (especially infrared thermography), pressure, hygrometry and the physical-chemical analysis methods (mainly nuclear, mass, absorption spectrometry, chromatography).

The main monitoring techniques used give rise to operational applications at EDF, as shown in the table above. It shows that the main monitoring requirements are covered.

These techniques may be used continuously, periodically or sporadically before a shutdown. Feedback demonstrated fairly quickly that users were encountering difficulties in directly working out a diagnosis from the information produced by the first generation monitoring systems. In fact, on the one hand, the raw data produced by these systems are not always easy to interpret and require a certain level of expertise, on the other, failures being rare, an on-site user does not, generally speaking, have prior experience of similar events enabling him/her either to recognise a known problem or to gain diagnostic expertise.

Decision was therefore made to offer support for the diagnostic activity, to guide an operator's maintenance services and to simplify their interpretation work. Thus, for several items of equipment (the turbo-generator set, auxiliary rotating machines, the detection of loose parts, etc., for example), "diagnostic handbooks" were drawn up, step-by-step describing a procedure leading from carried out observations to the identification of likely failures or degradation. In order to supplement the assistance offered by the diagnostic guides and make them easier to use, EDF started in the 1980s the development of computer-based diagnosis support facility tools. These "knowledge based tools” rely on an explicit representation of diagnostic expertise; they have generally been created in close association with equipment manufacturers, such as ALSTOM for the turbo-generator sets (DIVA tool) and JEUMONT SA for the reactor coolant pumps (DIAPO tool) or internally for the transformers (MICROBULLES tool)

In order to make for easier data collection and trend monitoring, EDF is also developing computer tools able to collate operating data (operation inspection, Control data base, vibration inspection) in a machine monitoring dashboard used by the equipment manager.

4.2. Modernization of existing monitoring systems

Continuous monitoring of the main components of nuclear power plants is currently in place at EDF. This mainly involves vibration monitoring of the turbo-generator set and the intake components, the detection of loose parts in the primary circuit and monitoring of the internal structures.

Feedback on these systems confirms the relevance of the principles of monitoring but highlights the limited use today of outdated technology first-generation systems, which have become hard to maintain.

Thus, in response to both the limits of the current monitoring systems and new requirements for the monitoring of certain equipment, a Diagnosis Support Facility System (PSAD) was designed, built and deployed on an initial installation. This modular tool includes the monitoring functions for all the equipment covered within the same analysis unit. It enables the monitoring functions for different equipment to share joint resources and formats (storage, consultation, processing operations, etc.). Its modular structure provides a framework for integrating monitoring systems designed for new equipment.

The study for replacing the existing systems with this new system is in the process of examination. In any case, implementation of this system or the renovation of existing measurement collection and processing systems implies that these new tools have to be assimilated by all players in the organisation, presented below in chapter 7

4.3. Updating of the maintenance programmes

Basic preventive maintenance programmes (BPMP) are drawn up when commissioning an installation. On the basis of design and feedback data on similar equipment, these programmes define the preventive maintenance operations to be effected and their periodicity in respect of each item of equipment.

These programmes have subsequently been updated on the basis of feedback data. Thus, for most equipment, an FMECA (Failure Modes Effects and Criticality Analysis) has been carried out. This analysis has led to the identification of critical components in terms of availability, safety and maintenance costs. It can be used to propose monitoring actions resulting in less frequent routine inspections and even to exemption from these in some cases, thus avoiding unnecessary shutdowns and dismantling operations. It can also allow definition of the maintenance method most appropriate to the stakes and issues involved and offering the best economic advantage. The maintenance method selected then corresponds to either systematic maintenance or condition-based maintenance or even - for a given period - maintenance by inspection of pilot equipment, or a combination of these methods in some situations.

4.4. Organizing expertise at EDF

The diagnostic tools which have been developed are intended for an operator's maintenance services. These services carry out a so-called "first level" analysis at a power station.

However, the following must also be carried out:

- comparison of the experience feedback acquired at various plants;
- setting up of studies and test campaigns applicable to all or part of the fleet units;
- incorporation of maintenance optimisation requirements for all fleet units; and
- incorporation of the constraints associated with exceptional maintenance work.

Furthermore, the skills necessary for optimum monitoring of the machines, diagnosis of their defects, prognosis and the maintenance decision, as well as for performing exceptional maintenance work are available for the main equipment among the players spread around the various structures of the company.

In order to encourage optimum use of these skills, it seemed relevant, for certain components, to create a formal "expertise network" with the following tasks:

- to provide operational services to support the operator, in particular "level 2" diagnosis services (more detailed diagnosis than level 1, processing of delicate cases, etc.) and training in first level expert investigation (these services are provided by an operational service included in the Nuclear Generation Division),
- provide national support to take account of the overall maintenance strategy for the equipment concerned,
- provide support by exceptional maintenance specialists for optimum performance of this type of work,
- to capitalise on, maintain and develop skills in respect of monitoring and diagnosis (Research and Development division).

The active installed base support centre (CAPE) co-ordinates these expertise networks.

The aim of this organization which is detailed in chapter 7 is to optimize use of the skills within the company, offer a service to all power plants consistent with the overall strategy and to capitalize on skills in the area of monitoring and diagnosis.

5. APPLICATION OF THE PILOT EQUIPMENT MAINTENANCE METHOD

5.1. What is pilot equipment maintenance?

In a certain number of special cases, preventive inspections have shown that the inspected equipment changes little or not at all: no degradation was detected or the degradation observed evolved only very slowly.

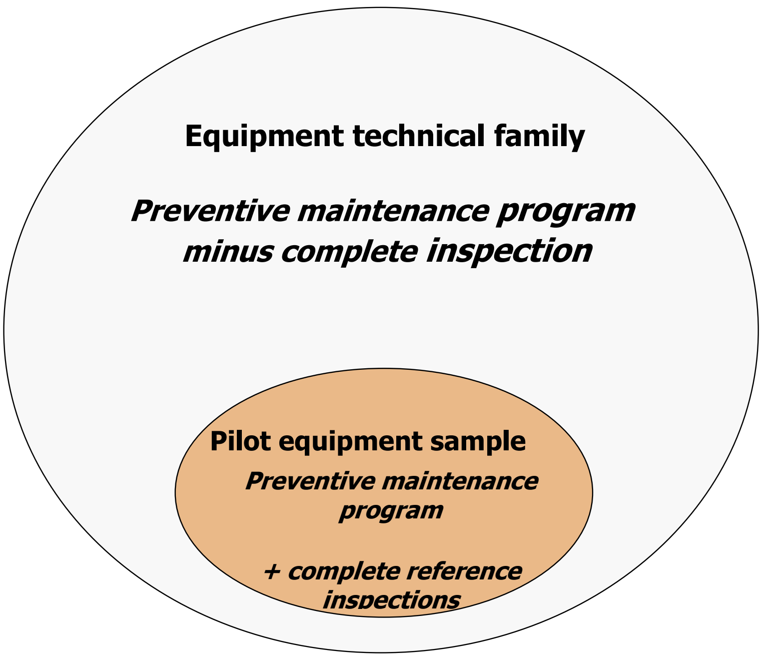
In other cases, the available experience feedback, knowledge of the degradation modes likely to affect an item, and the possibility of following these degradation modes by appropriate monitoring leads to condition-based maintenance being chosen. However, this monitoring does not rule out the appearance of new degradation modes which were not observed by the monitoring system put in place. Consequently, it may be desirable in some cases to consolidate the monitoring system put in place by an additional means of detecting these new degradation modes.

If, in one or other of these two cases, there are also numerous identical or very similar examples of the equipment considered, operated in a similar way in one or more installations, it is possible to adopt maintenance applied to the entire family of equipment considered, dependent on the results of inspections and checks performed on just a part of the equipment in the family. The equipment which is the subject of the inspections determining the maintenance performed on the entire family is then known as "pilot equipment", and this particular form of condition-based maintenance is known as "sample-based maintenance" or "pilot equipment maintenance", the designation we will use in the rest of this report.

The uses for pilot equipment maintenance identified and employed by EDF in nuclear power plant maintenance are exclusively the following:

1st case:

This is a case in which - without increasing the risk of failure - we want to extend the interval before maintenance involving removal and replacement of wear parts to an optimum time corresponding to wear of the replaced parts at limits which are acceptable given their function.



This is for example the case of certain emergency pumps which are little used during operation and for which the maintenance intervals defined by the designer at commissioning on the basis of normal industrial operation are inappropriate to their use in a nuclear power plant.

An initial inspection of the pump as required by the preventive maintenance programme, with disassembly, replacement of wear parts and appraisal of the parts removed, means that an extension of the reasonable maintenance interval on this equipment could be envisaged. From then on:

- no further maintenance with disassembly is performed on the equipment in the family, although the individual behaviour of each pump is then closely monitored.
    - from the family of pumps, we select those likely to be the most degraded following a multi-criterion analysis by experts, in particular taking account of the number of hours of operation, the number of start-ups, the test results, and so on. From among this sample, we select the most exposed pump which then undergoes the complete inspection specified at the new interval determined for preventive maintenance,
    - from this action we deduce the new reasonably conceivable interval and so on, changing the pilot item each time, until an optimum interval is defined,
    - When the optimum interval is defined, we then abandon the pilot equipment maintenance process and return to systematic maintenance at the new defined intervals.

The savings achieved, for example for the steam generators emergency feed water pumps (ASG) could correspond to a complete inspection with disassembly, checks and replacement of seals, at intervals more than twice as long.

2nd case:

This is the case in which the family equipment considered is affected by degradation mechanisms that are extremely slow or which are potential but usually absent, and in which inspections with disassembly conducted to measure the risk of these degradation mechanisms occurring may themselves lead to operational failures.

This is for example the case with certain families of valves, which are too often systematically disassembled and for which, in practice, pilot item maintenance will consist in:

- elimination of inspections with disassembly of all the equipment in the family considered, except for the set of items known as the pilot equipment
- collecting the experience feedback from the inspections conducted on the pilot equipment and the experience feedback from the operational behaviour of the equipment of the family which is no longer subject to inspection
- accepting the possibility of returning to a systematic inspection rapidly should experience feedback prove negative, in other words highlight an unexpected risk situation or a rise in the number of corrective maintenance operations.

The problem with the method here is the selection of the sample of pilot equipment items, determining the number of items in the sample and the choice of the items.

When the total number of items making up the family in question is more than 1000, it is possible to use a statistical analysis to determine the size of the sample, with selection of the items in the sample then being possible on a random basis.

When the total number of items making up the family in question is less than 1000, the size and choice of the sample is the work of an expert, with the items chosen those being those which in principle are exposed to the highest risk.

In both cases, the method is implemented for a limited period, followed by an analysis of experience feedback. Following this analysis, either the method is renewed for a further period, possibly with a different reference sample size, or if negative feedback is received, maintenance with systematic inspection of the whole family of equipment at regular intervals is resumed.

This method was for example applied to a family of 1100 similar valves used in comparable conditions on all EDF nuclear power plants, for which 80% of the 10-yearly inspections concluded that there was no degradation.

These inspections were maintained on all 300 valves of this family belonging to the primary system and chosen by experts as the sample of pilot equipment items for the entire family. To date, these inspections have revealed no degradation such as to cause concern for the performance of the family as a whole, while the number of corrective maintenance operations during operation on the entire family would for the time being seem to be stable, if not falling slightly.

3rd case:

In this case, we go from systematic, periodic preventive maintenance to condition-based maintenance determined by monitoring of a family of identical or similar equipment items. We also wish to consolidate this change by implementing an additional system for detecting any degradation mechanisms not covered by the monitoring arrangement.

For a given period and a number of pilot equipment items defined by experts, it is then possible to maintain the previous inspections and periodic checks.

In this case, as in the two previous cases, the study manager must collate experience feedback for the entire family for a given period during which condition-based maintenance is used in conjunction with inspection of pilot equipment items. After this period, and based on an analysis of these data, the decision can be taken:

- either to return to systematic maintenance for the entire family,
- or to implement condition-based maintenance on the whole family with or without reinforced monitoring, and give up the additional detection system using pilot equipment items,
- or to maintain both systems, with a new period for the inspection of the pilot equipment items and possibly a new definition of the number and choice of the pilot equipment items in the sample.

This is for example the case of the emergency diesel motors, for which the monitoring carried out could lighten the systematic maintenance burden. This monitoring, supplemented by detailed inspection of a limited number of reference cylinders in a sample of machines, allows monitoring of the entire family concerned.

6. QUESTIONS LINKED TO THE CHOICE OF CONDITION-BASED MAINTENANCE METHOD

Before bringing a monitoring system into general use or selectively installing a new monitoring system on an item of equipment, it is necessary to look at the essential matters of the functional or organizational requirements and considerations to do with monitoring.

6.1. Functional benefits of monitoring

When wishing to set monitoring in relation to all the degradation and failure that may affect an item of equipment, it is necessary to distinguish between:

- the degradation detectable by on line monitoring,
- the degradation not detectable by normal monitoring, but which can be shown up by non-intrusive examinations (ultrasound checks, for example),
- so-called hidden degradation which can only be identified and quantified by an intrusive inspection.

