2001 EPRI International Maintenance Conference

Maintaining Reliable Electric Generation

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Proceedings, August 2001

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REPORT SUMMARY

EPRI's Energy Conversion Division organized and presented a three-day conference on fossil and nuclear generation plant maintenance during August 2001, in Houston, Texas. This CD presents the proceedings of that conference.

Background

Maintenance of generation assets is a key challenge for the electricity generation industry as it moves to a future of competition, changing asset ownership, and new business goals. Modern maintenance techniques and technologies—as well as business management processes supporting the maintenance function—will be increasingly important to the generation fleet. This will be especially true as competition grows and as the drive to improve reliability and performance with fewer resources intensifies. Optimizing maintenance practices and coordinating with plant and system operations will be critical to (1) ensure reliability when it is most needed and most profitable, (2) save costs and increase performance, (3) effectively deal with the realities of aging equipment and work-force, and (4) balance reliability and availability when factoring risk into the maintenance function.

Objective

To explore ways of optimizing maintenance practices in fossil and nuclear generation plants.

Approach

EPRI's Energy Conversion Division (ECD) targets organized the conference around a broad range of maintenance-related issues. Venues for presentations included strategic and technical sessions, panel discussions, and special topic workshops. ECD designed the conference for a wide range of power generation professionals, including engineering, operations, maintenance and management personnel, equipment manufacturers, vendors, architect- engineers, and consultants.

Key Points

The conference focused primarily on fossil and nuclear generating assets, but also included topics applicable to other assets. Specific sessions included the following:

- Keynote Session: Emerging Pressures of the New Marketplace
- Panel Discussion: Strategic and Tactical Guidance for Power Plant Maintenance Practices
- Plenary Sessions: Predictive and Preventive Maintenance Approaches
  Focus on Plant and Component Reliability

Innovations in Component Maintenance

Help for Predictive Maintenance Processes

- Parallel Sessions: Materials Issues and Innovations

  Innovative Maintenance and Repair Practices

  Diagnostic Techniques

  Innovative Predictive Methods

- Plenary Session: Tales from the Field—Stories of Successful Innovation

EPRI Perspective

This conference is part of EPRI's efforts under Target 69, Plant Maintenance Optimization (PMO). The PMO mission is to lead the industry by developing and demonstrating products and services that will improve use of power plant maintenance resources and increase profitability for generation businesses. The previous EPRI International Maintenance Conference was held in 1999 at Atlanta.

Keywords

Fossil
Nuclear
Power
Plant
Maintenance

SESSIONS AND PAPERS

2001 EPRI International Maintenance Conference

Maintaining Reliable Electric Generation

1. Keynote Session: Emerging Pressures of the New Marketplace

Welcome by David Tees, Senior Vice President, Reliant Energy

Philip Curtis, President, EPRISolutions

Vicki Bier, University of Wisconsin

Glen Schinzel, South Texas Project

Robert McQueen, Organizational Learning Center

2. Panel Discussion: Strategic and Tactical Guidance for Power Plant Maintenance Practices

Panelists: Keynote session speakers

3. Plenary Session: Predictive and Preventive Maintenance Approaches

Distributed Knowledge-Based Maintenance Assistance for Nuclear Power Plant Components
Benoit Ricard, Electricite de France

The EPRI Preventive Maintenance Database
David Worledge, Applied Resource Management

Manufacturing's High-Tech Revolution
Noah Bethel, PdMA Corporation

Sustain Reduced Maintenance Costs with Management Processes and Practices
Frank Frisina, New York Power Authority

Precision Lubrication for the Power Generation Industry
Drew Troyer, Noria Corporation

4. Plenary Session: Focus on Plant and Component Reliability

Managing Gas Turbine Maintenance Risks
Jason Makansi, Pearl Street, Inc.

Asset Reliability for the Deregulated Electric Power Economy
Robert Matusheski, Meridium, Inc.

Boiler Reliability Optimization
Pat Abbott, EPRI

Applying RCM to Optimize Maintenance
Jim August, Operations Management Engineering, Inc.

5. Plenary Session: Innovations in Component Maintenance

Boiler Automated Welding System®
Charles Giancola, Dynegy Midwest Generation, Inc.

Automatic Motor Winding Dry-Out Machine
Jerry Honeycutt, TVA

Condition-Based Maintenance of Reactor Coolant Pumps
R. Chevalier, Electricite de France

Reliable Plant Performance: Labor Solutions for the 21st Century
David Joiner, Welding Services

6. Plenary Session: Help for Predictive Maintenance Processes

Field Experience of a Novel Monitoring System for Improved Control of Power Plant Steam-Water Chemistry
Jose Bueno, Norcontrol Soluziona/Union Fenosa (Spain)

EMI Diagnostics Provides Condition Based Information for Triggered Maintenance in the Nuclear Environment
James Timperley, American Electric Power

PlantView – An Automated Tool for Maintenance Optimization
Rich Colsher, EPRI M&D Center

7A. Parallel Session: Materials Issues and Innovations

A New Stainless Steel for Erosion-Corrosion Control in Power Plants
William Schumacher, AK Steel Research

Deep Cryogenic Tempering
Michael Stickney, 300 Below, Inc.

Fitness for Service Program and Local Thin Area Repair Component for Pressure Retaining Items
Paul Manzon, Asta Engineering

7B. Parallel Session: Innovative Maintenance and Repair Practices

Cost Effective Repairs of a Loop Stop Isolation Valve: A Unique Approach
Brian Schumel, PCI Energy Services

Control of Suspended Sediment Concentration of Intake Channel at Yongkwang Nuclear Power Plant, Korea
Hyoseob Kim, Kookmin University (Korea)

Troubleshooting a Centrifugal Charging Pump – A Rotordynamics Analysis Approach
Mammar Maghraoui, Duke Engineering

8A. Parallel Session: Diagnostic Techniques

Infrared Thermography – Past, Present and Future
Robert Hammaker, EPRISolutions

Ultrasonic Test Technique on Insulation Hose of Generator
Hideo Tanahashi, Hitachi Ltd. (Japan)

Case Studies in Maintaining Piping Reliability by Economical Predictive Methods for Inspection Planning
Peter Jackson, Tetra Engineering

8B. Parallel Session: Innovative Predictive Methods

Development of Expert System with Bayesian Networks for Application in Nuclear Power Plants
Bilge Yildiz, MIT

Fuzzy Diagnosis System to Generators
Wang Shizheng, Shanghai Second Polytechnic University (China)

Gaining Strategic Leverage through Planning & Scheduling
Kirk Samsel, EPRISolutions

9. Plenary Session: Tales from the Field – Stories of Successful Innovation

Inspection Data Interactive Processing System
Paula Cortizo, Norcontrol Soluziona/Union Fenosa (Spain)

Overhauling the Plant Maintenance Process
Dennis Watson, Hoosier Energy R.E.C.

Exelon Nuclear Proactive Maintenance Program and Best Practices
Steve Maloney, Exelon Nuclear Corp.

Reliability-Centered Maintenance
G.P. Singh, National Thermal Power Corporation (India)

PREVENTIVE MAINTENANCE STRATEGIES FOR DEREGULATION

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Abstract

Companies do not emerge into a competitive environment knowing immediately how to compete safely and effectively, and can therefore inadvertently make excessive cutbacks in preventive maintenance. In particular, some electric utilities have suffered adverse consequences in recent years because of such cutbacks. Companies interested in re-optimizing their preventive maintenance programs should eliminate activities that have little value added, look for ways to accomplish their current maintenance activities at lower cost, and consider alternative activities to meet the same goals. Moreover, successful re-optimization requires increased economic sophistication. In a competitive market, where electricity prices can vary by more than two orders of magnitude, optimal economic performance requires moving beyond simple engineering-oriented figures of merit such as capacity factor. Better economic decision-making tools can improve plant economic performance while maintaining safety and reliability.

1. Possible Pitfalls in Preventive Maintenance Strategies

This paper discusses how deregulation affects preventive maintenance strategies. As noted by Carroll et al. (1998), "In the short run, a plant can always cut preventive maintenance; the problems emerge later because preventive maintenance is an investment in the future." In other words, "Sparse allocation of resources to maintenance is not a rational strategy for the organization as a whole," but can nonetheless occur.

Under economic regulation, most preventive maintenance costs were recoverable in regulated rates. However, in a deregulated environment, changes in costs go directly to the bottom line. Therefore, deregulation increases the incentive to cut preventive maintenance costs, at the same time as it increases the potential impact of inadequate preventive maintenance programs. This makes it more important to get the tradeoffs right. For example, companies can (perhaps inadvertently) adopt policies that lead to cost savings in the short run, but result in problems later. Carroll et al. note, "Preventive maintenance…seems to be a low priority in the face of immediate demands to keep the machines running at lower cost," partly because "the ultimate effects of deferred maintenance can be denied, ignored, or blamed on others."

The experiences at the Millstone nuclear power plant in the late 1990's show that cuts can in fact go too far. As the General Accounting Office (1998) noted about Millstone, "The need to trim costs in the face of future competition resulted in managers' choosing to defer maintenance and allow backlogs of corrective actions to grow, eventually creating a situation that led to a shutdown and several hundred million dollars worth of repairs." The shutdown also resulted to opportunity costs of lost sales during the period of the shutdown. One reason that such problems can arise is because the feedback for cutbacks is delayed and ambiguous, so plants that do not heed early warning signs could cut too far.

Some plants are turning to reliability-centered maintenance (RCM) to avoid such problems. However, appropriate use of RCM creates increased demands for testing (e.g., non-destructive evaluation), data collection, and analysis. The lack of such data collection and analysis appears to have been a problem in the electricity distribution outages in Chicago in summer 1999. In reviewing those outages, the Department of Energy Power Outage Study Team (2000) noted that "Many fixed, periodic, substation maintenance programs had been scaled back or discontinued in transition to a 'reliability-centered maintenance' philosophy. However, the collection of data and measurements necessary for successful reliability-centered maintenance was not fully in place." As a result, "the ability to predict possible component failures from the inspections that were performed and data that were collected was limited."

Another area in which companies can inadvertently make excessive cuts is maintenance of spares. Under economic regulation, spares might have seemed like an obvious place for cutbacks when cuts were needed. After all, spares obviously cannot be safety-critical (since they are not even installed); moreover, they are not used in routine operation, and some spares may not have been used at all in many years. This combination of factors makes spares appear to be an easy target for cutbacks. However, this is actually an old way of thinking that is no longer appropriate in a deregulated environment, where generating companies can no longer expect ratepayers to cover the cost of outages, even if they do not result from "imprudence" per se. The transformer fire at the Hope Creek nuclear power plant on May 24, 2000, showed that spares maintenance could be critical to managing outage duration. In that instance, the spare transformer and spare oil pumps had not been in working order at the time of the fire, and as a result ended up being on the critical path in what became a 28-day forced outage that lasted into the peak summer season.

2. New Ways of Thinking about Preventive Maintenance

Airline industry experience shows that companies can cut costs safely. A study of engine maintenance after deregulation by Kennett (1993) found "a significant increase in the number of engine hours between major overhauls following deregulation," but noted, "engine 'failures' …have not increased as a result of deregulation." Kennett's findings suggest that airlines may have been doing more maintenance than necessary prior to deregulation, and then optimized their maintenance programs after deregulation—"perhaps by improving the quality of service performed but paying less attention to minor problems between scheduled shop visits."

This is consistent with experiences after deregulation of the United Kingdom (U.K.) nuclear power industry. A recent study of the effects of economic deregulation on nuclear power safety (Bier et al., in press; see also Bier et al., 2001) found that in the U.K., electricity deregulation appears to have increased the emphasis on reliability and regulatory compliance (despite some problems associated with extensive downsizing). In an interview summarized in Bier et al. (in press), a power plant site manager in the U.K. noted that managers now find themselves telling the staff not to rush: "Don't make mistakes which can lead to a non-compliance with the regulations." He emphasized, "We'd rather have the job done slowly but right."

These observations suggest several strategies for allocating resources to preventive maintenance:

1) *Identify those maintenance activities that are truly cost-effective and/or risk-significant.* Cutbacks can then be considered in those activities that provide little real value added, and are done mainly because "that is the way we have always done maintenance around here." For example, South Texas Project managers estimate that they will save roughly $1 million annually by "optimizing maintenance frequencies, [reevaluating] how detailed post-maintenance testing needs to be and reconsidering how detailed plant documentation packages need to be" on components with little or no risk significance (Stellfox, 1999). Those activities that contribute significantly to productivity may actually justify increased levels of resources after deregulation.

2) *Seek ways to accomplish needed maintenance at lower cost.* For example, companies may seek competitive bids for activities that were formerly contracted to the original equipment manufacturer. With the economies of scale associated with consolidation, companies may also find it cost-effective to have their own staff perform work that had formerly been done by contractors—for example, to permit greater management control.

3) *Seek alternative ways to achieve the same goals.* For example, careful use of non-destructive evaluation may make it possible to postpone or even eliminate some formerly routine overhauls.

3. Conclusion

Electricity deregulation changes the incentives for preventive maintenance at power plants, and increases the importance o getting the tradeoffs right. Therefore, generating companies will need more sophisticated measures and tools to meet this challenge. For example, generating companies used to focus on engineering-oriented figures of merit such as capacity factor and forced outage rate. Under economic regulation, annual average capacity factor made sense as a performance measure for use by electric utilities, especially since some regulators used it as a performance benchmark. However, in a competitive market, electricity prices can vary by more than two orders of magnitude between high-cost and low-cost hours, so achieving good annual average capacity factors is no longer sufficient. Instead, the *timing* of when a plant is available also becomes critical to its economic performance.

Under these situations, *reliability* is more important to profitability than it used to be. Thus, avoiding a day of forced outage (which could occur at a costly time of year) may be worth several days of planned outage at a low-cost time of year. In fact, as future electricity markets evolve, forced outage rates may have yet another direct financial consequence for utilities, since they may affect the cost of required reserves to cover possible forced outages (equivalent to an insurance premium).

Moreover, controlling the *duration* and *timing* of forced outages is as important as controlling their *frequency*. One way to control the duration of forced outages is through effective spares maintenance. This obviously does not mean that an organization should not cut maintenance of spare parts—only that it should not do so blindly, under the erroneous assumption that spares maintenance is unimportant. Rather, optimal spares maintenance must carefully weigh the savings from any cutbacks against the possibility that failure to maintain spare parts in working condition could extend the duration of a forced outage. In this context, arrangements with other plants or vendors (to ensure that spares will be available on short notice) can provide one mechanism for reducing spares maintenance with diminished downside risk.

The idea of controlling the timing of forced outages at first would appear to be a contradiction in terms. After all, if an outage is truly forced, how can a plant be expected to control the timing of that outage? However, the timing of forced outages can in fact be influenced by paying careful attention to the circumstances that can cause such outages—for example, by limiting on-line maintenance to times when outages would not be excessively costly.

Optimizing financial performance rather than conventional engineering figures of merit requires increased economic sophistication. Moreover, with the advent of electricity deregulation, responsibility for making economic decisions is now being pushed down to lower and lower levels within power plant management structures and organizations. The types of decisions where economic considerations are important range from relatively long-term decisions (such as deciding which work to include in a particular outage), to short-term decisions (such as whether to call in a maintenance crew on overtime versus waiting until the next weekday), to general decision rules (such as whether and when to perform on-line maintenance). While the specifics of these decisions are often unique, certain categories of decisions arise over and over. Therefore, it is important for power plants to develop better tools for economic analysis of such situations. Better economic decision-making can result in plant performance that is more consistent with corporate financial goals and policies, while still incorporating the technical knowledge of plant decision-makers.

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Utility Maintenance Applications
Using Risk-Informed Insights

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South Texas Project (STP) Overview

- South Texas Project is a two unit, four-loop Westinghouse PWR rated at 1250MW each

  -Initial power generated-Unit 1 in 1988, Unit 2 in 1989
  -Each unit is physically separate-few common systems
  -Reactor package includes a rapid-refueling design
  -Main Turbine Deck is open to the atmosphere

- South Texas Project is located about 85 miles southwest of Houston, Texas - located near the Gulf of Mexico

- South Texas Project Nuclear Operating Company is co-owned by four power companies

Why a Risk-Informed Approach?

A risk-informed approach to safety-related maintenance activities:

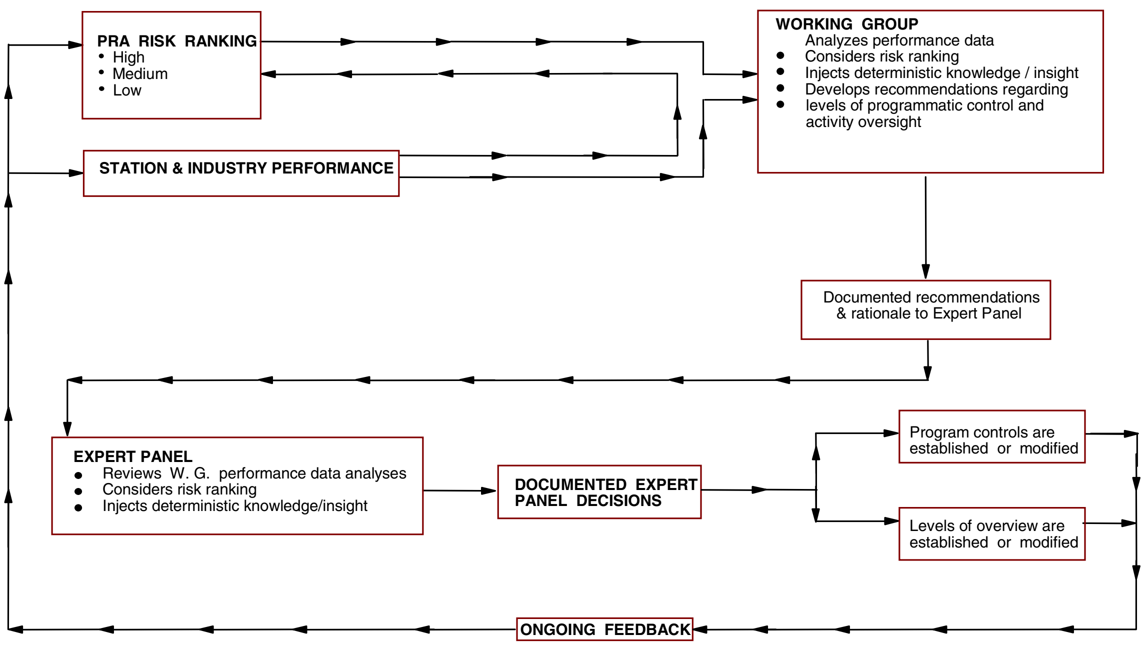
- Allows a documented basis for identifying what components are important (safety significant) and what components are not important (non-safety significant)

- Once identified, maintenance resources can be focused on the safety significant components

- This results in:
  - Reduced burden for the power plant
  - Reduced burden for the regulator
  - ***Improved*** overall safety

- This approach does requires a change in the 'nuclear culture'

Importance Determination Flowchart



Importance Determination Controls

- Decision-Making process is made up of two groups - a Working Group and an Expert Panel
  - both groups use experienced, qualified personnel
  - both groups use personnel from maintenance, operations, engineering, licensing, and quality organizations
- Procedures govern the component importance determination process
- Through this process, components are placed into one of four categories:
  - HSS - high safety significant
  - MSS - medium safety significant
  - LSS - low safety significant
  - NRS - not risk significant

Importance Determination Approach at STP

- Importance Determination Process for components consists of probabilistic and deterministic insights:
  - PRA
    - PRA models about 1200 components for Unit 1
    - PRA categorization based on importance measures of Fussel-Vesely (FV) and Risk Achievement Worth (RAW)
  - Deterministic
    - Identify functions performed by the system
    - Determine risk importance of each function using five ‘critical questions’ as a guide
    - Identify functions supported by each component
    - Determine resulting risk importance of each component
- Overall importance based on the higher of PRA and deterministic risk
- Working Group identifies component risk; Expert Panel independently reviews and approves

Categorization Results

- 29 systems (43,688 components) categorized to date
- Components have been categorized as follows:
  - HSS - 3%
  - MSS - 7%
  - LSS - 15%
  - NRS - 75%
- HSS/MSS components are safety significant (important)
- LSS/NRS components are not-safety-significant (least important)

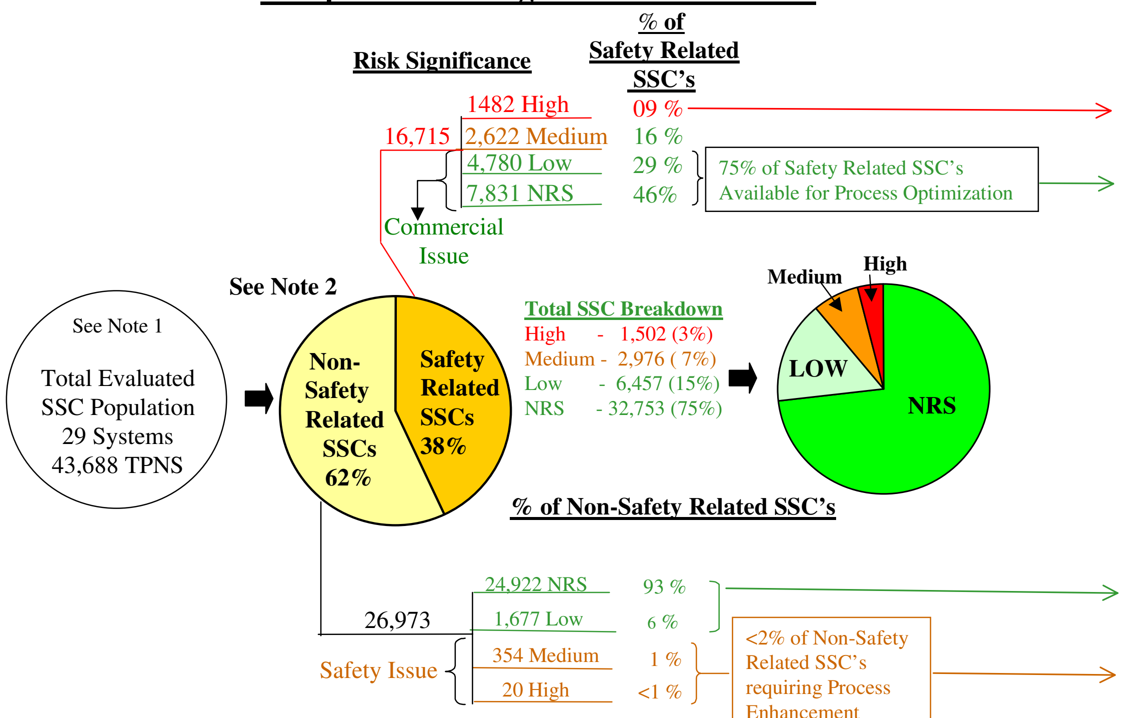
Results Broken Down Further

RISC - 1 Safety-Related, Safety Significant 4,104 (9.4%)	RISC - 2 Non-Safety Related, Safety Significant 374 (0.9%)
RISC - 3 Safety-Related, Not Safety Significant 12,611 (28.7%)	RISC - 4 Non-Safety Related, Not Safety Significant 26,599 (60.9%)

COMPONENT RISK SIGNIFICANCE - MAINTENANCE APPLICATION BREAKDOWN

As of 4/16/01 (See Note 1)

Component Risk Significance Breakdown



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Note 1: Inclusive of Systems AF, CC, CH01, CV, DG, DI, DO, DX, EW, FC, FW, HC, HE, HF, HG, HM, IA, JW, LU, MS, PS,RA, RC, RH, SB, SD, SI, WL and XG.

Note 2: Includes Augmented Quality Related 7F, 7S, 7P and 7R.

Why is it okay to categorize components and treat them differently?

- Commercial practices have been demonstrated to be acceptable through improved power plant capability and reliability factors
- Safety-related/non-safety related component failure rates are generally the same
- It is expected that the least important components will continue to function when demanded
- Even if one of these components were to fail, it would result in little to no impact on safety

Special Treatment Requirements

- Special Treatment Requirements (STR) provide additional assurance that safety-related components will function beyond what commercial practices provide
- STR may provide benefit for the most important components, but not for the least important components
- The least important components (LSS/NRS) only need reasonable assurance that the design functional requirements will be met
- The least important components must still perform their functions when demanded

Scope of the STP Exemption Request

- 10CFR Part 21 (Vendor Notification)
- 10CFR50.49 (Equipment Qualification)
- 10CFR50.55 (ASME / ISI, IST)
- 10CFR50.59 (Change Control)
- 10CFR50.65 (Maintenance Rule)
- Appendix B (Quality Assurance Program)
- Appendix J (Containment Leak-tightness)
- 10CFR Part 100 (Seismic)

What Will the Exemption Mean to STP?

- An **opportunity** for STP to adjust the treatment on the least important safety-related components:
  - failed components could be replaced with commercial replacement parts
  - ASME Class 2 and 3 components could be repaired or replaced following an ANSI commercial code
  - components will generally be outside of the Maintenance Rule scope
  - seismic and environmental qualified parts could be replaced with non-qualified replacement parts
  - containment penetration leakage tests could be eliminated
  - maintenance documentation could be reduced

Summary

- Importance determination (categorization) allows the importance of components to be recognized - not all safety-related components are equally important

- Some non-safety-related components are actually more important than safety-related components

- If risk-informed insights were available 20 years ago, today's plant design and maintenance would be much different

- The nuclear industry must continue to pursue risk-informed activities to improve the safety of plant operation and the effectiveness of plant maintenance

Assessing the Innovation Infrastructure in Fossil Power Generation Plants

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INTRODUCTION

The seeds of this paper were sown over ten years ago, when the Electric Power Research Institute (EPRI) decided to explore how to apply the improvement methods that were used successfully in other industries to improve power generation plant performance. To achieve this goal, EPRI contracted with the Organizational Learning Center (OLC) to lead the investigation, and established a working group to guide the effort, consisting of leaders from over twenty utilities involved in improving power generation plant performance.

The priority needs identified by utility leaders were:

a. to develop a clear understanding of the primary purpose towards which improvement efforts should be directed

b. to see real-world case examples of how to achieve improvement

c. to understand ways in which to measure progress towards improvement

This paper provides an overview of the findings of a ten-year development effort that included numerous OLC on-site projects in power generation plants and parallel development efforts by the San Jose State University College of Engineering Center for Process and Quality Improvement. Information is presented on the importance of focusing improvement efforts on the organizational infrastructure needed for high performance. Descriptions are provided of the primary infrastructure components important to achieving high performance, and benchmarking results are provided of assessments obtained on fossil power generation projects.

One of the most important findings from OLC research is the need for organizational leaders to expand their views of infrastructure to include factors needed for learning and change (innovation). The organization’s innovation infrastructure supports the efforts of managers and employees at all levels to solve problems and to identify innovations that improve performance. Today's managers are challenged to understand the components of innovation infrastructure and to include the development of these components in their strategic plans.

IMPROVING ORGANIZATIONAL PERFORMANCE: THE CHALLENGE

The challenge for most organizational leaders is not *whether* they should embrace the ideas of continual improvement, rather *what* to improve and *how* to achieve the needed changes. The work environment in most fossil power generation plants was established during times when the electric power industry was regulated. The management style used was one normally referred to as a “command and control” style, typical of a military organization. This fostered division and confrontation between organizational groups, which often led to unresolved issues and a breakdown in respect and trust, particularly between management and front-line workers. Deregulation is now a reality, and the traditional management style of the past is not effective in today’s competitive work environment.

It was in response to the challenge to change that, in 1991, EPRI established the work Process and Quality improvement (WP&QI) Board. This board consisted of power generation plant leaders and represented employees who guided the development of resources over a six-year period to improve generation plant performance. A listing of individuals who supported OLC and EPRI WP&QI Board activities is provided in Appendix A.

The work of the EPRI WP&QI Board has provided a portfolio of valuable resources to help fossil plants plan and improve performance. The systems approach to improvement is described in *Guide for Building a High Performance Generation Plant: A Systematic People Based Approach*, EPRI TR-114002. This guide also includes a case example of the implementation of the systems approach at Nevada Power. One of the primary engines of change is the improvement of the processes for getting work done, and for transferring and implementing new technology. A “learning by doing” case example is provided *Work Culture and Process Improvement – Predictive Maintenance Case Study Report*, EPRI TR-114324, which covers the enhancement of the PDM capability in Nevada Power’s Clark/Sunrise Station.

In his recent book, *The Human Equation: Building Profits by Putting People First*, Jeffrey Pfeffer of Stanford University emphasizes the importance of using self-managed teams and decentralizing decision-making as basic principles of organizational design, and providing extensive training to help the organization continually learn and change. In a similar fashion, Stephen Covey’s book *The Seven Habits of Highly Effective People* stresses the importance of “sharpening the saw” (continual improvement) to organizational success.

In today’s competitive and changing marketplace, high performance levels can best be achieved by having self-managed multi-disciplinary teams undertake much of the daily work effort. These teams need to have the ability to continually learn and adapt to changing circumstances. The components of the Innovation Infrastructure Assessment are associated with the ability of multi-disciplinary work teams to effectively self-manage much of the daily work that needs to be done to maintain and operate power generation plants.

THE IMPORTANCE OF INNOVATION INFRASTRUCTURE TO ORGANIZATIONAL SUCCESS

Continually increasing power plant performance is essential in a deregulated marketplace. In times of increasing competition and advancing technology, an organization must innovate to improve its performance in delivering its existing products and services and in developing new products and services. Innovation is important to all organizational groups and applies equally to managers, supervisors and front-line workers.

It is management's role to establish the organization's physical infrastructure. The organization's *physical* infrastructure consists of a variety of capital resources (physical facilities, technology, and materials) that enable it to *produce* its products and services. However, simply continuing to provide existing products and services is not enough. To remain competitive in today's deregulated environment, the organization must innovate. It is also management's role to establish the organization's *innovation* infrastructure.

Most senior managers have developed long-term strategic plans that incorporate the physical and technical changes they foresee as necessary to organizational success. However, most of these managers have not incorporated into these plans the cultural or work environment changes needed to support the physical and technical changes. To achieve long-term success, an organization must include the innovation infrastructure in its improvement strategy.

An organization's innovation infrastructure consists of the competencies that enable it to continually improve its products and services to improve bottom line performance. A description of the Innovation Infrastructure Model and its components is provided in Appendix B. The organization's innovation infrastructure is the basic underlying framework that supports the design, development and delivery of new products and services, as well as influencing the efficiency and effectiveness of daily work. An organization with a good Innovation Infrastructure is able to empower and motivate employees to achieve a high level of organizational cooperation and commitment to the organization's goals.

The innovation infrastructure is the "grease" that facilitates the organization's ability to seamlessly learn and adapt to changing circumstances. A strong innovation infrastructure is indicative of a work environment that fosters innovation and enables organizational members to seize opportunities and solve problems in ways that benefit the organization as a whole. A description of the characteristics of an innovative work environment developed by the Innovation Network is provided in Table 1. A well-developed innovation infrastructure provides a foundation for tapping into the initiative and creativity of organizational members. It also has a positive influence on key performance indicators such as employee retention, customer satisfaction and bottom-line performance.

Table 1: Characteristics of An Innovative Environment

Shared vision	Shared values
Close link between business goals and innovation	Tolerance of small beginnings
Crossing departmental boundaries	Recognition and rewards
Having sponsors	Decentralized resource allocation and control
Willingness to experiment	A willingness to learn
Access to people and tools	Open communications
Questioning the status quo	Self organizing
Trust	Perseverance
Local autonomy	Risk taking
Participation	Mutual respect
	Lateral thinking

Today's managers understand the need to enhance the existing innovation infrastructure (particularly the components of human skills and culture) in order to remain successful in a deregulated environment. Many international utility conferences include tracks focusing on plant culture and its impact on performance. For example, Track 2 of the *Electric Power 2000 Conference*, held April 4-6 in Cincinnati, Ohio, was entitled "The Impact of Plant Culture on Profitability." However, managers are not as clear about *how* to develop a work environment that supports organizational innovation, particularly in industries (such as utilities) that have historically had a relatively stable environment, and have not had to continually innovate in order to succeed in the marketplace.

Undertaking an innovation infrastructure assessment provides organizational leaders and members with an understanding of areas where organizational members believe the innovation infrastructure is strong and areas where improvement is needed. For the past ten years, the Organizational Learning Center (OLC) has focused on providing organizations with the internal capability to assess and improve their Innovation Infrastructure. OLC partners with customers to tailor the Innovation Infrastructure Assessment to fit the organization's circumstances.

INNOVATION INFRASTRUCTURE: GAINING A SHARED ORGANIZATIONAL VISION

A shared vision provides the framework within which effective action can take place. Taking the time to *aim* before *doing* is the greatest challenge for many organizations. According to Joel Barker, "action without vision just passes the time, but action *with* vision can change the world." Aiming involves creating a vision of what the organization seeks to achieve, understanding why achieving that vision is important, and gaining agreement by those involved on the approach that will be used.

A vision for the change effort that is shared and supported throughout the organization is the foundation for a successful change effort. The first step in achieving this requires that organizational leaders (managers *and* front-line workers) take time away from the pressures of daily work to understand, envisage, and commit to building the competencies needed for long-term success. Recognizing the need for this effort and getting the right coalition of people involved is an important part of the challenge.

The foundation for successful change involves knowing what to change, why the change is necessary for improved performance, and how to achieve the desired change. Understanding *what* to change and *why* requires a valid theoretical framework for analyzing operations and identifying high-leverage change areas. Understanding *how* to change requires improvement competencies and a culture supportive of change.

Organizations must avoid the temptation to have external groups *tell* them what to improve rather then help them *learn* what to do to achieve improvement objectives. It is by learning through experience that organizations develop competencies in areas important to achieving high performance. A valuable early step in any change effort is to undertake an evaluation of where the organization stands to identify the areas where change would be most beneficial. This evaluation needs to cover both the technical and human factors influencing performance.

Organizations are normally better equipped to identify areas of technology that can help improve performance, and less equipped to identify opportunities to improve existing practices and human skills. A study of the literature reveals that there are relatively few tools and methods available to diagnose problems with a utility's culture let alone achieve positive cultural change. OLC has identified the following cultural problems that can block improvement efforts:

a. A lack of trust between managers and workers
b. A lack of cooperation between different departments
c. Fear in the workplace
d. Apathy and low levels of morale
e. A lack of accountability
f. Resistance to change
g. An “us vs. them” mentality
h. Clinging to past practice (“we’ve always done it this way”)
i. A lack of commitment
j. A “what’s in it for me” attitude
k. Poor communication
l. Reward systems that foster internal competition

TAILORING THE INNOVATION INFRASTRUCTURE ASSESSMENT TO ORGANIZATIONAL CIRCUMSTANCES

OLC’s purpose is to help organizations develop the knowledge, skills, and work environment needed to achieve high performance levels. To achieve its purpose, OLC works with its customers to design, plan and implement activities that concurrently improve bottom-line results and contribute to developing a high performance organization. The specific activities undertaken depend upon the organization’s circumstances and priorities. Examples are:

a. enhancing project management and work integration skills to help reduce costs and development cycle times

b. addressing critical problems influencing performance using the tools and methods of process analysis and improvement

c. gaining increased employee support and involvement in achieving an organization’s goals by enhancing the organization’s strategic planning processes

d. enhancing the human skills and self-organizing competencies of multi-disciplinary teams

UNDERSTANDING THE INNOVATION INFRASTRUCTURE ASSESSMENT

The value of any assessment is highly dependent on the design of the data collection instrument and the way in which the information is collected. The Innovation Infrastructure Assessment developed by OLC has been structured in three levels. The rationale for this is to enable OLC to design an assessment approach that best fits an organization’s needs. The Level 1 assessment covers human effectiveness skills and culture. It provides valuable information helpful in developing the work environment in ways that increase the effectiveness and efficiency of daily work. The Level 2 assessment covers the additional areas of communications and shared vision. These areas are important when an organization is attempting to gain a better focus throughout the organization on its strategic objectives and creating climate within which employee empowerment can be more successful. The Level 3 assessment adds the areas of process improvement and process management. A Level 3 assessment is particularly useful to organizations that seek to measure their progress in understanding the network of processes they use to deliver their products and services and the level of their internal competencies to continually improve these processes. OLC provides workshops to help organizational leaders understand the components of the Innovation Infrastructure, their importance to achieving high performance levels, and how they can be assessed.

One important step essential to the development of the assessment methodology was getting an understanding of factors important to survey respondents. It was also important to base the survey on solid theoretical ground. The theoretical basis for the survey was Vroom's Theory of Motivation. This theory states that people need two specific items before they will be motivated to do something new (change). First, people need to believe that the change will be beneficial, and second, they need to believe they have a reasonable chance of being successful in making the change.

EPRI-supported projects have contributed to the development and testing of the Innovation Infrastructure Assessment. Level 1 Innovation Infrastructure Assessments (covering human skills and culture) have been undertaken in ten separate situations is fossil power generation plants and in a number of different industries. The results of these assessments provide valuable benchmarking comparison data to help organizations identify their strengths and weaknesses.

A valid and tested measurement system such as the Innovation Infrastructure Assessment is an essential asset in today's competitive marketplace. The assessment enables an organization to identify its strengths and weaknesses in the processes and human area competencies important to achieving high performance. The evaluation provides a framework to compare (benchmark) competencies with those of other organizations, as well as the ability to measure the influence of change initiatives on the organization (benchmark against oneself over time).

The Innovation Infrastructure Assessment:

- provides a comprehensive view of employee perceptions of the current status of areas important to achieving high performance, and employee perceptions of the levels needed to achieve high performance
- enables the organization to undertake internal and external benchmarking comparisons
- provides a long-term system for tracking the organization's improvement potential, and assessing the effectiveness of improvement efforts
- facilitates open and constructive discussions about attitudes, behavior, and culture

INNOVATION INFRASTRUCTURE ASSESSMENT: CASE EXAMPLES

Level 1 assessments were undertaken by the OLC to support a number of projects in fossil plants. One power generation plant completed three assessments over a period of five years, as a means of tracking changes in the factors important to achieving high performance. One of these assessments covered all three levels of the assessment. In addition, assessments have been used to track changes resulting from successful improvement projects.

OLC has established a method for categorizing performance ratings, based upon experience gained in the utility industry and other industries. These categories are provided in Table 2.

Results are provided in Figures 1 through 6 of the summary or "Area" results obtained in seven power generation plant Level 1 assessments. More detailed descriptions of these Areas are provided in Appendix B. The percentages shown in the Area results are averages of the ratings for each factor in that Area.

In the assessment, employees rate their perceptions of the *current* rating for a particular factor and the rating *needed* to achieve high performance levels. The percentage for each factor is calculated based upon the gap between the current and needed ratings, and the *priority* rating for each factor. If employees believe the plant is currently performing at the level needed for high performance, the gap for that factor would be zero, and the percentage would be 100%.

It is interesting to note that Plant 5 had the highest rating in five of the six areas of the assessment. The Plant 5 assessment was undertaken as part of a benchmarking project in which Plant 5 was selected as a benchmarking partner, based upon its excellent bottom-line performance. Thus, the plant with the highest ratings in human skills and culture was also a plant recognized for its excellent performance.

Table 2: Description of Ranges of "Factor Ratings"

Category	**Range**	**Description**
Excellent	88 - 100%	Scores in this range indicate that the organization is performing in approximately the top 10% of business organizations. A gap of 1 point or less between the Present and Needed condition for a particular factor would achieve an "excellent" rating for that factor.
Good	81 - 87%	Approximately 25% of the scores fall in this range. This normally translates to a gap of 1 to 1.5 points between the Present condition for a particular factor and that Needed to be a high performing organization.
Satisfactory	74 - 80%	Approximately 25% of the scores fall in this range. A gap of 1.5 to 2 points between the Present condition and that Needed to be a high performing organization would achieve a "moderate" rating for a particular factor.
Moderate	67 - 73%	Approximately 25% of the scores fall in this range. A gap of 2 to 2.5 points between the Present condition and that Needed to be a high performing organization would achieve a "poor" rating for that particular factor.
Poor	60 - 66%	Approximately 10% of the scores fall in this range. A gap of 2.5 to 3 points between the Present condition and that Needed to be a high performing organization would achieve a "unsatisfactory" rating for that particular factor.
Unsatisfactory	<59%	Only 5% of the scores fall in this range. A gap of greater than 3 points between the Present condition and that Needed to be a high performing organization would achieve a "dysfunctional" rating for that particular factor.

CHANGE READINESS AREA RESULTS

This is the ability and openness of an organization and its members to change the existing practices and processes to be fully responsive to both the needs of internal and external customers and to changes in the business environment.

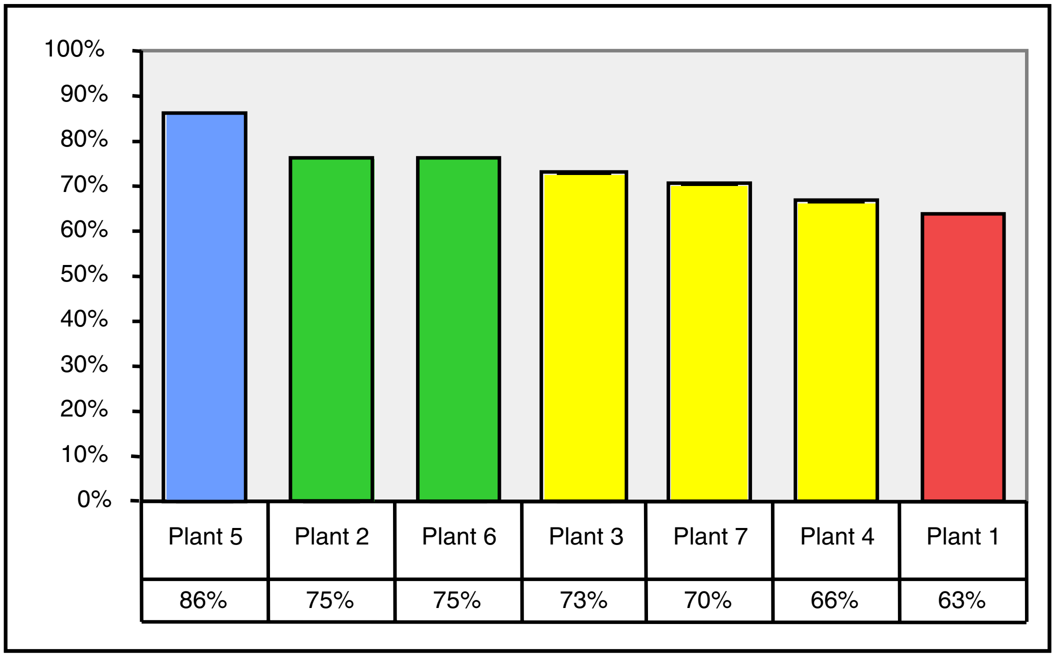

Figure 1: Change Readiness Area Results

LEADERSHIP AREA RESULTS

This is the ability to influence and guide people by means of communication and example to establish a shared purpose and to achieve it.

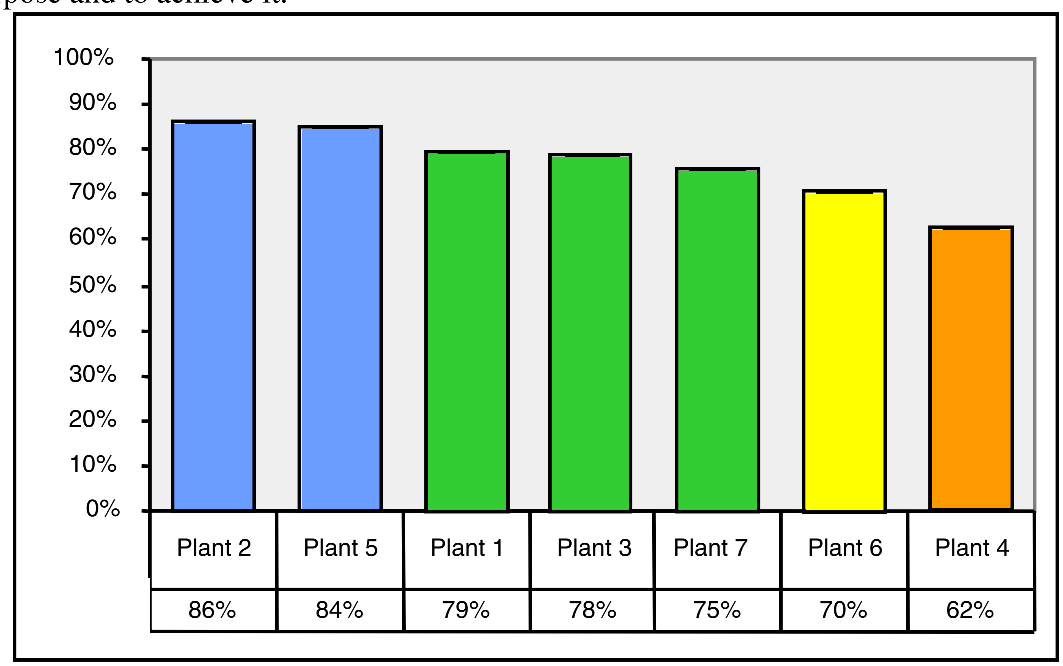

Figure 2: Leadership Area Results

CUSTOMER FOCUS AREA RESULTS

This is the ability to recognize the paramount position of the organization's customers and the nature and importance of the chain of customers and suppliers who, by taking care of each other, provide high quality at low cost to these external customers.

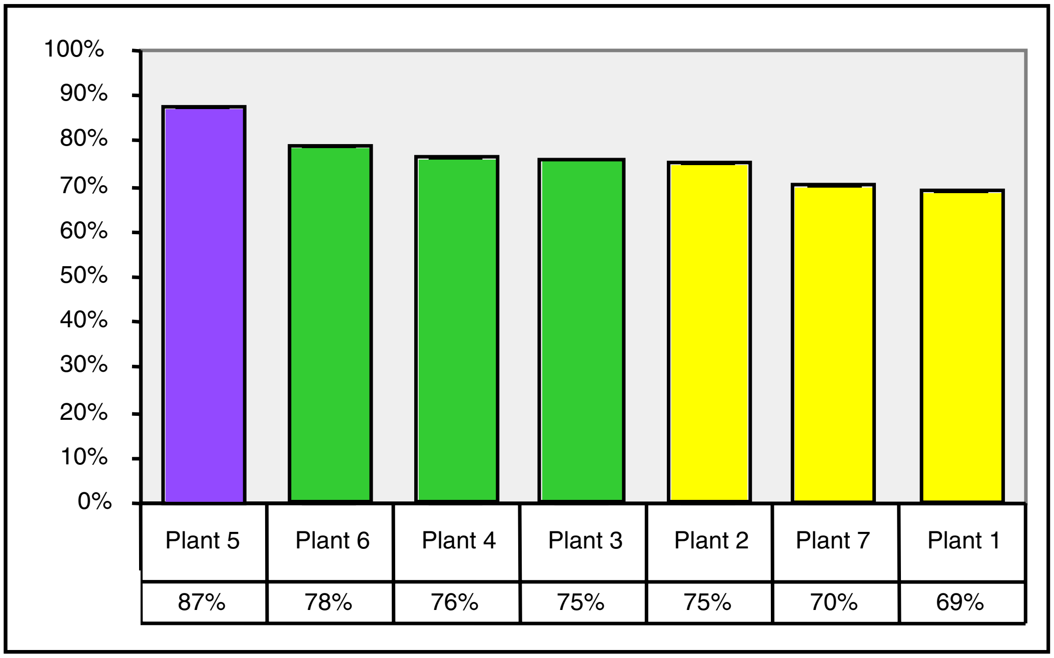

Figure 3: Customer Focus Area Results

SYSTEMS THINKING AREA RESULTS

This is the ability of the organization's members and groups to understand 1) the way their work activities interconnect with the activities of others to form processes that provide value to customers, and 2) the impact of their actions on the rest of the organization.

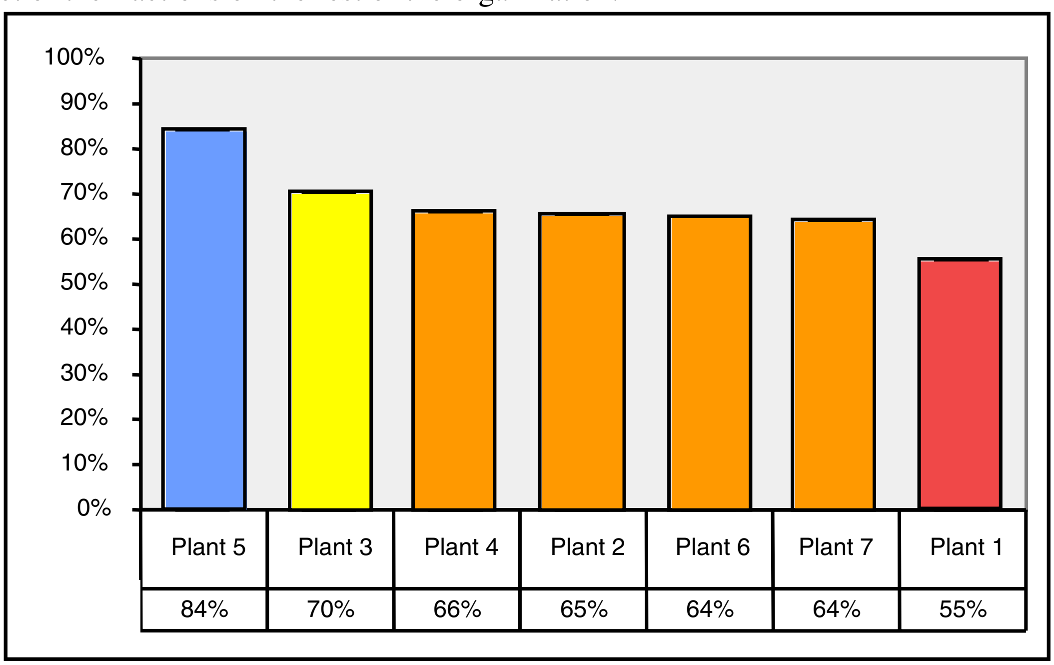

Figure 4: Systems Thinking Area Results

TEAMWORK AREA RESULTS

This is the ability of a group of people to be committed to a shared purpose and to work together in a spirit of cooperation and mutual support.

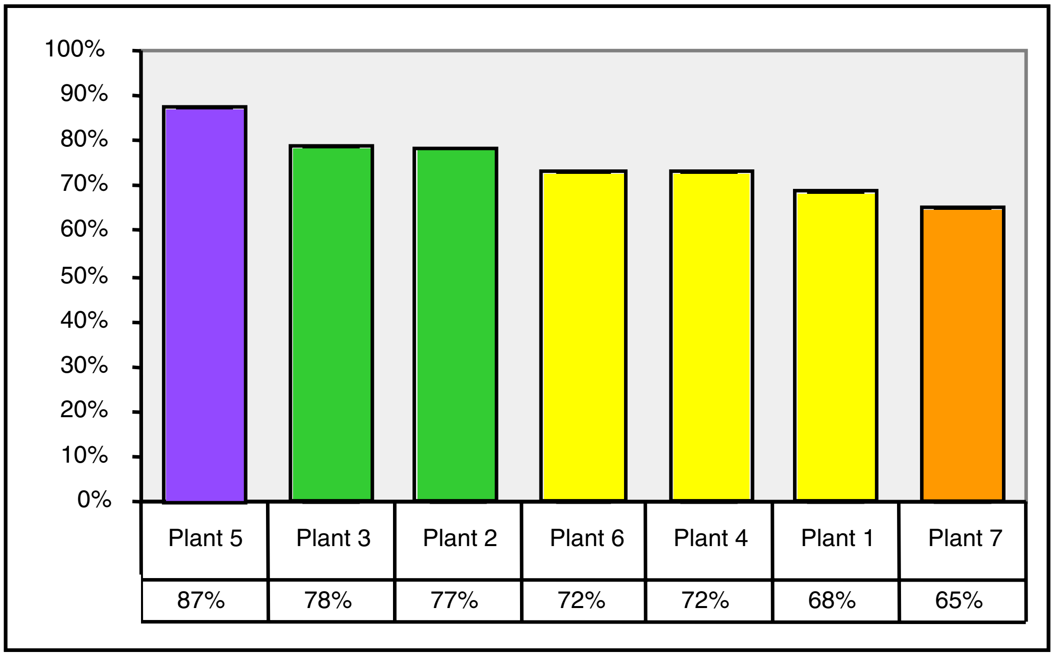

Figure 5: Teamwork Area Results

ORGANIZATIONAL CULTURE AREA RESULTS

The organization's culture consists of an interrelated pattern of attitudes and beliefs that have been established over time. These are reinforced by the symbols, processes, and structure sustained by employees.

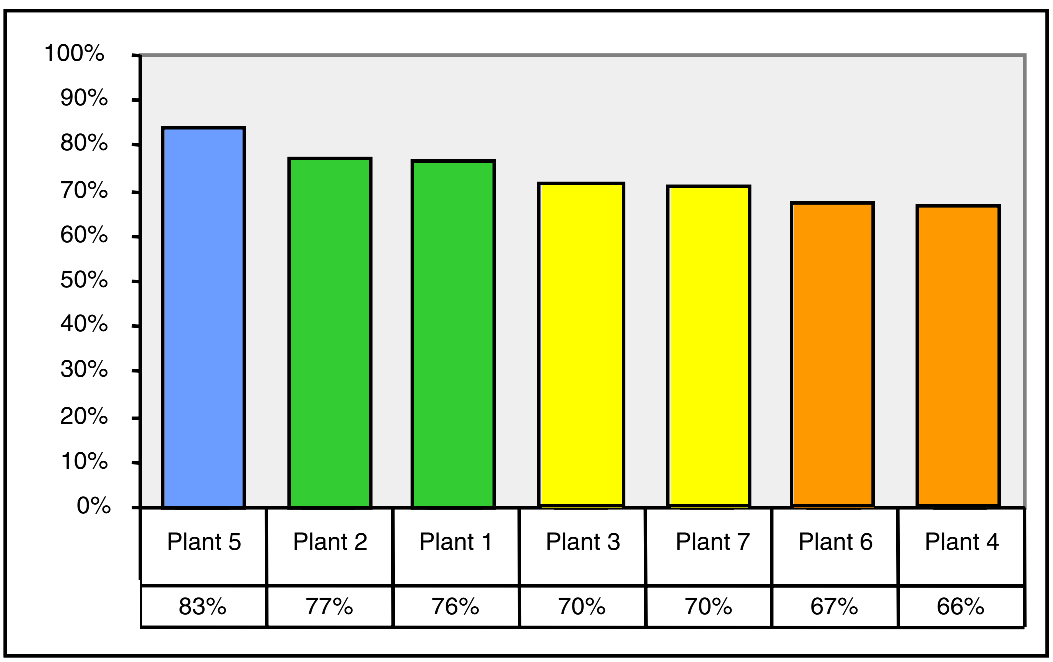

Figure 6: Organizational Culture Area Results

TRACKING CHANGES RESULTING FROM IMPROVEMENT PROJECTS

The value of the Innovation Infrastructure Assessment in tracking changes in factors important to achieving high performance levels is illustrated in Tables 3 and 4. These tables show some of the factors included in the assessment. The changes in the shown in Tables 3 and 4 were calculated from assessments undertaken on improvement projects at the beginning and end of the project. Similar positive results have been obtained in other improvement projects in power generation plants.

Table 3: Project A – Changes in Factor Ratings After Improvement Project

Factor	Change
The readiness of employees to risk doing things a new way	+ 41%
Employee belief that improvement efforts have the ability to really cause positive change	+ 42%
The degree to which the organization takes time to understand the underlying cause of problems rather than the symptoms	+ 54%
The degree to which the organization has driven fear out of the work environment	+ 29%
The level of trust the members of your work group have in your supervisor	+ 39%
The degree to which employees feel proud to work for the plant	+ 59%
The degree to which employees are enthusiastic about being at work	+ 63%

Table 4: Project B – Changes in Factor Ratings After Improvement Project

Factor	Change
The degree to which you are encouraged to take risks and try new things at work	+ 42
Employee belief that improvement efforts have the ability to really cause positive change	+ 32
The degree to which your supervisor's communications are open and sincere	+ 41
The degree to which your supervisor works with your work group to establish the group's goals	+ 41
The degree to which the organization takes time to understand the underlying cause of problems rather than addressing the symptoms	+ 46
The level of trust your supervisor shows in the members of your work group	+ 23
The level of trust between employees at your own level	+ 24
The level of respect your supervisor shows for the members of your work group	+ 27
The degree to which employees are enthusiastic about being at work	+ 35

CONCLUSION

In today's marketplace, the customer is paramount. EPRI's decision to establish a working group of customers to define their high priority needs was the first step in developing resources to help fossil power generation plants improve performance. The next step was a team effort between OLC, EPRI, and utility customers to develop and test resources that help address the priority needs.

The result of this effort was a template (the Innovation Infrastructure Model) that defines the competencies that underlie the achievement of high performance. Along with the template is an assessment methodology that enables organizations to measure and benchmark the levels of these competencies, identify areas where increases in competency levels are most needed, and measure the influence of various improvement initiatives on the competencies needed to achieve high performance levels. The Innovation Infrastructure Assessment has proven to be a valuable tool for many fossil power generation plants by helping them develop and implement improvement strategies that support their strategic goals.

The foundation for achieving high performance levels is the commitment and involvement of employees in improvement activities. Experience gained by the OLC on performance improvement projects has been that the majority of employees would like to participate in improving their organizations. They believe that the success of their organization contributes to society and to their own security. Many employees already have good ideas for improvement, and often feel they have no way to get them implemented. Employees often hold back from involvement in improvement activities, not because they lack the *desire* to change but because they don't believe the change effort will be *successful*.

The factors covered in the Innovation Infrastructure Assessment are ones fossil plant workers have identified as being important to their success. Positive changes in these factors indicate an increase in the belief of employees that their work environment is supportive of their efforts to improve, thus increasing their motivation to participate in improvement efforts.

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APPENDIX A:
SUPPORTERS OF THE EPRI WORK PROCESS AND QUALITY IMPROVEMENT BOARD

Pete Acimovic	United Illuminating Company
Jim Anzinger	IBEW
Henry Avila	Tucson Electric Power Company
Mike Barr	Tucson Electric Power Company
Glade Barton	Sierra Pacific Power Company
Mike Belter	Public Service of Oklahoma
Duane Bledsoe	Salt River Project
Ian Bobbitt	Hoosier Energy
Glenn Brannen	South Carolina Electric & Gas
Gary Brooks	United Illuminating Company
John Buffa	United Illuminating Company
Paul Burdeaux	Central and Southwest Svcs., Inc.
Ron Campbell	Alabama Power Company (Southern Company)
Charles (Buddy) Cole	Nevada Power Company
George Colgan	Tri-State Generation
George Davis	Central Illinois Public Service
Mike Davis	Arkansas Power (Entergy)
Gary Davis	Tucson Electric Power Company
Al DeWeese	San Diego Gas and Electric
Bruce Dyas	New England Electric
David Edmisson	Public Service of Colorado
Earl Evans	Nevada Power Company
Shannon Fitzgerald	Public Service of New Mexico
Albert Flowers	Carolina Power & Light
Elton Floyd	Texas Utilities
Fred Forchtner	Public Service of Colorado
John Ford	Philadelphia Electric Company
Glenn Freeman	Arkansas Power (Entergy)
Jimmy Gonzales	Public Service of New Mexico
Rory Grounds	Kansas City Power & Light
Fred Haller	Potomac Electric Company
Tom Hansen	Tucson Electric Power Company
Rick Harless	Sierra Pacific Power Company
Lee Harrow	Omaha Public Power District
Andy Hoekstra	Tucson Electric Power Company
Bruce Humes	Nevada Power Company
Richard Kolvek	Public Service Company

APPENDIX A (Cont'd.):

SUPPORTERS OF THE EPRI WORK PROCESS AND QUALITY IMPROVEMENT BOARD

Tim Kurtz	Ohio Edison
Mike Laurence	Associated Electric
Dave Leochler	Dairyland Power Cooperative
Mike Long	Central Illinois Public Service
Tom Lovas	Chugach Electric Association
Don Lynch	Jersey Central
Jose Marti	United Illuminating Company
Steve Martin	Indianapolis Power & Light
Jim Mathews	Duke Power
Bob Matthews	Delmarva Power & Light
Danny McMillan	Alabama Power Company (Southern Company)
Joe Miller	Kansas City Power & Light
Mike Moran	South Carolina Electric & Gas
Ed O'Brien	Boston Edison Company
George Pigg	Tennessee Valley Authority
Carl Piper	Nevada Power Company
George Powell	United Illuminating Company
Glen Reeves	Salt River Project
John Rich	Potomac Electric Company
Dave Riley	New England Power
Ronn Rodgers	Salt River Project
Stephanie Roy	Nevada Power Company
Mark Sandoval	Nevada Power Company
Mike Serafin	Ohio Edison
Pete Shead	Arkansas Power (Entergy)
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Bob Wery	Dairyland Power Cooperative
Margaret Zachman	United Power Association

APPENDIX B:

INNOVATION INFRASTRUCTURE MODEL AND COMPONENT DESCRIPTIONS

Introduction

The following are the innovation infrastructure components identified by EPRI WP&QI research as having a large opportunity to improve in ways that would results in higher bottom-line performance. All six components are illustrated in Figure B-1: The Innovation Infrastructure Model.

One of the high priority needs identified by utility leaders who are members of the EPRI WP&QI Advisory Board was for a template which could be used to assess areas important to achieving high performance. The Innovation Infrastructure Model was developed in response to this request. Its development drew on a wide variety of sources, including experience gained at the San José State University Process and Quality Improvement Center.

Description of Innovation Infrastructure Components

1. Shared Vision

   This component involves the ability to achieve a shared vision throughout the organization of the strategic goals and objectives and to develop a shared vision among employees for specific projects or tasks. It also includes the ability to involve employees in the strategic planning process, and gaining an understanding and agreement, within a project team, of what is to be achieved, why it is important and how it will be achieved. An organization that is strong in this area is able to focus its resources on the key objectives that are most important to the organization's long-term success.

2. Process Management

   This component consists of the ability to manage the key processes the organization uses to get work done. It includes the competencies to define and assign ownership of key processes such as strategic planning, new product development and project management. It also includes competencies associated with identifying and defining when process improvement is needed.

3. Process Improvement

   This component involves the ability to analyze and improve the processes the organization uses to get work done. It includes the competencies needed to measure process performance, identify the root causes of problems and undertake cost/benefit analysis to support improvement recommendations. This component includes the following areas:

   Improvement Planning
   The improvement planning process enables organizational members to work together to gain agreement on what needs to be improved, why it is important, and how to make the change.

   Process Improvement
   Process improvement enables the organization to understand and analyze its work processes, and identify the sub-processes within the overall system upon which to focus the change efforts. It also involves determining what changes need to be made to a process area and implementing the improvements.

APPENDIX B (Cont'd.):

INNOVATION INFRASTRUCTURE MODEL AND COMPONENT DESCRIPTIONS

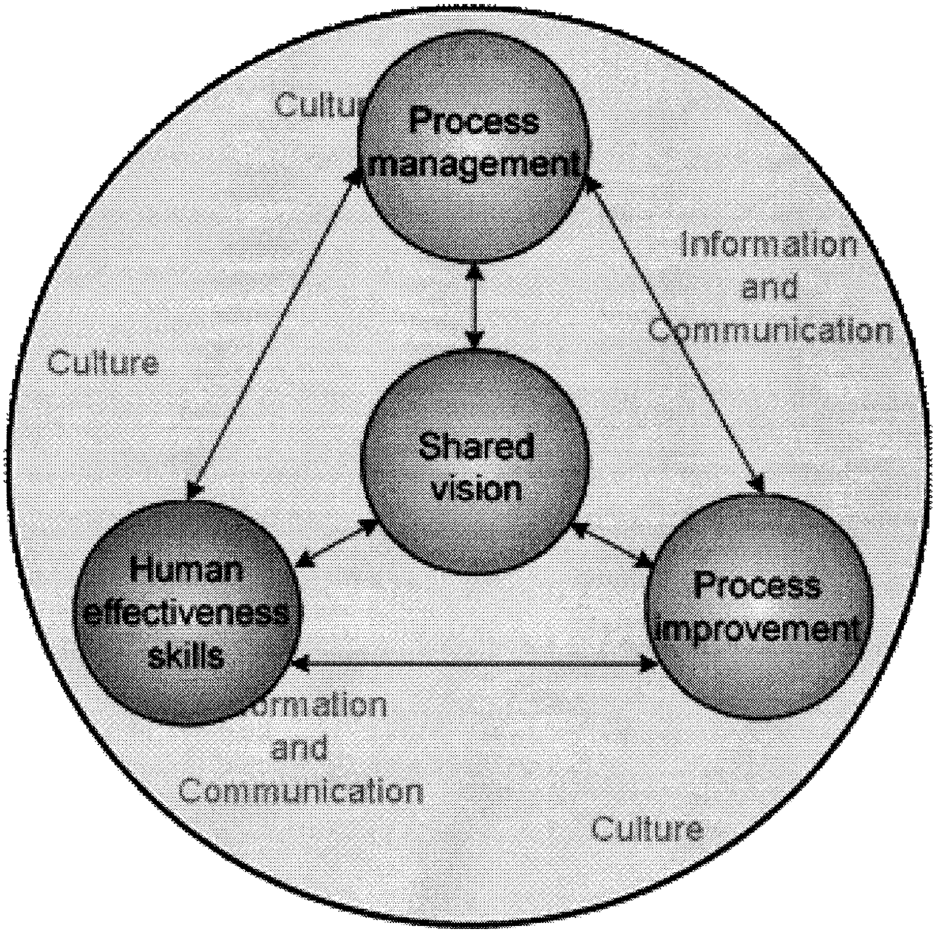

Figure B-1: Innovation Infrastructure Model

Organizational Learning
The organizational learning process involves undertaking activities to encourage individual learning and team learning, particularly as they pertain to making improvements in the organization's improvement skills, culture, and human skills.

Nurturing the Organizational Climate
This process enables the organization to develop the culture needed to support improvement and learning. It involves establishing the values and principles the organization needs to support long-term success. It also involves organizational leaders and members visibly supporting these values and principles.

Measurement and Assessment
This process provides the organization with the capability to measure how well customer needs are being met (both internal and external), identify high-leverage improvement opportunities, make decisions on improvement objectives, and track changes in performance.