The functional benefits of monitoring are very important and of different kinds:

- prevention of major risks,
- optimisation of maintenance,
- aid in regard to equipment operation.

6.1.1. Prevention of major risks

It is an operator's continual concern to prevent major equipment failures and incidents (e.g. cracked shaft on a rotating machine, etc.). The primary aim of "effective" monitoring is therefore to contribute to such prevention. Consequently, it revolves around the early detection of degradation and their diagnosis. It thus helps to increase the availability and reliability of the installations and safety as far as people are concerned.

Monitoring enables the consequences of an incident to be minimised by:

- reducing repair costs and, for inspection and maintenance operations in a nuclear environment, radiation exposure. Thus, the failure to detect at an early stage the coming loose of a reactor coolant pump bearing has generated high repair costs and nearly two weeks' unavailability.

- limiting periods of unavailability by scheduling shutdowns as efficiently as possible, i.e. by replacing chance unavailability, following an unexpected failure, by scheduled unavailability (by taking advantage of a weekend shutdown, for example) which is far less damaging in terms of costs.

Monitoring contributes to safety through early detection of anomalies which might lead to serious consequences affecting safety last of all. It makes it possible to lower radiation exposure by reducing routine inspections and improving operating safety.

6.1.2. Optimization of maintenance

Monitoring is a condition-based maintenance facility which helps to better find out the state of the equipment through early detection and diagnosis. It may form an economic alternative to intrusive preventive maintenance tasks which require dismantling operations. It also enables longer intervals between inspections, with the gap depending on experience feedback on the life of certain components.

By way of example, monitoring makes it possible to:

- suppress some inspections of the reactor coolant pump bearings by detecting early whether they are coming loose through vibration monitoring,
- suppress the inspection of the turbo-generator set bearings by monitoring the temperatures of the bearings at nominal conditions and during a speed transient,
- replace a check using ultrasounds, which require the turbine casings to be opened, by vibration monitoring whilst in operation in order to detect a crack at an early stage.

The savings from monitoring are seen through the possibility of not taking into account serious faults as far as defining opening periodicity of machines is concerned.

Generally speaking, monitoring makes it possible to optimise the maintenance of the items of equipment monitored on an individual basis, according to their own characteristics and performances.

6.1.3. Aid in regard to operation of the equipment

Monitoring makes it possible to improve operation of the equipment, for example by substituting specific operating conditions (e.g. load reduction to meet a vibration criterion) for total unavailability. In addition, it provides the facts making it possible to remedy the problem (diagnosis) and consequently to restrict these specific operation times.

One specific important operating instance of aid is the reduction in the time needed to balance a rotating machine due to the setting up of vibration monitoring. Such monitoring in fact avoids having to add an additional measuring sequence to monitor the balancing.

6.6.4. Technical-economic analysis of monitoring

The decision to replace an obsolete monitoring system or to purchase a new monitoring system is often the subject of a request by the power plant for the financial justification of the purchase of such a system. A full study has been carried out for different types of equipment for the nuclear power plants (TGS, reactor coolant pump, detection of loose parts in internal structures).

A "profit cost" approach is used to gauge the relevance of a monitoring operation. It is a case of comparing the cost of an "unmonitored" incident with the cost of a "monitored" incident.

A failure has a direct cost (parts to be replaced, labour needed to carry out repairs, etc.) and results in costs associated with the relating unavailability (product of the down-time due to the cost of the day's unavailability).

With regard to the occurrence of the failure, the contribution of monitoring may be to enable the failure to be detected at an earlier stage, resulting in less costly repairs, and to more accurately identifying it (improvement in the quality and speed of the diagnosis) before any intervention. As a result, monitoring may make it possible to:

- reduce the direct cost of the failure (less costly repairs in terms of labour, necessary parts, etc.),
- reduce the down-time (there again, by simplifying the repairs to be carried out),
- reduce the cost due to unavailability by making it possible to replace chance unavailability by scheduled unavailability.

7. MAIN BENEFITS EXPECTED FROM CONDITION-BASED MAINTENANCE DIAGNOSES (examples of actual applications)

7.1. Valves

The use of condition-based maintenance enables intrusive maintenance operations to be replaced by diagnoses. In most cases, this involves checking the tightness and operability of the valves.

The diagnosis allows a relaxation in the maintenance intervals and a drop in the level of non-quality following internal inspections. On some items, this non-quality can account for 25% of maintenance repairs, which in certain cases impacted the duration of the outage. Furthermore, the periodic check that the valves are correctly adjusted and operating is a further guarantee of reliability.

For example, the maintenance programmes for the electric servo-motors stipulated complete maintenance at average intervals of 10 years. The use of diagnosis of leak tightness (measurement of falling pressure) and operability (force test) performed every 5 years, enables these intervals to be raised to about 15 years. Eventually, the use of new long-life greases should enable us to avoid having to perform these operations outside the regulation inspections. In safety terms, diagnosis highlights operability deviations (of about 5 to 7%) and reduces downtime due to incorrect operation by one third. Finally, given the number of valves (6000) in the EDF fleet, the savings are about 0.3 M€/year.

The annual acoustic tightness tests on the condenser bypass valves allow targeting of the valves to be inspected instead of the systematic inspections every 4 years. In addition, significant gains are obtained on the unit availability coefficient, ranging from 2 to 20 MWe as observed on the units in the EDF fleet.

Furthermore, the valves on the secondary systems, primarily those with an impact on efficiency, are tested using a variety of techniques (acoustic measurements, IR thermograph).

Leaktightness diagnoses on the pump discharge check-valves, in particular on the secondary system, mean that these items (previously inspected internally every 10 years at a cost of about 60K€/check-valve) are only inspected on the basis of leak criteria measured using the diagnostic tools. In addition, supervision has done away with numerous post-maintenance repairs (flange leaks).

To check the effectiveness of the diagnosis, inspections are carried out on the most heavily stressed reference valves to confirm the measurements and ensure that there are no hitherto unknown faults or defects.

7.2. Rotating machines

One doctrine of condition-based maintenance on auxiliary rotating machines defines the statistical criteria to be applied to each machine in relation to the initial health check-up following a complete overhaul.

A supervision and diagnosis methods guide drawn up by the R&D Department is based on machine monitoring and defines the descriptors and criteria used to diagnose the type and scale of the degradation in progress.

The use of condition-based maintenance does not replace periodic full inspections. A machine health check-up is periodically conducted on the basis of monitoring of parameter changes (vibration, temperature, pressure, oil analysis, etc.). It allows definition of the maintenance operations to be performed or the decision to postpone the inspection. The approach mainly leads to:

- elimination of the generally intermediate inspections, replaced by operational monitoring: line-up check, check on transmission gear teeth (coupling, up/down gearing), visual packing check,
- longer intervals between full inspections according to the analyses and the health check-up. These inspection postponements are however limited because certain components have a limited lifespan: bearings, mechanical seals, packing box stuffing, pump body seals, etc.)

For example, the use of condition-based maintenance on the seals and bearings in the reactor coolant pump units enables the intermediate inspection intervals to be doubled, provided that the health check-up criteria are met.

Inspection	*In systematic maintenance*	*In condition-based maintenance (compliance with health check-up criteria)*
Type 2A: inspection of 3 shaft seals	3 years	6 years at latest
Type 2B: inspection 2A + check on bearing and US inspection of shaft	6 years	12 years at latest
Type 2C: inspection 2A + standard replacement of seal 1	9 years	12 years at latest

For the auxiliary rotating machines, the average saving per machine subjected to a condition-based maintenance programme is estimated at about 20 %.

7.3. Electrical equipment

Generally speaking, electrical equipment is maintained following monitoring.

IR thermographs are extensively used to check hot spots on energised electrical systems (inverters, rectifiers, switchboards, power transmission, etc.). Maintenance is adapted to the faults observed. One plant has initiated an approach in which certain electrical switchboards are maintained while energised.

Maintenance of the 6.6KV motors is totally condition-based, according to measurements (oil analysis, vibrations, isolation measurement, and so on). Replacement of the bearings depends on the results of the vibration checks.

The particular case of transformers is detailed in chapter 7.

7.4. Generators

Since the units were commissioned, all the generator functions have been the subject of in-service monitoring, in particular by recording of generator parameters at regular intervals. Condition-based maintenance requires a diagnosis capacity capable of assisting with maintenance decisions, by providing criteria and indicators concerning the gravity and evolution of the degradation.

Generator parameter analysis guides and diagnosis aids are produced by the R&D Department based on machine monitoring, descriptors and the criteria allowing diagnosis of the type and scope of the degradation in progress.

The approach means that certain intermediate inspections can be eliminated, while maintaining the complete inspections at 10-yearly intervals.

Inspection	In systematic maintenance	In condition-based maintenance (compliance with health check-up criteria)
Type 1: draining, drying, isolation measurement, internal check by video camera	2 years	Condition-based + isolation measurement No more internal checks except for health check-up
Type 2 : draining, drying, isolation measurement, removal of flanges and US inspection of binding bands	5 years	27 Generators equipped with stainless binding bands (NMF18): Condition-based + isolation measurement 29 Generators equipped with corrodable binding bands (NMF3) inspection every 2 to 5 years
Type 3: Complete inspection	10 years	10 years

The average saving is about 3% per machine

8. ORGANISATION

8.1. Impacts of condition-based maintenance on the tasks

Condition-based maintenance is a powerful approach making it possible to reduce certain costs by "individualising" the maintenance. It is based on analysis of the effective behaviour of the equipment through monitoring.

Its implementation infers risk-taking in terms of budgetary forecast (spare parts, etc.), management of maintenance work resources (labour) and availability of the equipment (risk of hazards). It requires skilled personnel with experience and knowledge of the history of the equipment and of interpreting its behaviour. Its implementation also creates an additional data collection and analysis task for personnel. However, it does lead to greater interest in maintenance tasks on the part of the personnel along with acquisition of knowledge through training and through recognised daily activities.

Before setting up condition-based maintenance, it is nonetheless essential to conduct analyses demonstrating its technical and economic advantages, including the induced extra workload, the necessary training and recognition of the tasks performed. Condition-based maintenance clearly appears as an alternative to preventive maintenance, both of which have advantages and drawbacks which need to be weighed before any decision is taken.

8.2. Expertise network:

8.2.1. What is 2nd level expertise at EDF:

Implementation of condition-based maintenance presupposes a measurement analysis, diagnosis and rapid prognosis capability if a risk situation is detected by the monitoring system. This expertise can usually be put in place in the plant through personnel training if necessary and using analysis tools such as expert systems or data analysis guides.

In more complex cases concerning the more important equipment, it is nonetheless necessary to set up expertise to support the plant personnel, known as 2nd level expertise, capable of understanding and analysing all dimensions and aspects of the problem.

At EDF for the main equipment of nuclear power plants, we have set up expert networks concerning the generator, the turbine and its input devices, the primary motor-driven pumps, the transformers and other more specialised aspects such as detection of loose parts in the primary system, or voltage control and the generator-grid interface.

For a clearer understanding of the arrangement in place, we will present the generator and transformer expert networks below. Illustrations are given of implementation of these networks in their plant support function and EDF nuclear generating division head office support function.

8.2.2. The generator expertise network:

When the plant is faced with a risk situation during operations, or when a long-term maintenance programme needs to be established in order to ensure generator availability while optimising maintenance costs, it must be possible to mobilise the following in good time, commensurate with the urgency of the problem to be dealt with:

- measurement, measurement analysis and complex diagnosis skills,
- maintenance strategy skills concerning the entire EDF fleet of identical machines,
- exceptional maintenance skills, exceeding the capabilities of the plant's personnel,
- R&D skills covering the entire generator field, in terms both of tools - new monitoring system, database and knowledge base - and methods development: risks analysis, maintenance optimisation.

EDF, which operates 58 nuclear production generators of more than 1000 MVA, 60 thermal production generators of intermediate power and nearly 1000 hydraulic production generators of small to medium power, these skills are available in-house. Even if this situation does not rule out calling on outside skills, as we will see later on, nor conversely the provision of company skills to meet external demand, the primary role of the persons concerned is to provide this support to the plants.

These persons, who physically are members of teams whose duties correspond to their type of skills are therefore grouped within an in-house generators expertise network (REA).

In concrete terms, if the plant needs support, it turns first of all to the measurement and diagnosis specialists and, if the situation so warrants, to the maintenance strategy specialists of the nuclear generating division. This can be done with the machine in service or the machine shut down during a refuelling outage or further to a failure.

Support involves production of the diagnosis and the required response in the form of an advice sheet from the expertise network, although the plant has sole responsibility for its decision provided that it has no national impact, as would for example be the case with management of spare generator rotors.

The two other types of skills, R&D and exceptional maintenance, are involved in plant support in particularly complex cases requiring the use of tools such as simulation tools for R&D or a contractual analysis, planning and exceptional maintenance monitoring for engineering.