APPENDIX B (Cont'd.):

INNOVATION INFRASTRUCTURE MODEL AND COMPONENT DESCRIPTIONS

4. Human Effectiveness Skills

   This component involves human competencies important to achieving innovation. It includes the competencies in leadership and teamwork necessary to understand and solve problems, and competencies in customer focus, systems thinking and change readiness to support the achievement of innovations that benefit the organization as a whole. This component includes the following areas:

   Change Readiness
   This is the ability and openness of an organization and its members to change the existing practices and processes to be fully responsive to both the needs of internal and external customers and to changes in the business environment.

   Leadership
   This is the ability to influence and guide people by means of communication and example to establish and achieve a shared purpose.

   Customer Focus
   This is the ability to recognize the paramount position of the organization's customers and the nature and importance of the chain of customers and suppliers who, by taking care of each other, provide high quality at low cost to these external customers.

   Systems Thinking
   This is the ability of the organization's members and groups to understand the way their various work activities are interconnected with the activities of others to form the processes that provide value to customers. It also includes the ability to understand the impact of one's actions on the rest of the organization.

   Teamwork
   This is the ability of a group of people to be committed to a shared purpose and to work together in a spirit of cooperation and mutual support.

5. Information and Communication

   In a competitive and dynamic marketplace, the ability to communicate the right information to the right people at the right time is a key factor in achieving optimum performance levels. This component influences daily operations as well as innovation. It involves the communication of information to support daily work, and the interpersonal communications between employees that support problem-solving and decision-making. It includes a broad spectrum of information and communication processes that enable organizational members to understand the organization's purpose and any changes, internal or external to the organization, that could influence day-to-day operations and long-term strategy and plans.

INNOVATION INFRASTRUCTURE MODEL AND COMPONENT DESCRIPTIONS

6. Organizational Culture

   The organization's culture consists of an interrelated pattern of attitudes and beliefs that have been established over time. These are reinforced by the symbols, processes, and structures sustained by all employees. The organization's culture strongly influences the way in which organizational members behave. Culture can make a significant difference to the organization's ability to adapt to take advantage of new opportunities in the marketplace, and therefore direct influences the organization's performance. The components of organizational culture included in the Innovation Infrastructure Model are trust, respect, enthusiasm, commitment, pride, cooperation, and security.

Distributed knowledge based maintenance assistance for nuclear power plant components

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Abstract

This paper presents developments which have been undertaken to provide plant operators with automated maintenance assistance. This assistance relies on services which were applied for diagnosis and predictive maintenance for components such as reactor coolant pumps, turbine-generators. Services range from reference knowledge browsing to health assessment and diagnosis ; there are available as web intranet services ; this services are implemented using the eKCM environment (eKnowledge for Competitive Maintenance). eKCM is a Java servlet based tool jointly developed by EDF and DECAN.
This article focuses on some significant operational examples. It describes the way the system can be integrated in maintenance activities and associated expected benefits. The article expose the methodology used to efficiently manage expert knowledge and develop adapted operational tools.

Keywords

knowledge management, rapid prototyping, automated decision assistance, telecooperation, energy, diagnostic, maintenance, information systems

1. Introduction

Preservation of technical expertise and its availability to local operators is a key challenge for a large electricity generating company such as Electricité de France. Past experience in diagnostic expert systems and a study of requirements for efficient preservation and access to expert knowledge, together with reflections on how to enhance reusability of proven techniques in order to enhance consistency and reduce development costs, yielded to the development of an industrial software framework, called eKCM (e-Knowledge for Competitive Maintenance) and an accompanying method.
The method relies on the definition (or reuse) of models which enforce knowledge structuring and of rapid prototyping in order to have an efficient support for knowledge acquisition and validation.
Paragraph 2 of this presentation describes the main requirements for the development of eKCM and the corresponding architectural choices.
Paragraph 3 explains our methodology for technical knowledge management application development and how eKCM is used within this methodology.
Paragraph 4 describes some operational applications that use the eKCM framework.

2. eKCM framework

2.1. Identification of operational needs in maintenance for nuclear power plant components

Electricité de France (EDF) sees preservation of expert know-how as a major issue, especially in the field of nuclear power plant maintenance. This can be related to a growing interest in corporate knowledge management.
Furthermore, in the past fifteen years a significant amount of work has been devoted to the development of knowledge-based systems for diagnostic and maintenance support of plant components[2], [3].
During this period, various and numerous needs have emerged from operational equipment maintenance as performed at EDF ; among them :

- update diagnostic handbooks according to experimental feedback,

- access a description of monitoring equipment that would allow detection of a given fault on an equipment,
- when an incident occurs, identify measures and information to acquire on a plant to improve diagnostic efficiency,
- provide an automated assistance for complex diagnoses…

All these needs are based on the exploitation of diagnostic and maintenance knowledge mastered during the past years by EDF operational experts.

More precisely, field maintenance of large power plant components (such as reactor coolant pumps, turbine…) requires specific technical know-how and expertise. Expertise is gained from studies and experience by a limited number of specialists. Noteworthy consequences of this statement include the following facts:

1. specialists are not available in every plant at all the time ;
2. application of this expertise is needed locally in the plant, in ways that are most useful for maintenance operators ;
3. this expertise is a strategic asset for an electricity generation company ;
4. this expertise improves as feed-back experience is gained by experts ;
5. although each type of equipment has specific features, generic approaches can be observed (e.g. fault diagnosis from observed malfunctions always follows a similar pattern).

These observations and the objective of improving efficiency and homogeneity in dealing with that type of problem has been the incentive to undertake a project with the main goal of designing a *unified framework for diagnostic and maintenance knowledge management*.

One of the key results of this project is the development of a software environment called eKCM. This environment was jointly developed with DECAN software company[1].

This framework relies on the following basic principles:

- knowledge capitalization cannot be restricted to the sole aim of preserving expert know-how, but should also provide means to generate gains from capitalized knowledge. Hence, this knowledge management tool must contain features allowing the operation of knowledge;
- as shown by many research and applied works [1] and by our experience in development of diagnostic knowledge-based systems, an efficient way to acquire, manage and reuse expert knowledge is to focus on model-based representations, relying on utilization of generic models, whenever suitable;
- together with its knowledge acquisition and representation capabilities, this framework must also provide experts and end-users with software modules implementing various operational services : automated diagnosis for effective control and maintenance decision support, knowledge validation, production of handbooks for end-users, and expert training;
- the framework should rely on a very modular structure, in order to allow easy implementation of new types of models and operational services

2.2. Overview of eKCM

A. General overview

Our past experience was synthesized in 1997-1998 in an internal prototype called Dialog [4]. Lessons learned from this prototype and analysis of end-users needs led to set up the following requirements for eKCM :

- efficient acquisition and preservation of existing expert knowledge esp. in the field of diagnosis and maintenance of power plant equipment ;
- ability to derive various ways of using expert knowledge depending on field requirements (textbooks, software tools, decision trees, etc.) ;
- facilitate reuse of previously developed methods and their application to various pieces of equipment ;
- easy tool deployment ;
- easy update of encompassed knowledge ;
- reliance on state-of-the-art software solutions
- avoidance of strong dependencies towards proprietary "black-box" software environment.

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[1] DECAN's property rights and know-how towards eKCM has recently been transferred to a new company called eKCS.

eKCM enables the representation of expert knowledge and supports its acquisition by means of generic models, *and* provides experts and end-users with software modules implementing various operational services: automatic diagnosis for effective control and maintenance decision support, knowledge validation, production of handbooks for end-users, and expert training.
eKCM includes the following functions :

- generic representation structures which allow formalizing operational knowledge ;
- "services", using this knowledge in order to provide operation assistance
- access to non-formalized knowledge (photos, documents…) or external databases

Services can range from basic knowledge browsing and visualization to automated document generation or specific algorithms (e.g. automated diagnosis).
eKCM-based applications are available through a standard Web server (i.e. accessible via an Intranet or Internet).

B. Modelisation and operationalisation of the capitalized expert knowledge

All knowledge relative to a component (turbine generator, turbine, reactor coolant pumps, etc.) or to an application field are grouped together in a « knowledge base ». Each knowledge base regroups a set of models, each model giving a point of view on the material (its functional decomposition, its known dysfunctions, the pieces of information relative to its monitoring, etc.). This way of decomposing a global and complex system using multiple « point of views » is aimed at limiting the complexity of each model so that it can be easily understood, validated and used (it is a way to avoid computational problems). On the other hand, dealing with several models for a given component (or application domain) allows to represent its multiple facets and reflects the different ways it can be seen by experts.
An operational eKCM model is easily and directly derived from the structural description of the domain knowledge : once the domain is described as a set of concepts and relations, it can be implemented in an eKCM model.
The diagnostic and maintenance applications already addressed have given us the opportunity to define a set of models. These existing models, which are now part of our model library, can be re-used in other application when relevant for describing a facet of the problem. In fact, model re-usability range from total to partial re-usability provided the adequacy of the existing model to the studied domain. As models are easily re-usable or adaptable, the first step of our methodology for conceiving - and developing - a new knowledge management application is to analyze the addressed domain ontology to find the existing models that could be re-used. This is a way to make new development easier and to benefit from validated and tested existing representational structures.
In the eKCM environment, a « service » is an operational function that manipulates knowledge ; a service performs a specific task for a set of identified - and autorised - users. As a service operates on capitalized knowledge, it can makes hypothesis about its structure ; thus a service is dedicated to relavant models.
A service is implemented in a specific and well identified software component.
Re-usability of the existing « service », combined to the (relevant associated) model re-usability, allows rapid prototyping and generate savings of time, money and software reliability.

There are two types of services :

- « general purpose services » that make no hypothesis about the models the operate on, and which are applicable to all kind of models ;
- « specific services » that make hypothesis about the models they manipulate and which are only relevant for one or several specific models.

One set of models combined with the appropriate services is enough to construct a knowledge management tool allowing domain knowledge acquisition, structuration and operationalisation in a given application field and for a given purpose.
For example, a fault model - that enables representation of possible faults for an equipment and their manifestations) combined with diagnostic dedicated services (such as a diagnostic table generator or an automated interactive diagnosis service) constitute an eKCM « domain module » for diagnostic applications. As we can define several different « domain module », we are able to easily generate different eKCM derived tools, each of whom being dedicated to a specific domain (and to its special associated needs).
The three following points : formal modelisation, problem decomposition based on multiple model description (to limit model complexity and allow model understanding and validating), validated model and service re-usability, constitute a major advance in our way to deal with knowledge management applications.

C. Architecture

The eKCM tool runs under an intranet server (a standard HTTP commercial server compatible with **Java servlets**) to which users can connect via a web browser (Netscape, Internet Explorer…). The end users can navigate through the eKCM available models and services like they do with standard web services ; so they can use the well-known exchange functions (copy, cut and paste functions, etc.) to export knowledge or results producted by the services to their standard word-processing, database or spreadsheet softwares.
For application that need highly interactive user interface, the « light » client (the web browser) can be replaced by an autonomous client application written in JAVA which allow complex and dynamic interface functions ; the global architecture of the eKCM-derived application remains the same.
A synthetic description of the eKCM architecure is given in the following figure.

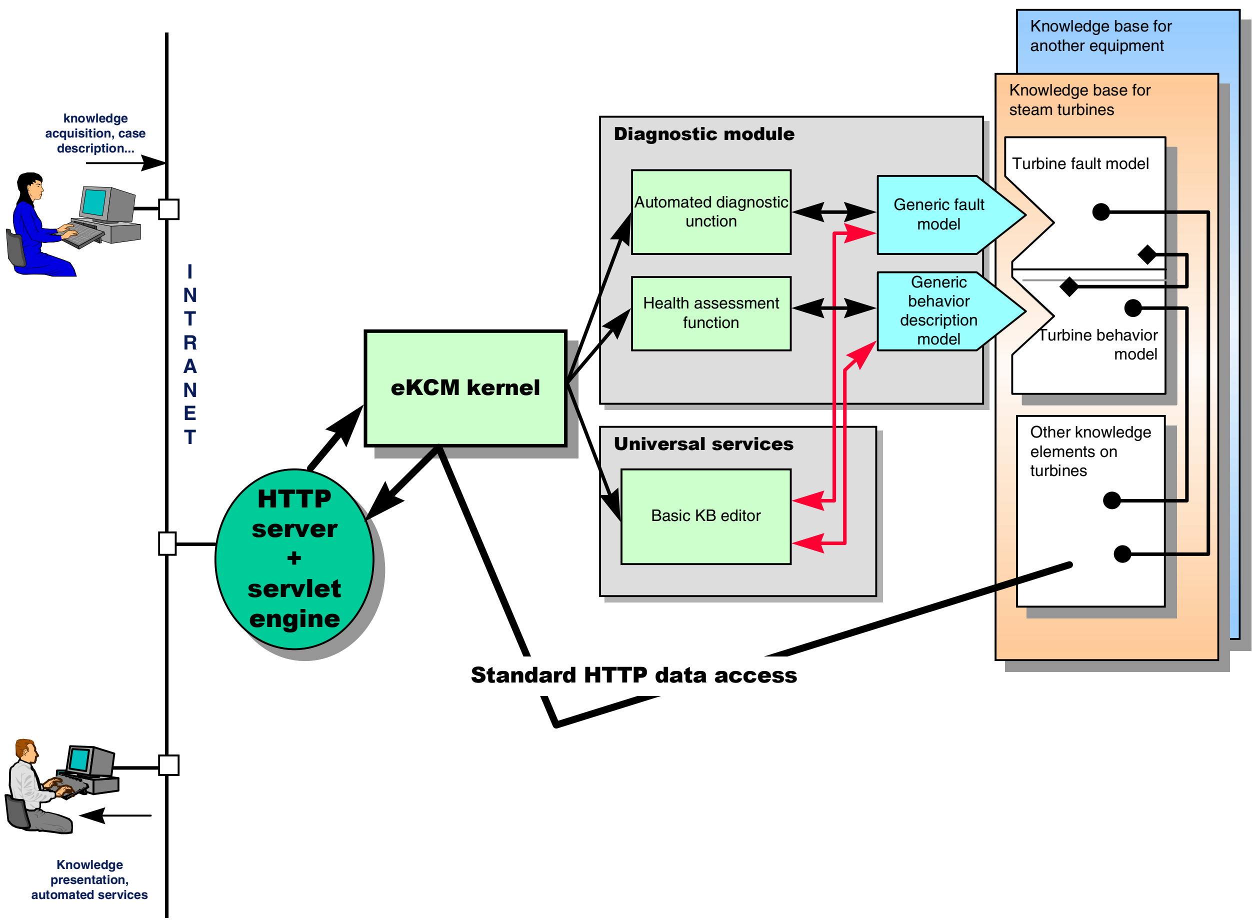

Figure 1 : the eKCM intranet knowledge server architecture

NB : the mentioned models and services are only used to illustrate the eKCM architecture ; there are many other available models and services in the present eKCM version.

A description closer to modular design of eKCM can be presented in figure 2. It shows the main blocks of this framework.

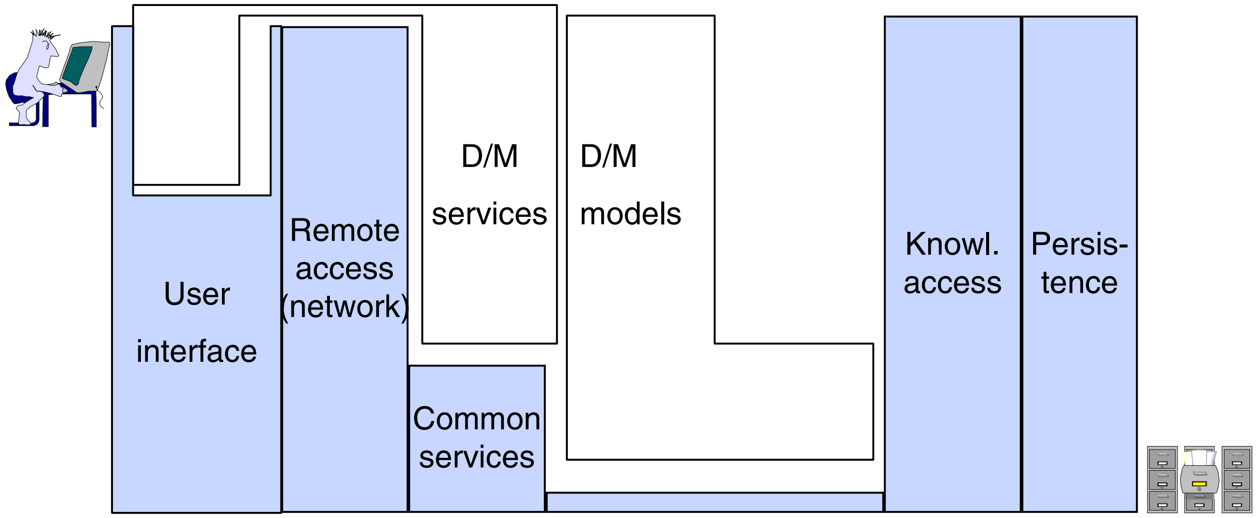

Figure 2 : General overview of the eKCM environment

Plain grey modules are the one that are included in the generic environment. Textured blocks represent application specific modules (D/M stands for "diagnosis and maintenance"). The following table exposes technical choices for implementation of these modules.

Module	Function	Choice
Persistence	Read/write knowledge on persistent storage devices	**XML** files or **relational DB** (ORACLE, ACCESS…)
Repository	Manage application access to knowledge (locks, concurrent access…)	Software modules in **Java**
Knowledge representation	Put knowledge in a form which can be understood by services	Sets of **Java** classes, matching some writing requirements
Knowledge operation (services)	Implement functions that are used by application end-users	Services, implemented through **Java** classes matching some writing requirements
Network access management	Allow service access and operation from a remote user machine	**HTTP** (commercial server) and communication filtering through **Java servlets**
User interface	Present the user with displays enabling him/her to use the application	**HTML + Javascript** and (scarcely) **JAVA Applets**. The user needs a Web Browser (Netscape, IE…) Possible autonomous client application written in **Java**

Table 1 : eKCM implementation choices

3. Knowledge modeling methodology and use of eKCM

The kind of technical knowledge management and operational application described here relies on a methodological approach that we implement on our new projects. This method relies on the cooperation of two skills:

- knowledge engineering,
- tool specification and development.

These two skills should not be seen as independant or separated; on the contrary, efficiency is a result of their close cooperation, especially in the beginning of a project. The use of eKCM facilitates this cooperation and efficiency: rapid prototyping for knowledge validation, using models as a key point in application software design, consistency between knowledge representation structure and their usage…

A key point in this method (which appears in the diagram) is the fundamental role played by the modeling activity, viz. the design (or reuse) of generic structures and relations that will be used to acquire and represent knowledge. Another key point is the central role of a prototyping activity for which eKCM is a time-saving and efficient framework. This rapid prototyping allows:

- when the ultimate goal is the development of a software tool, to validate specifications, check feasibility,
- when the final software environment is close to eKCM fundamental choices, to serve as a basis for industrial development,
- in every case (even when final results do not include a software tool), to help manage knowledge acquisition, tracing, and to maintain and preserve resulting knowledge bases.

Prototypes are also useful to concretely show to end-users and managers what knowledge management can bring to a project.

The figure below displays a block diagram of these activities. The following table outlines the main activities and corresponding benefits brought by eKCM.

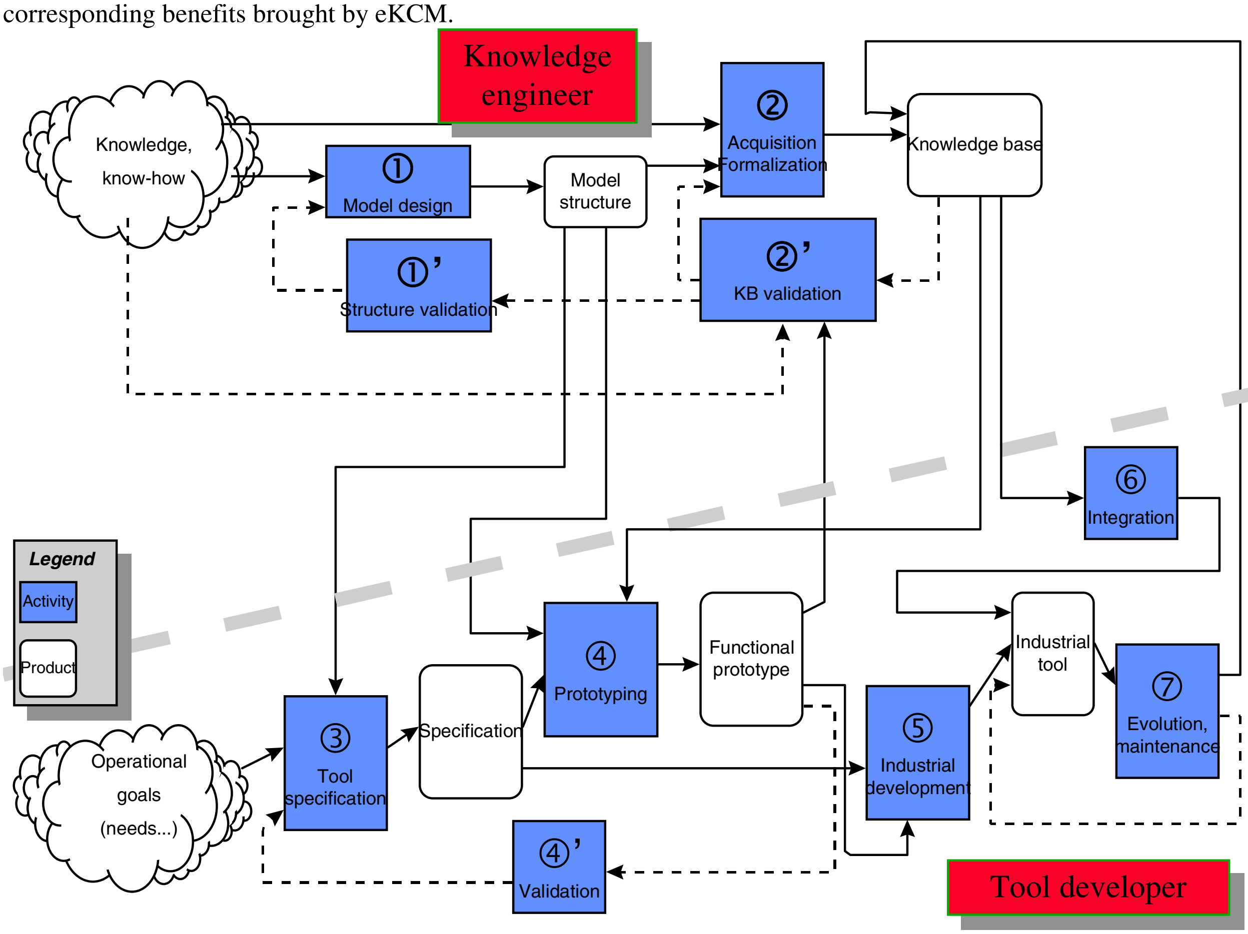

Figure 3 : eKCM-based knowledge modeling activity

Activity	Contents	What eKCM can bring
1 Modeling	Identify relevant structures for efficient knowledge representation	Existence of already developed, reusable and expandable models. Framework for design of new models.
1/2 "Modeling/ Acquisition/ Modeling" cycle	Validation of proposed models by confronting them with knowledge collected from experts. Failures when building the knowledge base might induce modifications of the model.	eKCM enable easy display and output of entered knowledge bases. Prospective modeling structures can be tried out and modified.
2 Knowledge acquisition	Fill in models by translating expert knowledge into the structures that models define. A model can be seen as a specification of the knowledge to be acquired.	Tool for storage of acquired knowledge elements. Ability to trace evolution of knowledge with time. Immediate exploitation of knowledge for prototyping or industrial software development.
3 Software specification	Specify knowledge presentation and exploitation solutions wrt. operational requirements.	Provides a basic structure for a distributed knowledge handling application which must be confronted to actual requirements.
4 Prototyping	Design a working prototype to check feasibility, interest and adaptation to requirements.	Industrial development framework with built-in basic knowledge management functions. Only application specific functions need to be coded.
4/2 Knowledge validation through rapid prototyping.	Rapid design of a prototype, filling of the knowledge base and use of the prototype to check validity of the knowledge base.	eKCM allows to quickly build operational software elements to present and process modeled knowledge. These functions can be presented to experts to allow them to visualize the validity of knowledge translated into models.
5 Industrial software development	Design and code an industrial software tool using relevant knowledge management functions and accessing validated knowledge bases.	Industrial environment for integration of knowledge management functions in an Intranet environment. Time saving through reuse of generic functions and data structures, allowing focus on specific parts of an application. Possible incremental coding from an existing prototype (activity #4)
7 Evolution and maintenance of industrial tools	Maintain a software knowledge management tool in operation	Maintenance of eKCM kernel can be shared between several applications that use it.

Table 2 : KM activities & eKCM features

Due to its flexibility and to its modularity, eKCM constitute a perfect tool to develop new knowledge management applications (building solutions matching new needs or new types of knowledge).
In fact, as it the case for models and services, each eKCM software component can be re-used (directly or after modifications) to build a new server.

4. Automated maintenance assistance based on eKCM

eKCM has been used for several internal project in EDF. Here are presented the most significant features of some of these applications.

4.1. Reusable models and services in eKCM "basic" version

In its current state, eKCM provides different models and services which have been specified and build from experience in past developments. These elements are shown in the following tables:

Model	Description	Main types of knwoledge	Use
Associative fault model	**This model enable representation of possible faults for an equipment and their manifestations**	Faults, symptoms, occurence contexts…	DIAPO (Coolant pump diagnosis)
Health assessment model	**This model allows representation of conditions on monitoring data which expose a possible internal degradation of a part of an equipment**	Equipment components, symptoms, monitoring parameters…	Coolant pump condition maintenance
Prototypical fault model	**This model allows the representation of abnormal situations which can be the result of a fault in the equipment**	Abnormal situations, symptoms, faults, monitoring parameters	DIVA (turbine diagnosis)
FMEA model	**This model allows to bind a material decomposition to failure modes and to associated information : blueprints, experimental feedback, gravity…**	Material decomposition (from equipment to components), associated faults, failure laws, diagrams, past cases…	Coolant pump condition maintenance

Table 3 : Available eKCM models

Service	Description	Applicable to models
FMEA walkthrough	This is a navigation service dedicated to the FMEA model. It is based on a specific filtering based on the type of knowledge. It makes visualisation of information attached to different components easier.	FMEA model
Fault form generation	From an associative model, the service established text forms presenting faults and symptoms in a structured way. Outputs can be displayed in the browser or sent to a MS-Word RTF document.	Associative fault model
Diagnostic table generation	From an associative model, the service automatically generates an array symptoms vs. faults. This array can be filled interactively to screen possible and excluded faults given observed symptoms.	Associative fault model
Interactive diagnosis	Through queries to the user, the system establishes a diagnosis, via a set of faults which can be a explanation of observed symptoms (the basis for this algorithm can be found in [5], [6]).	Associative and prototypical fault models
Equipment health assessment	Through queries to the user who fills in monitoring data, the system gives estimates on the current state of main parts of a complex equipment (satisfactory, dubious, abnormal).	Health assessment model

Table 4 : Available eKCM specific services

A quick look at these modules shows that eKCM holds a rather complete set of elements to build diagnostic and maintenance applications for large monitored pieces of equipment. This can be achieved by a relevant selection of models and services together with an adjustment of the user interface. Of course, when dealing with a new material, the specific knowledge base hase to be filled.

4.2. The Reactor Coolant Pumps Condition-based Maintenance (RCPCM) Tool

The aim of condition-based maintenance is to reduce maintenance costs by optimizing maintenance inspections according to the real state of a component. To do so, we must provide the user with a tool that assist him in assessing the feasibility of deferring a BPMP (the Basic Preventive Maintenance Program) scheduled inspection by drawing up a health assessment of the considered component.

EKCM has been used to develop a distributed software tool for condition-based maintenance of the reactor coolant pumps.
The RCP condition-based maintenance tool is aimed at capitalizing knowledge related to the degradation and, more specifically, at providing the following services to the maintenance operators :

- access, in an exploitable form, to several information relevant to the activities associated with condition-based maintenance (FMECA, experience feedback, etc.);
- the drawing up of a RCP “health assessment” on an operating cycle on the basis of operating data (leakage flow rate from the seals, temperature of the bearings, vibrations),
- a diagnosis support facility (DIAPO) [2], [3] making it possible, in the event of the health assessment detecting an anomaly, to search for the fault behind the anomaly;
- different support facilities based on a reliability analysis of the pump's different components (in particular, joints and bearings), making it possible, before a shutdown or inspection, to assess the impact of the different maintenance scenarios with respect to maintenance costs and availability of the unit.

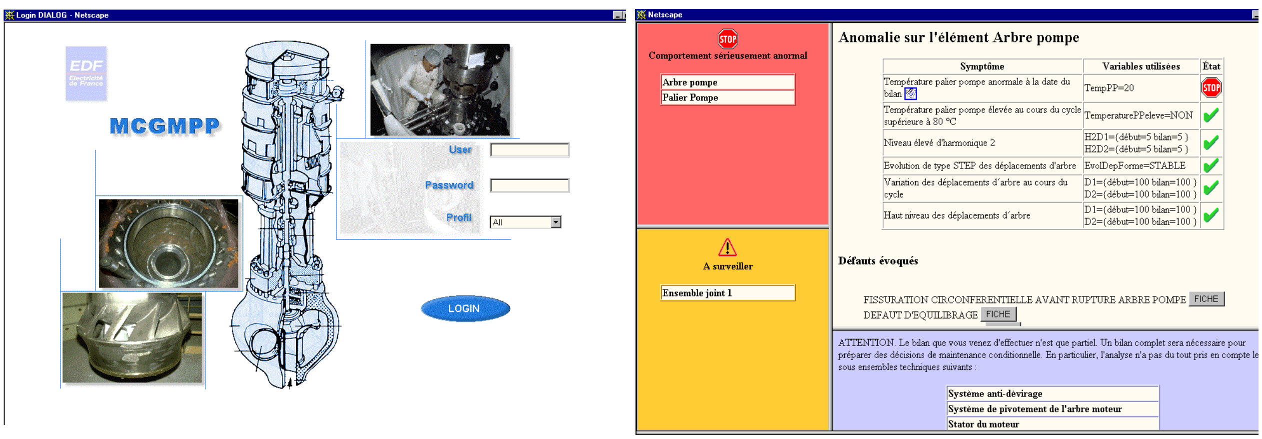

Figure n° 4: Health assessment service

The deployment of the eKCM-based RCPCM tool is currently being held.

4.3. The industrial version of DIVA, a knowledge-based system for turbine failure diagnosis

DIVA is a knowledge base expert system dedicated to turbine failure diagnosis [3]. The previous version of DIVA, issued in 1995, has allowed to validate the diagnostic algorithm and the associated knowledge base. However, it has been developed in a proprietary (now unsupported) environment and needs a UNIX autonomous machine to be run ; thus, each potential user needs to have it installed on a dedicated UNIX machine, which is very complex and expensive. More over, the management of the knowledge base is a key issue as there are as many bases as there are installed version of the software. Another difficulty stands in the fact that the current version has not been optimized for a client-server use.

For all these reasons, we have decided to port DIVA to the eKCM environment to improve its maintenance and its deployment. DIVA is now accessible as a "traditional" web service via our corporate intranet.

4.4. Other applications

In many internal projects, eKCM has been used as a rapid prototyping tool to quickly validate suggested solutions. For example, we have recently used eKCM to develop the « Monitoring Techniques Catalogue », a knowledge management tool which allows the capitalization and the share of useful pieces of information relative to the monitoring techniques and tools relevant for a set of components.

We also use eKCM - and the associated knowledge modeling methodology - to address other domain problems ; we actually use our methodology in the fields of risk management and nuclear power plant decommissioning.

5. Conclusion and future works

Various diagnostic and maintenance knowledge bases and services have been developed or ported in the eKCM environment.
Basically, benefits from eKCM include making time-saving knowledge-based aids in diagnosis and maintenance easily available to power plant specialists, helping in the tutoring of experts-to-be, improving productivity in diagnostic and maintenance knowledge acquisition and management, and in the development of new diagnostic and maintenance services and applications.
eKCM-based solutions have been economically competitive with respect to alternate technical choices when comparing tenders for various industrial application developments.
Development of eKCM amounted to about 750 000 Euro and can be considered as being paid off by 2002.
Main benefits of using the eKCM environment as a supporting tool for knowledge-based tool development and knowledge management projects can be summarized in the following table:

Uses of eKCM	Description	Main benefits
Develop an eKCM-based knowledge server.	Access to services on knowledge bases stored on a server. This is the "standard" use of eKCM.	Flexible access to up-to-date centralized expert knowledge on a device through end-user oriented services.
Use eKCM as a support tool for knowledge capitalization.	Use eKCM knowledge base editors to enter structured knowledge and diagnostic and delivery services as validation tools.	Use proven models as a basis for knowledge modeling and acquisition. Use existing services to check and validate knowledge.
Use eKCM as an environment in which a new operational service is designed and implemented	Add a new service to eKCM (either generic or applicable to specific models).	Reuse a validated architecture. Focus on application specific functional requirements.
Use eKCM as an environment in which a standalone application is prototyped	Use eKCM models and services as the basis for functional specifications and as a test bench for application validation.	Focus on application specific functional requirements. Test the final application by comparison with eKCM.
Reuse software components from eKCM libraries.	Use software modules of eKCM (e.g. knowledge storage and access, model management…) to alleviate development of a new software architecture.	Only develop specific modules. Benefit from already validated parts. Reduce application maintenance costs.

Table 5 : Benefits of using eKCM

By allowing easy reuse of advanced knowledge modeling and processing elements together with the ease of deployment provided by its reliance on a standard Web server, eKCM appears as a fruitful tool for knowledge capitalization and management in the field of diagnostic and maintenance of power plants components, providing advanced services for automatic diagnosis, expert training support, supervised knowledge validation, production and update of documents for plant operators.

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The EPRI Preventive Maintenance Database

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Abstract

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

1 EPRI Preventive Maintenance Basis

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

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

1.1 Published PM Basis Reports

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

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

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

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

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

The technical experts were charged with recommending the best technically justifiable PM programs, not necessarily the programs which already existed in their plants. The technical justification had to be at the level of equipment failure mechanisms, sufficient to enable translation to different plant conditions, and with additional input, to variants of the generic equipment types. For each component type, the PM recommendations cover critical applications (i.e.

those which provide extremely important safety or generation functions), as well non-critical applications (i.e. those which do not provide extremely important functions but which nevertheless require some level of PM protection). The recommendations also cover high and low duty cycles, and severe and mild service conditions.

Data for each component type consists of:

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

Much of this information is to be found in tabular form as shown in Figures 1 and 2.

1.2 Access 97 Database

An electronic database is available which contains essentially all the data in the published reports. This enables the user to display and query the information on a Microsoft Access platform using Windows 98 or Windows NT. The Access database is obtainable on CD as EPRI Product Number 1001447, under license, from the EPRI Program Manager, Martin Bridges (704-547-6175). The User Manual is available as EPRI Product Number 1001448, May 2000. The main advantages of the electronic database are that, 1) it enables users to apply data filters to distinguish, e.g. all the degradation mechanisms which are not addressed by any combination of PM tasks, and 2) it contains a hyperlinked Application Guideline.

1.3 Application Guideline

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

The seven decision areas covered by the Application Guideline are:

1. PM Task Evaluation – Do you have the right task(s) – either as part of a PM program optimization or for a single task?
2. Task Interval Evaluation – Are the tasks being done at the right intervals?

3. PM Assessment – Make a quick assessment of how your PM tasks and intervals compare with the database recommendations.
4. Evaluation Of As-Found Condition - How to use as-found condition data to adjust PM tasks and intervals.
5. Task Deferral – Justify a one-time task deferral, and place limits on the duration of a task deferral.
6. Cause Evaluation – Use the database to support cause evaluation.
7. Predictive Maintenance Enhancement – Develop and justify increased usage of predictive PM tasks.

1.4 PMIR Web Site

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

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

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

2 Technical Aspects Of The Data

2.1 Degradation and PM Strategies

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

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

Battery Plates:

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

2.2 Degradation Progression And Failure Timing

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

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

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

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

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

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

2.3 Common Degradation Mechanisms

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

2.4 Task Effectiveness

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

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

2.5 Template

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

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

		1	2	3	4	5	6	7	8
Critical	**Yes**	**X**	**X**	**X**	**X**				
	*** No**					**X**	**X**	**X**	**X**
Duty Cycle	**High**	**X**		**X**		**X**		**X**	
	Low		**X**		**X**		**X**		**X**
Service Condition	**Severe**	**X**	**X**			**X**	**X**		
	Mild			**X**	**X**			**X**	**X**
PM Task									
Battery Monitoring		NA	1M	NA	1M	NA	3M	NA	3M
Cell Inspection		NA	3M	NA	3M	NA	3M	NA	3 M
Detailed Inspection		NA	1Y	NA	1Y	NA	1Y	NA	1Y
Battery Capacity Test		NA	5Y	NA	5Y	NA	5Y	NA	5Y
Battery Service Test		NA	NR	NA	2Y	NA	NR	NA	NR

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

3 Applications Of The PM Basis Database

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

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

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

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

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

3.1 PM Assessments

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

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

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

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

Figure 3 Completed Data Form For A PM Assessment

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

3.2 Developing a Plant PM Basis

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

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

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

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

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

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

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

3.3 Information On Equipment Condition

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

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

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

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

4 Status and Conclusions

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

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

Future potential enhancements might include:

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

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

MANUFACTURING'S HIGH-TECH REVOLUTION

Through the adoption of a standard communication protocol, software for the manufacturing industry will bring it into the 21st century.

by Pak Wong, Software Development Manager, PdMA Corp.

It's late on a Friday afternoon. You just got an email from your boss' boss that he's impressed with the predictive maintenance program you have implemented at the plant. By combining the technologies of vibration, infrared, electric motor analysis and ultrasonics, you've been able to spot possible motor failures and diagnose problems, saving the company many financial and production headaches.

As you walk to your car, your pager goes off. You recognize the code. The automated monitoring system on one of your remote critical motors has detected an alarm condition, one that could result in motor failure and lost production.

Not long ago, you would have had to return to your office, load up your motor testing equipment, strap on a tool belt and call your spouse to say that you won't be home for dinner.

Instead, you pull your palm computer out of your shirt pocket and view the affected motor's electrical information, which was collected, saved and routed to a desktop computer in the maintenance office. You run another electrical test remotely. The data, collected and analyzed by the permanent equipment on the motor, is sent back to your palm computer. You review the results and compare them to the previous alarm data, then retrieve the maintenance history of the motor, cross check it against the motor's vibration data and correlate the information. You send a work order request, the Condition Maintenance Management Software (CMMS) generates the work order and notifies the resource planning system, which adjusts the production schedule accordingly.

Finally, you continue on to your car and perhaps, take your family out to dinner.

Sound like a dream? It's actually a reality in the process of becoming mainstream.

The future is right around the corner.

For years, most proprietary systems have occupied their own data islands, making it difficult to share information between the different applications. In an effort to improve productivity, very large companies invested huge amounts of capital, hoping to integrate their business and streamline operations. Maintenance systems, however, were seldom considered in these plans and were often excluded from integration all together.

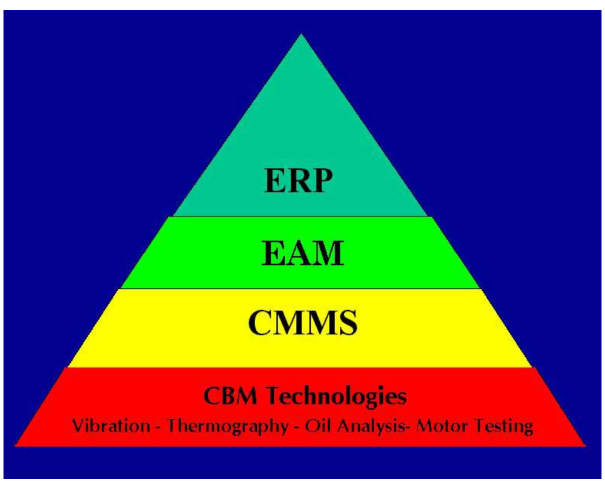
There are many Enterprise Resource Planning (ERP) applications available to help businesses handle product fulfillment, logistic and resource allocations. However, without critical information from the maintenance systems, unexpected machinery failures result in serious down time. With more ERP applications linked to electronic commerce businesses for "make to order" services, the reliability of the machinery is

alarmingly critical. If an ERP were integrated with the Condition Based Monitoring (CBM) and maintenance systems, then the ERP would be advised at the first sign of equipment trouble. Thus, the production schedule, logistics and resource allocations could be adjusted accordingly.
The Internet, emerging standards, wireless devices, broadband technologies, new business models and high customer expectations are forcing individual applications to work together to improve productivity and remain competitive.

Addressing the integration and automation of the manufacturing industry.

In the predictive maintenance world, vendors specialize in individual technologies with no single system able to provide every requested technology. In some cases, in their attempt to provide solutions for their clients, vendors end up venturing into areas they are not familiar with. CBM vendors try to develop their own maintenance modules, CMMS vendors try to diagnose the problems from imported data and ERP applications attempt to manage maintenance activities. To make matters worse, since few of the systems share data, duplicated information is stored in different systems. If one of the systems changes the data, the other systems with the same data must be updated as well. This can be chaotic for the user.

To answer the needs of the manufacturing industry, a group of member companies have joined together to create industry-wide standards that will allow different technologies to work together, thus automating and simplifying the work of the predictive maintenance engineer. Machinery Information Management Open System Alliance (MIMOSA) is the group of member companies who are working together to define functional message sets that can be exchanged by different systems. MIMOSA standards are designed to allow seamless integration of CBM software with CMMS, Enterprise Asset Management (EAM) and ERP programs. Information is designed to flow upward from machinery information at the base of the pyramid to the resource planning at the top.



The top priority of MIMOSA is to get application vendors in the maintenance world to adopt a standard communication protocol that will end the burden of data conversion and allow the end user to use their information collectively among various applications. EXtensible Markup Language (XML) is the emerging standard that will ease the pain associated with integration. If you think of the different software applications as pieces of a puzzle, with no standards in place, they fit together like a jigsaw puzzle, each application custom fitting only to its adjacent piece. However, using XML, these applications act more like Lego® blocks, each piece fitting easily with any other.

XML is a specification developed by the World Wide Web Consortium. It is a pared-down version of Standard Generalized Markup Language (SGML) especially designed for the transferring of documents over the Internet. XML specifies neither semantics nor a tag set. In fact, XML is really a meta-language for describing markup languages. In other words, XML allows a facility to define tags and the structural relationships between them. Since there is no predefined tag set, there cannot be any preconceived semantics. It allows designers to create their own customized tags, enabling the definition, transmission, validation and interpretation of data between applications and organizations.

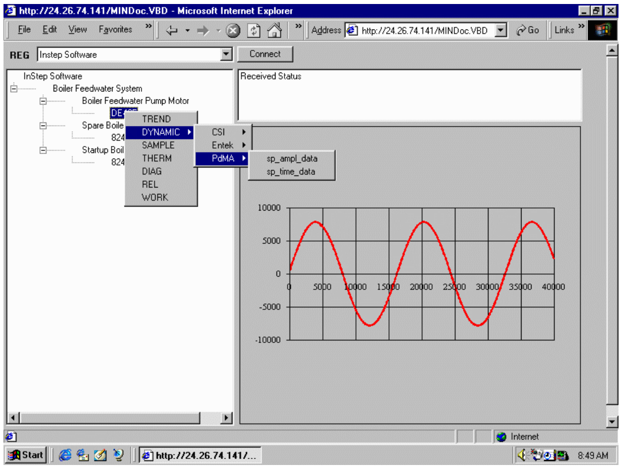
With XML, the contents of a message are defined by an interface. Applications being sent or received can interrogate, extract and interpret message contents by the tag, rather than by special translations. From a broader enterprise architecture view, this allows applications to leverage a common interface message framework.

XML can represent any information. That is very different from the usual ERP model, where every application has to know exactly how the data looks.

The XML standard allows vendors to focus on the business that they do the best. It lets the end user customize their maintenance system by selecting the products that best fit their needs. The data is stored in one location and is accessible throughout the organization by other applications. For example, there is no need to import the data from an EAM into any other system. A new CBM system will be able to retrieve asset information from the existing EAM. If the CMMS wants to know the condition of a machine, the CBM system provides the information. Everything works together simply, without duplication or fuss.

Maximizing Business to Business Relations Through the Internet.

Due to its initial design for Internet data transfer, adopting the XML protocol allows applications to take full advantage of the Internet. Geographical location will not be a factor anymore. As long as an Internet connection is available, information can be accessed from anywhere and at anytime, regardless of location. An expert residing in Tampa, Florida can diagnose a problem in Seattle, Washington without ever leaving the office.



New software standards will facilitate seamless integration of CBM vendors and allow testing and analysis independent of machine or technician location.

More importantly, XML will bring Business-to-Business (B2B) integration into the predictive maintenance world, just as it has in other industries. With B2B integration, it is possible to track the repair and maintenance records of components directly from the service providers. Quality assurance information can be reviewed, questions answered and equipment condition verified prior to shipping. This prevents the delays and expenses associated with unsatisfactory repairs. On the other hand, service providers are able to receive work orders in advance, giving them the opportunity to schedule the necessary resources before a component arrives. The workflow between businesses will be tightly integrated and access to the latest information will always be available, independent of component location.

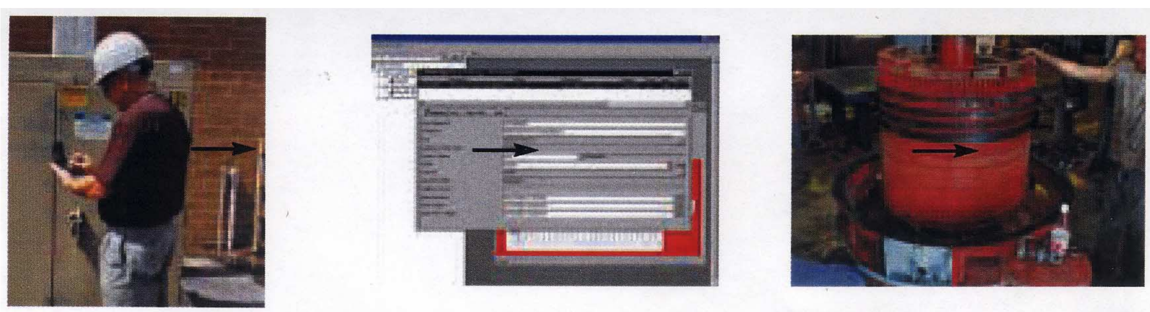
Expect remote network storage and application hosting to be popular trends in the next few years. As the cost of bandwidth drops, high speed Internet access will become more common, offering a new breed of applications which were once too expensive for small businesses. Many small and mid-size businesses long to run their operations in the same efficient manner as Fortune 500 companies. However, the high cost of ERP implementation presents a significant barrier. By outsourcing application hosting and support services, companies gain a virtual IT staff and infrastructure. Application service providers will deliver applications in a secure, high performance infrastructure with network support, implementation and maintenance expertise. Information will be available to all users - under a single roof or at remote locations. Outsourcing enables a company to focus on their core competencies, directing resources to implement new technologies and create business processes.

Some EAM and CMMS vendors are already beginning to offer application hosting for their clients over the Internet. Facilities, regardless of size, are able to implement

EAM/CMMS at minimum cost by avoiding initial investment and support fees. Hardware upgrades, technology dead-ends or inflexible system scalability will be of no concern. Data exchange standards, such as MIMOSA compliance, will enable end users to order different application hosting services to meet their specific needs. Your CBM vendors will work with the EAM/CMMS seamlessly over the Internet without special integration effort.

Go Wireless, Go Mobile

With this new integration, access to information through wireless, handheld devices is a logical progression. Devices already exist that provide wireless connection to the Internet. They utilize Wireless Markup Language (WML), a language based on XML that specifies content and user interface for narrowband devices. Similar to XML, WML is also platform independent. This paves the way for handheld devices to become the mobile terminals for employees on the move.



In the very near future, technology and software standardization in the maintenance industry will allow monitoring, diagnosis, work order generation and repair of equipment all through wireless handheld devices.

Integration will be a necessity, not a luxury.

Fluid communication between ERP, EAM, CMMS and CBM systems will help businesses make timely and qualified decisions. Companies will be able to select the best applications available to build systems designed for their specific needs. Maintenance/monitoring systems will provide detailed machinery information and play a larger role in enterprise resource planning. Maintenance personnel, with the help of wireless devices, will have unlimited access to information from anywhere at anytime. This method of maintenance and operation is not too far in the future. As technology improves, the opportunities to streamline operations expands. Standardizing communication between systems is only the start.

###

EPRI 2001 Maintenance Conference

Sustain Reduced Maintenance Costs with Management Processes and Practices

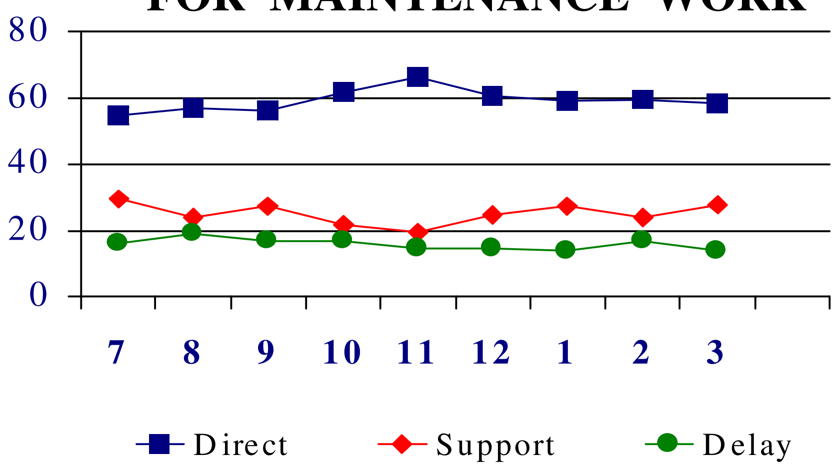
Franklin P. Frisina PE, MBA, MSEE

New York Power Authority

Westin Galleria Hotel
Houston, Texas
August 14, 2001

Objectives

- **SUSTAINABLE PRODUCTIVITY FOR MAINTENANCE WORK**



Objectives

Improve staff productivity by increasing the Craftsperson's time at the jobsite.

Assess the effectiveness of the work management process for the Craftsperson.

Drivers

Is your culture ready to increase productivity?

Is your culture ready to increase profits?

Drivers

- Planning and scheduling are the primary source of productivity.
- Planning answers the question “what” and “how” about a job.
- Scheduling answers the question “who” and “when”.
- Answer these questions in advance and you will have the right craftsperson, doing the right job, using the right method, at the right time.
- That’s job planning and productivity!

Resources

- People
- Materials
- Tools and Equipment
- Documentation

Resource: People

<u>PERFORMANCE LEVEL</u> is 100% if the craftsperson use the time allotted in the Job Plan.

A four person crew had a job plan estimate of 8.0 man-hours.Two of the four crew members were trainees. The job took 10.0 man-hours.

The Performance Level was 80%.

Resource: Materials

<u>UTILIZATION LEVEL</u> is 100% if the craftsperson is able to work at the job site for the entire shift.

A Job Plan estimated a 4 man crew to complete a job in 8.0 man-hours. They waited one hour for materials. They spent an extra 4 man-hours.

The Utilization Level was 67%.

Resource: Tools and Equipment

METHOD LEVEL is 100% if the craftsperson use the method that the Job Plan is based upon.

A Job Plan for a 2 man-hour rigging job required the use of a truck crane. The truck crane did not show up, and a chain fall had be used. The job took 8.0 man-hours.

The Method Level was 25%.

Manage Resources to Reduce O&M Costs

From the previous examples:

Productivity = Performance x Utilization x Method
= 0.80 x 0.67 x 0.25
= **13.4%**

Ineffective management of resources provide lower productivity and higher O&M costs.

Manpower Activity Analysis

Manpower activity analysis is the systematic observation and reporting of time utilization. Based upon statistical random sampling, observations of predefined activities are made within a given time frame.

Work Sampling Measures

Direct Activity:

Performing an element of a task that directly advances its completion.

i.e. Wrench Time, the actual time the Craftsperson is at the jobsite performing the work.

Work Sampling Measures

Support Activity:

Performing an element of a task that, by itself, does not directly advance its completion.

i.e. Getting Equipment, Getting Material, Equipment Travel, Material Travel, Planning the task, Travel

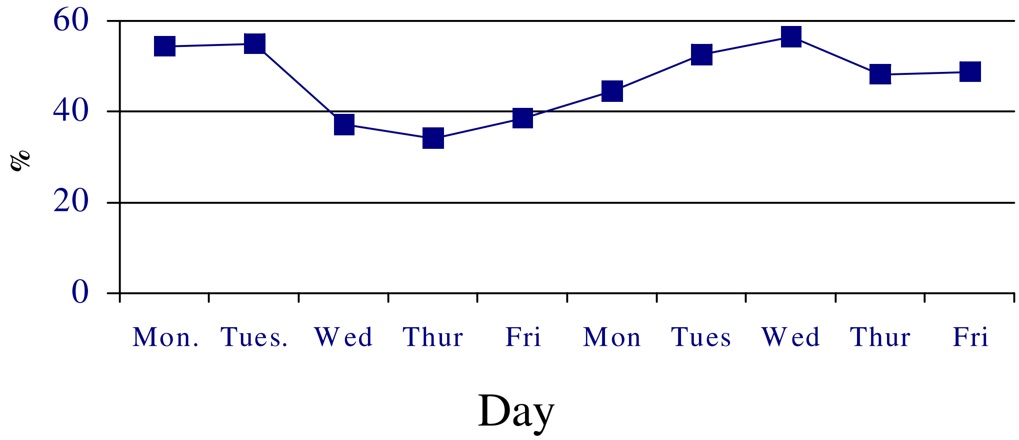
Work Sampling Measures

Delay Activity:

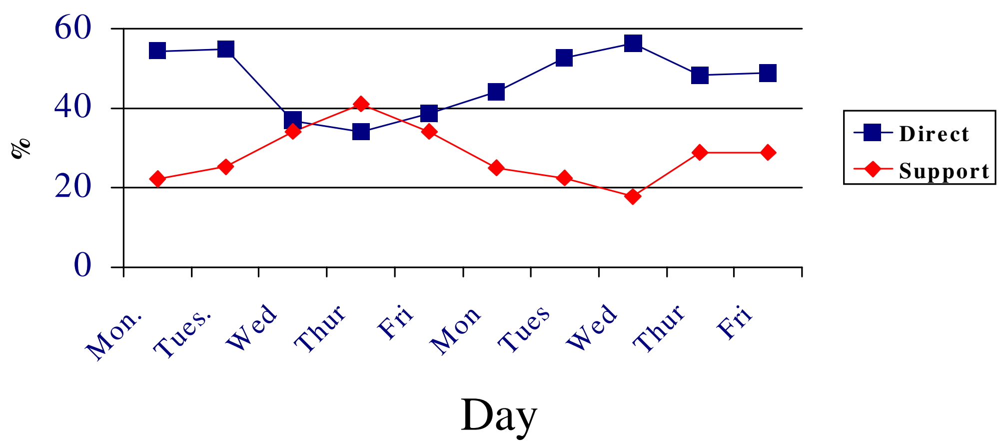
Craftsperson is available for and ready to work. However, the Craftsperson is not performing either "Direct" or "Support" activity.

i.e. Equipment, Material, Crew, Supervisor, Misc., or Personal delays.

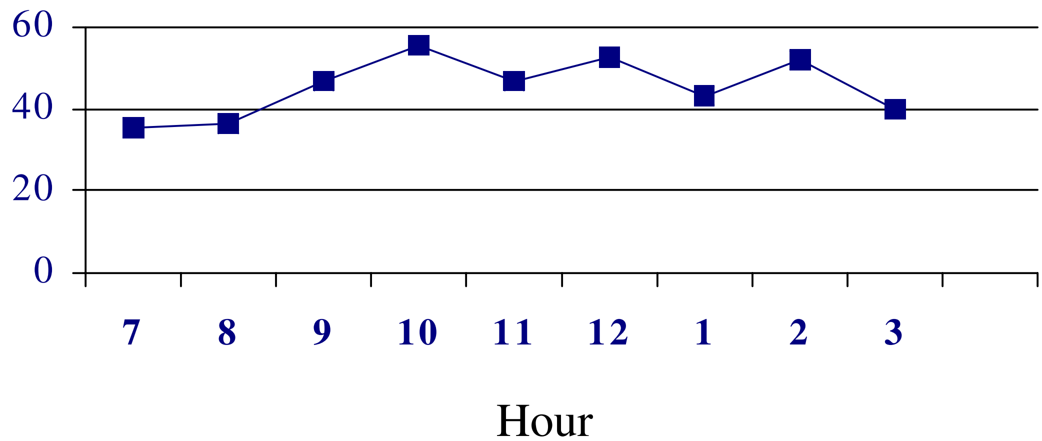
Direct Activity



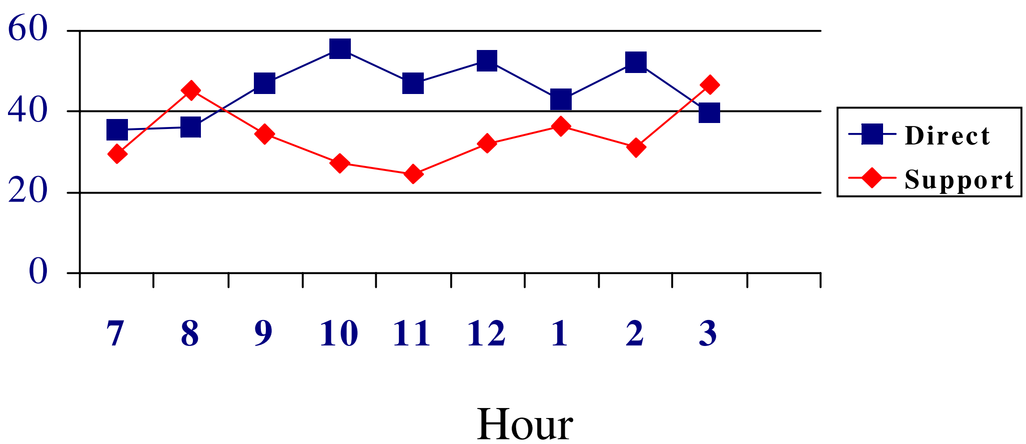
Direct & Support Activities



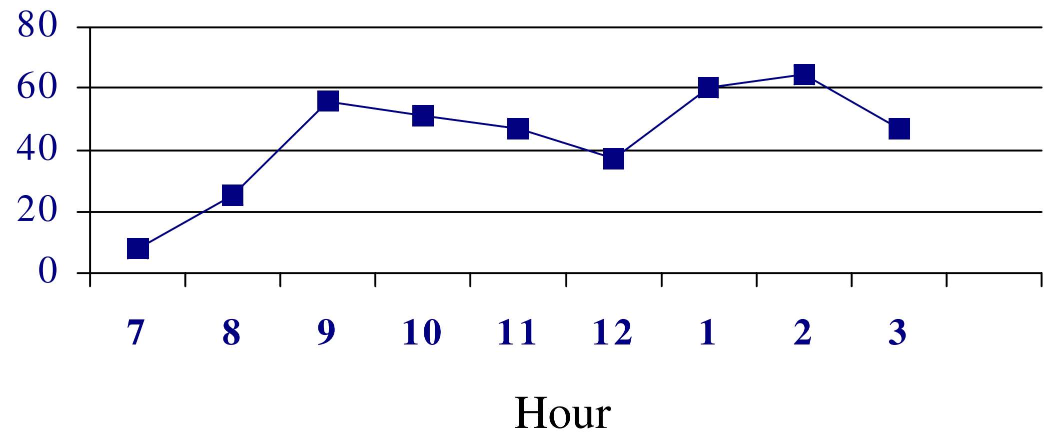
Direct Activity



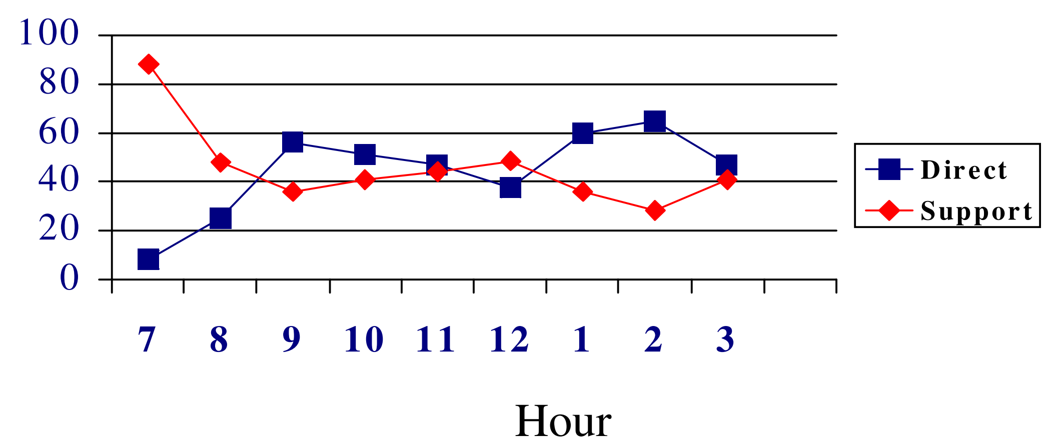
Direct & Support Activities



Direct Activity



Direct & Support Activities



Action Plan

Evaluate Work Management Process that include the following procedures:

- Work Identification
- Work Planning
- Work Scheduling
- Work Documentation
- Work Completed
- Work Analysis and Measurement

Action Plan

Evaluate Work Planning Procedure for Materials to reduce Craftsperson's travel time:

- Complete the material requirements for the job plan.
- Communicate with warehouse tomorrow's material delivery.
- Identify delivered material at the warehouse.
- Ensure materials are pre-staged.
- Establish a pick and drop material delivery process.

Action Plan

Evaluate Work Planning procedure to improve Estimating Process:

- In most instances, job estimating is based on experience estimates, i.e. estimates are in multiples of two, four, or eight hours.
- Expand the use of pre-determined time standards with best method clearly defined.

Action Plan

Evaluate Work Scheduling Procedure to provide Supervisors with ready to work backlog:

- Load weekly schedule to 110 - 125 % of the available man-hours, for each discipline.
- From the weekly schedule, develop a daily schedule for day to day maintenance.

Action Plan

Evaluate Work Completed procedure to improve Craftspersons' start time:

- Supervisors should line out the craft within ten minutes of the start of the shift.
- At the end of the shift, Supervisors should hold a ten minute briefing.

Action Plan

Evaluate Work Analysis and Measurement procedure to improve feedback:

- Establish maintenance result measures at the Craftsperson's level.
- Provide weekly reports to Supervisors and Craftspersons to inform them of the results of their efforts, i.e. work sample actual results vs. actual goals, actual maintenance costs vs. budgeted, performance factor for completed work orders.

Summary

- The work is effectively planned and scheduled.
- Equipment, material, and documentation necessary to perform the task are at the job site, or included in the Job Plan before Work Order is issued.
- The Job is manned correctly, both number and skill.
- Time Standards support the Job Plan's estimated man-hours for large jobs.
- Progress and process are reviewed frequently and process improvements are made.
- Sense of urgency surrounds the Job.

Precision Lubrication for the Power Generation Industry

By Drew Troyer and Jim Fitch
Noria Corporation
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Abstract:

Machinery lubrication is critical to reliability efforts at a power plant. Numerous studies cite poor or ineffective management of the lubrication process as a leading cause of forced plant outages. Poor lubrication also compromises efforts to extend intervals between and reduce the duration of scheduled outages. Precision machinery lubrication is a profit-driven, holistic strategy to engineer lubrication maintenance activities and the organization that carries them out. It employs engineered, procedure-driven techniques to optimize lubricant selection, lubrication management and application techniques, organization training and development, and the employment of world-class lubricant analysis techniques. It delivers consistently high lubrication quality that maximizes profit by optimizing lubrication-related costs to own and operate machinery.

Introduction

Due in large part to changes in the business environment, the demand for power plant equipment reliability has never been higher. Management demands zero unplanned outages, increased duration between scheduled outages and reduced duration of scheduled outages. This represents a difficult challenge for equipment maintainers. In response, plant operators are purposefully increasing the precision with which they carry out equipment maintenance.

In response to the challenge, power generation companies have been implementing Reliability-Centered Maintenance (RCM) and other techniques designed to optimize equipment maintenance. These techniques involve a systematic evaluation of the reliability of the plant's systems, subsystems and components relative to mission criticality and cost of failure (Figure 1). For critical and important machines, deployment of advanced maintenance tactics is usually the least expensive way to achieve reliability goals, and it does not require capital expansion of the plant. A significant portion of the reliability goal can be achieved through the deployment of precision lubrication, which combines engineered machinery lubrication practices with effective lubricant analysis. Pareto analysis reveals that poor lubrication induced failures are a major contributor to maintenance costs and machine failure, and should be an area of focus for the typical power plant.

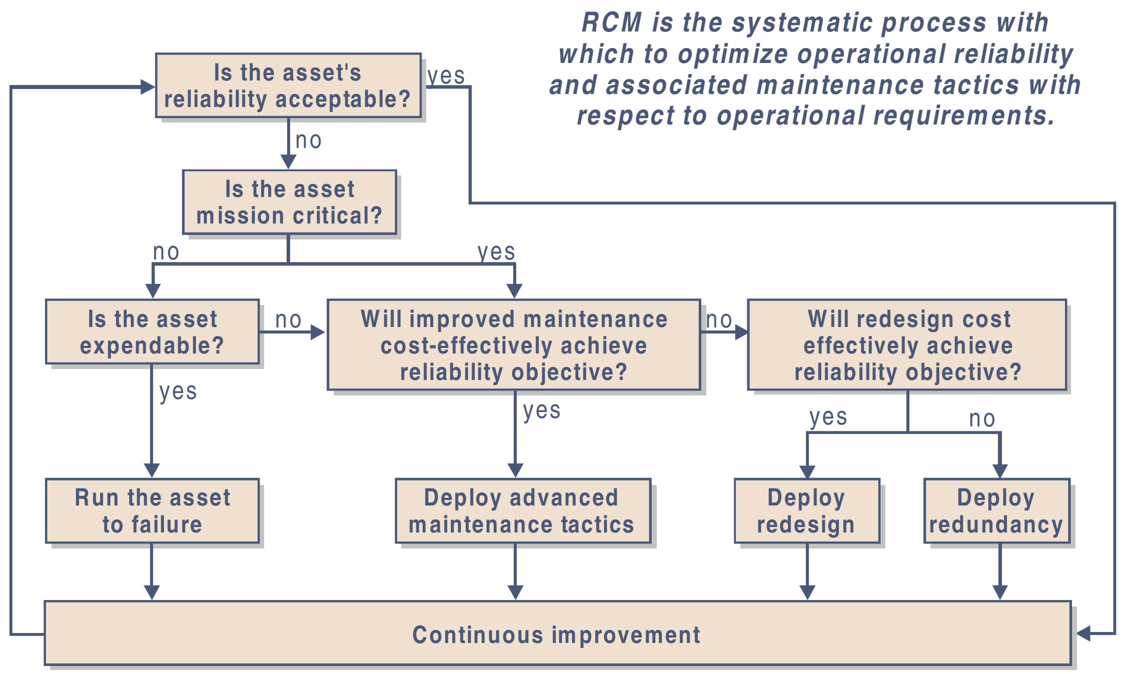


Figure 1 – Reliability Centered Maintenance (RCM) Evaluates Equipment Reliability Relative to Mission Requirements. In-Plant, the Typical Choice for Reliability Improvement is Through the Deployment of Advanced Maintenance Tactics, Including Precision Lubrication.