Most of the time, as soon as the external maintenance contractor is known, it also becomes an active contributor to the diagnosis and definition of the response to be applied to the machine.

In complex cases, the original designer of the machine participates with the plant and its expertise network in drafting the diagnosis and prognosis applicable to the machine, thus making a significant contribution to in-house development of the maintenance strategy applicable to the machine in question.

In the light of the proven benefits of this diagnosis/prognosis approach on a number of specific cases, EDF in 2003 took the decision in principle, in other words barring emergency situations, to extend this exercise to all nuclear production generators. Consequently, 5 to 10 generators will be subject to this approach every year.

In concrete terms, the EDF representatives of the generator expertise network, the EDF representatives of the plant concerned and the representatives of the original designer/manufacturer - ALSTOM - collate and share all available data on the machine, from the early design and construction data up to the most recent operating and maintenance data resulting from inspections and monitoring.

An initial part of the approach is joint production of the machine diagnosis, identifying and quantifying its various weaknesses on the basis of the available data and the experience of all involved: for EDF, sound knowledge of the behaviour of its machines and the measurements and checks conducted, for the designer-manufacturer, sound knowledge of the technology, its strengths and weaknesses as highlighted on the entire fleet designed by itself and in service around the world.

The second part of the approach is to draw up the most probable scenarios for the evolution of the degradation modes affecting the machine and the best answers in terms of the checks and the maintenance operations to be performed, given the various repair options possible and the various windows of opportunity for doing the work offered by plant operations, particularly management of its fuel. Here EDF in particular offers extensive knowledge of the constraints on the plants, while the designer/manufacturer offers particularly its extensive knowledge of the available machine repair processes and their foreseeable long-term effects.
The approach is synthesised by EDF in-house, on the one hand to draft the maintenance strategy applied to each machine, and on the other to draft the maintenance strategy applied to the entire fleet and subject to annual review by the Division head office.

8.2.3. The transformer expertise network:

The transformer problem, while paralleling the generator problem, is interesting in that it is to a certain extent its opposite. Monitoring and maintenance of a generator involves "routine nursing" of the machines, with a whole range of maintenance operations and partial repairs to be carefully scheduled as the machine gets older. Monitoring and maintenance of a transformer however involves no really significant maintenance operations and tends more to involve "medical emergencies" with generally large-scale economic consequences.

For a nuclear power plant specialist, the problem of the main transformers can be quite simply summarised as follows: Does my transformer contain a worrying fault requiring particular attention, and if so, can I take the risk of continuing to generate with this equipment or should I replace it?

Unfortunately, the answers to these simple questions are anything but simple and the equipment usually resembles a black box that is most often mute but which, when it does begin to draw attention to itself, can rapidly go from "nothing or almost nothing happening" to "explosion imminent".

For EDF it thus became apparent that it was essential to give the in-plant specialist a tool to help differentiate between healthy and dubious equipment, in the same way as it became apparent that the plant needed support from an expertise network capable of guiding it in the investigations to be conducted in the event of a risk situation and help it take equipment replacement decisions. With regard to its organisation and its members, the transformer expertise network is constructed along the same lines as the generator expertise network. It works in the following way:

Based on dissolved gas analyses carried out periodically or after tripping of a protection device, the plant conducts its initial diagnosis the sole aim of which is to differentiate between healthy and dubious equipment items. If this initial diagnosis concludes that the item is dubious, or if a protection device has been tripped, help from the expertise network is systematically requested. This will as rapidly as possible lead to issue of a recommendation sheet which, further to complete analysis of the data by the experts and depending on the case, can lead to:

- either reclassification as a healthy equipment item,
- or a recommendation for mobile instrumentation without plant shutdown, or tests with plant shutdown, for further investigations, or on-line monitoring of a confirmed risk situation at least until the next scheduled plant outage,

- or, in the more serious cases and after investigation, the recommendation to shut down the plant and switch with one of the spare items.

In these last two cases, the opinion of the designer-manufacturer is also requested in addition to the in-house decision process.

The R&D experts are only called in if the behaviour of the transformer concerned does not correspond to the known behaviour for this type of equipment.

The exceptional maintenance engineering experts are only called in when the decision has been taken to replace the equipment.

The expert responsible for drafting transformer maintenance strategy at the nuclear generating division level is however called in whenever the risk has been confirmed and is likely to have an impact on plant availability and management of the spare transformers.

This expert, with the help of the experts in the expertise network, is also in charge of drafting a transformer maintenance strategy which is updated on an annual basis. The transformer diagnoses used in drafting this strategy are those produced periodically by the dissolved gas analyses conducted every 24 months in normal operations, without any particularly extensive diagnosis/prognosis approach.

Only in the event of a proven risk is the designer-manufacturer called on for an additional opinion on the appropriate response.

In any case, the decision to shut down the plant for tests or to replace the faulty transformer by a spare item is the responsibility of the plant, jointly with the Division Head Office.

9. CONCLUSIONS AND PROSPECTS

The process of condition-based maintenance consists of four main phases: monitoring, diagnosis, prognosis and the resulting maintenance action.

The power plants have support tools for diagnosis (guides and expert systems), which enable them to carry out diagnoses with the support of the parties in the expertise network.

In guaranteeing the prevention of major risks, monitoring has enabled EDF to optimise the periodicity of inspections of critical equipment. This aspect of condition-based maintenance constitutes the biggest saving from monitoring contribution to maintenance.

To ensure totally efficient condition-based maintenance, it will be necessary to develop monitoring and diagnostic knowledge in order to enable to link faults and degradation actually observed during dismantling operations to observations able to be carried out on the machine whilst it is in operation. When there is a possibility that the monitoring system adopted will not cover potential new degradation modes, it may in certain cases be possible to adopt an additional system for detecting them by inspecting pilot equipment items.

As far as monitoring is concerned, our feedback and our current expectations highlight the following points:

- the monitoring systems set up must be open-ended, modular and economical (both to set up and to run),
- it is applicable to establish a connection between monitoring and control of the installation, both because the control operations must be known in order to correctly interpret the monitoring data and because monitoring can, by giving an accurate picture of the behaviour of the equipment, support control.

The setting up of a condition-based maintenance procedure greatly changes the maintenance activity: it goes from an approach involving the systematic carrying out of scheduled operations to an activity involving behavioural analysis and decision-making based on that analysis. This therefore implies that the field players involved be given the required skills and support: for example the expertise networks for certain components important to EDF.

Before being set up, condition-based maintenance must be quantified in terms of economic profitability, taking account of the creation of an appropriate organisation and the use of experience feedback acquired during the course of operations.

The diagnosis approaches can be consolidated, in particular in order to achieve diagnosis of degradation that is as yet relatively minor, offering maximum flexibility in ensuring that the best maintenance decisions are taken. However, the economic profitability of these potential advances must be weighed prior to deployment.

Studies need to be carried out on prognosis tools. We need to refine our knowledge of the phenomena and their trend over time, develop models of an efficiency comparable to those used for diagnosis, and derive from feedback the relevant data for completing these models, including, when necessary, supplementing them with experiments.

REFERENCES

[1] R. Chevalier, S. Brasseur, B. Ricard, General review of diagnostic systems used in EDF’s PWR units. - IAEA Technical Committee Meeting on Diagnostic Systems in Nuclear Power Plants, Istanbul, Turkey (June 1998).

[2] F. Duffeau, P. Bernard, Vibration Monitoring of Large generator Stator End-Windings. - Acoustical and Vibratory Surveillance Methods and Diagnostic Techniques - Senlis, France (October 1998).

[3] D. Le Reverend, Condition monitoring and diagnostic of auxiliary machines in EDF's nuclear power plants: new trends in diagnostic procedures for predictive maintenance. EPRI 6th Incipient failure detection conference. Philadelphia. USA (May 1994).

[4] R. Chevalier, O. Pohlenz, Besoins et enjeux de la surveillance des grandes machines tournantes à EDF. Journée « surveillance des Machines et Procédés » au CETIM - Senlis (March 2000).

[5] A. Despujols, A survey of Reliability Centered Maintenance applications in power plants. - Euromaintenance - Goteborg , (March 2000).

[6] A. Despujols, J.P. Delbos, J.P. Meilland, G. Zuliani, Reliability Centered Maintenance applied to gas turbines. - Euromaintenance - Copenhague – (May 1996).

[7] M. Porcheron, B. Ricard,, A. Joussellin, DIVA and DIAPO: two diagnostic knowledge based systems used for French nuclear power plants. - 5th International Topical Meeting on Nuclear Thermal Hydraulics, Operation and Safety (NUTHOS-5), Péking, China, (April 1997).

[8] J.M Maujean, J.P Patelli, Maintenance of Nuclear Power Plant Generators at ELECTRICITE DE FRANCE: Motor and Generator predictive maintenance and refurbishment EPRI Conference - Orlando, Florida, USA (1995).

[9] J.P. Patelli, A. Tanguy, J.P. Taisne, F. Devaux, S. Ryder, E. Chemin, French Experience with Decision Making for Damaged Transformers –- Rapport CIGRE 2002 SC 12 – Paris, France (2002).

[10] J.P. Patelli, Differences between economics of transformer and generator management -Rapport colloquium CIGRE 2001 SC12 Dublin, Ireland (2001).

ANNEX V. ADVANCED MONITORING AND MAINTENANCE PLANNING BASED ON INTEGRATED CANDU PLANT LIFE MANAGEMENT

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Abstract

In cooperation with CANDU® utilities, Atomic Energy of Canada Ltd. (AECL) has developed and implemented a comprehensive and integrated CANDU Plant Life Management (PLiM) programme for reliable operation through design life and beyond. The systematic and integrated CANDU PLiM programmes provide identification of the plausible aging degradation mechanisms and strategies for mitigating or preventing the effects of these aging phenomena on the Critical Structures, Systems, and Components (CSSCs). The objective is to maintain the CSSCs in the best possible operating condition. A fully functioning and mature PLiM programme promotes greater awareness of current condition, together with proactive and efficient plant decisions based on condition. The integrated AECL CANDU PLiM programme is designed to ensure that outcomes of the various types of CSSC aging assessments are connected to and influence improvements in the plant. This includes ensuring the appropriate transfer of system and component related knowledge over time, and providing a means for controlled and continued optimization of the plant maintenance programme through a “System-based Adaptive Maintenance Programme (SAMP).” As utilities endeavour to get more value out of their plant programmes, the timely flow of important aging related information to key decision makers becomes a greater challenge to manage. To help utilities meet this challenge and to facilitate the changes to condition based decision making, AECL is developing advanced monitoring and maintenance information systems that interface with the existing CANDU plant computers and engineering databases. These systems make more efficient and effective use of plant data. The paper outlines AECL’s integrated approach to PLiM, as well as the development of the advanced monitoring and maintenance planning initiatives associated with the CANDU PLiM programme.

1. INTRODUCTION

The drive to meet increasing energy needs in increasingly competitive markets around the world is resulting in a greater emphasis on performing the right maintenance at the right time to achieve high capacity factors. This emphasis is also seen in the desire to make plant maintenance more proactive than reactive. The result is that plant programmes must not only meet safety requirements, but be expanded to explicitly address plant production requirements as well. It is widely accepted that to be a top performer it is not enough to simply address safety issues and as a result plants need to also take on an asset management perspective.

An interest in managing the assets of the plant not only adds economic and risk criterion, but also demands a more integrated approach to plant Operations and Maintenance (O&M) activities. This includes greater control over why each maintenance, surveillance, and inspection (MSI) task is performed, and control of changes to those tasks over time.

Over the past 20 years, the application of PLiM technology has generally led to the separation of aging assessment techniques along the lines of components subject to active vs. passive degradation mechanisms or components considered short vs. long lived. A result of this separation was that maintenance programme assessments and passive component aging assessments were treated as separate and distinct from one another.

However, many components have both active and passive degradation and an integrated approach to the various aging assessment technologies was needed. AECL has evolved the CANDU PLiM programme to incorporate a highly integrated approach for both the various aging assessment strategies and how they are incorporated into plant programmes (including ongoing adaptation with new knowledge).

Section 2 will discuss further the integration of assessment techniques, and section 3 will show how the results of the assessment are adapted into plant programmes. The discussion of implementation will highlight the importance ascribed to the flow of aging related information into both plant programmes and into health monitors, which are discussed in section 4. Section 5 looks at the fundamental knowledge base that underlies all aspects of this technology.

2. INTEGRATED ASSESMENT STRATEGIES

2.1. History

In an effort to streamline approaches to aging assessment, the components are typically grouped into those with passive vs. active degradation mechanisms or similarly, grouped as “short lived” vs. “long lived”. While the aging assessment approach is similar in each case, there are small, but significant differences in the detailed techniques. For instance, assessments of components subject to active degradation mechanisms can typically be carried out at a higher level (i.e. lower level of detail). Although the knowledge gained from assessments at a more fundamental level is useful for optimizing and focusing strategies, many mitigation strategies can be selected based upon higher level assessments of the component. However, critical components subject to passive degradation mechanisms typically require that more fundamental issues be addressed to develop an adequate aging management strategy.