In one study, General Electric reported that lube oil problems are the single largest contributor to turbine generator-related forced outages, which as an equipment class, is responsible for approximately twenty percent of the forced outages at a power plant. When considering the plant as a whole, effective lubrication is a must-have element in the pursuit of equipment reliability. As an example, Baltimore Gas & Electric reported exceptional value from their focus on precision lubrication (Figure 2). Management should look closely at lubrication practices as an opportunity to increase the reliability of plant equipment. This paper outlines the key elements necessary to achieve precision in machinery lubrication and is designed to serve as a high-level checklist of the key parameters required to succeed. A detailed evaluation of the plant's performance on each of these key elements is suggested to identify and prioritize opportunities for improvement and to develop and implement an action plan.

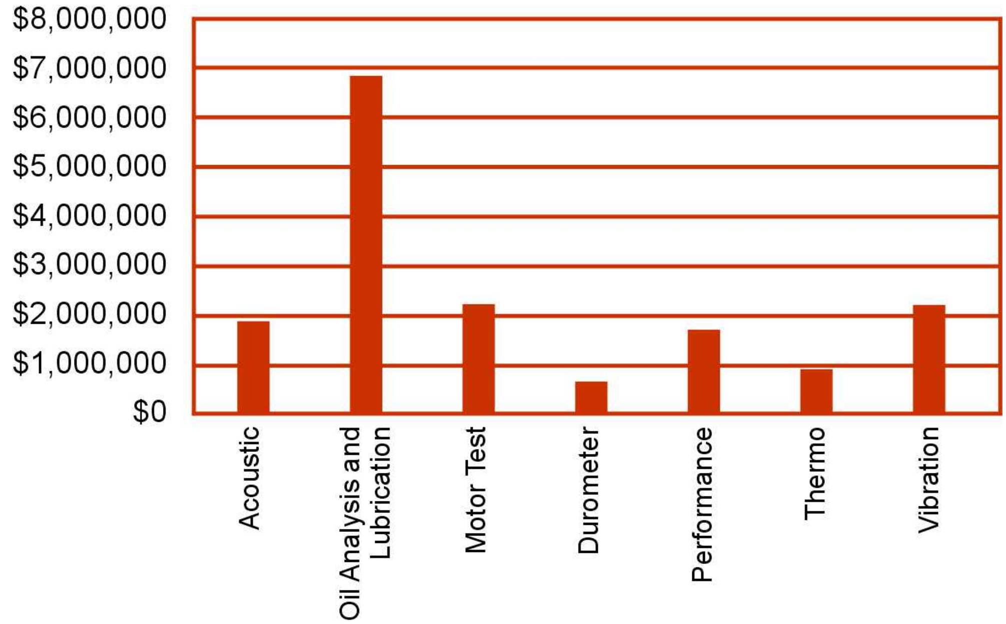


Figure 2 - Baltimore Gas and Electric's Reported Savings from Deploying Advanced Maintenance Techniques – Lubrication and Oil Analysis is a Key Contributor.

Elements of Precision Lubrication

Precision lubrication can't be simply defined on one dimension. Rather, it is a collective of several dimensions of machinery lubrication. We have identified 12 key elements of precision lubrication, which are addressed here (not in order of importance). Each of these key elements represents a component of the foundation of a precision lubrication program. As is often the case, a glaring weakness revealed during an audit in one area can substantially compromise the effectiveness of the program as a whole (Figure 3). Recognition of these weaknesses empowers management to effect change. Each key element has numerous sub-elements. These subelements are not detailed herein. Rather, this paper serves to provide management with an overview of the major points.

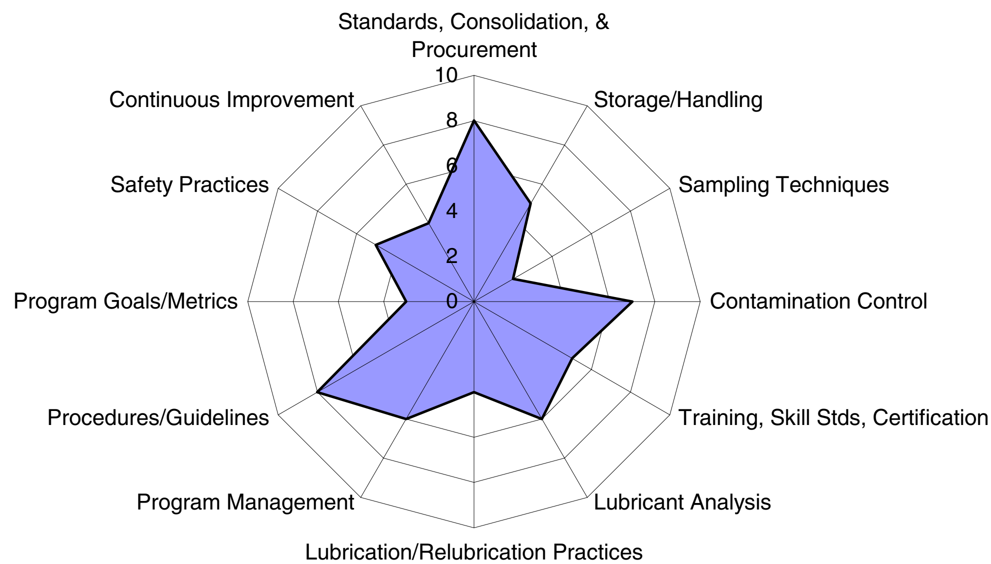


Figure 3 - The "Spider Diagram" is a Multidimensional Scaling Technique to Provide a Quick Look at the Plant's Overall Performance on the Key Indicators of Precision Lubrication.

Standards, Consolidation and Procurement

In an ideal world, the perfect lubricant should be used for each machine, given its mechanical design and the demands of the application and the environment in which it operates. Unfortunately, this is often impractical because of the need to keep the number of products used to a manageable level. The objective of lubricant consolidation is to reduce the number of products being used without compromising the quality of equipment lubrication. Begin the process by identifying obvious duplicates, or identical specification products bought from multiple suppliers. Next, evaluate the technical requirements of the machine to determine which lubricant is actually required. This should incorporate a review of service manuals and specifications and make adjustments as required to account for application and environment severity.

In conjunction with consolidation, technical standards should be developed for each lubricant. A technical standard defines, in technical terms, the required physical, chemical and performance properties required for each lubricant in use. Developing technical standards for lubricants is a departure from the common use of brand-oriented specifications, but it adds precision to machinery lubrication, and improves the effectiveness of the purchasing process. We often hear purchasing organizations blamed for buying an inferior product. Typically, a review of these situations reveals a lack of a standard, or a standard that is incomplete or imprecise. Good engineering is a must for effective lubricant purchasing.

Periodically it is necessary to adjust the lubricant specification for a machine, but these decisions should not be made casually. The practice of making *ad hoc* changes to the lubricant specification, or employing miracle additives in hopes of finding a "silver bullet" is usually a counterproductive activity, leaving a trail of sludge, deposits and failures in its wake. While changes or upgrades to the lubricant specification are occasionally required to solve problems and/or take advantage of new lubricant technology, proposed revisions should go through a technical review process. Once a change has been made, revise technical specifications and machine assignments accordingly.

Storage and Handling

Proper storage and handling are critical to effective lubrication. It is common to see lubricants stored outside, in improperly marked containers, with little or no attention paid to inventory management. Likewise, lubricants are often delivered to the machine in incorrect containers, or using poor procedures. These poor practices substantially compromise the quality of machinery lubrication. It is wrong to assume that new oil is by definition good oil. Lubricants can degrade in storage, especially if they are exposed to water and/or high temperatures. More commonly, however, they arrive to the plant contaminated or they become contaminated during storage (Figure 4). Precision lubrication can't be achieved without taking control of storage and handling practices.

Good lubricant storage starts with good receiving practices. Bulk deliveries should be filtered during transfer and, if possible, tested for cleanliness and properties conformance. Drum deliveries should be visually inspected for container condition and labeling. As with bulk oil deliveries, testing drum-packed new lubricants upon delivery provides positive feedback about their cleanliness and quality.

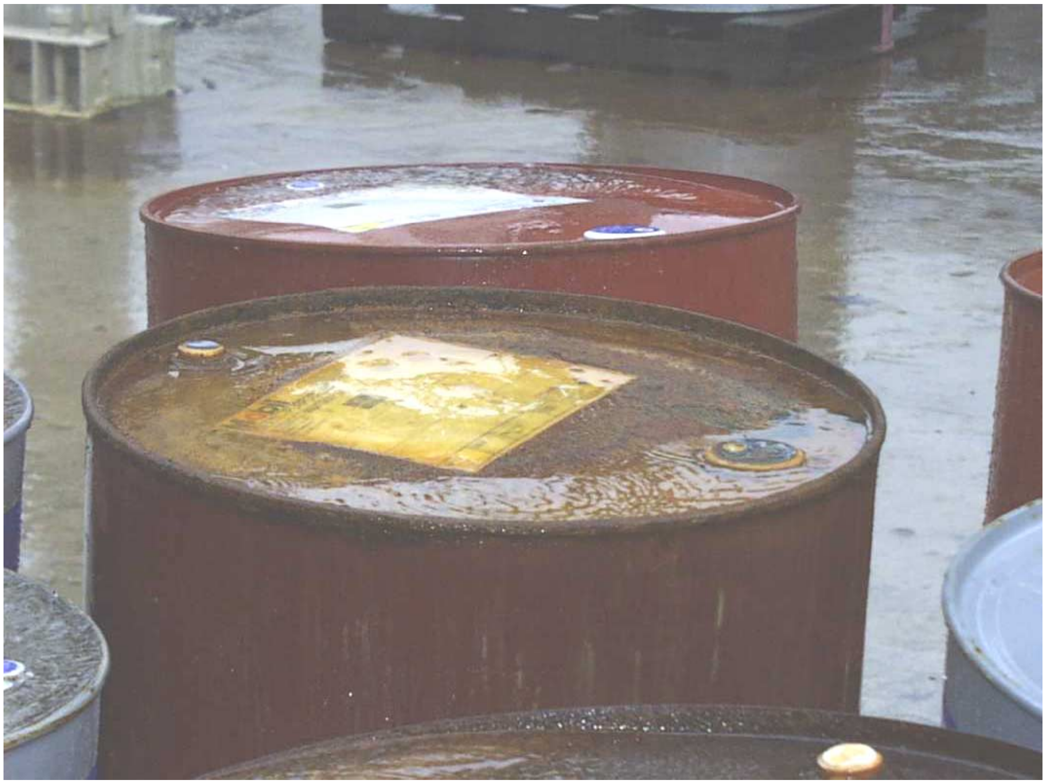


Figure 4 - Outdoor Storage of Lubricants is a High Risk Activity.

Once properly received, protect the lubricants in storage by storing them in cool areas, minimizing variation in temperature and protecting them against exposure to contamination. Setting storage life limits, using date stamps on drums and containers and employing a first-in, first-out (FIFO) inventory system reduces the risk that a lubricant will be put into service past its prime.

Oil Sampling Techniques

Oil analysis is a critical component of precision lubrication, and no activity is more important to oil analysis than sampling. The sample creates a quality ceiling above which the overall oil analysis process can't pass. When photographing a person or an object, the set-up of the camera and even focusing the camera are secondary in importance to pointing the camera's lens in the direction of the person or object being photographed. Representative sampling assures that the oil analysis is pointed in the right direction.

The location from which the sample is drawn largely determines the usefulness of the oil analysis data. Sampling from reservoirs or after filters dilutes and removes information from the lubricant that is important to evaluating machine health. Installing appropriate hardware on the machine, proper flushing, consistent use of the right procedure and correct handling of sample all influence the quality of oil analysis. The task of obtaining a representative sample has numerous subelements, any of which can compromise quality if overlooked. Fortunately, none of the elements are particularly difficult or expensive to achieve.

Contamination Control

Contamination, in its various forms, is a root cause of machine wear and lubricant degradation, which leads to equipment failure and unreliability. Hard particles abrade, erode and fatigue machine surfaces by interfering with the razor-thin film of separation that the lubricant provides. This can significantly compromise equipment life and reliability. Conversely, precision contamination control can be a real moneymaker for the organization (Figure 5). Chemically reactive particles of (i.e., copper and iron) promote degradation of the lubricant itself by catalyzing the oxidation process. Water contamination results in rust on iron and steel surfaces, promotes acid corrosion, exacerbates particle-induced wear, and results in vaporous cavitation. Air, heat and other contaminants further compromise machinery and lubricant reliability.

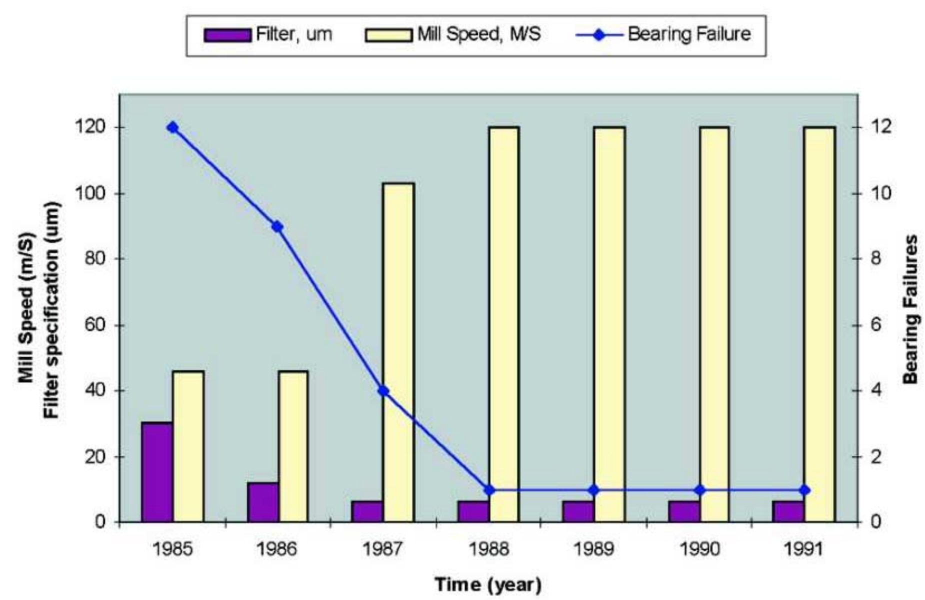


Figure 5 - Reducing Contamination at BHP Steel Resulted in a Substantial Reduction in Bearing Failures, Despite the Fact that Throughput Speed Doubled!

A good contamination control program starts with application specific target cleanliness levels, and balances exclusion and removal techniques to achieve those targets. The machine's mechanical sensitivity to contamination and its criticality to the operation drive the selection of cleanliness targets. As a rule, it is less expensive to exclude contaminants by managing new oil, employing high quality vent filters and upgrading and maintaining seals. After exhausting reasonable options to exclude contamination, attention turns to filtration. Increasingly, filtration systems are being upgraded to achieve modern target cleanliness levels. In many cases, portable lubricant conditioning rigs are being used to periodically purify the lubricant in machines that are not equipped with filtration. This technique is being used effectively on machines where contamination control has never been considered, like gearboxes, vertical motors, etc.

Training, Skill Standards and Certification

Unfortunately, machinery lubrication has not historically enjoyed much prestige in the plant. Many organizations have completely eliminated the “lube tech” and pushed activities to operators, or simply dealt with lubrication tasks on a catch-as-catch-can basis. Of those organizations that do dedicate employees to equipment lubrication, the best performers are often lifted away and redeployed in other activities that are deemed “more important.” Despite the fact that improper lubrication is regularly cited as a leading cause for equipment failure, the act of lubricating machines is usually trivialized. To achieve precision lubrication, this scenario must be replaced with one where the skills of the lube tech are valued and rewarded.

Lubricating machinery properly combines elements of science and an art. It requires attention to detail in performing the “Four Rights” of lubrication: Right Lube, Right Place, Right Amount and Right Condition. While this may sound simple, it requires a skilled and trained individual to perform the Four Rights effectively. Evidence of this can be seen in the frequency with which oil analysis reveals that the wrong lubricant went into the wrong machine, or in the failed bearing seals and corroded windings of motors that have been overgreased. Individuals who are responsible for carrying out and/or supervising lubrication tasks must receive adequate training to build skills, and have those skills certified in order to truly achieve precision lubrication. Management should value the skills offered by the lube tech and provide the individuals responsible for carrying them out have a career track so they can perform their work with a sense of pride and purpose.

Lubrication/Relubrication Practices

Odd as it may seem, few organizations have engineered processes for lubricating and relubricating machines. This often prompts the question: once the lubricant is properly selected, what is involved to properly lubricate a machine? There is more to it than meets the eye. Greasing bearings, for example, requires calculation of the optimized volume of lubricant to apply and the frequency with which to apply it. Is a grease gun really the best method for greasing that bearing, or would a single point applicator, centralized system, or even a mist system do a better job, reduce cost, or eliminate safety risks associate with lubricating a hard-to-reach component? Likewise, should a gearbox be fit with a quick-connect fitting so that oil can be added through a filter cart without opening the system and exposing it to the environment? These and many other questions must be addressed.

Even the apparently simple act of draining the lubricant is deceptively complex. An oil drain usually leaves between five and sixty percent of the old lubricant in the system, unless the system is flushed. Leaving even a small residue of oxidized lubricant in the sump or reservoir can compromise the entire anti-oxidant additive package of the new oil, making the oil change a temporary stop-gap solution at best. Tagging of machines, selecting appropriate containers for intermediate transfer, labeling containers, calibrating grease guns, adjusting and maintaining automated lubrication systems are a few of the many other elements of effective lubrication and relubrication (Figure 6).

Tagging Method	Advantages	Disadvantages
Stamped Metal or Plastic Tag	▪ Easy to make. ▪ Can be painted over without losing information.	▪ Requires some knowledge of lubricants. ▪ Not intuitive for operators and craftspeople. ▪ Can easily be knocked off of machine.
Color-Coded Tag (UV resistant)	▪ Available from many suppliers. ▪ Unique color communicates clearly and quickly what lubricant goes where. ▪ Most tags include words in addition to color.	▪ Can be painted over. ▪ Color-blind individuals have trouble with these and must refer to words. ▪ All new lubricant sources, including transfer containers must be color tagged. ▪ Can easily be knocked off of machine.
Shape-Coded Tag	▪ Unique shape communicates clearly and quickly what lubricant goes where. ▪ Most tags include words in addition to shape. ▪ Color-blind individuals unaffected.	▪ Not many suppliers use shape-based tags. ▪ Can easily be knocked off of machine. ▪ All new lubricant sources, including containers must be color-coded.
Computer Chip Tag	▪ Enclosed in a waterproof, paint-proof can (about the size of a watch battery) that is installed on the machine with epoxy. ▪ Lots of information can be programmed on the chips. ▪ Chips can be reprogrammed in-situ.	▪ Not intuitive to craftspeople and operators. ▪ Requires instrument to retrieve data. ▪ More expensive than other methods.

Figure 6 – Tagging the Machine is Just One of the Many Elements of Achieving Effective Lubrication and Relubrication.

Lubricant Analysis

For oil-lubricated systems, lubricant analysis is the feedback loop that assures the effectiveness of the plant's equipment lubrication program. Historically limited to supporting oil change decisions, lubricant analysis is coming of age in plant maintenance programs. While monitoring the health of the lubricant is still important, the role of oil analysis has expanded to include contamination control and wear debris analysis. The additions of which significantly increase the value of oil analysis to the plant.

Given the importance of contamination control in the pursuit of machine reliability, oil analysis is a natural requirement to provide positive feedback that target conditions are controlled. Likewise, when something does go wrong with the machine, wear debris analysis is often the first technology to detect it. Once it is detected, microscopic analysis of the wear debris produced provides important clues about the failure mechanism and its root cause. Because a wear particle is in effect the mirror image of the score or pit left on the machines surface, wear debris analysis provides information about the machine's surfaces without actually tearing it down. The size, shape color, surface condition and edge details of a wear particle enable the skilled analyst to explain what is happening inside of the machine with remarkable accuracy, and typically long before it adversely affects production (Figure 7).

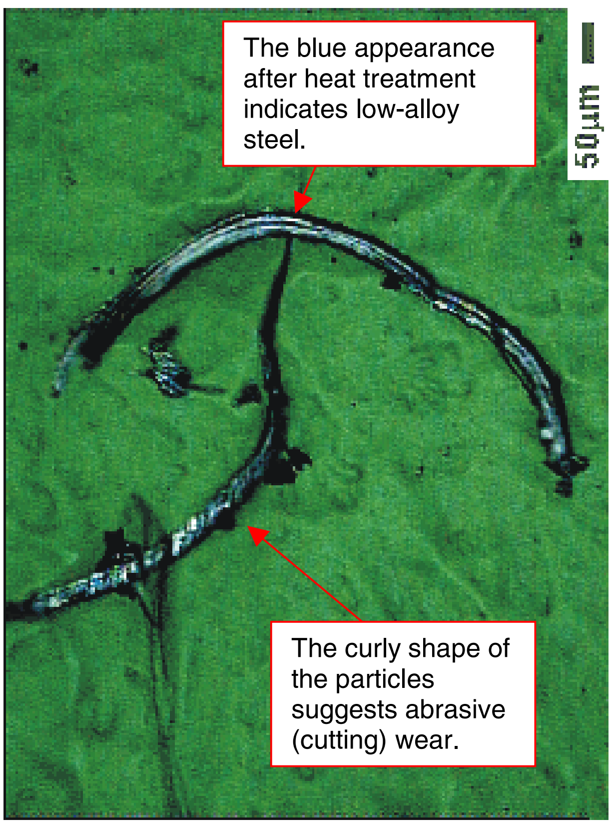


Figure 7 - The Size, Shape and Appearance of a Wear Particle Reveals a Lot About the Condition of the Machine's Surfaces.

Program Management

A precision lubrication program must be managed to be effective, and effective communication plays a critical role. Communication between team members, between the lube team and plant management, between the lube team and other stakeholders in the plant and between the lube teams of different plants within the organization is necessary for the program to succeed. Communication is the key to spotting issues, solving problems, implementing solutions and keeping skills up-to-date. Bilateral communication is critical to success, and rightfully receives a great deal of attention. However, unilateral communication is important too, and definitely has its place in precision lubrication. Lubrication teams rarely communicate progress toward their goals to the entire plant. The bulletin boards located around the plant provide a great opportunity to unilaterally communicate the lube team's performance on key success indicators like overall equipment cleanliness (Figure 8). This kind of charting and communication changes the behavior of people who come into contact with the lubricant, thus serving as an "invisible filter." Other important forms of unilateral communication include distribution of newsletters and memos to stakeholders and subscribing to appropriate journals, magazines and newsletters to keep skills up in order to stay abreast of new technologies, products and services that might add value to the program, and to see what is happening within the lubrication community.

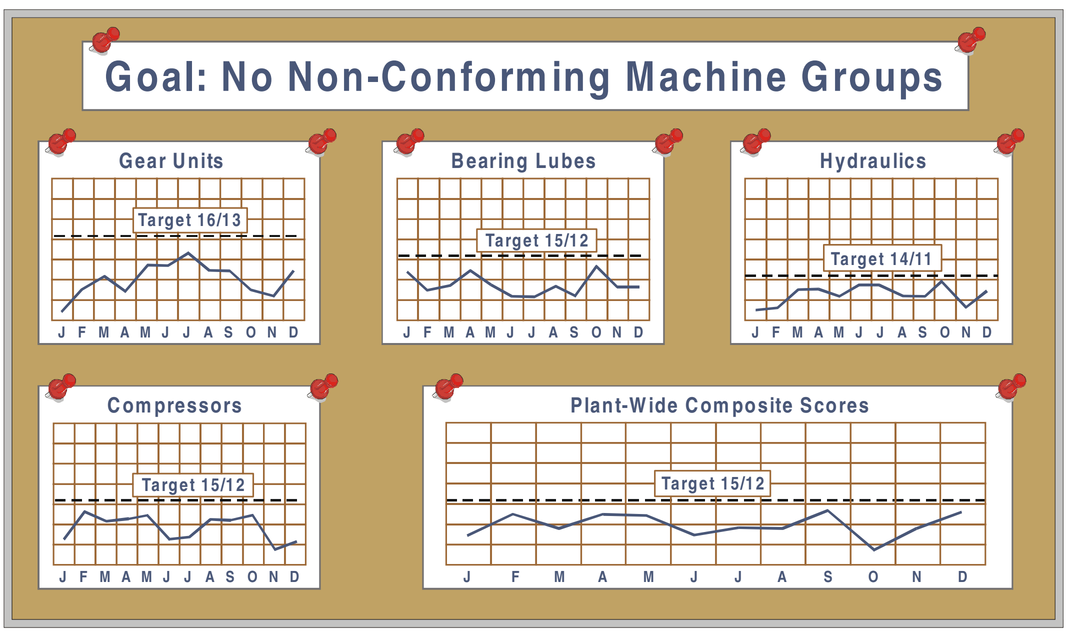


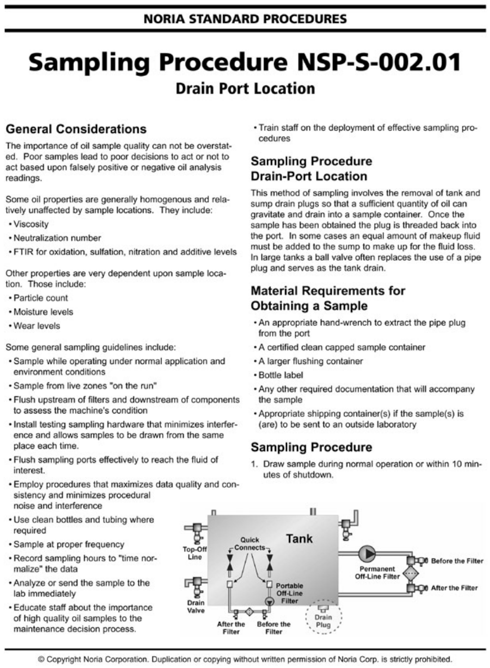
Figure 8 - Conspicuous Charting of Fluid Cleanliness Communicates its Importance to the Entire Organization.

Other important management issues include staff reward systems (both formal and informal) and cost benefit analysis of new or expanded program initiatives. Reward structures for lubrication techs need to be revised in most organizations. Unfortunately, maintenance organizations have historically rewarded reactive behavior. In fact, most organizations indirectly and unintentionally reward failure. Consider the case of the mechanic who comes to the rescue of the plant in the middle of the night to repair a failed machine. Besides time and a half or double time pay (formal rewards), the craftsperson is showered with accolades (informal rewards). Where are the accolades and rewards when the lube tech is working hard within the 40-hour week to keep all the systems properly lubricated and sparking clean? Both deserve recognition and rewards, but the proactive behavior of the lube tech puts money on the bottom line, but often goes unnoticed.

Procedures and Guidelines

Like any managed activity, precision lubrication requires clearly documented procedures to properly carry out lubrication tasks. There are several reasons why this is important. First, the creation of procedures usually requires that a skilled individual evaluate the tasks and what they are intended to achieve. Second, they assure that everybody performs the tasks in a consistent manner. And, when a new person is added to the team, they provide a defined framework for training.

Unfortunately, there are few plants that have lubrication procedures. Where they do exist, the procedures are grossly oversimplified and inadequate. Procedures need to be clear, complete and readily accessible, preferably on the company's intranet. Use digital photos and graphics to supplement the words in the procedures. Photos and graphics simplify the communication of complex aspects of the procedure that are difficult to clearly describe with words alone. For extremely complex tasks, digital video provides even greater clarity. Procedures should exist for draining, filling, top-ups, changes, flushing, sampling, greasing and other important aspects of the lubrication process.



NORIA STANDARD PROCEDURES

Sampling Procedure NSP-S-002.01

Drain Port Location

General Considerations

The importance of oil sample quality can not be overstated. Poor samples lead to poor decisions to act or not to act based upon falsely positive or negative oil analysis readings.

Some oil properties are generally homogenous and relatively unaffected by sample locations. They include:

- Viscosity
- Neutralization number
- FTIR for oxidation, sulfation, nitration and additive levels

Other properties are very dependent upon sample location. Those include:

- Particle count
- Moisture levels
- Wear levels

Some general sampling guidelines include:

- Sample while operating under normal application and environment conditions
- Sample from live zones "on the run"
- Flush upstream of filters and downstream of components to assess the machine's condition
- Install testing sampling hardware that minimizes interference and allows samples to be drawn from the same place each time.
- Flush sampling ports effectively to reach the fluid of interest.
- Employ procedures that maximizes data quality and consistency and minimizes procedural noise and interference
- Use clean bottles and tubing where required
- Sample at proper frequency
- Record sampling hours to "time normalize" the data
- Analyze or send the sample to the lab immediately
- Educate staff about the importance of high quality oil samples to the maintenance decision process.
- Train staff on the deployment of effective sampling procedures

Sampling Procedure Drain-Port Location

This method of sampling involves the removal of tank and sump drain plugs so that a sufficient quantity of oil can gravitate and drain into a sample container. Once the sample has been obtained the plug is threaded back into the port. In some cases an equal amount of makeup fluid must be added to the sump to make up for the fluid loss. In large tanks a ball valve often replaces the use of a pipe plug and serves as the tank drain.

Material Requirements for Obtaining a Sample

- An appropriate hand-wrench to extract the pipe plug from the port
- A certified clean capped sample container
- A larger flushing container
- Bottle label
- Any other required documentation that will accompany the sample
- Appropriate shipping container(s) if the sample(s) is (are) to be sent to an outside laboratory

Sampling Procedure

1. Draw sample during normal operation or within 10 minutes of shutdown.

Figure 9 - Procedures Add Clarity and Consistency to Lubrication Tasks

Program Goals and Metrics

When Alice reaches a fork in the road, and asks the rabbit which road she should take in the story "*Alice in Wonderland*" the rabbit asks Alice where she is going. When Alice responds that she doesn't know where she is going, the rabbit replies that it doesn't matter which road she takes, both will lead her to her destination. Lacking a goal, Alice's decision and subsequent actions were not relevant. A precision lubrication program must have clearly defined goals, which must be aligned to the goals of the maintenance department, which in turn must be aligned to the plant's goals, which must be aligned with the goals of the corporation or owners. Just as misalignment produces friction in mechanical equipment, misalignment of goals causes friction in organizations.

Goals for machinery lubrication revolve around proactive and predictive maintenance success. The goals must be measurable, driven by economics, safety and/or environmental compliance and relate to the goals of the organization. Individual and group rewards should be tied to these goals, and when goals are reached, they should be celebrated. When they fail to achieve a goal, they should shift into a figure-it-out mode. Some examples of lubrication related metrics, include percent conformance to target cleanliness levels, percent conformance to lube schedules, lubricant consumption ratio and percent conformance on lube type (getting the right lube into the right place). These examples can be easily measured and tied to the goals of precision lubrication, and they are clearly aligned with maintenance, plant and corporate objectives.

Safety Practices

When we think of lubrication safety practices, handling of lubricants immediately comes to mind. Some lubricants present health risks to the handler, ranging from toxicity and dermatitis to cancer (Figure 10). Action must be taken to minimize health risks to lubricant handlers. Other less obvious risks are also present. For instance, changing filters or sampling fluid on high-pressure hydraulic systems is a potentially dangerous activity.

	Risk Area		
Lubricant Type	Acute Toxicity	Dermatitis	Cancer
Mineral Oil	Some Risk	Care required	Care required
Synthetic Hydrocarbon	Very Slight	Care required	None reported
Di-Ester and Polyol Ester	Slight	Care required	None reported
Phosphate Ester	Some Risk	Care required	None reported
Silicone	Nontoxic	Little risk	None reported
Polyglycol	Believed to be low	Believed to be low	None reported
Chlorinated diphenyl	Irritant vapor when hot	Care required	None reported
Fluoroether	Toxic vapor when overheated	Not known	None reported
Soluble Oil	Care required	Care required	Same as Mineral Oil
Grease	Very Slight	Little risk	Little if any risk

Health hazards of lubricants

Figure 10 - In Select Cases, Lubricants Can Pose Safety Risks to Handlers.

Lubricants also create safety risks to general plant personnel, which must be given their due attention. Leaks, for instance, can create slippage hazards, and in some cases fire hazards. Reducing leakage and minimizing its effects by containment and selection of fire resistant fluids where appropriate, are just few of the safety assurance practices necessary in a precision lubrication program.