Another difference stems from the intended use of the assessments. Since assessments of components with passive degradation mechanisms have been used for life or license extension arguments, they typically include an assessment of the remaining lifetime of the component. This requires an understanding of the current condition of the component, the potential for degradation in the future, how degradation is detected, and what constitutes failure. Assessments of components with active degradation mechanisms typically do not look at current condition, as it is assumed that components can be relatively easily maintained, refurbished, or replaced. As such, the supporting assessments are geared towards determining the appropriate maintenance strategy.

2.2. Understanding the Similarities

When put into the context of an overall PLiM programme, it becomes evident that, whether a component is subject to active degradation, passive degradation, or both, the detailed assessment techniques are more alike than they are different. This can be seen in ***Fig. 1***, which shows the various assessment techniques as parallel activities with similar process flows.

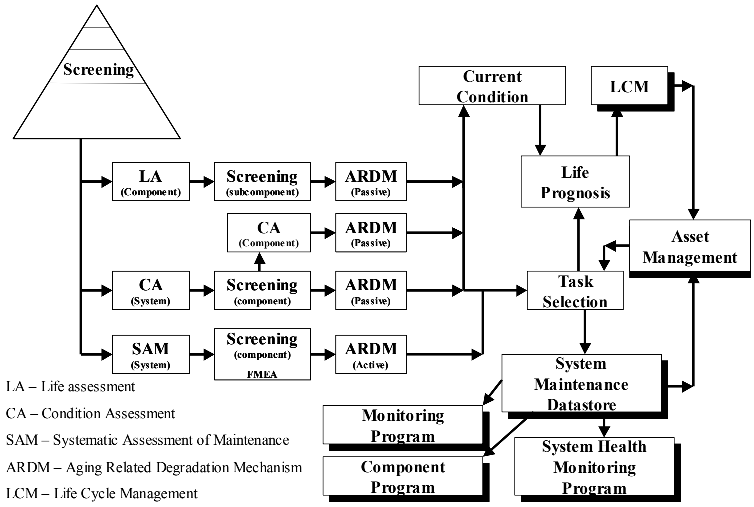

Fig. 1. Integrated PLiM

The assessment elements, as shown in Figure 1, are:

- Screening: The screening becomes a first level assessment and provides the framework for decisions regarding those CSSCs that require a specific assessment technique. To properly assign and use the individual assessment techniques requires an understanding of the relationships between the techniques. A similar screening process is applied within each assessment technique to focus assessment scope and understand risk associated with not assessing specific components (ie. residual risk).

- Passive degradation assessment:

1. Condition Assessments (CA) can be applied to systems, components, or commodities, with minor adjustments.
2. Life Assessments (LA) are effectively more detailed component condition assessments. These tend to be applied to highly critical structures and components.

- Active degradation assessment:

3. A Systematic Assessment of Maintenance (SAM) develops the technical basis behind the component maintenance strategy on a system basis.

Whether applied to a component or a system, the processes are very similar. The process similarities derive from the fundamental need to ask the same basic questions which are:

- What are the functions and associated performance standards of the asset in its present operating context (functions)?
- In what way does it fail to fulfill its function (functional failures)?
- What aging mechanism causes each functional failure?
- What happens when each failure occurs and does it matter (Is it important)?
- What can be done to predict or prevent each failure (mitigation strategy)?

These common questions show the similarities, where the detailed differences capture the different applications (i.e. system vs. component, level of detail, and passive vs. active).

Understanding the similarities creates opportunities for additional efficiencies, enables improved integration of the assessment process, and allows for a better use of advanced health monitor tools. This resulting assessment process can then be more easily translated into a comprehensive and interrelated implementation process.

3. INTEGRATED IMPLEMENTATION

The integration of assessments provides for synergies in the way the outcomes are implemented. Since the assessments provide the technical basis for MSI strategies, organizing the information into a single data store (or database if electronic) provides the means for enhancing the level of integration within the plant programmes. Instead of programmes being derived from a generic component perspective, programmes can be based upon component MSI strategy needs derived from a system perspective. This is the final area of ***Fig. 1*** (shaded boxes), which shows the outcomes feeding into component programmes, system health monitoring programmes, In Service Inspection (ISI) programmes, Life Cycle Management (LCM) programmes, and asset management.

Understanding this relationship enables optimal control of both the MSI technical basis (that is derived in the assessment process) and the related information flow requirements. The System-based Adaptive Maintenance Programme (SAMP, see Fig. *2*), as with other ongoing aging management concepts such as INPO AP-913, provides the infrastructure elements to enable effective control to be exercised. For instance, SAMP has implications on how assessments are conducted, and on information transfer requirements within the plant (represented by the small and large arrows in ***Fig. 2***). It provides the needed links to information management and to the advanced condition monitoring concepts.

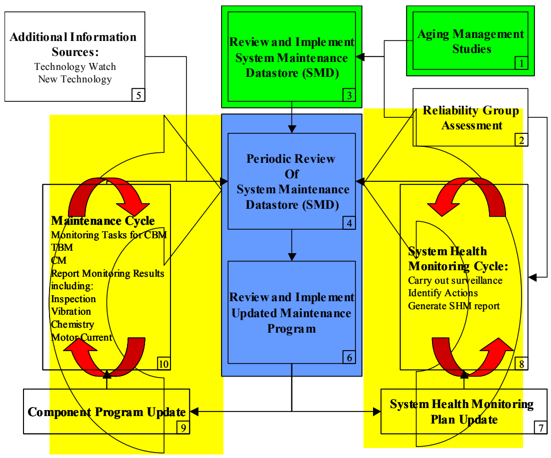

Fig. 2. System based Adaptive Maintenance Programme (SAMP)

AECL has developed the SYSTMS™ tool to facilitate systematic assessment while also providing implementation tracking, feedback tracking, and long-term SAMP support. Currently, the resulting assessment database created through SYSTMS™ is focused on components with active degradation. The database is being enhanced to include all passive aging assessment information, thus providing a means of developing a comprehensive System Maintenance Data store (SMD). Such a capability enhances the ease of assessment of the overall maintenance programme and facilitates asset management.

The SMD concept represents an integrated technical basis that when augmented with economic factors and risk factors provides, over the life of the plant:

- A focal point for control of the integrated MSI strategy and the necessary information flows (see *Fig. 2*)
- A direct relationship between MSI strategy technical basis and current plant MSI programmes
- The basis for improved asset management assessment, now and looking to the future.
- This, combined with risk information, facilitates improved decision making potential.

4. IMPLICATIONS ON THE FLOW OF INFORMATION

The latest engineering tools and information management systems allow for improved configuration management throughout plant life, from the drawing board to the final decommissioning. AECL is significantly advancing the quality of information available in new designs, and the ease of access to that information. In existing plants, significant quantities of information are being gathered, but the difficulty is ensuring that the right information is gathered. Further, this information must be tracked, the appropriate personnel must have access to this information in a timely fashion, and ultimately appropriate actions must be taken when needed in response to the information.

The concept of an integrated approach to assessment, implementation, and control of system MSI strategies through an SMD provides the mechanism to define the information flow requirements and track them with time. These can be translated into specific programme requirements, leading to the collection of the right information based upon current strategies. However, there is a need to ensure that the information feed back is effective and is acted upon appropriately. The advent of improved health monitoring requirements at the component, system, and plant level, makes enhanced information flow management both possible and effective.

Key requirements for effective health monitoring are data management, diagnostic assessments, and reporting. In most cases, effective aging management of CANDU plants requires more effective use of plant data trends, using instrumentation, monitors and/or sensors that are commercially available or already in use at the plant. For example, PLiM programme assessments of fluid-bearing components show that the effects of improper chemistry control and chemistry transients are among the most important factors affecting degradation. To manage this information and to assist in minimizing degradation of critical CSSCs, AECL has developed an advanced software product for system chemistry monitoring and diagnostics, called ChemAND®. ChemAND includes diagnostics to help identify the cause of a given chemical transient, and predictive tools to assess the impact of the transient conditions on steam generator (SG) fouling and tubing corrosion. ChemAND also provides users with on-line access to historical data, thereby permitting past trends to be compared to current condition. This enables appropriate responses, including comparison with past actions, to facilitate planning for shutdown maintenance such as cleaning of specific CSSCs.

The PLiM programme has identified other areas where advanced monitoring and diagnostics tools can improve station performance and reduce costs. For instance, two other tools (a system and component health monitor known as ThermAND™ and maintenance information and monitoring/control system, known as MIMC™) are under development. These tools demonstrate the effectiveness of integrating the PLiM programme with an appropriate R&D

activity in aging mechanisms and mitigation strategies in order to develop models for life prediction and maintenance optimization.

The following sections will explore the requirements of providing diagnostic and reporting capabilities for health monitors, beginning with the need for data management.

4.1. Data Management

Plant data come in several forms:

- Online data

  "Online data" is used here to designate data from on-line instrumentation, producing readings at frequent intervals (every few seconds) for such important parameters as reactor neutronics and header temperatures. In CANDU plants, which have been fully computer controlled since first put into service in the 1970s, data are recorded by Station Control Computers and archived as part of the normal plant data stream.

- Field logged data (may be gathered manually or automatically)

  "Offline" operational data (e.g., pressures, temperatures) that are not logged by the station control computers may be gathered in the field, either on paper or logged locally in electronic form.

- 'Grab samples' taken to a laboratory for analysis.

  Chemistry 'grab samples' represent another type, collected manually once a shift or less, analyzed and where possible, recorded directly into another database.

Other valuable information, such as performance indicators or 'ratings', may be generated as the result of analysis of any or all of these plant data. The challenge is to intelligently process and archive daily data that represents a time stamped stream of tens of thousands of parameters. Even modern online storage facilities (hard drives) are somewhat limited with respect to a weekly GB (gigabyte) data stream, and of course systems in place in nuclear plants tend to be older. So the data are stored sequentially on tapes and CDs, and archived as physical media. This leads to a significant 'needle in a haystack' problem: to scan the archives for a particular parameter, and to trend or otherwise plot the behaviour of this parameter over many years, perhaps the life of the plant, may involve handling hundreds of CDs or tapes. Usually this sort of forensic investigation is limited to 'events' and is not useful for plant life management.

Some CANDU plants, such as Hydro-Quebec's Gentilly-2 and New Brunswick Power's Point Lepreau Nuclear Generating Stations, do have large online archives or 'data historians', allowing users access to 3 to 5 months worth of data. In those cases storage of offline data is integrated with the online data for ease of correlation.

Such data archives are essential to system health monitoring. Without them a 'broad view' in time and parameter space is practically impossible. However it is not always practical to rely on them for direct access each time a particular data set is requested. Servers can be congested or unavailable, and so on. It is advantageous to maintain a 'local' subset of the archive, for chemistry related parameters for example, available for fast access on a routine basis. The local archive can be kept in a format more appropriate to the health monitoring application, such as a Pi Historian™, while the overall plant data historian may be in another 'legacy' format. The local historian is updated on a regular basis over the plant LAN (Local Area Network), with the update frequency governed by the need for current 'alarm' information in the health monitoring application.

4.2. Health Monitoring

Effective management of plant systems throughout their lifetime requires more than data acquisition and display. It requires that the plant's system health be monitored and managed continually. To that end, health monitors are designed to help answer the following questions:

- How good is 'system' performance now?
- How does this compare to, for example, past performance, commissioning data, or the original design?
- What does this mean for managing the future performance at the station (what action is required)?

As mentioned previously, this implies providing the right information to the right people at the right time and in the right format. As there usually is no shortage of plant data, the key issue is selecting the most appropriate data, and the minimal set of data, to meet the above requirements. Plant specialists must therefore have access to both real-time and historical data, in a seamless fashion, for example to compare behavior across several returns-to-service (coming out of an outage).

There are 3 requirements that health monitors need to address so that they facilitate the right information flow. These are:

- Organize information to facilitate diagnosis of system health
- Avoid information overload
- Provide predictive capabilities

4.2.1. Information Organization

The term 'system' above is used broadly. It may refer to a physical system such as a heat transport system or to a 'programme' such as 'plant chemistry' or 'motorized valves', which crosses many systems. In the health monitors developed by AECL, information architecture is a 'function based' representation, which describes the plant from an operations perspective, rather than from a construction or design perspective.

The plant is operated using functions such as 'Control Reactivity', 'Monitor Cooling', and 'Transfer Heat to Boilers'. Each physical system may have more than one functional goal. Systems (or components) may fail to meet their functional goals through certain failure modes that can be characterized by groups of (failing) performance and health indicators. This 'function based' approach may become 'problem based' or 'failure mode based', according to the context. This facilitates diagnostics. There may be other, related, parameters in alarm, which constitutes a 'fingerprint' of a problem.

An example of such a function based display is shown in Fig. ***3***, which is designed to monitor for condenser leaks. Correlated 'spikes' in each of the monitored parameters, as observed for the concentrations of sodium, chlorides, and sulphate, are characteristic of the in-leakage of raw water associated with a condenser leak. ChemAND displays these data and calculates the leakage rate permitting the chemistry specialist to determine the appropriate action.