Continuous Improvement

Precision lubrication is a control process. Therefore, all aspects of quality management apply, including SPC charting and continuous improvement. Continuous improvement can take several forms as it relates to precision lubrication. We automatically think of system upgrades like improved filtration, upgraded lubricants, better or more frequent oil analysis and assignment of additional staff or resources. However, continuous improvement can also involve system downgrades if overspending is occurring. It can also relate to the reallocation of resources from less productive areas to more productive areas, or replacing costly, inefficient or ineffective processes with new ones that incorporate new ideas and technologies.

Continuous improvement is management's way to keep pouring on the coals until we get it right, optimize it or don't need it, whether "it" refers to equipment lubrication or cost accounting. When we do get it right, we continue to measure, compare and close gaps because the macro-environment (economic, political, technical and social) is ever changing and dynamic.

Conclusions

This paper has highlighted the key elements of a precision lubrication program, which should be an important component of every power plant's production reliability assurance and equipment maintenance program. Audit your plant, find your opportunities for improvement, prioritize your actions, design corrective solutions, deploy those solutions and continuously improve your plant's lubrication practices, and you will see the benefits of a managed, precision lubrication program quickly begin to materialize.

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Abstract

Gas-fired power plants anchored by today's advanced gas turbine (GT) technology overwhelmingly dominate new capacity additions. Upwards of 90% of all planned capacity is now predicated on these machines in simple or combined cycle arrangement. Ten years ago, some industry observers suspected that these machines could not live up to all of the performance and economic demands expected of them. Five years ago, as operating and maintenance (O&M) experience began to accrue, many owner/operators wondered, "Are we sacrificing low initial capital costs for higher operating costs over the life of the facility?" Today, that question is no longer an "if," but a "by how much?" The life-cycle costs of these machines are substantially higher than most owner/operators anticipated in the project financials. However, gaining a full understanding of these costs is made difficult because of site-specific factors, because of the ambiguity inherent in root cause analysis of O&M "events," and because of an industry trend towards long-term service agreements (LTSA) with original equipment manufacturers (OEMs) governing these machines. This paper provides guidance to owner/operators on how to manage the life-cycle maintenance costs and risks of advanced gas turbines.

Introduction

Over the last decade, the advanced gas turbine, in peaking or combined cycle configuration, has come to dominate new capacity additions in the United States. However, early on in this trend, some industry experts were extremely wary about whether this technology could live up to its expectations. After all, a machine that could simultaneously (1) achieve ultra-low NOx emissions levels with no downstream cleanup or water or steam injection, (2) achieve efficiencies in the 35-40% range in simple cycle mode (rivaling the best fossil steam units!), (3) provide cycling capability with little impact on the machine's durability, (4) reduce capital costs of new plant construction by 50% or more, compared to other alternatives, (5) start and stop quickly to meet peak demands, (6) reduce water consumption, and (7) reduce project schedules so that facilities would be on-line quicker all seemed too good to be true. Maybe it was.

Numerous publications have documented the O&M problems associated with these machines. In fact, the technology went into a tailspin, as it were, in the 1996-1997 time frame when the dominant supplier, General Electric Co, resorted to a massive recall of F-class machines from around the world because of design problems in the hot-gas path. Since then, the other suppliers of these machines, Siemens/Westinghouse and Alstom, have experienced their share of difficulties as well, although perhaps not as pronounced or as well-publicized as those GE faced at the time of the recall. In the meantime, the demand for these machines reached unprecedented heights in the 1997-2001 time frame.

As was expressed in earlier publications, it is important to understand that there is no single entity to blame for the GT O&M problems now being faced by the industry. Instead, the situation has arisen from a conflagration of issues. 90% of the nation's new electric generating capacity is now based on advanced gas turbines and combined cycles. Because of this reality: *Electricity demand continued unabated and a gas-fired plant was the only power plant that had a hope in hell of being permitted or being considered economic by investors*. It was also the only option that could meet the requirements of the changing industry: independent and merchant power production (IPPs), privately financed projects, the lowest emissions possible, the least amount of water consumption, the smallest physical "footprint," the lowest first costs, the best financial returns based on the high system efficiencies, the need for dispatching flexibility to capitalize on market prices in the on-peak period, and so on.

As long as natural-gas prices remained favorable and the GT technology continued its design advances (at least in theory), the dominance of gas-fired systems was inevitable, especially in a competitive market for generation. Over the last year or so, the gas forward price curves have changed for the worse (at least from the perspective of someone buying gas). Therefore, the dominance of gas-fired systems has changed. Up to 30,000 MW of proposed new coal capacity has come out of the woodwork and at least a few generating companies (Gencos) are now willing to at least talk opening about new nuclear units.

Most observers do not expect all of the gas-fired capacity to actually come on-line. In fact, a consensus is emerging that up to 50% of these projects will never see the light of day. However, if even half of this capacity comes on line, representing nominally 150,000 MW, that means that *a lot of people are going to have to get a lot smarter about advanced gas turbine O&M*.

The nature of the problem

The issue of advanced gas turbine maintenance risks has many facets. Although specific O&M maladies are difficult to categorize, maintenance risk events can be categorized as follows:

- Design deficiencies. There's little question (except perhaps from the OEMs' marketing staffs) that many of the advanced gas turbine designs were rolled out to the field too early, before adequate full-scale testing was conducted. Most of these design deficiencies are focused on the combustor and hot-gas path, where much of the new technology resides. However, significant problems have also been encountered in other components as well, such as the compressor. Unfortunately, GT vendors, encouraged by financially driven project developers and zealous environmental regulators have been preoccupied with the next generation designs, gunning for a 60% efficient combined cycle with single digit NOx emissions, instead of ensuring the robustness of the current fleet.
- Operator error. Vendors and users alike now agree that these machines are extremely sensitive to operating conditions, such as natural gas fuel being slightly out of spec, temperature profiles of the hot-gas path blades and vanes outside of their normal range, etc. *However, it is our experience that very few of the problems currently being experienced can be directly attributed to operator error.*
- Fuel limitations. Natural gas quality has become an industry hot button over the last several years especially with, but not limited to, dry low-NOx combustion systems. In addition, many of the advanced gas turbines being installed today are sold with the capability to burn either natural gas or fuel oil. However, capability

and reality are often two ends of the spectrum. Any operator will tell you that they prefer to not to run distillate, but the cold hard reality is that for some projects this capability is a must from a project Pro-Forma standpoint. This forces the operator to occasionally switch fuel to validate/maintain the integrity of the system. This consumes additional machine life, adds to outage durations, adds to the labor cost for maintenance, and adds a layer of complexity to an already complex system. This is in stark contrast to five years ago, when it was promised that these machines could change fuels "on the fly," and even operate someday on gasified coal.

While we could single out many "generic" problems with gas turbines, perhaps the one of noise, or "humming," best represents the design deficiency category. Back in the late 1980s, gas turbine designers were wrestling with this problem, most peculiar to dry-low NOx combustors, or DLN machines. Quoting from a very recent article in *Mechanical Engineerin*g on advanced gas turbines: "The humming problem continues to be a major concern. The degree of this difficulty varies considerably from one manufacturer to another. In order to meet new environmental regulations and to lower NOx emissions, gas turbine manufacturers are using lean premixed combustion systems. These systems have proven to be subject to induced pressure oscillations that can cause a hum. The precise mechanisms that lead to combustion-induced pressure oscillations are not fully understood, and most manufacturers are dealing with it (or not dealing with it) by recommending lower power levels, until a better solution is found." Later in the article an executive from Duke Energy North America is quoted as saying, "[they've] learned to predict the onset of humming, and hence avoid it, but cannot solve it."

In the best of cases, humming significantly increases maintenance costs because it results in gradual deterioration of the combustor hardware. In worse cases, the humming problem can lead to catastrophic failures with gas turbine equipment. The humming problem has even contributed to whole machine designs being taken off of the market. The GT24 and the 84.3A designs, while not publicly "abandoned" by their OEMs, are certainly not pushed aggressively and part of the reason is the large volumes of their DLN combustors make them most susceptible to damage from humming.

It is our belief that the fundamental problem with advanced-class GTs is still not being addressed by OEMs. That problem is rapid scale-up of equipment without proper stress analysis and validation prior to introduction of new models into the field.

Quantifying the problem

Instituting a GT maintenance risk mitigation strategy should start with analytical data about the problem. In practice, this is difficult to achieve, at least on a generic industry level. Information about O&M problems is available in several ways, each with its own problems and limitations:

- OEM databases. Each vendor documents maintenance events for their fleet of machines and even purports to feed this data back to the operators through user group organizations. In practice, the user groups, at least the ones these authors are familiar with, serve more as a means for the vendor to control access to the O&M data. In meeting notes we've seen, users report that their "event" data is not present in the general fleet data set presented by the vendor, that critical pieces of data important to planning scheduled outages, staffing, and spares are not tracked or provided by the OEM, and that figures like total trips are aggregated but root cause information is not.
- Strategic Power Systems ORAP database. A "generic" database on operations, reliability, and availability (ORAP) is kept by a third party with one fatal flaw: The database and the third party are funded by the OEMs. Users have been complaining for years that the data here is useful for some purposes but not for many others and that, to maintain the confidentiality of reporting facilities, the data is aggregated and conditioned to the point of being not very helpful to individual sites.
- Genco database. Gencos with large fleets of gas turbines are able to maintain an O&M database. However, this data is often not accessible to others in the industry because of the competitive nature of the business. Many of the top Gencos,

however, rely heavily on the ORAP database and OEM information for their risk mitigation strategies, if they have one.

- Facility by facility. Direct information on performance and experience is often available from the facilities themselves. It is the authors experience that the folks at the plant who live and die by the equipment are not shy about detailing their experience. However, this information is often "off the record" because of competitive reasons, because of legal restrictions binding the partners to the project, or because of limitations inherent in the LTSA with the vendor. Unfortunately, because of this, information generated plant by plant is often considered "anecdotal."
- EPRI database. The Electric Power Research Institute (EPRI) also has performed detailed analysis of GT performance experience at select sites. However, the details of this experience are available only to the EPRI members who fund the organization.
- Insurance firm database. Several insurance firms, Hartford Steam Boiler in particular, have amassed impressive statistics on gas turbine failures and maintenance histories. While these may be the most "independent" of the available statistics, they are not accessible to everyone and they are built primarily to understand and settle individual "claims."

Because of the database problem, the magnitude of the GT maintenance risk issue is understood by only a few industry experts and it is difficult if not impossible to establish an "industry" or even a "vendor" trend. The emergence of the LTSA has compounded the problem, creating nothing but "gray" for OEMs and owners to wrestle over, often with their legal eagles and expert witnesses in tow.

However, the numbers, when you have access to them, are deeply disturbing. For example, our research reveals that the hot-gas path components for many late-model GTs no longer reach expected service life. Turbine hot section components are experiencing extremely high rejection rates at the first hot gas path inspection, in general conducted at approximately 24,000 fired hours, three years of baseload operation, or some equivalence based on starts, trips, fuel type and quality, and operating modes. Some rejection rates are as high as 60%, with costs for one set of replacement first stage rotating components approaching $3-million! Note that early Pro-Formas for advanced-class machines often assumed a rejection rate of just 1-2%; today, the number is more likely 20-30%.

Scrap rates are defined as the percentage of components in any given set (for example, first stage turbine blades) as not being repairable at the recommended interval. In some cases, OEMs have recognized some of these issues and have resorted to reducing recommended repair intervals. Most notable is General Electric's current recommendation for its MS7421 machines to replace third stage turbine blades after 24,000 factored hours. Note that this component on earlier models, the 7EA, is capable of life expectancies several times longer.

Many rotating components don't make it to the 24,000 fired-hour interval. Blades and vanes typically only last between 8000 and 16,000 operating hours. The accelerated mean time between overhauls that result can cost a project $5-10-million in direct costs, plus lost generation! The total damage from what an OEM might describe as a "single blade failure" often approaches $10-million. That's because one failed blade that breaks loose cascades downstream and often damages another 200 to 300 on its destructive path.

In fact, the need for hot gas path repair and replacement has grown so much that the worldwide OEM host-section replacement business now stands at more than $1-billion annually, with margins to the OEMs reportedly exceeding margins on the original sale for the entire GT! In fact, the market has grown so much, it has enticed several non-OEM repair facilities to at least evaluate, if not pursue, the manufacturing capability for various hot section components in advanced class machines. In some cases, Gencos too have taken notice and are bringing repair capability into their organizations, either through acquisition or internal development.

LTSA/CSAs: Risk mitigation?

Many owner/operators have bought into the LTSA, now referred to by GE as a contractual service agreement (CSA) as the principal maintenance risk mitigation tool. According to GE, 95% of the advanced F-class fleet is now governed by a CSA. Indeed, on the surface, it appears that the OEM picks up much of the responsibility for maintenance and associated costs. Also, because the demand for gas turbines is so great and the queue so long for new projects, the OEMs often can hold a buyer “hostage” and compel, if not outright demand, that an LTSA be included with the project. Some projects are compelled to sign for a CSA by financing organizations to improve the risk profile for the project.

OEMs have recognized that service agreements provide revenue streams far into the future that can be “monetized” today. That is, depending on accounting practices, the revenue can be “booked” upstream of when the actual revenue arrives. From the OEM point of view, the CSA recognizes that “service,” meaning spares, replacement parts, consulting, testing, monitoring and diagnostics, etc, can represent up to three times the initial cost of the machine. OEMs are loathe to give up this service revenue as they have in the past.

The LTSA/CSA may not serve the owners best interests however, especially if the owner does not enjoy “favored customer” status with the OEM. Gencos which have purchased dozens, in some cases hundreds, of machines are in a far better position to negotiate LTSA/CSAs on favorable terms. Other purchasers have less clout and may be at the mercy of the OEM. Ever wonder why suppliers of automobiles, printers, music systems, computer systems, appliances, etc try to push a “service agreement” onto consumers? Because it’s a continuous revenue stream over the life of the product and because consumers rarely read the fine print about what the agreement really covers.

Fundamentally, these agreements presents a contradiction. The owner wants to minimize or at least levelize maintenance expenditures, but the OEM wants to maximize service revenue. Although “shared savings” elements in the agreement can mitigate some of this contradiction, the agreement has to be written very tightly from the owners' point of view. In many cases, the agreement is simply an invitation to argue over “who’s to blame.” These agreements can vary in scope, from supply of parts and/or materials to full plant operations and maintenance.

GT maintenance risk mitigation strategy

What constitutes a sensible and practical maintenance risk mitigation strategy? We think the following elements should be considered:

- Don't just read the LTSA/CSA fine print, write it! Owner/operators need to tailor the LTSA to their specific operating requirements. If possible, the LTSA/CSA should be reviewed, if not negotiated, by someone who has true expertise and intimate experience with these machines. Owners should absolutely, positively have an active and engaged feedback loop between the operations side of the house and the project development side. Our experience shows that this feedback loop is missing in many Genco organizations.
- What applies to the LTSA/CSA applies to all documents governing the relationship between the OEM and the owner/operator. Make sure you have an intimate understanding of the technical specifications the facility must abide by before you start running the machine. Also, make sure you are up to date on each and every revision set forth by the OEM.
- Install better fuel monitoring and fuel cleanup capability. Even in this, the so-called information age, power plants are inadequately equipped for monitoring and diagnostics. Consider having a reliable fuel-monitoring instrument installed. "Pipeline quality" gas is a term that people bandy about with little thought. Depending on where you are located with respect to the gas supply line, you may be getting slugs of unwanted hydrocarbons or moisture, which can devastate the hot gas path. Without an indication as such, the OEM can find numerous other reasons why something failed in the hot gas path. It is a process-engineering fact of life, but still woefully unrecognized, that fuel quality affects everything downstream.
- Monitor for things likely to go wrong. Humming or pressure pulsations in the combustor affect all advanced GTs to some degree. Progressive gas turbine

operators now install expensive, full-time, on-line instrumentation just to monitor pressure fluctuations. But the expense may prevent far more expensive routine and catastrophic damage to the machine. Likewise, monitor blade temperatures. While the sensors to do this are expensive and have short lifespan, they can indicate which blades are running hotter than others, suggesting blocked cooling passages, etc.

- Monitor exhaust gas temperature. Performance specialists concur that the measurement of GT exhaust temperature is the single weakest element in condition monitoring and is the one area for which investment in improved instrumentation is justified. Exhaust gas temperature profiles indicate problems with emissions, fuel nozzle problems, and general problems in the combustor.
- Destroy a blade—before it destroys you! Savvy GT owners now cut up in-service blades and even new ones and have their metallurgy thoroughly analyzed. Time after time, specialists have found that the OEM has mishandled the coating process—such as coating over oxidized blades, or just plain failing to use the proper coating materials. If you are facing a multi-million dollar "event" you need to know the condition of the blades *in advance*, especially if the OEM uses the common accusation, "operator error."
- Understand how the new technical specifications affect the project's finances. *This point cannot be stressed enough*. Many gas turbine and combined cycle project financials are not based on the latest maintenance experience. In fact, much of the fuel and operating flexibility once ascribed to these machines has evaporated under the heat of control and operating system changes in the technical specifications. Such changes have grave consequences for the financials of dispatchable and cycling machines! Consider the limitation on fuel alone: Power plants once had an economic ace against gas suppliers in that they could "switch" to fuel oil. No longer. The technical ability of these machines to fire distillate, and still meet performance, emissions, and durability goals, is greatly suspect now. Another limitation is that machines spinning on turning gear, waiting for the call to "go on-line," must now count these hours as the equivalent of two full operating hours when calculating rotor life because of rotor durability

> issues. Other OEM recommendations extend the time it takes to start up the unit. Such changes to the tech specs significantly impact the project's ability to make money in the on-peak market. For one thing, time between overhauls and inspection outages shrinks faster than was planned. Longer startup times means less time profiting from the on-peak rates..

And don't think of these suggestions in isolation either. Consider this real-world example: A facility experienced a flashback termed by the manufacturer as a "combustor system anomaly." Root cause proved to be liquid hydrocarbons in the fuel gas. A thorough review of the OEM design data indicated that a previously unnoticed clause had been modified in the latest version of the OEM's fuel gas specifications. The clause called for a minimum of 50F superheat in the fuel gas, as compared to the technical specification which called for only 20F superheat. Thus the OEM contradicted itself as well. The problem from the user standpoint was how to precisely determine the fuel gas dew point and thereby ensure that the superheat spec was being met. Testing done at this facility revealed that the industry standard fuel gas analysis produced dew point readings that were artificially low, resulting in a false sense of security. A more comprehensive fuel gas analysis, including higher order hydrocarbons was performed and this revealed *that the dew point of the fuel gas under normally fluctuating pipeline and ambient conditions can vary by as much as 100F*!

OEMs, in an attempt to minimize collateral damage caused by flashbacks or "combustion system anomalies," have taken steps to either detect the incident, or by means of control system or mechanical design changes, respond to it. However, on the most advanced of the GE combustors, the DLN 2.6+, the control system based detector is unavailable.

Another problem with no solution in sight is the rotor problem with the 7F and FA machines. In fact, the OEM appears to have resigned itself to never solving the problem. Now O&M recommendations include an unprecedented "rotor overhaul interval." The hot gas path components of any GT have always required overhaul at select intervals, but never the rotor! This may be a suitable technical fix for lingering design problems but it is not economically acceptable. Pro-formas did not account for the cost of a rotor overhaul interval, nor did the project's economics account for the weeks of downtime required to perform it.

Conclusion

Superior GT maintenance risk management will help determine how much money a gas turbine or combined cycle facility can actually make. In a recent document issued by DRI-WEFA, it is noted that "several other forecasting organizations have taken the position that [the spreads between on-peak and off-peak rates) will narrow dramatically. It is clear that these forecasts are premised on the assumption that combined cycle units will be able to cycle without incurring large maintenance expenses." The report continues, "Unfortunately, the engineering studies sponsored by WEFA have demonstrated that this opportunity does not exist. It is not possible to operate a combined cycle power plant as configured today and cycle it aggressively to pick off only the high value hours of the day. The result of such a practice—according to the operators we have surveyed—is to incur future maintenance costs in the amount of $30,000 to $50,000 for each time the unit is cycled. [These figures are] coincidentally the same ranges that EPRI reports for the cycling of coal plants. Over the course of only a month of operation, these maintenance costs could accumulate to millions of dollars."

Authors note on sources

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Asset Reliability for the Deregulated Electric Power Economy

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Asset reliability is becoming increasingly important for those power-generating companies facing lower margins caused by deregulation. These lower margins require the smart use of maintenance dollars to maximize the reliability and effectiveness of existing assets. Better utilization of operation and maintenance manpower will reduce costs and improve profitability. High reliability will turn performance rate issues into non-issues and allow plants to run more efficiently. In addition, the plant-wide asset reliability programs can help focus on inventory requirements, to reduce expenditures needed to replenish inventories and minimize costs associated with maintaining these inventories.

To enable the asset reliability program requires the use of a sophisticated set of analysis tools combined with an overall strategy that employs the results into everyday decision-making. These analysis tools include:

- Reliability modeling of systems and components
- Simulations for estimation and prediction
- Condition information combined with criticality in a risk model
- Accurate information about equipment, people, and processes that exist in the organization
- A single source of information for analysis, repair and decision making
- Automatic recognition and notification of high risk situations, based upon multiple data sources

This paper describes theses methods and the data required which are in use at various industrial sites. Examples using real plant data are combined with available possible maintenance options that give managers a way to make the best decision for a given situation and, in turn, optimize return on investment.

Introduction

What does the term "reliability" actually mean in the power industry? If you were to ask a power plant manager, he or she might tell you that it is a measure of forced outage rate. If you ask Maintenance personnel, they might talk about minimizing rework. If you asked the operators, they might refer to trouble free operation. If you ask the customers, it would most certainly be the continuous supply of power to their homes and businesses.

Does this mean that the measurement of reliability is different for all of these different types of people? Not necessarily. If we restrict our idea of reliability to simply mean "dependability", then all these different types of people can describe reliability as a probability of success (or failure). Most customers don't even think about the reliability of their electrical supply (until the lights go out), and then reliability becomes everybody's problem.

Understanding MTBF

There are many ways to estimate reliability parameters. One of the more popular ways is to count the number of failures that occur in a specified period of time. Dividing the period time by the number of failures leaves you with an estimate of Mean Time Between failures (MTBF). The reciprocal of this value is known as the Failure Rate. When calculating reliability in this fashion, you are immediately confronted with a problem: What is the definition of failure? Furthermore, what is the value of MTBF as a measure if the definition is not consistently applied? Some would argue that the MTBF measure is meaningless, yet we are constantly striving to improve this important, yet illusive concept. Other barriers to the successful use of this approach are the definitions that are applied. For example, we need to measure the reliability of the pumps in the plant, but the data that is available does not support the analysis. There have been 4 failures over the past year. All of these failures occurred between August 3 and September 25. There are a total of 30 pumps in my plant. What is the MTBF?

Several simple formulas are in popular use for the calculation of MTBF:

MTBF = Observation period / Number of failures

Or

MTBF = Observation period * Population / number of failures

Table 1 – The same situation, three different results

Case	Method used	MTBF	Comments
Case 1	Period time to be the time from the first failure until my last failure	MTBF =53 days/4 failures = 13.25 days	Pretty poor reliability
Case 2	Period time to be the calendar year	MTBF = 365 days/4 Failures = 90 days	Better than case one, but nothing to write home about
Case 3	Period time to be the calendar year, include all of the pumps in the population	MTBF = 365 days/4 failures * 30 pumps = 2700 days, nearly 8 years	Not bad, but is the answer useful?

But which one is right? Strangely enough, they are all correct. The answer is that the measure of MTBF, calculated using a linear estimation method, is not absolute. It can only be quoted in the context of the business issue that it is trying to address. If the business use is to understand repair frequency so as to optimize cost then perhaps I could use Case 1 to underscore the need for attention. If the business use is to show how effective my maintenance program is then perhaps case 3 is the most appropriate.

The calculated MTBF dilemma is solved with data, complete and detailed. By “complete” we mean no gaps in data collection (every failure has been accounted for). By “detailed” we mean that failure modes as well as failed parts are documented. In order to accurately measure reliability, the analyst needs failure data that covers at least one characteristic life of the assets being measured. Other methods for estimating reliability are the application of statistical models, such as Weibull Analysis and AMSAA Growth Modeling. These methods are quite flexible, but require some understanding of the behaviors of complex mathematical functions for the answers to be useful. These methods are explained later in the paper.

Reliability and Deregulation

In the past, plants generating units were dispatched based upon electrical demand. The order in which these plants were activated was simply based on heat rate. The lower the cost per kw-hr, the higher up the unit was in the dispatch priority list. Should a unit come down for an equipment failure, the next unit on the dispatch list would be dispatched.

In a deregulated environment, each piece of equipment involved in generation plays a greater role in the success of the plant. Plants can no longer look to other units with the system to “bail them out” in the case of equipment failure. Each unit within the plant must carry its own weight in order for the plant to be a successful supplier of wholesale power. Since each plant must now operate as a merchant plant, plant managers are driven to worry about what makes this piece or that piece of equipment able to do its job.

Measures and Benchmarks

Utilities have been using benchmarks for many years. These measures have been developed to a high level and are quite effective in helping utility managers control a regulated electric utility industry. Most of these benchmarks and performance indicators focus on two measures, Availability and Forced Outage Rate. These measures will remain important under deregulation but they will be joined by other important metrics such as, reliability, maintenance costs, capital costs and production capacity. While some power companies already manage to goals that involve these measures, it will become increasingly important for companies to have accurate, up to date measures available at all times. Since the basis for these measures are the costs and reliability experienced at the Asset level, managers will need a way to have access to data at the asset level.

Reliability Based Asset Management

Under deregulation, Reliability Based Asset Management (RBAM) will be more prevalent as more and more of the power plants become deregulated. Simply stated, the concept of RBAM is becoming widespread as these plants begin to operate as merchant plants, providing wholesale power to an unregulated marketplace. In order to conduct reliability based asset management, the life cycle costs and value for these assets need to be understood. An explanation of RBAM what this means: A 500 MW Unit, at 80% Availability will produce approximately 3.5 Million MW-Hrs, which has a wholesale value of between $150Million to $200Million dollars, annually. Critical assets that make up this unit are valuable enough to track consistently, as each component is critical to producing this revenue. Failure prediction and ultimate prevention of forced outages is and will be the goal for both current and future operating schemes.

Under a Reliability Based Asset Management strategy, plants do not manage to minimize cost, but to maximize value. The simple reason is that if we do not accomplish the mission, then costs (minimized or not) were wasted. In some cases high cost yields low value and in other cases, low cost yields high value. This would imply that there always exists some optimum. This is not always the case either. Sometimes the costs are simply the price of admission, they do not guarantee success. A successful asset management strategy should include an estimate of the criticality of the asset, remaining life of the asset and it's current and future probability of failure.

The short-term effects of improved reliability include lower costs and less "Fire-fighting", which in some cases is a welcome relief. Once maintenance needs have been met, operations now have become more stable, more predictable. Over time, design related problems come into greater focus. In the long term, design changes can be implemented that extend run times, further improve reliability and lower costs.

The cost benefits of RBAM for a power generation facility show up in several places, some are unexpected. The obvious categories for savings are improved production time (more uptime) and labor, materials and capital costs through the reduction of catastrophic failures. Some of the more unexpected categories are the savings associated with improved efficiency, which actually results in more, high value work contributed by operations and maintenance personnel. Through reliability, comes a better understanding of the causes and effects of equipment failure. A failure, once experienced and analyzed from the reliability point of view is more easily avoided in the future.

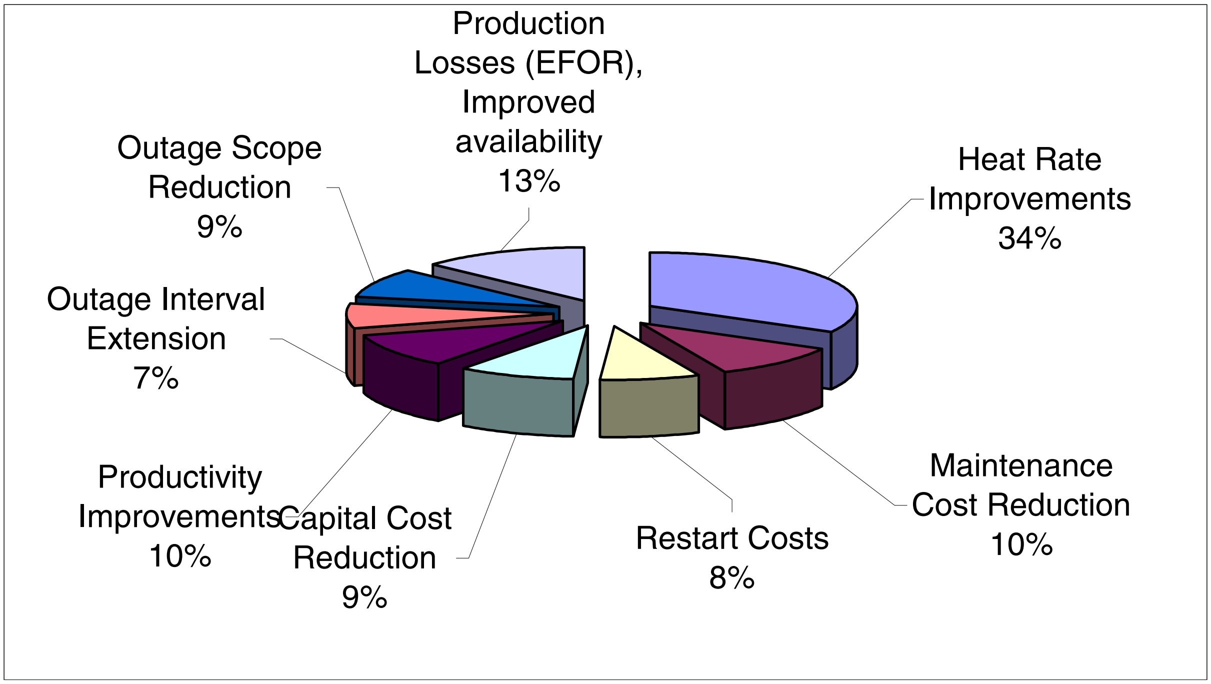


Figure 1 - Categories for Savings from Improved Reliability

Another significant area for savings is the impact of reliability analysis on planned maintenance outages. Reliability analysis results can identify work on equipment due to fail, but that would be otherwise overlooked. Additionally, reliability analysis can be used to defer work to a future date, reducing outage cost, scope and duration. This can improve operating availability for those units struggling to meet demand in a deregulated power market. Typical savings from reliability improvements for a medium size plant site range from $2-4 Million per year. The relative contribution each of these categories is shown in Figure 1.

In addition, savings can also be achieved in heat rate improvements. The reduction of forced outage events means less time spent in a transition state, which means lower average heat rates. With today's high cost of fuel, even small improvements in this area can yield big returns. A true cost benefit analysis must account for the incremental costs of analysis and repair activities. These costs, while easily justifiable and consistent with business goals, are often met with skepticism. The implementation of a plant-wide reliability improvement program often competes with other programs and initiatives. In this case, each project needs to be evaluated on the basis of its potential impact to profitability.

Reliability Based Asset Management Work Flow

In order to begin to conduct analysis in support of Reliability Based Maintenance, data needs to be extracted and analyzed. One of the key functions for this approach is to use the plant's existing data for analysis. When the data is not available or is not being collected, then estimates or industry data can be used until such time as appropriate data is collected. Among the various existing resources are:

- Plant Maintenance Data
- Inspection Records
- Operations records
- Outage plans from previous years
- Design and construction records
- Condition and performance data

Once all of these data sources have been reviewed and analyzed, a chronological history can be constructed. If RCM analysis has not been completed, then perhaps this is a good time to get started. Combining this information often leads to a decision about the reliability behavior of the equipment and opportunities for improvement.

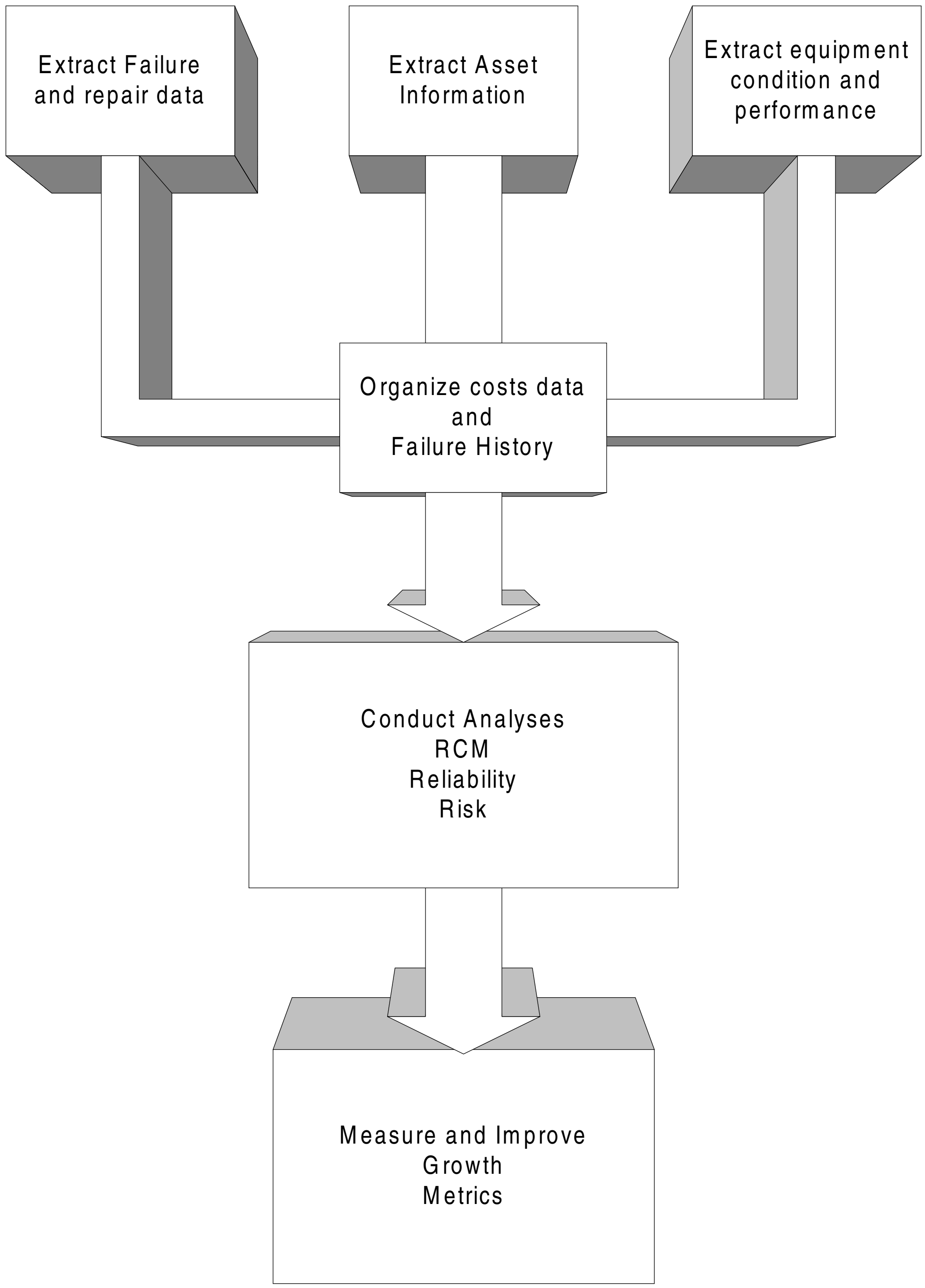


Figure 2 Reliability Based Asset Management Workflow

Tools for Reliability Based Asset Management

Many procedures and tools have been developed to fill the growing need for information based decision analysis. Among the more popular tools that are in use today for Reliability Based Asset Management are:

- Reliability Centered Maintenance (RCM)
- Component Reliability Analysis
- System Reliability Analysis
- Predictive Maintenance
- Risk Models

These tools and procedures are often implemented as computer software. A variety of software solutions are available in the marketplace to help plant personnel to analyze this data effectively.

Reliability Centered Maintenance (RCM)

RCM has the reputation of being tedious, complex and time consuming. This depends upon the level of sub component that one would wish to carry the failure mode analysis. A complete analysis would look at actual and potential failures for each sub-component (down to the nut and bolts!). Some people think that this is extreme and most practitioners would limit the analysis to the first sub-component level. Below is listed the general four step procedure used to carry out RCM Analysis.

Step 1 System Definition - Critical Asset Identification

System Based Approach

The system-based approach to RCM requires the practitioners to identify critical processes or units. A critical system is one that is defined as a failure of the system causes a failure of the production unit or process. To conduct a system analysis, the analyst needs to identify system boundaries that dictate which components belong to a system. In some cases, the system definition is simple and is limited by the physical boundaries.

Create list of equipment contained in the system

In order to determine criticality of the system, the analyst must understand what happens when system failure occurs:

- Does unit fail if system fails?
- Define System Function – What function does the system perform?
- Define System Criticality – Is the system critical for operation, can we operate the plant or circuit without this system? Does the system contain redundancies or back-ups
- Define Each Functional Failure – For each functional failure, describe ways in which
- Does system fail if a component in the system fails?

Component Based Approach

The component-based approach, specified in reference 2, looks at each asset within its operating context and attempts to answer the following questions:

- Is Failure hidden or evident?
- Does Failure cause safety problem or potential loss of life?
- Does Failure cause environmental problems?
- Does Failure cause loss of production?
  Determine component criticality - Does production unit fail if the component fails?

Step 2 RCM Failure Modes and Effects Analysis

The next step in Reliability Centered Maintenance is to conduct a failure modes and effects analysis (FMEA). The Failure Modes and Effects Analysis is a powerful tool that helps analysts to understand what causes failure and, more importantly, what happens when certain types of failures occur. Many advanced maintenance strategies employ this methodology for thinking through potential problems. In some cases, the identification of critical failure modes can be addressed by changes in design. In other cases, a regular material replacement strategy is most cost effective at preventing failures.

To conduct the FMEA For each component contained within the system, the analyst needs to answer the following questions:

- What are the functions and associated performance standards of the asset within its present operating context?
- In what ways does it fail to fulfill its functions?
- What causes each functional failure?
- What happens when each functional failure occurs?
- In what way does each functional failure matter?
- What can be done to prevent each failure?
- What if a suitable preventive task cannot be found?

When conducting an RCM analysis using software, the answers to each of these questions are represented as fields in a database, filled out by the RCM practitioner. This table is then related to the asset or system for which the analysis was conducted.

Step 3 RCM Task Development

Once the FMEA has been completed, the analyst has two analysis options for selecting RCM Failure Mitigating Tasks: System Based Analysis or Component Based Analysis. For system-based analysis, the analyst needs to develop tasks that only preserve system function. This approach assumes that redundant equipment, contained within a system, are not critical with a "run to failure" strategy applied. For component-based analysis, the analyst needs to develop tasks that will mitigate or diminish the effect of the failure mode identified with FMEA.

Both approaches result in the specification of a task type. The task types for this analysis are as follows:

Scheduled On-Condition Task
Scheduled Restoration Task
Scheduled Discard Task

RCM Task Definition

For each failure mode identified, a task needs to be developed that conforms to the following criteria:

Will the task effectively mitigate the failure?
How often does it need to be performed?
Is it worth doing?
What is the cost?
What is the benefit?

Each RCM task is subjected to the above reasoning to ensure that improved reliability goals and reduced costs are met.

Step 4 RCM Task Comparison

At this point, the analyst needs to compare existing tasks with PM Tasks that already exist for the equipment under study. In some cases, existing tasks may be part of the maintenance of the equipment. The RCM analysts recommend adding new tasks or modifying existing tasks. Analysts may delete existing tasks, provided that they proven to be ineffective. To know if a particular task has been effective an analysts need only review past work order data.

To facilitate RCM Analysis, work order data, asset data, functional location data, reliability analysis, condition analysis, FMEA and RCM task development need to be brought together into a single computing environment. The following discussion describes how the reliability analysis is conducted.

Component Reliability Analysis Methods

The Weibull Distribution probability gives an estimate of the probability of failure as a function of based on lifetime or time in service. The formula for a two parameter Weibull can be written as:

$$P(f) = \exp[-(t/\alpha)^{\beta}]$$

Where, α is the Scale Parameter and β in the Shape Parameter.

This distribution is used when the failure rate of the equipment under study changes as a function of its lifetime. For failure modes that have an infant mortality failure pattern, the failure rate is high early in life and improves with age. Failures with an infant mortality failure pattern do not respond to a preventative strategy for maintenance. These failures are usually related to poor parts quality or inadequate repair procedures. Infant mortality is signified by a Weibull shape parameter (β) of less than 1.

To understand the expected life of equipment, distribution analysis can be used to model the expected life of the equipment based upon the actual experience of the plant. These answers may differ from the manufacturer's expectation. By performing this analysis, these plants can predict failures and implement corrective tasks before failure can occur. This reduces or eliminates the production downtime, safety hazards and environmental cleanup normally associated with in-service failures.

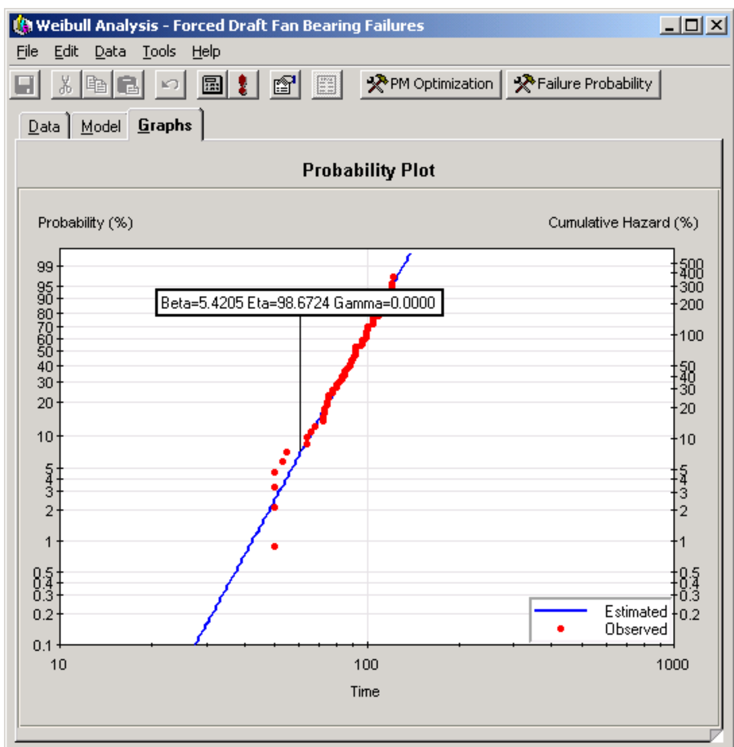


Figure 4 - Weibull Analysis of Failure Data

Using an enterprise reliability management system, these plant personnel compare equipment of different types, from different manufacturers to under stand the pattern of failure. Variations in reliability related to design, installation quality and operation all have a different pattern of failure, which can be easily identified using the Weibull Distribution.

Statistical methods also allow us to understand not only why equipment has failed, but also helps us to understand the failure mode. Did the parts fail in a "break-in" mode or did they simply wear out? Do the failures occur at random and do the machine meet manufacturer's expectations for mean life? Analysis of the failure data answers all these questions and, in the process, improves the overall reliability of equipment at these facilities.

AMSAA Growth Analysis

Growth can be used in cases where the failure mode is unknown or failure rate is changing over time. Growth analysis conducted on a set of failure data is also used to predict the time until next future failure. Figure 5 shows a Growth plot, which gives cumulative failures vs. cumulative time. A second plot in Figure 5 shows MTBF vs. Cumulative Time, which gives and indication of reliability improvement or deterioration over the specified analysis period. When MTBF Plot has a positive slope, reliability is improving. A negative slope implies that reliability is getting worse.

Growth gives a good estimate of the current MTBF (failure rate) and can tell the user if reliability is improving or declining. Unlike Weibull, Growth models can include data from various failure modes and is a good alternative when the failure causes are unknown. Growth models parameters can be used in forecasting failures. Growth is particularly useful when trying to gauge the effect of a reliability improvement program such as Reliability Centered Maintenance (RCM) or when extensive capital improvements have been made to an area of the plant.

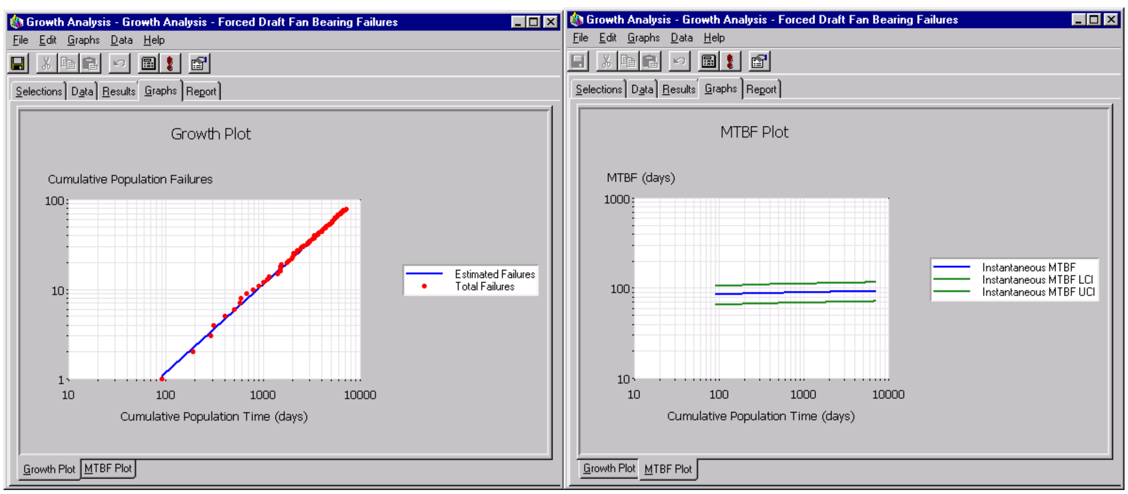


Figure 5 Growth and MTBF Plots

System Reliability

System Reliability (also called RAM Analysis) combines the reliability of individual components into a mathematical model that can be used for prediction and simulation. RAM stands for Reliability, Availability, and Maintainability. The prediction element of a RAM Analysis can give the user estimates for the reliability (probability of failure) of a system. In addition, availability, expected downtime and expected costs for the system are also provided.

System Reliability involves the combining of the reliability parameters and also taking into account the configuration of the equipment in the system. Items configured in series will have a lower overall reliability than items that are configured in parallel. Each plant system consists of a start node, one or more components configured in a network and an ending node. Systems can be made up of the subcomponent parts of an asset or can be groups of assets that make up a system in a plant or even an entire production unit. An example of a reliability model for a combustion air system is shown later in this paper.

A system reliability analysis results in an estimate of “mean time between failure” (MTBF) for the system as a whole. Because the system is made up of the reliability parameters of the subcomponent parts, a user can simulate the effects of changes to those parts on the reliability of the system as a whole. The “probability of mission success” is defined as the probability that the system will survive without failure for a given mission time.

In order to estimate the number of component and system failures that will occur in a given period in the future, some modeling programs use Monte Carlo simulation. This simulation can be run on any system to give the estimates for downtime, lost production cost and availability. Does a particular maintenance activity actually improve the reliability of the system? By manipulating the model parameters such as component MTBF, last repair date, or even the configuration of components, one can get a feeling for the sensitivity of the model to each change. This will focus the maintenance effort to those areas of a plant that actually improve reliability.

Predictive Maintenance

Another powerful method that is used as a Reliability Based Asset Management strategy is to periodically inspect equipment for signs of deterioration. RCM Tasks designated, as “Scheduled On-condition tasks need a condition inspection in order to trigger the on-condition task. Many have employed the application of predictive maintenance methods for plant equipment. Among the more popular technologies in use used are:

Vibration Monitoring –with vibration sensors, mounted at or near the bearing of a rotation machine, maintenance technicians use specialized electronic devices to detect faults within the running machine. Dynamic unbalance, misalignment, bearing wear, coupling problems, gear wear and bent or broken parts can all be detected using vibration analysis techniques.

Lubrication Oil Analysis – samples of the lubrication oil circulating within a machine can be analyzed for wear particles contained within the sample. These samples are taken while the machine is running and are sent to laboratories for specialized analysis. Small pieces (less than 5 microns) of ferrous or non-ferrous particles at low concentrations are considered normal wear. When small particle concentrations increases dramatically or larger particles (greater than 50 microns) are detected, serious machine wear is indicated.

Infrared Imaging requires the use of an infrared camera to detect areas of abnormally high temperatures. These images provide a two dimensional view of the temperature distribution of plant equipment. This technology is particularly effective for electrical equipment because a key failure mode for high voltage equipment is the corrosion of contacts and deterioration of high voltage connections. Prior to failure, elevated temperatures are experienced at or near the connections.

Ultrasonic Leak Detection – like vibration monitoring, ultrasonic leak detection uses specialized electronic transducers to measure the presence of ultrasonic energy (between 20 and 200 kHz) indicative of leaks in pressurized systems. Additional applications for ultrasonic measurements are the detection of bearing faults in rotating machinery and partial discharge arching in high voltage equipment such as transformers.

Electrical Measurements – electrical testing of electrical components such as electric motors, drives, switchgear, transformers and circuit breakers can give indication of insulation breakdown within the components. Insulation resistance measurements are made phase to phase and phase to ground to check for deterioration. Polarization index and DC Hi-pot checks the dielectric strength of the insulation. Current modulation is also checked on electric motors to reveal broken rotor bars or high resistance connections.

Statistical Treatment of Diagnostic Data

One of the challenges in using this data to make decision on maintenance is relating the severity of a measurement to the severity of the fault. Often experience will dictate at what severity level should action be taken. A difficult question is: “How much is too much?” The answer to this question may lie in statistical distribution, specifically Weibull Analysis. If we were to extract the diagnostic data just prior to a failure of a class of machinery, we could construct a Weibull Plot of severity vs. Probability of failure. For example, the horizontal axis of the Weibull plot would give the severity of the measured parameter, while the vertical scale would give the probability of failure based upon the measured value, as shown in Figure 6 below.

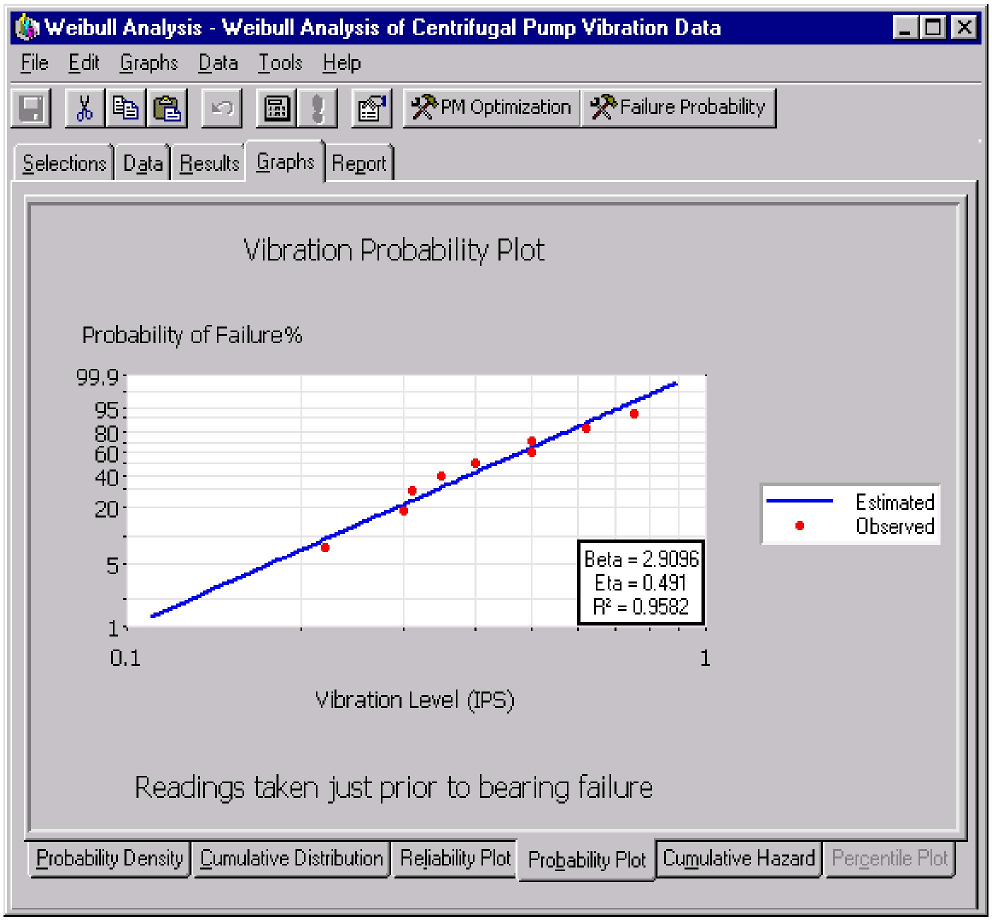


Figure 6 – Weibull Analysis of Vibration Data

In order for the Weibull Analysis shown above to be valid, two conditions must exist:

1. Readings were taken just prior to failure.
2. Bearing wear caused the excessive vibration.

Similar graphs could be built for other types of diagnostic monitoring techniques and is especially useful when no severity criteria are available for the particular diagnostic technology; such is often the case for oil analysis particle counts, and some electrical measurements.

Risk Models

Risk is defined as the consequence of failure combined with the probability of failure. The RCM Methodology described in the section above describes a way to generate consequence of failure on an asset or system basis. Through failure modes and effects analysis (FMEA), the consequence of failure is understood. Through component reliability analysis and predictive maintenance, probability of failure can be estimated.

Risk calculations are embedded in a methodology called Risk Based Inspection (RBI) popular in industry today. The risk levels (criticality ratings) are color coded, with the highest risk are shown in red, with values 1-5. Medium high values (6-12) are shown in pink. Medium values (14-19) are in yellow and Low values are in green (20-25).

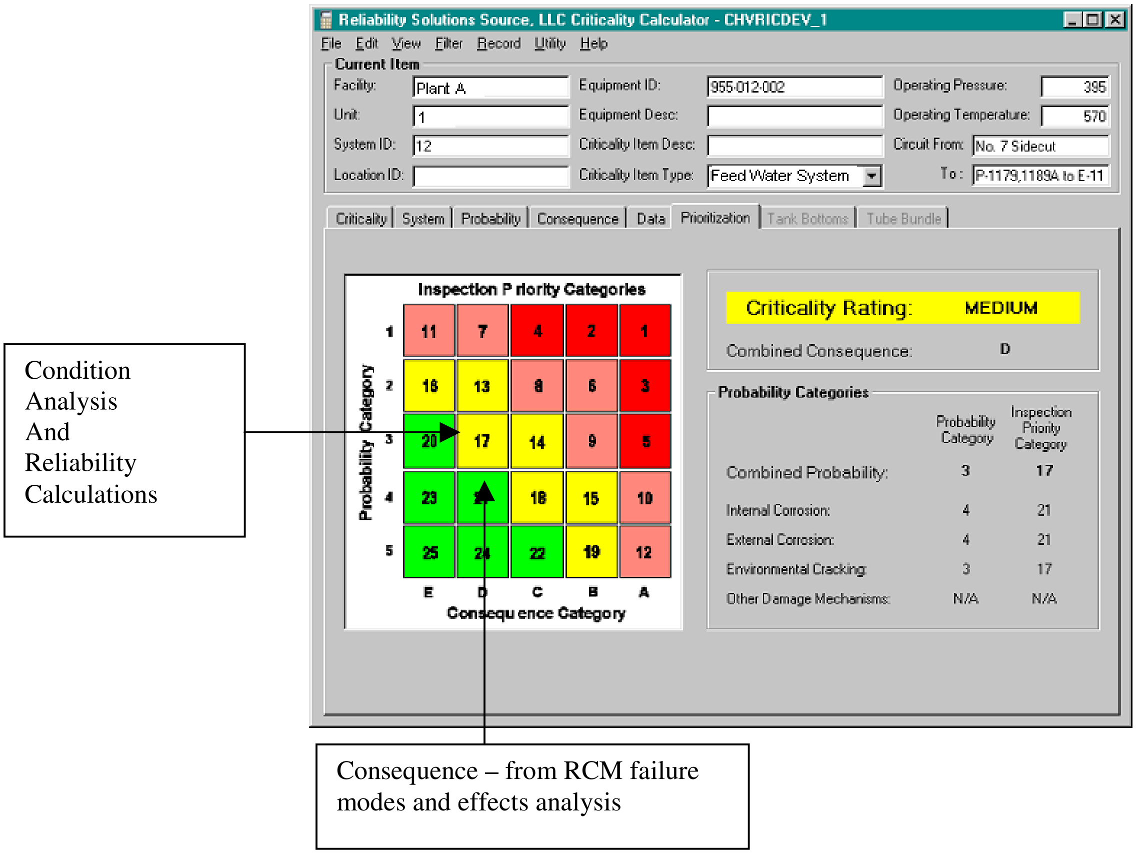


Figure 7 Example of a Risk Model

The same logic used for inspection can also be used for equipment maintenance. Combining information from predictive technologies with reliability and criticality gives an estimate of the current risk of failure. In this case the risk is not high enough to call for a shutdown, but as the condition further deteriorate, a shutdown can be scheduled if the risk value decreases to 13 or even 7. Please note that the equipment in this equipment will never result in a criticality rating of greater that 7.

Examples and Case Histories

Case History #1:

Component Reliability Analysis Example - Boiler Feed Pump Seals

Description of the problem: Excessive failures on Unit 4 Boiler Feed Pump, 12 failures over a two-year period. What are the causes of these problems and what should be done?

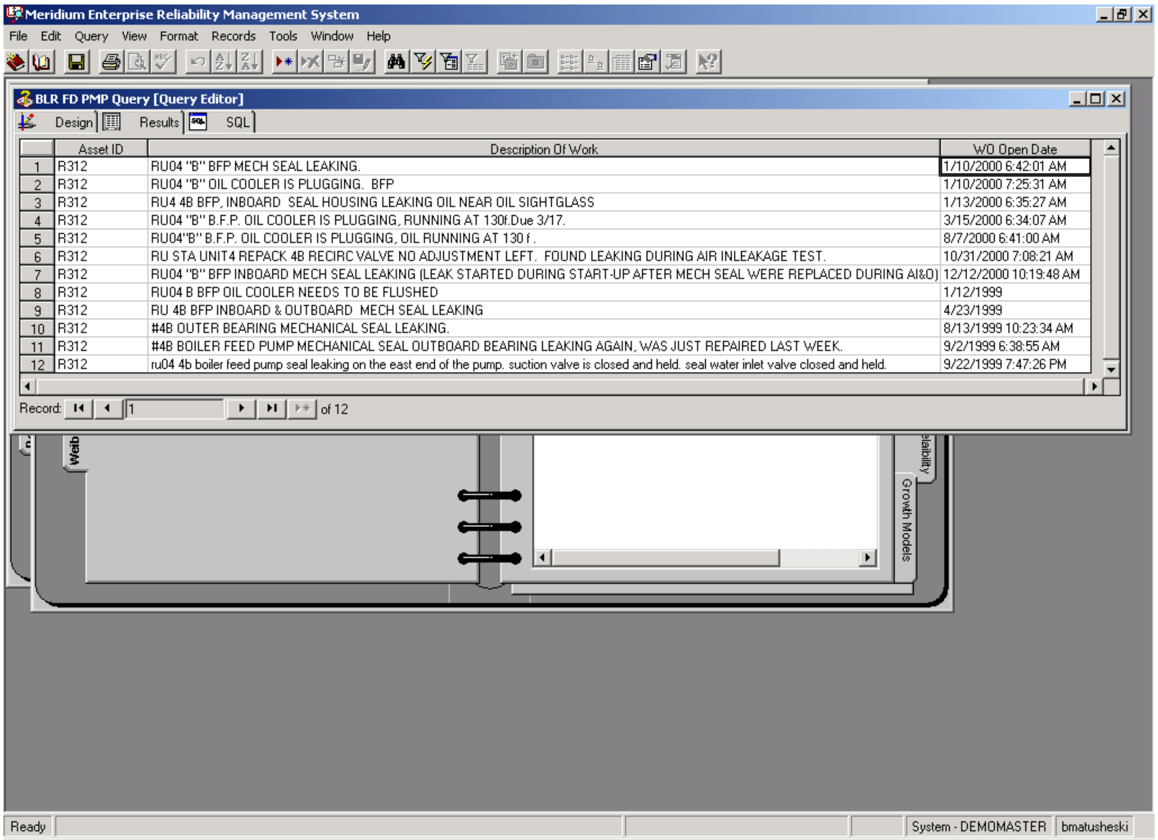


Figure 8 - BFP Work History

The failure history over a two-year period shows that 12 events on this piece of equipment in a two year period. Examination of the data shows two predominant failure modes: mechanical seal leakage and oil cooler fouling. Extracting just the seal failures and building a Weibull analysis gives an MTBF of 191 days and a Weibull shape parameter of 0.5, see Figure 9 below.

Interpretation of Results

MTBF of 191 days means that the seal maintenance on this pump will need to be conducted twice per year. The Weibull analysis beta of 0.5 indicates a strong infant mortality failure mode. Poor quality replacement parts or improper installation procedures most often cause this. Management will need to investigate this further to find the cause. Some questions to ask:

- Does a written procedure exist for the replacement?
- Has this procedure been followed?
- Are the failed seals still under warranty?
- Have the seals been checked for quality prior to acceptance?

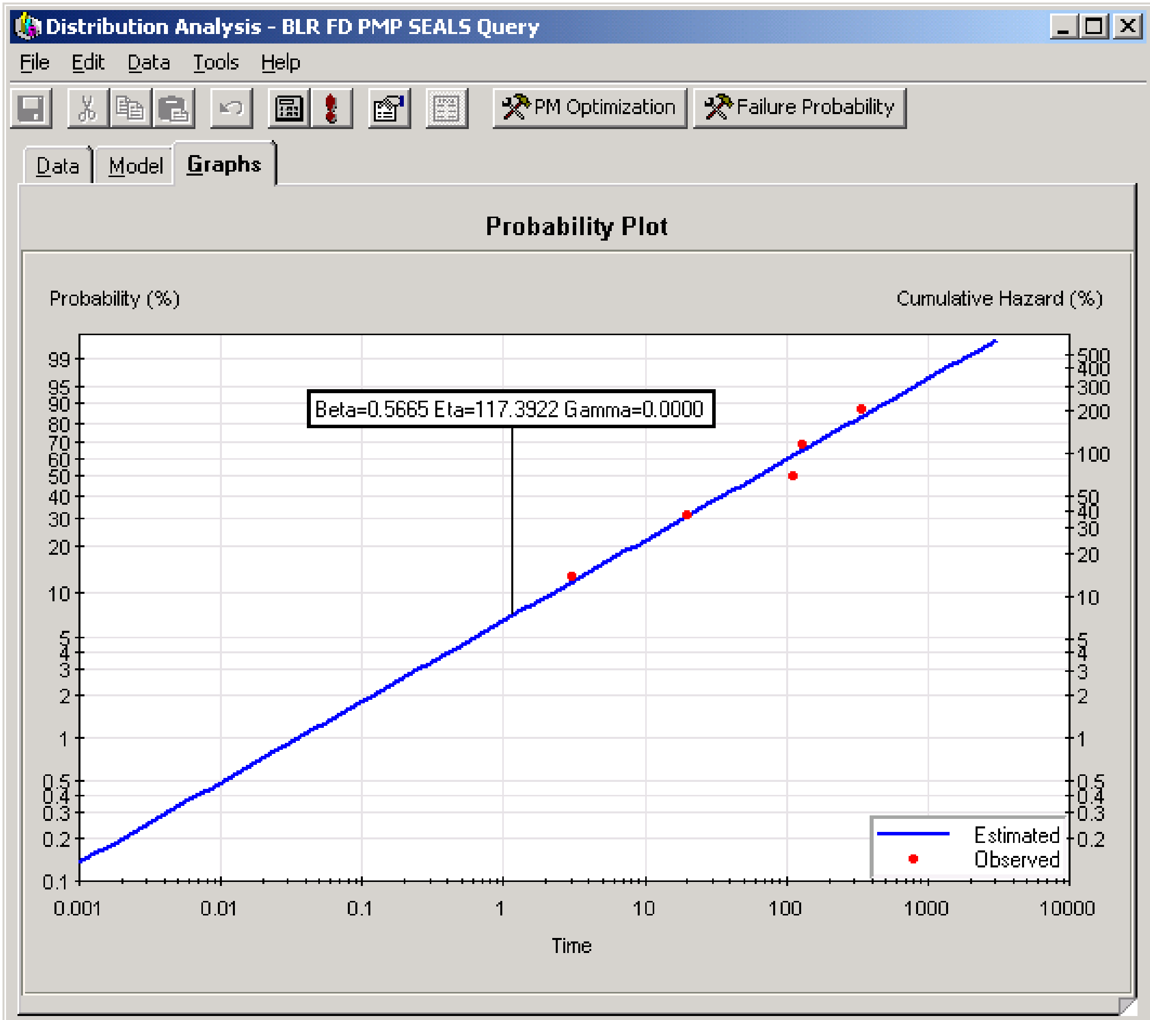


Figure 9 Weibull Analysis of Boiler Feed Pump Seal Failures

Case History #2

System Reliability Analysis Example
Combustion Air System

Description of Problem: Past history shows the Unit 1 Combustion Air System has been the source of several shutdowns and de-rates. Plant management wants to upgrade the reliability of the combustion air system during the next planned. Which component (s) should be upgraded, repaired or replaced to improve the reliability of this system? How much will the system cost if the plant (a) Does nothing, (b) Rebuilds the fans and motors only (c) Rebuilds on all components

The first step in addressing this problem is to assemble a list of components contained within the system. Once this is completed, the components are assembled into a system by connecting them. When this is complete a Reliability Block Diagram can be viewed. (See the picture on the right in figure 10, below)

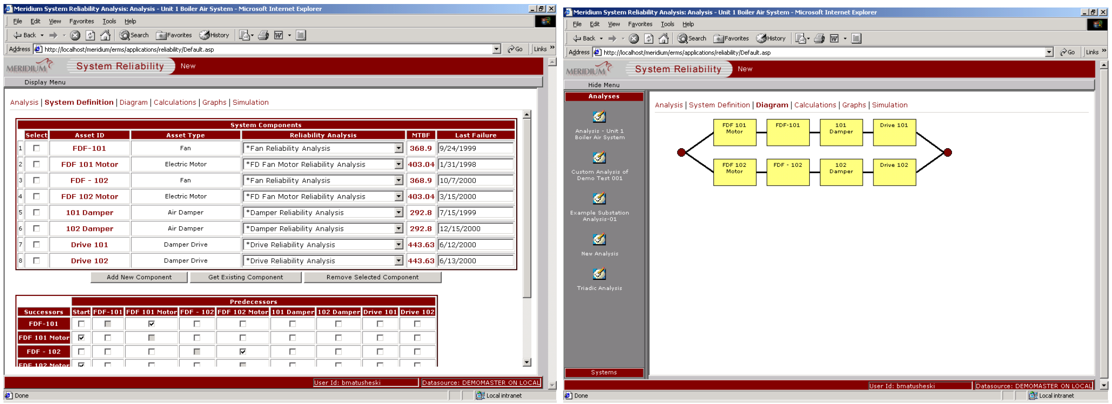
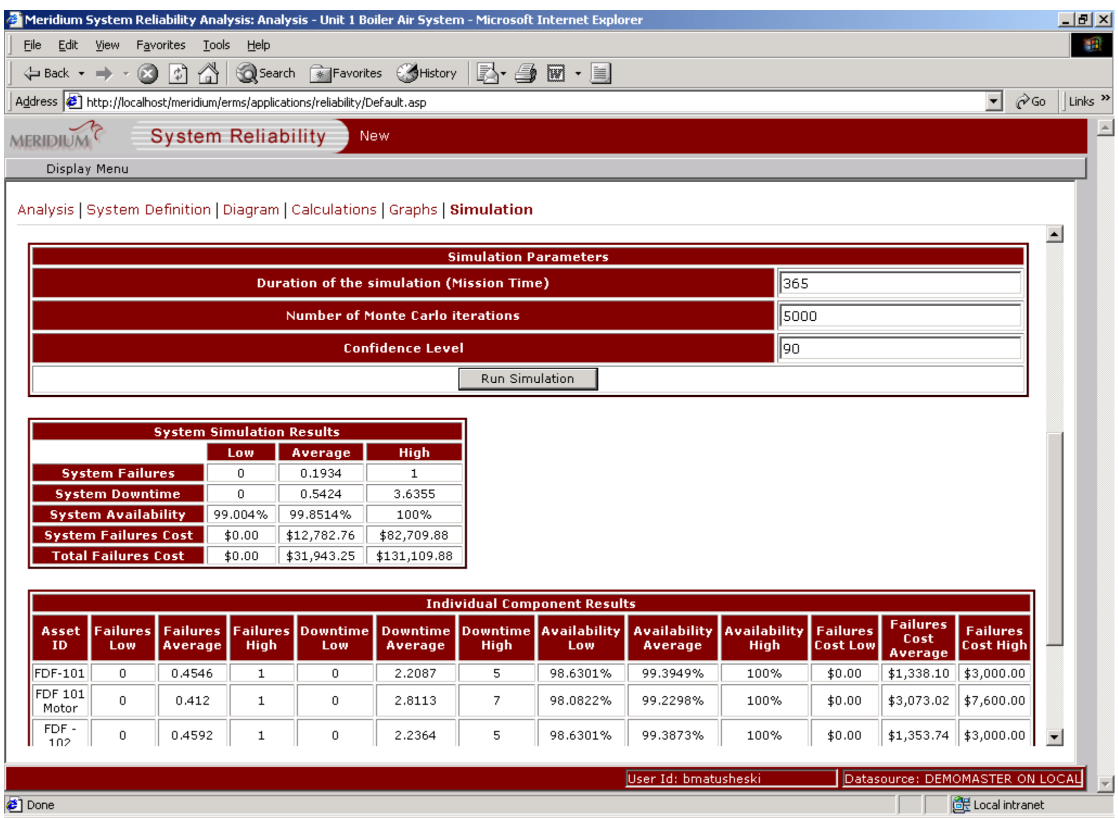


Figure 10 System Definitions and Reliability Block Diagram

System Reliability Analysis Results

This system in its current system has a MTBF of 45 days and probability of making a 1-year run without failure is 0%. Over the next year, the total system repair costs will be $107,475 and could be as high as $285,687 including lost production. Rebuilding the only fans and motors raises system MTBF to 101days but probability of a successful 1 year run without failure is still less than 1%. Rebuilding all components brings system MTBF up to 276 days with chance for a success one year run up to 11%. Total system failure costs are expected to be less than $35,000 over the coming year. To improve the system further would require the upgrade of more reliable components.