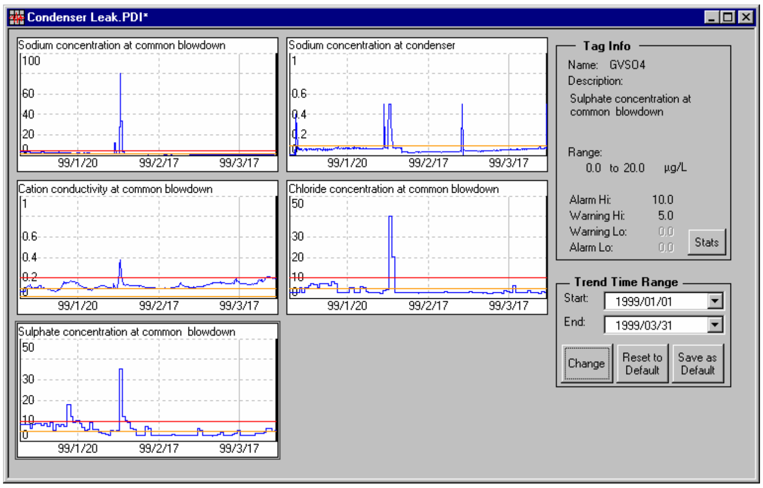

Fig. 3. ChemAND function based display for detection of condenser in-leakage.

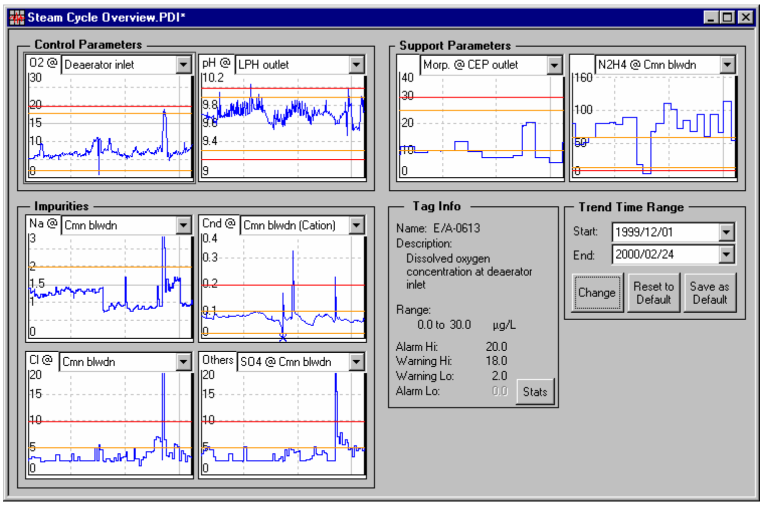

Fig. 4. ChemAND steam cycle overview.

The more complicated systems have an overview display, such as the one shown in Fig. 4 for the steam cycle. The overview display shows all the parameters of interest at a glance and provides a quick assessment of how well the system is operating. In the ChemAND example, the chemistry parameters in the overview display are arranged in drop-down menus, grouped as ‘support parameters’, ‘control parameters’, and impurities. Support parameters are chemicals added, in this case morpholine and hydrazine, to control the system chemistry, whereas control parameters are those that are being controlled, in this case dissolved oxygen and pH. The trends showing impurity concentrations tell the operator how well the system is functioning with regard to in-leakage of cooling water, performance of the water treatment plant, etc.

4.2.2. Avoiding Information Overload

Operations personnel and system specialists are concerned with the smooth operation and continuing health of the plant overall and of their particular domains, but have limited time for routine detail. They want the 'broad view' first, and will delve into detail as necessary. Therefore a hierarchy of information must be established within each health monitor, with 'alarm' information at the highest level, 'function based' or 'problem based' at the next level, and supporting detail.

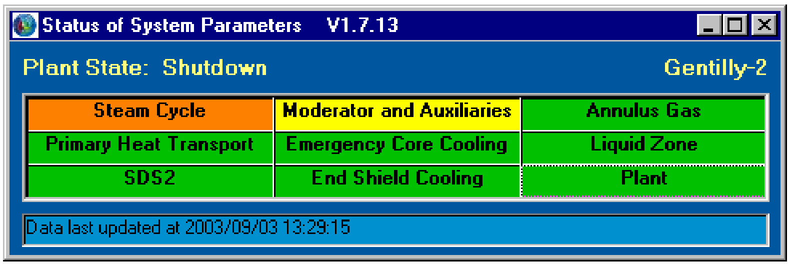

Fig 5. ChemAND® Status Panel

The 'broad view' is provided by a 'status panel' modelled after the hard wired 'tiles' found in conventional plants and designed to run as a stand alone application on the user's desktop, as shown in *Fig 5*. Each major system or function is assigned one window. If any parameter in that system is out of specification (or is forecast to trend out of specification soon) the window will change colour. There may be several levels of alarm and colour for a given parameter) Clicking on the window reveals which parameter(s) is(are) out of specification, and clicking on a given line leads to the function based display containing that parameter.

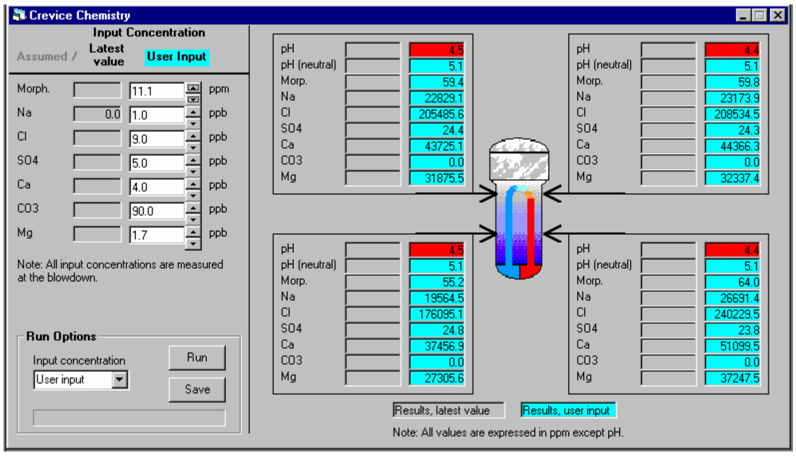

Fig. 6. ChemAND display of SG crevice chemistry predicted using ChemSolv™

This approach focuses the attention of the user to those areas of primary interest. It also complements the function based displays by facilitating improved and timely diagnosis of problems as they are developing.

4.2.3. Providing Predictive Capabilities

Most importantly, health monitors must provide tools to look beyond current performance, to monitor and predict health. In terms of predictive modelling, these health monitors incorporate analytical models to show the effect of present conditions (on long term health) and to run 'what if' scenarios to help manage degradation.

For example, ChemAND incorporates models to predict sludge build-up patterns in the steam generators, a kinetic model for transport and breakdown of volatile water treatment chemicals, such as morpholine and hydrazine throughout the steam cycle, radionucleide transport, and a model to predict the chemistry that develops in steam generator (SG) crevices as a result of the concentration of non-volatile impurities, such as sodium, sulphate, and chloride, in these regions. A display from ChemAND showing the steam generator crevice chemistry tool in use is shown in Fig. 6 for a plant operating with a condenser cooled by river water. This application has been very useful in helping plant personnel manage the summertime addition of chlorine to the feedwater, to limit microbial growth without upsetting the pH in SG cervices, i.e., making the crevices acidic and hence, susceptible to corrosion.

The ThermAND prototype has capabilities to trend available data for any monitored component or system and identify specific modes of degradation, such as environmentally assisted cracking of piping, thermal performance degradation of heat exchangers, and wear of bearings in pump/motor sets. Aging related models for prediction of reactor inlet header temperature increase have been added, and another for monitoring pressure tube elongation is under development.

4.3. Information Flow Control

The PLiM studies have highlighted that there is a need for intelligent plant databases for maintenance (hence the development of the MIMC tool), and also to retain inspection information for future use in aging management. Typically inspection data are available only for specific systems or components, and not integrated with that from other plant systems and with health monitoring tools. The inspection data are also typically not organized with respect to a PLiM approach, where current condition needs to be compared to past condition in order to determine the rate of system and component degradation, and the effectiveness of remedial measures.

5. PROVIDING A FOUNDATION

The application of the PLiM techniques and tools requires that aging assessors and designers understand key aspects of age related degradation mechanisms, the parameters that impact on their plausibility, and the potential effectiveness of MSI strategies to deal with them, as part of their experience and capabilities. This same information is the basis of functional health monitor displays and predictive models.

A considerable amount of operating history has been accumulated by CANDU owners that have generated a significant level of experience and lessons learned. AECL has worked with utilities over the years, and has been able to gather valuable knowledge via operation of its own nuclear facilities. Moreover, the experience gained from plant construction and commissioning activities has further enhanced AECL's knowledge of the existing plant O&M experience.

Several condition assessments have highlighted the impact on plant life of frequent shutdowns, of lack of maintenance (reactive maintenance approach), and improper chemistry control during shutdowns and layups. Coupled with these factors is the impact on plant condition of uninspected components, such as small heat exchangers, which may, because of conservative design, not impact plant performance, but which compromise the ability to correctly assess current condition with respect to extended operation. During these assessments, and the subsequent development of life management plans, extensive use of comprehensive CANDU R&D knowledge and expertise provided efficient diagnosis of applicable degradation mechanisms and the development of diagnostic models based on the plant databases and mechanistic understanding. While development of these models is ongoing, the models are extended and new system models developed, as more PLIM assessments are performed.

The CANDU R&D activities have been tailored over the past 5 years or so to address the issues arising from PLiM assessments. In effect, much of the R&D has moved from technology oriented examinations to system oriented studies closely linked to current plant issues. This shift in focus has, however, made significant use of the more than 50 years of R&D that has supported CANDU technology, in particular with respect to degradation mechanisms (fouling, corrosion, vibration), chemistry, and instrumentation and control. In the latter case significant past experience with human factors requirements has led to more effective displays for tools such as ChemAND and ThermAND.

Throughout its history, AECL has made a significant effort in research and development. Much of this effort has been directly related to understanding components, their performance, and the fundamental science associated with materials and their potential degradation mechanisms. In addition, AECL has engaged in the development of detection techniques and overall mitigation strategies, addressing specific and integrated aging effects. This effort represents a wealth of information that is beneficial to PLiM assessments.

Today, AECL continues to develop products and perform fundamental research into degradation mechanisms and mitigation strategies. This is serving to further enhance the overall quality of the services available. In combination with an understanding of CANDU system interrelationships from design experience and an understanding of Age Related Degradation Mechanism (ARDM) interrelationships from history and R&D, the necessary support elements for a complete PLiM programme are established.

6. SUMMARY

AECL, as a developer and provider of PLiM/LCM products and services, is providing effective and efficient tools and processes to support implementation of PLiM programmes. Although there has historically been separation between PLiM approaches on various types of components, a much more integrated set of assessment techniques is now available. These can be used to work in a complementary and effective manner.

The integrated aging assessment process is also the foundation for improved implementation integration. A well integrated technical basis for MSI strategies, developed through the assessment process, can and should be linked directly to plant programmes. Both the technical basis and the plant programmes are subject to ongoing adaptation as experience is gained and new technology is developed.

The need to be adaptive and the need to ensure information to carry out MSI strategies is available when required, imply the need for advanced support tools, such as health monitors. These enable the efficient tracking of important age related information, and making it available to decision makers when needed.

Effective health monitoring implies intelligent tools with diagnostic and predictive capabilities. Much of the intelligence in these monitors must be based upon the results of plant life condition and life assessment, especially with respect to maintenance management.

Understanding of the relevant degradation mechanisms, and of system behaviour, based on R&D programmes and plant data, provides the basis for the diagnostic features in the health monitors.

The key to success of health monitors is integration of the needs of plant operators with plant life management requirements and a sound knowledge of the factors affecting system health, and activities required to optimize it.

Finally, through an integrated technical basis, which would include risk and economic factors, the opportunity exists for enhanced overall asset management. It is here that a fully integrated and implemented PLiM programme can lead to improvements in plant operation and maximizing plant potential.

REFERENCES

[1] Dam, R. F., et al, "The CANDU Experience with Reliability Centred Maintenance and Plant Life Management", paper presented at IAEA Specialist's Meeting on Optimization of NPP Maintenance Programmes, Charlotte, NC, USA (June 2001).

[2] J. X. Yang, et al., "SYSTMS™: Systematic Approach for the Development of Strategies for Maintenance and Surveillance", paper presented at 25th Annual CNS Conference, Toronto (June 2004).

[3] P. Watson, et al., "Using The System Maintenance Datastore To Characterize Lifetime Maintenance For PLiM", paper presented at 25th Annual CNS Conference, Toronto (June 2004).

[4] J. Nickerson, et al., "Application Of Plant Life Management Programme And Experience At NRU", paper presented at 25th Annual CNS Conference, Toronto (June 2004).

ANNEX VI. DEVELOPMENT IN RELIABLE CENTERED MAINTENANCE AND ON-CONDITION MAINTENANCE AT GUANGDONG NUCLEAR POWER STATION

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Abstract

Reliable Centered Maintenance (RCM) was introduced in Guangdong Nuclear Power Station (GNPS) from the US in 1998. RCM has demonstrated real and pragmatic benefits and GNPS has developed a RCM analysis system that suits the local environment. This paper, in the first part, introduces the RCM concept and analysis method as applied by GNPS. This part will enable the reader to have a basic understanding of the importance of RCM theory and how it contributes to safe, stable, economic operations. However, just applying the RCM logic itself does not solve all the issues. The RCM programme requires a radical change in the skills, thinking and management systems. A traditional TBPM (Time-based Preventive Maintenance) programme mostly requires skilled mechanics, a spares management system, and outage planning. The RCM world is far more complex. One of the biggest challenges is determining the unacceptable criteria or datum (p-point) in on-condition monitoring (predictive monitoring/maintenance). These issues are discussed in the second part of this paper.

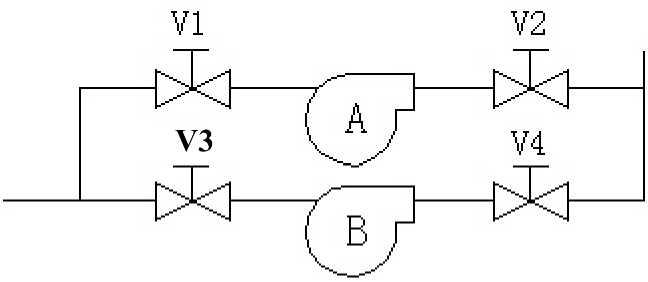
1. THE RCM PROCESS EXPLAINED

Our understanding of maintenance has changed rapidly because of the development of new maintenance technology and the way equipment fails. 50 years ago our concept of equipment failure was simple: The older the equipment is, the more likely it is to fail. During the 1950's the age/reliability relationship model was the "bathtub" conditional failure probability curve. However, with the development of computer databases in the 1960's, aviation industry (and later the nuclear industry) found that the age/reliability relationship was much more complex, and there existed six conditional failure probability curves.

Aviation industry research found that three of these curves showed a decrease in reliability with asset age, but only represented 11 % of all failures. The other 3 curves totalling 89 % of failures showed either a random or an increasing reliability with asset age. The RCM analysis system was developed from this new understanding: increasing the frequency of maintenance often does not always increase the reliability of equipment and can be counter productive.

Hence RCM shifts our focus from managing failure modes to managing the effects of failure modes, i.e. the loss of function. So RCM is a scientific process used to determine what must be done in order to ensure any asset continues to do what its users want it to do in its operating context. RCM helps us insure the availability of the functions required by determining when and where it is most appropriate to apply one of the following maintenance strategies: corrective maintenance, scheduled overhaul/replacements, on-condition maintenance, functional failure testing, or redesign/modification.

Let us look at an example of RCM concepts. If we have Pumps [A and B], where Pump A is the operating pump and Pump B is the standby pump, then which of these 2 pumps is the most important? Some people might assume Pump A is more important than Pump B. Since Pump A is working, it is more like to fail at any time, and it appears that the loss of this pump would affect the primary function, However according to the RCM concept, Pump B is more critical. If the backup function is available, then Pump A's failure won't matter too much since Pump B can take over the primary function. However, if Pump B is already failed, we won't know until Pump A also fails, in which case the primary function is lost. Hence RCM shows that what matters most are the equipment's context and functions, and not the equipment itself. So while prevention of the failure itself may be impossible, however we can prevent, mitigate or eliminate the consequences of the failure.



For example, consider the functions of the pumps A and B versus the functions of their isolation valves (V1, V1, V3 and V4). Which of these functions is more critical for maintaining the ***long term*** uninterrupted supply of water? Some people might consider that the pumps are more important. However RCM shows us the valves provide a more critical function. If Pump A fails, then Pump B starts-- maintaining the water supply. However eventually Pump B also will fail. If the isolation valves function then Pump A can be restored to service as a backup to the operational pump without interrupting production, thus restoring the inherent reliability of the system. *Even if the pumps are fairly unreliable, we can maintain water supply by rebuilding failed pumps until the valves can no longer isolate the pumps.* From this example we can see that RCM analysis helps us find where our limited resource can do the most good.

RCM helps us determine which maintenance tasks are technically feasible and how frequently they should be done. RCM providing a simple, accurate and easily understood audit trail for these decisions. On-condition maintenance (predictive maintenance) is given priority. Scheduled overhauls/replacements are only applied when on-condition maintenance is not feasible plus a clear increased probability of failure with age exists. RCM methodology reinforces a focus on the appropriateness of each maintenance task.

2. REAL LIFE CHALLENGES-APPLYING ON-CONDITION MANITENANCE

Lets now look an example of a special challenge for maintenance management from our first pilot project in RCM, which was done some 5 years ago. The Condensate Extraction System (CEX) is an important auxiliary system, whose primary assets are 3* 50% capacity pumps. 2 CEX pumps operate with a 3rd pump as back up. If one pump trips and the back-up pump fail to start up, the effects of this failure are reduction to 50%Pn, and in severe cases a turbine trip with a resulting reactor shutdown. These pumps are vertical caisson multi-stage pumps with 10 meter drop between the mechanical seal and the foot bearing at the impeller intake. The pumps had a notorious reputation in the GNPS as being difficult to maintain and suffered high vibrations. Each pump was scheduled for rebuilding each 3 years. The first rebuild attempt usually failed to meet re-commissioning criteria and it would take 2 or 3 rebuild attempts to get a minimal acceptance. Then after only a few days of operations pumps vibration levels would begin to deteriorate, and temporary measures to restrain vibrations would have to be taken.

The RCM analysis studied past maintenance records, pump design and performance criteria. We found that there was no cavitations occurring in the pump nor was there any wear occurring in either the Michel bearings or the foot bearings. Since there were no reasons to justify a periodic rebuild of the pumps, the RCM team cancelled it. Instead we applied vibration monitoring of the bearings and the impeller balance, supplemented by oil analysis for the Michel bearing. A simple routine for measuring pump output with acoustic monitoring could mange any unexpected deterioration in the hydraulic surfaces. We also found the primarily causes of the vibration problems were incorrect procedures used to rebuild the pumps, which in turn were exasperated by frequent rebuilds.

Canceling the scheduled rebuild met strong opposition. The chemists, vibration technicians and mechanics were unhappy about taking responsibility for determining if and when equipment should be repaired. Also, our outage plan could change even hours before the plant was shut down due to on-condition maintenance based decisions. Because we depend on front line staff and engineers to make judgment calls, middle management was unhappy. Many of our front line staff were worried about what this responsibility meant for them. For example, they complained that acoustic monitoring was too subjective. Even today, many departments and sections are still unwilling to make a decision using on-condition monitoring technology if there is no “black or white” criterion. However, we finally received permission to implement the RCM programme for the CEX pumps.

Then, just 6 weeks prior the 207-outage a potential disaster for the RCM programme occurred. D2CEX003PO pump shaft, which is composed of 5 segments, sheered off in a segment joint just below the base plate. The RCM team came under intense pressure, particularly from sections of the company who were not happy with all the new responsibilities and demands imposed on them by the RCM programme. However, cooler heads were eventually able to prevail. First, the pump had less than 2 years ahead of its scheduled next rebuild, so the original 3-year programme could not have prevented the failure.

At that time, I recalled a statement by our RCM consultant for the CEX project: After the CEX pilot project was completed, and before starting any new projects the RCM consultant attended our 206-outage to examine our maintenance practices. He pointed to a support frame attached to D2CEX003PO that was not there before and said: ***“This is just like treating brain cancer with aspirin, keep putting off surgery and you’ll die. Trust the vibration readings and rebuild this pump now.”***

However the rebuild was put off because under the original schedule it was due for a rebuild during the next outage (the RCM programme had not yet come into effect). Complicating the issue was that a senior engineer had staked his reputation on the suitability of the frame. Also managers did not yet feel comfortable with the new RCM programme and resisted canceling the scheduled outage of the D2CEX002PO pump to make spares available for D2CEX003PO, even though the performance measures of D2CEX002PO were normal.

When we look at the original equipment supplier maintenance guide, there was no rigid requirement for a 3-yearly rebuild. We quickly recognized that the basis of the 3-years schedules was simply that we had 3 pumps and it was convenient to rebuild one pump each year. Taking this further, if humans were created with 6 fingers and 2 thumbs, then we would all be talking about 8-year major overhauls, and not 10. Similarly, if Earth had the same orbit as Mars, annual outages would only occur every 687 days. Is it logical to plan events in a nuclear power plant using the same rules that a farmer uses to decide when to plant his crops? The fact that we have actually seen better equipment reliability since extending the refueling cycle from 12-months to 18-month cycle is a pretty clear answer to this question.

A RCA (reliability Centered Analysis) analysis of D2CEX003PO showed that the RCM programme was correct. The cause of the problems in the pump was a poor quality rebuild during the 204-outage that included the use of undersized shims and non-qualified fastener suppliers. The RCA also showed that we had problems in where we placed our trust. More faith was placed in our scheduled 3-yearly rebuild. No faith was placed in the vibration analysis and other indicators that the pump was ready to fail. Also, we continued to believe the bracket to suppress the excess vibrations was effective even though the monitored sign indicated otherwise. The RCA found that the vibration suppression brackets were actually making things worse. Ever since fully implementing the CEX RCM programme in 2000, only two pump need to be rebuilt till today (one rebuild was due to defects induced during an earlier outage).

Now we all understand a mystic belief that the cycles of the sun and the moon control equipment reliability is nonsense. However our newly found scientific practice of predicting the future by observing how our equipments perform today is no easy path to walk. Our job does not begin and end with developing new sources of information i.e. new on-condition technology. We also must invest to develop the people and system that can make the appropriate decisions with this information. We need people who not only understand the technology being applied, but who also understand the design basis of the equipment being monitored. These people must be able to draw useful, accurate and timely conclusions about the near future and accurately assess risks of various pathways in the future. We need people who are confident, capable and courageous enough to choose a pathway that reflects the best long-term interest of the company yet does not sacrifice safety for production. We must maintain continuous introspection and self-examination even when things go well, as there is nothing as dangerous as overconfidence based on past success.

We all understand there is no point in taking vibration readings on a pump unless we are both able and willing to make decisions about intervention. Similarly, each new “predictive” technology must not only show it can give us the confidence to know the asset is fit for use, but also let us say with confidence when the equipment is no longer fit. It is not enough to “predict” the future; we must have the confidence to act on our predictions. This is our new challenge.

REFERENCES

[1] Nowlan, F.S. & Heap, H., Reliability Centered Maintenance. Springfield, Virginia, National Technical Information Service (1978).

[2] Resnikoff, H.L., Mathematical Aspects of Reliability Centered Maintenance. Los Altos, California, Dolby Access Press (1978).

[3] White, S. “Assembly Balance of Multistage Pumps” Reliability Magazine V.2 N.2 (1995).

[4] White, G. “Vibration Data Collectors & Analyzers” Predictive Maintenance Technology National Conference, Indianapolis, Indiana (1995).

[5] Wu, T., Lim, M., Hatch, S. D2CEX003PO Event RCA Report, Daya Bay Internal Document (2001).

ANNEX VII. AN INTEGRATED APPROACH FOR MOTOR-OPERATED VALVE DIAGNOSIS USING MOTOR POWER SIGNATURE AND DISCRET WAVELET TRANSFORM

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Abstract

Motor-operated valves (MOV´s) are widely used in industry to control fluid flow in several applications. In nuclear power systems they are crucial for the safe operation of plants and are applied extensively in safety related systems. Therefore, the necessity of improvements in monitoring and diagnosis methods started to be of extreme relevance in the predictive maintenance field, establishing as main goal the reliability and readiness of the system components. Especially in nuclear power plants, the predictive maintenance contributes in the security factor in order to diagnosis in advance the occurrence of a possible failure, preventing severe situations. Condition-based maintenance of MOV´s avoids unexpected outages and prevents unnecessary maintenance procedures. Therefore, maintenance programmes are being implemented based on the ability to diagnose modes of degradation and to take measures to prevent incipient failures, improving plant reliability and reducing maintenance costs. The approach described in this paper represents an alternative departure from the conventional qualitative techniques of system analysis. The methodology used in this project is based on the electric motor power signatures analysis, during the closing and opening stroke time of the valve. Once the measurements baseline of the motor-operated valve is taken, it is possible to detect long-term deviations during valve lifetime, detecting in advance valve failures. The technique applied in this paper is the wavelet transform analysis using wavelet toolbox, where the main goal is to obtain more detailed information contained in the measured data, identifying and characterizing the transients phenomena in the time and frequency domains, correlating them to failures situations in the incipient stage. The wavelet analysis has provided good results establishing a new qualitative methodology for monitoring and diagnostic of motor operated valves.

1. INTRODUCTION

Motor-operated valves are used in almost all nuclear power plant in fluid flow systems. The purpose of MOV’s is to control the fluid flow in a system by opening, closing or partially obstructing the passage through itself. The Figure 1 shows a motor operated valve gate type, emphasing the main parts.

Fig. 1. Motor operated valve, gate type.

The reliability of nuclear power plants depends strongly on the operational readiness of valves specially MOVs, they are applied extensively in control and safety-related systems. Non-intrusive diagnosis methods[1] have provided the ability to detect abnormal functions in plant components during normal operation. The measurement system is shown in the diagram in the Figure 2.

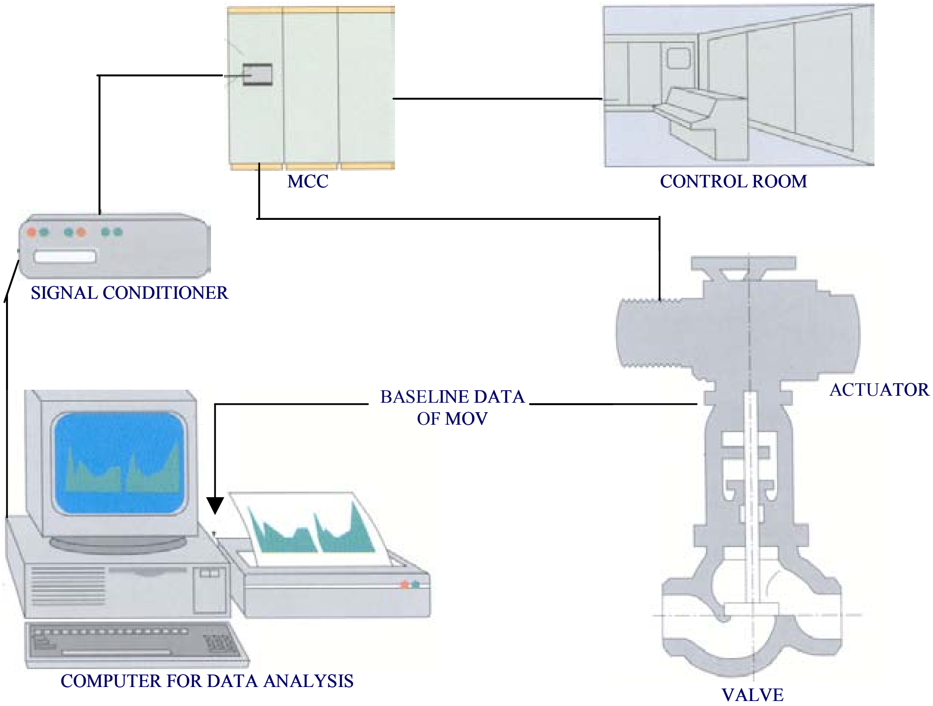

Fig. 2. Measurement system diagram

The methodology used in this research is the motor power signature analysis during open-to-close and close-to-open stroke time[2,3]. The motor power signature is acquired through the currents and voltages phases measurements from the motor control center. The typical motor power signature of a gate valve for open and close cycle are showed in Figures 3 and 4.

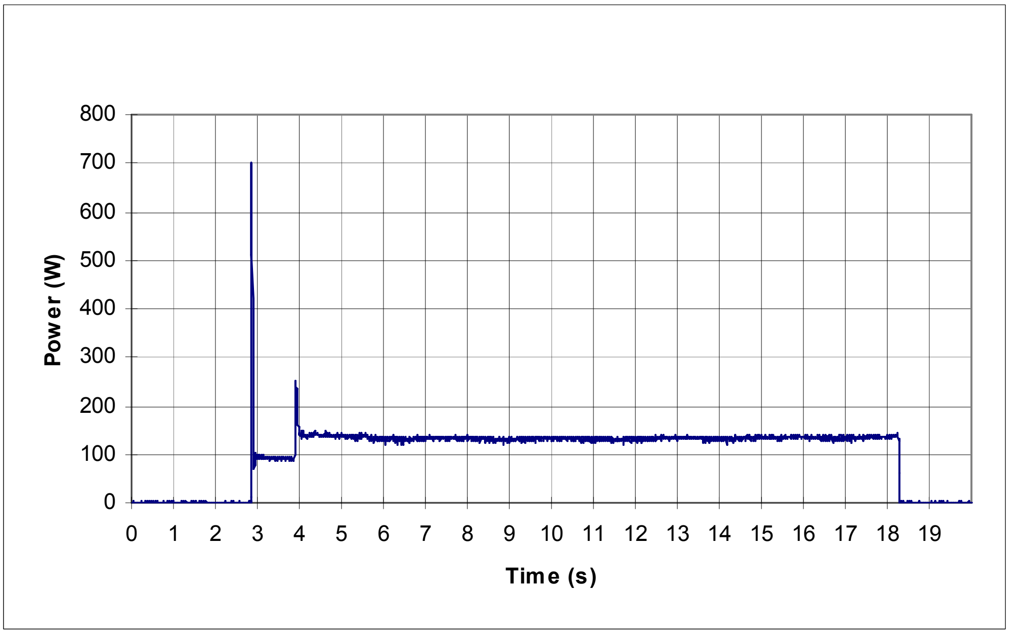

Fig. 3. Motor power signature close to open valve stroke open valve stroke.

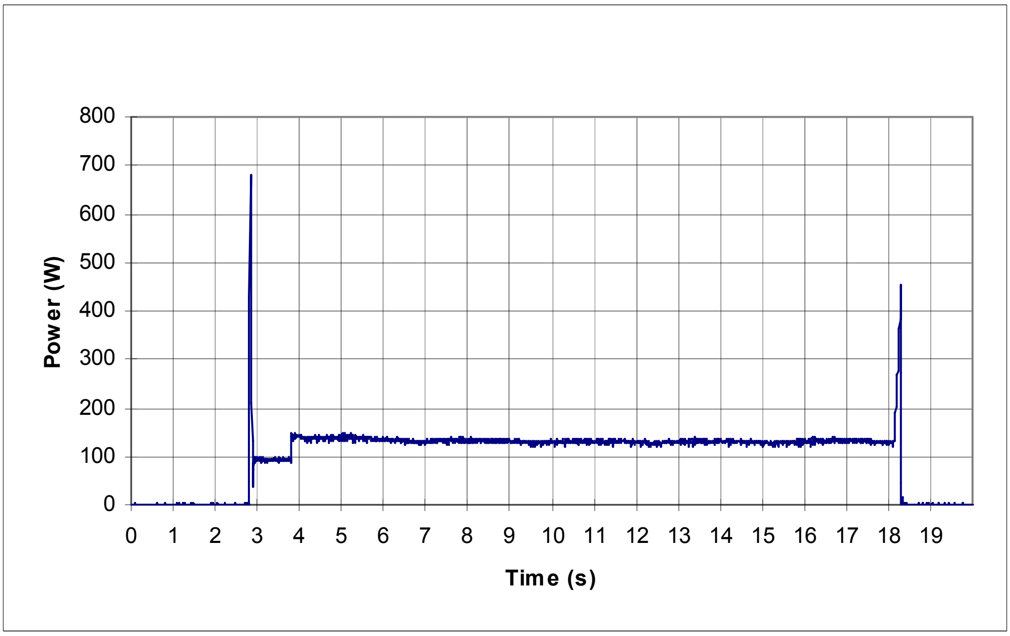

Fig. 4. Motor power signature open to close valve stroke

Once the baseline measurements of the MOV are taken, it is possible to detect long-term deviations during valve lifetime.

The aim of this paper is to present some results of incipients failures detection of motor-operated valves using wavelet transform analysis.

2. WAVELET TRANSFORM

The class of functions that represent the wavelet transform are those that are square-integrable on the real line[4,5]. This class is denoted as $\mathbf{L^2(R)}$. Thus, the notation $\mathbf{f(x) \in L^2}$ means:

$$\int_{-\infty}^{\infty} |f(x)|^2 dx \langle \infty \tag{1}$$

The sets of functions[6,7,8] that are generated in the wavelet analysis are obtained by dilating (scaling) and translating (time-shifting) a single prototype function $\psi\ (t)$, which is called a basic wavelet. The dilating and translating process is shown in figure 5.

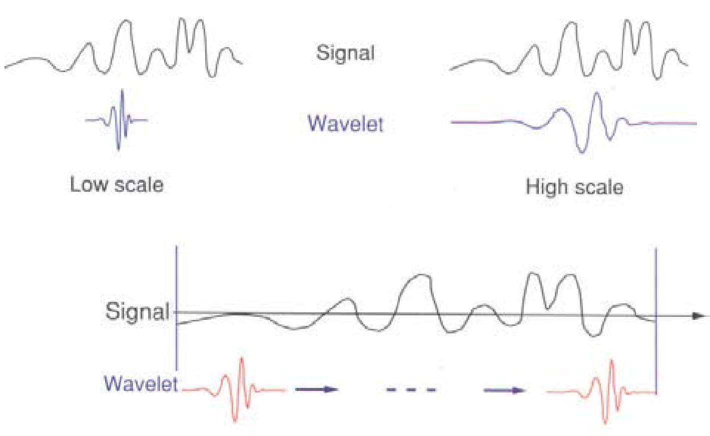

Fig. 5. Wavelet functions dilating and translating

The wavelet function $\psi(x) \in L^2(R)$ has two characteristic parameters, called dilation *"a"* and translation *"b"*, which vary continuously.

The basic wavelet ψ (x) is defined as:

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}} \psi\left(\frac{x-b}{a}\right); \text{where } a,b \in R; a \neq 0 \tag{2}$$

The continuous wavelet transform (CWT) is defined as the sum over all time of the signal multiplied by scaled, shifted versions of the wavelet function ψ :

$$CWT_{a,b}(f) = \int_{-\infty}^{\infty} f(x) \psi_{a,b}(x) dx \tag{3}$$

The results of the CWT are many wavelet coefficients C, which are a function of scale and position.

The computation of the wavelet coefficients using the continuous wavelet transform requires a considerable effort.

The purpose of using the discrete wavelet transform (DWT) is to reduce the computational burden. The scales and positions are chosen based on powers of two[9], so called dyadic scales and positions, which make the analysis much more efficient and accurate. Therefore, assuming that the dilation parameter *"a"* and translation parameter *"b"* take only discrete values:

$$a = a_0^j \quad \text{and} \quad b = kb_0 a_0^j \qquad (4)$$

where $k, j \in z, a_0 \rangle 1$, and $b_0 \rangle 0$ (5)

Therefore, the wavelet function may be rewritten as:

$$\psi_{j,k}(x) = a_0^{\frac{-j}{2}} \psi\left(a_0^{-j} x - kb_0\right) \qquad (6)$$

The discrete wavelet transform (DWT) is defined as:

$$DWT(f) = \langle f, \psi_{j,k} \rangle = \int_{-\infty}^{\infty} f(x) a_0^{-\frac{j}{2}} \psi\left(a_0^{-j} x - kb_0\right) dx \qquad (7)$$

An efficient algorithm can be constructed to evaluate the integral wavelet transform defined in equation (7). In this case, the frequency axis is partitioned into bands by using power of two for the scale parameter *"a"*. Considering only samples at the dyadic values, the parameters b_0 and a_0 assume the following values ($b_0=1$ and $a_0=2$) then, $b=k2^j$ on the time-axis, when $a=2^j$. The DWT equation can be rewriten as:

$$DWT = \langle f, \psi_{j,k}(x) \rangle = \int_{-\infty}^{\infty} f(x) \left\{ 2^{\frac{-j}{2}} \psi\left(2^{-j} x - k\right) \right\} dx \qquad (9)$$

The function $\psi_{j,k}$ is given by:

$$\psi_{j,k}(x) = 2^{\frac{-j}{2}} \psi\left(2^{-j} x - k\right) \; ; \; j, k \in Z \qquad (10)$$

The technique applied in this paper is the discrete wavelet transform analysis implemented at the MATLAB platform which is a powerful language with high performance, using wavelet toolbox of The Math Works Inc. The main goal is to obtain more detailed information contained in the measured data, identifying and characterizing the transients' phenomena in the time and frequency domains, correlating them to failures situations in the incipient stage.

Several families of wavelets have proven to be useful on diferents signal analysis applications such as Haar, Biorthogonal, Coiflets, Symlets, Morlet, Mexican Hat, Meyer and Daubechies.

The choice of the best wavelet to be used for analysis of a certain signal is a topic of a lot discussion, because there is no rule for the best wavelet function choice to be applied. Some basic aspects can be observed for an approach of the best choice, such as the similarity of the signal with certain wavelet functions and experiments as much as possible with known anomalies data situations points out the irregularities on the signal due faults.

The family of wavelet Daubechies[10] has been notified as a good option for signal analysis applications on different fields, diagnostic on vibration signals of rotating machinery[11,12] and applications in image processing[13].

After several experiments on this work, it was chosen for motor power signature analysis the wavelet Daubechies "db4"with decomposition level “6”.

The analysis technique using discrete wavelet transform presented previously was implemented for a certain group of data that contains mechanical faults with obstruction during the shaft motion due bent stem.

The technique has been implemented using MATLAB programming, by means the wavelet toolbox software of the MathWorks Inc[14]. Several wavelets families are available in the Wavelet Toolbox, allowing the exploration of the results of the analysis in a very efficient way.

3. DATA ANALYSIS

The case study[15], is the analysis of data of MOV with mechanical obstruction during the stroke time occasioned by bent stem.

There are some simulated data among the baseline (standard) and real fault.

The reasons for that are, first of all because the data with failures are somewhat evident the occurrence of fault and the second point is that the main aim of the monitoring and diagnosis system is to detect failures in the incipient stage.

Therefore, it was necessary to make a data regression of the signal with real failure bringing close to the baseline (i.e. standard situation with no fault) in order to check the sensibility of the system.

The Figure 6 shows the motor power signatures overlapped with the following situations:

Standard: *the baseline or no anomaly power signature,*
Incipient fault: *simulated power signature with incipient fault,*
Increased fault: *simulated power signature with increased fault,*
Real fault: *power signature with a real fault,*

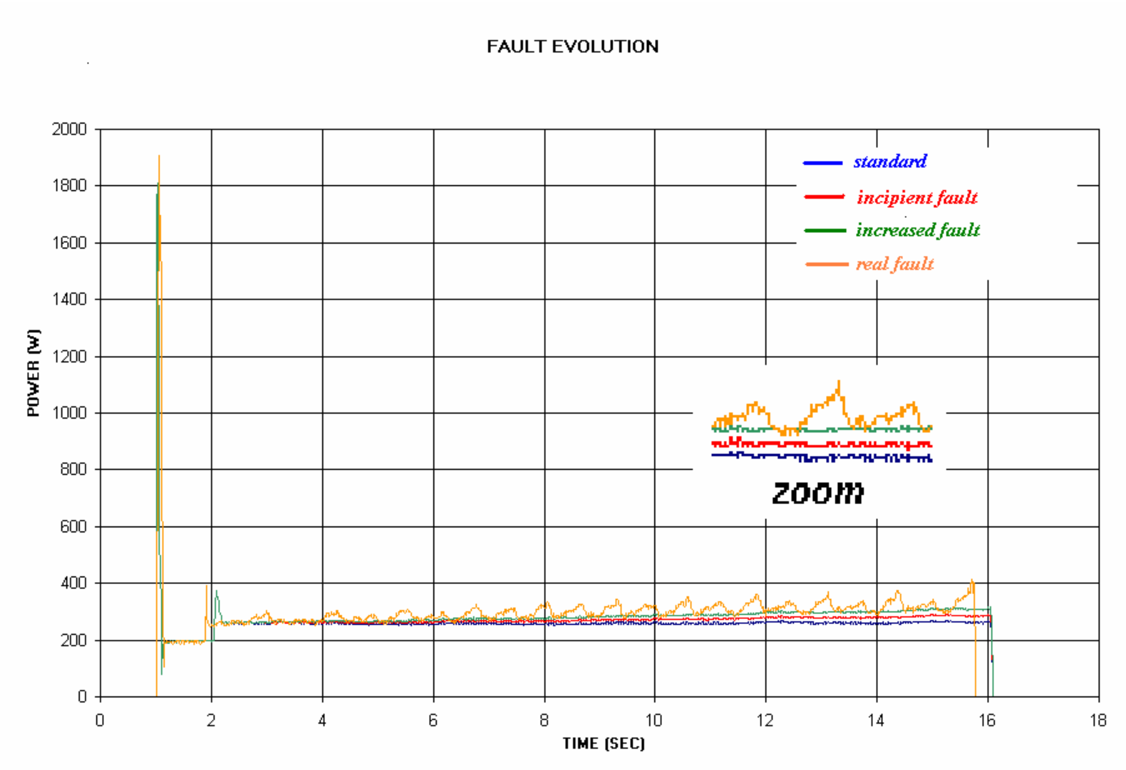

Fig. 6. Motor power signatures overlaped

Results analysis using wavelet function Daubechies "db4" decomposition level "6" are showed in Figures 7 and 8.

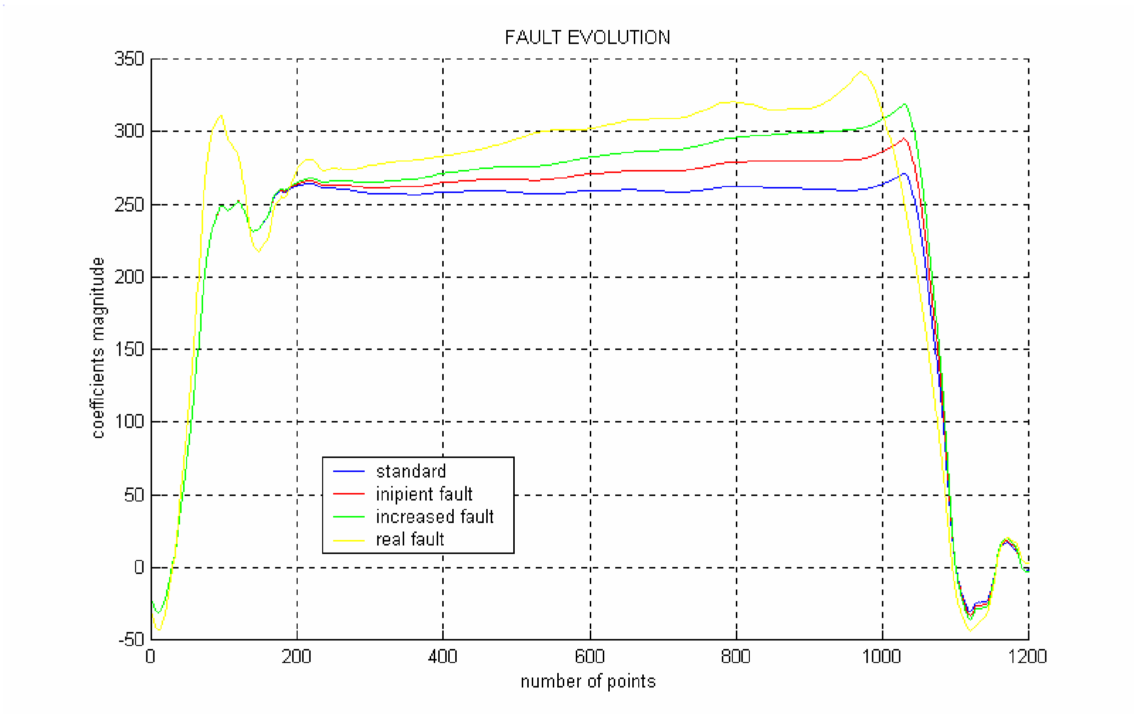

Fig. 7. Results during whole opening cycle (four situations)

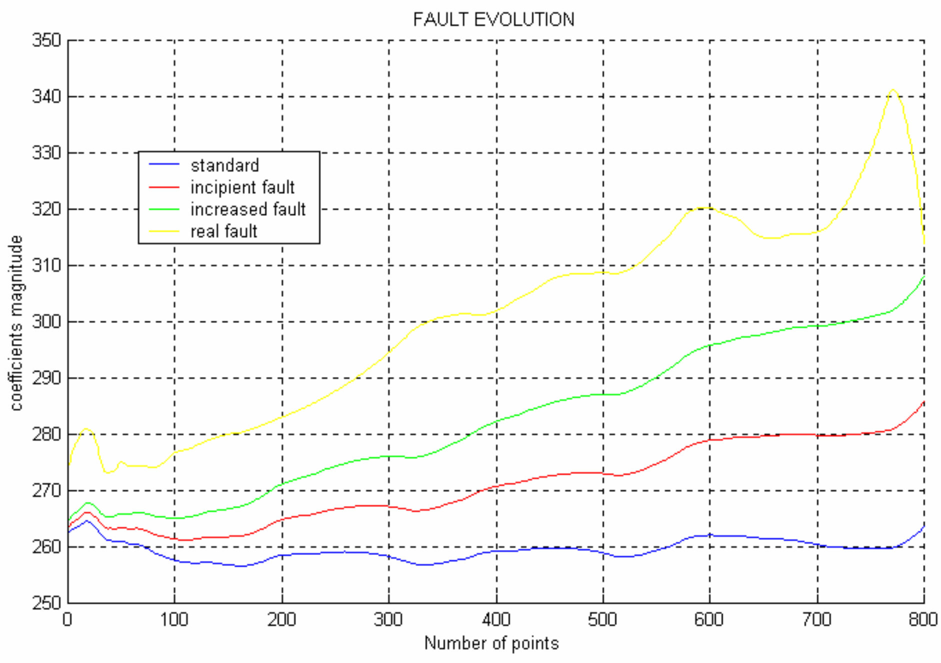

Fig. 8. Results during the shaft moving-opening cycle (four situations)

4. CONCLUSIONS

The development of non-intrusive diagnostics methods has provided the ability to detect failures in plant components during plant operation. Motor power monitoring and signatures analysis is being considered the most promising for a real predictive maintenance approach.

Diagnostic technique based on dynamics signal analysis have become an important tool for early detection of fault in components of systems of nuclear plants.

This paper shows good results with incipient fault detection of motor-operated valve using wavelet analysis technique.

In the case study with mechanical problem during the stroke time, it was observed with good evidence the identification of faults since the incipient stage, which has become clear the power increased during the shaft motion due to mechanical obstruction occasioned by bent stem.

The check of the efficiency on the system sensibility has been possible using the simulated data testing the analysis for the incipient stage that is one important point of monitoring and diagnostic system applied for predictive maintenance techniques.

The wavelet analysis gives a large amount of detail presented on the signals, it is fast and does not require intense computation process. The wavelet analysis showed the advantages of this method in detecting incipient changes in process signals that constitute the main aim of this project applied for motor-operated valves, diagnosing faults in the incipient stage.

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REFERENCES

[1] V. Bauernfeind, et al., "Development of diagnostic methods for on-line condition monitoring of primary system components", Kerntechnik 58, No.2 (1993).

[2] S. A. Snowden and B. R. Upadhyaya, "Automated Diagnosis of Motor-Operated Valves", Maintenance and Reliability Conference Proceedings (MARCON) (May 1997).

[3] Carneiro, A. L. G.; Da Silva, A. A.;Upadhyaya, B.R., "Development of an integrated condition monitoring system for motor- operated valves for Brasilian Nuclear Power Plants. In: Maintenance and Reliability Conference, Gatlinburg TN USA. Proceedings of MARCON, Knoxville TN, USA (May 2001).

[4] Chui, C. K., *An Introduction to Wavelets*. Academic Press, Inc (1992).

[5] Wu T., Lim M., Hatch S. D2CEX003PO Event RCA Report, Daya Bay Internal Document (2001).

[5] Chui, C.K., Monteforco L., Puccio L., "Wavelet Theory, Algorithms and Applications", Vol. 5, Academic Press, Boston (1994).

[6] Strang, G.; Nguyen, T. Wavelets and Filter Banks. Wellesley – Cambridge Press (1996).

[7] Kaiser G., "A Friendly Guide to Wavelets", Academic Press, Boston, 1992.

[8] Mallat, S., "A theory for multi-resolution signal decomposition: The wavelt Representation, IEEE Transaction on Pattern Analysis and Machine Inteligence, Vol.11, N.07 (July 1989).

[9] Da Silva, A. A. *An integrated approach for plant monitoring and diagnosis using multiresolution wavelet analysis*. Dec.1997.PhDThesis, The University of Tennessee, Knoxville, TN, EUA.

[10] Daubechies, I., "Ten Lectures on Wavelets", Philadelphia PA, Society for Industrial and Applied Mathematics (1992).

[11] Wang W.J., McFadden P.D., "Early Detection of Gearbox Failure by Vibration Analysis-I: Calculation of the Time –Frequency Distribution", Mechanic System and Signal Processing, Vol.7, pp.193-203, (September 1993).

[12] Wang W.J., McFadden P.D., "Application of Wavelçet to Gearbox Vibration Signals for Fault Detection", Journal of Sound and Vibration, Vol. 192(5), 927-939 (1996).

[13] Dennis M.H., "Two Applications of Wavelets a Related Techniques in Medical Imaging", Annals of Biomedical Engineering, Vol.23, pp.637-665, 1995.

[14] Wavelet Toolbox For Use With MATLAB, User´s Guide, The MathWorks Inc. (March 1996).

[15] Carneiro, A.L.G., "Desenvolvimento de Sistema de Monitoração e Diagnóstico Aplicado a Válvulas Moto-Operadas Utilizadas em Centrais Nucleares", PhD Thesis, Universidade de São Paulo, São Paulo, Brasil (May 2003).

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Consultants Meetings

Vienna, Austria: 13–16 July 2004, 7–9 June 2005

Technical Meeting

Daya Bay, Shenzhen, China: 29 November–2 December 2004