Simulation Parameters	
Duration of the simulation (Mission Time)	365
Number of Monte Carlo iterations	5000
Confidence Level	90

System Simulation Results	Low	Average	High
System Failures	0	0.1934	1
System Downtime	0	0.5424	3.6355
System Availability	99.004%	99.8514%	100%
System Failures Cost	$0.00	$12,782.76	$82,709.88
Total Failures Cost	$0.00	$31,943.25	$131,109.88

Asset ID	Failures Low	Failures Average	Failures High	Downtime Low	Downtime Average	Downtime High	Availability Low	Availability Average	Availability High	Failures Cost Low	Failures Cost Average	Failures Cost High
FDF-101	0	0.4546	1	0	2.2087	5	98.6301%	99.3949%	100%	$0.00	$1,338.10	$3,000.00
FDF 101 Motor	0	0.412	1	0	2.8113	7	98.0822%	99.2298%	100%	$0.00	$3,073.02	$7,600.00
FDF - 102	0	0.4592	1	0	2.2364	5	98.6301%	99.3873%	100%	$0.00	$1,353.74	$3,000.00

Figure 11- Monte Carlo Simulation Results with all components repaired

Conclusion

Reliability based asset management strategy is becoming more important than ever. A deep understanding of the reliability, risk and how they can effect production has never been more important. As the power industry continues to be challenged with issues surrounding deregulation, managers will need a singe source of data integrated with a high level of automation. RBAM requires the integration and automation of data sources so that decisions can be based on value, not cost. In order to operate successfully in a deregulated environment, power plants will need to manage the reliability of their generating assets.

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BOILER RELIABILITY OPTIMIZATION

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Co-author: Patrick Abbott, EPRI

ABSTRACT

Boilers, including all boiler auxiliary plant, in the United States of America and Canada still remain the major cause of Unit outages. EPRI (formerly the Electric Power Research Institute), in conjunction with a member utility has developed a ***Boiler Reliability Optimization process*** that, when successfully implemented, ***will assure and sustain an improved reliability and reduce boiler and auxiliary plant maintenance costs***. This process has been implemented at four separate utilities in the USA. This paper describes the approach taken, some of the results achieved and lessons learnt. The process uniquely combines and integrates a number of EPRI's products into four distinct phases - a condition assessment, failure defense plan development, defense plan implementation and validation/verification.

The purpose of the ***first phase*** is to establish the status of the management support systems and the condition of the boiler components/systems that need improvement. Industry norms are used to benchmark the data sources, work processes used, the organizational structure to manage the data/information collected and the causes of boiler unavailability.

The ***second phase*** deals with the development of a ***Boiler Failure Defense Plan***. Various root cause analysis and condition assessment techniques are used to develop the plan. Boiler tube and header failure mechanisms and their root causes are discussed, together with appropriate inspection techniques and prevention measures. Maintenance tasks are reviewed and optimized using EPRI's Streamlined Reliability Centered Maintenance software package. From this information a Failure Mechanism/Cause/Preventative Measure Matrix is developed which is used as the basis of a failure defense plan. A risk-based model for outage task evaluation and prioritization is explained using examples. The model is intended to create a means to make business decision on outage activities associated with the boiler using information on the condition of the various boiler components and the task's financial impact.

The ***third phase*** deals with the practical aspects of boiler inspections - dirty and clean and the implementation of the boiler failure defense plan. It also discusses the merits of the various predictive maintenance technologies and how they are applied in an Equipment and Technologies matrix and a Plant Condition Status Report. NDE and data mapping techniques used are also explained.

The ***fourth phase*** covers a the role of operation achieving low cost reliability, continuous improvement cycle, multi-functional monitoring processes, critical component condition indicators and the evaluation of long term plant health indicators. It focuses on how the operations group can add value to the process by using the additional information presented to them when performing routine monitoring tasks.

INTRODUCTION

In the United States and Canada, boilers, including boiler auxiliary plant, still remain the major cause of unit outages. They account for about half of the unavailability loss. Unit performance levels are dropping off and Equivalent Forced Outage Rate (EFOR) is increasing. These forced outages are short, three to five days, but frequent, resulting in reduced plant reliability. Many of these outages are caused by boiler tube leaks.

Deregulation and competition has brought on a new management culture, that of bottom line focus – generating megawatts, and sometimes at all costs. The pressure from top management to generate megawatts and cut costs is enormous. To achieve this a number of strategies have been implemented, one of which is down-sizing. While reducing staff may save some money, this is usually not the tactic that gives the greatest benefit. The greatest benefit comes from reducing fuel costs, improving heat rate, and improving reliability. Plants must be consistently capable of producing power in an economically reliable manner. Emphasis must be put on long-term sustainability.

EPRI recognized all of the above reasons for boiler unavailability developed a Boiler Reliability Optimisation Program to assist utilities to improve boiler reliability, and to reduce maintenance costs. Each Boiler Reliability Optimisation Project within this Program would be customized to address the specific needs of that utility, and is intended to include but not limited to the following:

- ♦ Steam and water system (economizer inlet through the finishing superheater including steam temperature control) – Tubing and Headers
- ♦ Air and gas system (forced draught fan inlet through the induced fan outlet including dampers and control loops)
- ♦ Fuel system (coal bunker outlet through the coal burners excluding the pulverizers)
- ♦ Pulverizers (primary fan inlet through pulverizer including fuel and air controls)

EPRI published a request to all members, asking utilities to participate in the program. Some utilities accepted the offer, and are participating in this program at present.

BOILER RELIABILITY OPTIMIZATION

What is it? ***Reliability*** is a measure of maintenance effectiveness as opposed to ***availability,*** which, in its simplest form, is up-time divided by total time period. The relationship between reliability and maintainability is synergetic. Reliability is the probability that equipment will perform its prescribed duty without failure for a given time when operated correctly in a specified environment. ***Maintainability*** describes the time required to carry out the required maintenance/repair to keep this equipment functioning. Therefore, improving either reliability or maintainability will improve availability. Boiler reliability optimization is about improving both boiler reliability and maintainability, i.e. lengthening the time between failures or to manage the risk of failure better and shortening the time taken to do the maintenance. To achieve this, a number of EPRI-proven technologies and methodologies were uniquely integrated into a single program, Boiler Reliability Optimisation.

The technologies/methodologies that were integrated are:

- ♦ Root Cause Analysis
- ♦ Streamlined Reliability Centered Maintenance (SRCM)
- ♦ Boiler Tube Failure Theory and Practice
- ♦ Cycle Chemistry Improvement Program
- ♦ Predictive Maintenance Guidelines
- ♦ Non-destructive Evaluation (NDE) Guidelines for Fossil Plants
- ♦ Condition Assessment Guidelines

PHASES OF THE BOILER RELIABILITY OPTIMISATION PROJECT

Each Boiler Reliability Project consists of four phases, involving EPRI technical staff, with participation from the plant's operating, maintenance and engineering support staff. The phases are:

1. Technical and Organizational Assessment
2. Development of the Failure Defense plan
3. Implementation of the Failure Defense plan
4. Continuous improvement and process automation

Phase 1 – Technical and Organizational Assessment

This assessment sets the stage for the rest of the program, identifying the technical and programmatic risks and offering appropriate corrective actions. Plant databases and historical information is reviewed; organizational and technological capabilities are studied. Boiler inspection plans are scrutinized and the current maintenance strategy on the auxiliary plant is reviewed for effectiveness.

The objective of this phase is to determine the effectiveness of the current management processes that are used to manage boiler maintenance. Effectiveness means different things to different people. Operators, maintainers and engineers may hold different views; each view undoubtedly has validity for the person holding it. A common belief is that the central question is 'Are we achieving our objectives?' This is only one among a number of critical factors that are essential to a meaningful understanding of effectiveness. Effectiveness contains subjective, value-laden components that will change with time and with viewpoint. Forming judgements about effectiveness often involves weighing multiple, competing and sometimes contradictory objectives and measures. Research has shown that there are certain attributes that are important to the understanding of effectiveness. These attributes are:

- ♦ Management direction
- ♦ Relevance
- ♦ Appropriateness
- ♦ Achievement of intended results
- ♦ Acceptance

- Secondary impacts
- Cost of Productivity
- Responsiveness
- Financial results
- Working environment
- Protection of assets, and monitoring and reporting

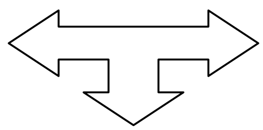
Some of these attributes of effectiveness are used during this assessment phase to determine the effectiveness of systems used to manage boiler maintenance and long term health.

The Technical and Organizational Assessments reviews a number of areas – benchmarking activities against best practice to determining opportunities for improvement. In addition to these assessments, root cause analysis of a number of incidents/failures is done and the results are trended to help focus the problem resolution effort**. *Root cause analysis is a logical process and is a core activity to a successful optimization process.***

Figure 1 identifies the topic and Figure 2 shows the results of an Assessment performed.

Plant

- Physical condition of boiler
  - Plant walk down
- Boiler performance
  - Availability
  - Load factor
  - No. of tube leaks/year
- Performance monitoring
  - Efficiency tests
  - Pulverizer tests



People

- Technical resource development
  - Skills and experience
  - On-job training
  - Specific training

Processes

- Business objective setting
  - Key performance indicators
- Roles and responsibilities
- Communication
- Work load planning and control
- Change management
- Maintenance strategy
- Operating practices
- Outage management
- Life cycle management

Figure 1

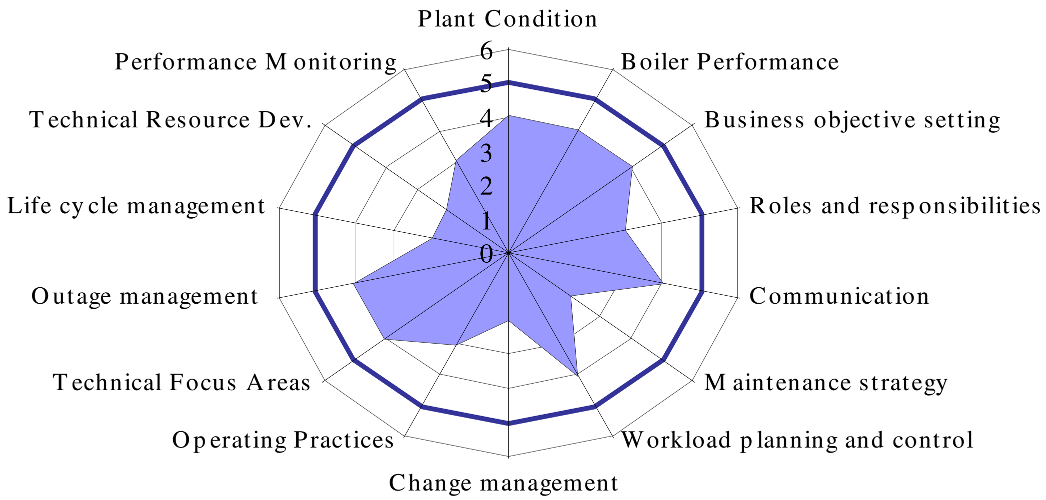


Figure 2

Phase 2 – Development of the Failure Defense Plan

A Boiler Failure Defense Plan is largely dependent on the findings of the Technical and Organizational Assessment Report. A typical plan would make provision for the following activities:

- Establishment of goals based on improvement potentials in each controllable cost area.
- Development of a number of Long Term Plant Health (LTPH) indicators. Measuring the effects of the current operating practices is an important. By using a number of indicators, plant management is able to get some useful pointers to highlight sub-standard operating practices.
- Analysis of auxiliary equipment/component maintenance strategies, using EPRI's Streamlined Reliability Centered Maintenance (SRCM) methods to develop a balanced maintenance strategy. SRCM is a process to determine what maintenance should be carried out to ensure that any physical asset continues to fulfill its intended function in its present operating context.
- Analysis of water- and steam-touched surfaces using EPRI's Boiler Tube Failure Reduction (BTFR) program, NDE and Condition Assessment Guidelines. The BTFR program is a management system that ensures all failures are systematically recorded and analyzed for root causes. This requires awareness by plant staff with supportive investigation activities from contractors and technical experts. An integral part of the program is the on going inspection and test plan activities during a boiler outage. This consists of visual inspections

for tube-metal wall wastage and detachment of tube, wall thickness measurements (UT), replication of the microstructure and physical removal of samples for further analysis. Once the specific failure mechanism has been correctly identified, a structured approach is used to identify causes of failure and their appropriate preventive measures – short and long term. This information is collated into a matrix as shown in Figure 3 (at the end of the paper). This forms the bases of a Failure Defense Plan for the boiler pressure parts.

♦ Application of EPRI's Boiler Maintenance Workstation (BMW) software for the tracking of information on boiler tube leaks. BMW is a Windows based computer program for trending boiler tube failure, correction, and prevention and control actions. It helps plant personnel to minimize boiler tube failures and reduce maintenance and inspection costs..

♦ Application of EPRI's Cycle Chemistry Improvement Program (CCIP). The CCIP assists utilities to identify the causes of equipment corrosion and deposition problems and to implement an effective cycle chemistry program.

♦ Application of a task Risk Evaluation and Prioritization (REAP) model to streamline outage work scopes to achieve maximum value with limited funds. This model is used to improve decision-making and the prioritization process, regarding outage activities. It makes use of information on the condition of the equipment and on the equipment task's financial impact. The model assigns a dollar value to the individual tasks to be performed. This derived value is then plotted against the cost of performing the task. From this plotted information, decisions on the combinations of tasks that will give the maximum value for the available funds can be made.

Figure 4 shows a plot of Value vs. Cost of outage activities to be performed. Recognizing, that building an outage scope of work entails selecting the highest value lowest cost activities first.

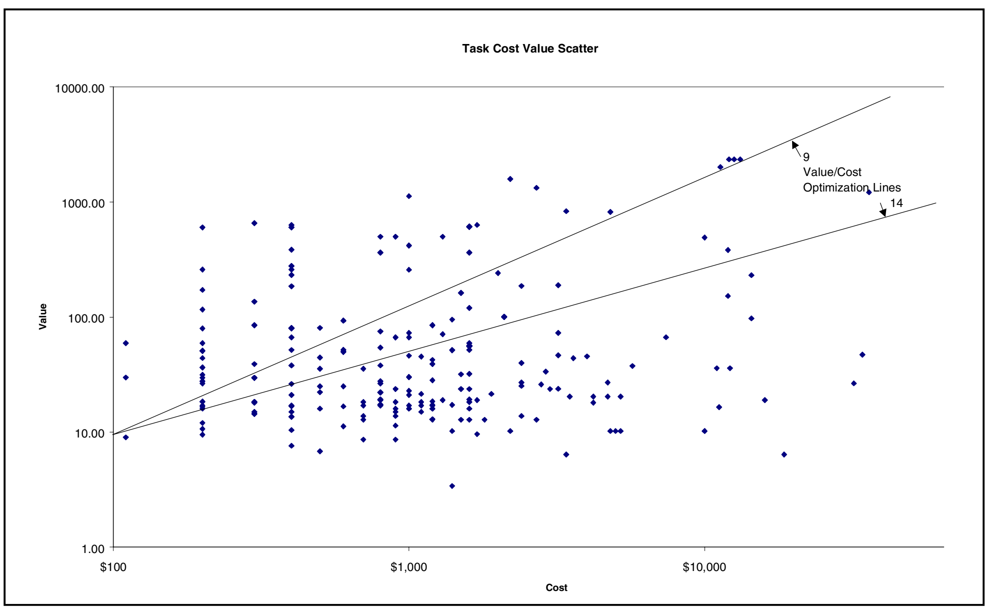


Figure 4

Figure 5 represents the accumulative value for task cost and value and the number of tasks. The shape of this curve shows that the value builds quickly until a point is reached where achieving further increases in outage value requires substantially more funding. A smaller portion of the outage costs can fund the majority of the value contained in all the tasks. Herein lies the value of prioritizing outage task using this process.

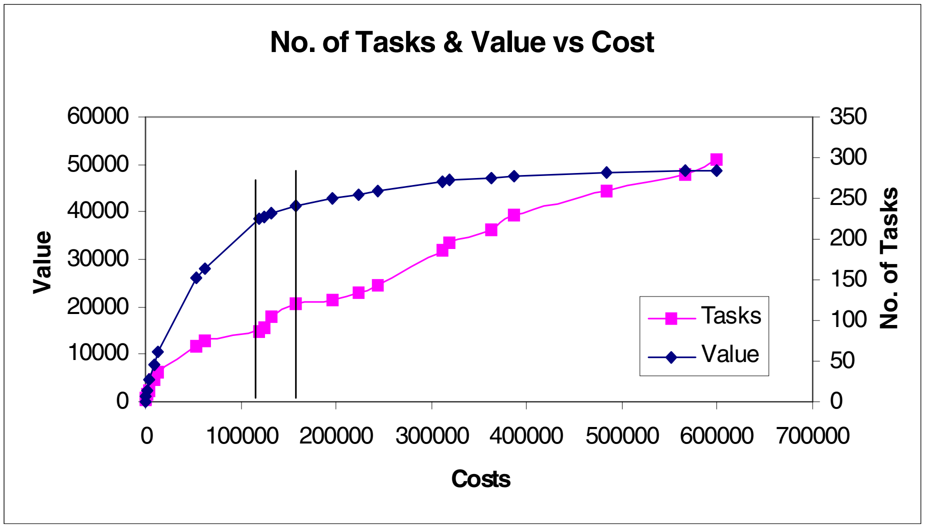


Figure 5

Phase 3 – Implementation of the Boiler Failure Defense Plan

This phase deals with the practical aspects of boiler inspections - dirty and clean and the implementation of the boiler failure defense plan. It also discusses the merits of the various predictive maintenance technologies and how they are applied in Equipment and Technologies matrix and a Plant Condition Status Report. NDE and data mapping techniques used are also explained. Activities undertaken during this phase:

- Participate in boiler inspection. Provide guidance on what to look for during an inspection. Focus on those items that preserve and/or add life to the boiler i.e. inspect for tube and tube shield erosion/damage, attachment damage, missing or damage sootblowers etc.

- Support/facilitate the implementation of the revised maintenance strategy for all plant/components analyzed using SRCM.

- Support/facilitate the implementation of the newly-developed Failure Defense Plan:
  - Development and implementation of boiler pre-outage check sheet
  - Development and implementation of boiler internal inspection check sheet.

♦ Development and implementation of databases to record and trend wear patterns, thickness measurements, NDT (non-destructive testing) data, process and performance data and predictive maintenance data.

<table>
<tr><td colspan="12">POWER STATION</td></tr>
<tr><td colspan="12">THICKNESS TEST REPORT</td></tr>
<tr><td>Item</td><td colspan="3">Reheater 1 elements</td><td colspan="4">Inspection report #</td><td colspan="4">Date:</td></tr>
<tr><td>Unit:</td><td colspan="3">Rev:</td><td colspan="4">Page of</td><td colspan="4">Compiled by:</td></tr>
<tr><td colspan="2">Machine type</td><td colspan="2">Serial number</td><td colspan="2">Probe type</td><td colspan="3">Velocity setting</td><td colspan="3">Frequency</td></tr>
<tr><td colspan="12">Thickness measurement results</td></tr>
<tr><td>Elevation ft.</td><td>Tube position</td><td>Element #</td><td>Tube #</td><td>B-SV-SH</td><td>Circum. Position o' Clock</td><td>Max. Thick. in.</td><td>Min. Thick. in.</td><td>Min. Allow. Thick. in.</td><td colspan="2">Nominal Tube size in.
OD WT</td><td>Material Type (Design)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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</table>

B-SV-SH = The position on the tube to be measured (B = a bend, SV = straight vertical section of tube, SH = straight horizontal section of tube

Figure 6

Figure 6 shows a typical data sheet used to record thickness tube metal thickness data

Phase 4 – Continuous Improvement and process automation

This phase deals with a continuous improvement cycle, multi-functional monitoring processes, critical component condition indicators and the evaluation of long term plant health indicators.

♦ Implement a continuous improvement process. This process makes use of an occurrence management process that is integrated into the normal work process.

♦ Review and implement multi-functional monitoring processes, alarms and surveillance schemes.

♦ Review and enhance critical component condition indicators. Critical component should be monitored continuously and the process adjustments made to ensure the component remains under the alarm limit.

♦ Review, evaluate and enhance long term plant performance indicators and goals

Phase 4 also focuses on how the operations group can add value to the process by using all the additional information presented to them when performing routine monitoring tasks.
At most utilities, the engineering, maintenance and operation groups are under pressure to increase reliability and reduce costs. This phase focuses on the role of the operators in achieving low cost reliability. Operators can have a significant impact on plant reliability and costs and there has been very little focus on understanding or utilizing the potential of the operators - the people that are closest to the plant. Engineers and system experts often spend time developing "bullet proof" technical solution to reliability issues, rather than cultivating a culture of operator involvement. This phase uses a model to show how the operator's role can be integrated into a continuous improvement process to improve plant reliability. It defines both what the operations group's role in plant reliability should be, and what is necessary for operator ownership to occur. The model proposes that the operations group is the focal point for most problems and issues related to plant, and not engineering or maintenance. The activities covered in the model are:

- Creating operator ownership and interfacing with maintenance and engineering. The four elements in creating a successful ownership are discussed. These elements are encouragement, reasonable expectations, adequate training and accountability. The operations group takes responsibility to oversee the entire reliability effort in a particular plant area. They must, however, be critically aware of the need for input and assistance from the maintenance and engineering groups that support them, and treat them as valued partners. Formal and on-job training programs are reviewed and evaluated.

- Reviewing and enhancing/developing surveillance programs, operator logs and checklists. Surveillance of equipment is one of the most important activities of an operator. It is critical to identify plant in distress as early as possible. Then either correct the problem or take the plant out of service, thus minimizing damage. A log is a record of particular process readings, while a checklist is a record of a specific action. Accurate, meaningful operator logs or checklists are a necessary component of plant reliability.

LESSONS LEARNT/SOME LEARNING POINTS

This program is only in its second year of implementation and, as such, needs to integrate lessons learnt, generic and specific, to optimize its content and practical implementation. It also requires greater participation from member utilities so that their input/results can be added to the databases to enhance to program.

Lessons that were learnt during the implementation of the program:

- Root cause analysis of failures is infrequently carried out. When it is done, few structured techniques are used, which results in inappropriate corrective actions, resulting in repeat failures. Knowledge of root cause analysis and its benefits needs to be enhanced, so training is important.
- Record keeping tends to be limited. Records that are kept are not centralized or linked, which sometimes results in duplication and inconsistencies.

- Maintenance strategies have not been reviewed. Many utilities still use the Original Equipment Manufacturer's (OEM's) maintenance requirements as set when the plant was erected, which, in many cases, revolve around time-based maintenance strategies. Condition-based maintenance strategies have proved to be move effective and utilities, who have reviewed and changed their maintenance strategies, have benefited.
- Limited use of available predictive maintenance technologies e.g. oils analysis, vibration and infrared. Application of these technologies has proved to be beneficial in reducing maintenance costs and improving reliability.
- Premature plant aging due to poor operating practices and inadequate past maintenance. Preventive/predictive maintenance is not being done, which resulted in an increase in corrective maintenance. This increase has kept the maintenance staff in a 'fire fighting' mode instead of enabling them to undertake preventive/predictive maintenance activities.
- Non-compliance with start-up and shutdown procedures, as well as ignoring water chemistry controls. Exceeding permissible temperature ramp rate because of poor combustion and inadequate water chemistry control are the major concerns. These actions ultimately result in equipment failure, tube failures in particular
- Outage planning is identified as a critical issue. The greatest benefit versus input is derived from planning, reviewing and re-planning activities before they star. Once execution begins the input required to modify cost and schedule can be significant for marginal corrective effect. The first requirement is to develop a 'plan of the plan'. This will ensure that all activities, issues and milestones in developing cost and schedule are reviewed, analyzed and refined before changes are impractical or too expensive.
- Most plants are well supplied with adequate systems to manage the workload. However, the integrity of the data/information is of concern. This is related to regular and disciplined input of all relevant data. The capability of these systems is not realized or exploited. The Computerized Maintenance Management Systems (CMMS) used are good systems however these systems are not fully utilized. Equipment histories and repair cost are incomplete. Work performed by a contractor, which is a significant portion of the work, is not recorded in the CMMS. To accurately track the cost performance of equipment and know the repair record is critical to lowering the overall cost of maintenance. Although contractors often issue reports detailing the work performed, these reports are kept in the outage office which makes it difficult for maintenance planners, supervisor and craftsperson to know the equipment work history.

Figure 3

	Possible Causes		Erosion Corrosion	Thermal Fatigue	Fly Ash Erosion	Pitting	Acid Dewpoint Corrosion	Fatigue	Corrosion Fatigue	Low Temperature Creep	Hydrogen Damage	Supercritical Waterwall Cracking	Acid Phosphate Corrosion	Caustic Gouging	Short Term Overheating	Coal Particle Erosion	Falling Slag Erosion	Fire Side Corrosion	Sootblower Erosion		Preventive Measures Short/*Long Term*	NDE Detection Technique	CRITERIA
		#	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	#			
Economizer - 1st R/H Side	Malfunction of a sootblower or the sootblowing system because of incorrect operation and/or inadequate maintenance (control logic - sequence, operating temperature and pressure, mechanical misalignment, drainage pipe slopes etc)	1																	•		• Confirm mechanism by inspecting tubes around and in the immediate vicinity of the blower.	VT	• Check for tube wastage - flat and/or 'shiny' surfaces or if the boiler has been washed check for a fresh layer of rust and gouges from steam cutting.
																					• Determine the extent of the erosion by mapping the tube thickness in the affected ares. Compare with previous readings and calculate an erosion rate and trend results - if applicable.	UT	• Use plant's standard for repairing or replacing tubes. Typically 70% of wall thickness is used. Pad welding should be discouraged because of the potential introduction of other detrimental failure mechanisms - copper embrittlement and hydrogen damage.
																					• Check, correct and verify the operation of moisture traps.	VT	
																					• Check, correct and verify blower or system operation to ensure correct sequence, angel of rotation, travel, misalignment, operating steam temperature and pressure.	VT	• Use the OEM's manual or site specific procedure.
																					• Check, correct and verify steam supply and drain slopes to ensure adequate drainage.	VT	
																					• Emergency repairs such as pad welding should be replaced at the next opportunity.		
																					• Optimize blowing sequence to ensure an effective boiler sootblowing program.	VT	
																					• Establish and implement a routine maintenance schedule to inspect and test blower operation.		

Applying RCM to Optimize Maintenance

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EPRI International Power Plant Maintenance Conference
August 15-17, 2001 Houston, Texas

Abstract: *In large plants scheduled maintenance software implements the maintenance program. Getting scheduled maintenance focused on the best PM tasks succinctly and cleanly is one key to useful, cost-effective maintenance. While some plants can spend millions for "finished" PM programs based upon detailed analysis, many can't. New software tools offer viable alternatives. This paper discusses the practical aspects of implementing RCM-based scheduled maintenance programs at large power facilities. Practical steps nuclear, fossil, and hydro facilities must take are discussed. Each group has common as well as unique requirements. What significant differences are there? What common ground does maintenance performance and RCM analysis share?*

Introduction

Reliability is key in competitive markets. Unreliability must be hedged. Units that deliver reliable performance can extract greater revenue. Practically though, the steps to improve unit reliability remain unclear. What must plants do to achieve higher reliability? What tools are available? The obvious objective of any reliability effort must be to reduce unplanned outages, and increase unit dispatch reliability.

Why then, do so many organizations struggle with reliability strategies? And if reliability-centered maintenance (RCM) is what its proponents claim, why don't more plants embrace RCM as their primary strategy? What is needed to achieve practical RCM benefits? What ties practice and plans at the implementation level? How does electric generation reflect airline experience? How can we use our knowledge of ourselves to identify implementation barriers, and get better doing the right things? What will tie plans and practices, at the implementation level? Answers involve three ideas:

- Simplicity
- Seamlessness
- Strategy

Unit failure study reveals many forced outage causes. To improve unit reliability we must first understand failure patterns, and their randomness. Reliability theory provides methods to understand statistical failure. Reliability centered maintenance provides practical tools to achieve reliability improvements once failures are understood. RCM has been validated by many credible organizations. RCM is technically correct, efficient, and effective.[1] My opinion is that RCM theory, performed well, provides strategic opportunities to simplify maintenance programs. Implemented carefully, this can introduce methods addressing each source of unreliability systematically in the operations-maintenance plan. This ultimately leads to asset utilization less subject to randomness and its negative outcomes.

Simplicity

A key premise of organizational PM (and RCM) is that if you know the right maintenance to perform, you can readily perform it. Practically, this simply doesn't reflect many experiences. Knowing the right maintenance to perform is necessary, but not sufficient. Maintenance reflects many interests and forces. Shop preference strongly influences work. The availability of a plan merely influences work performed. This assessment is based on the review of many performance statistics at many plants, as well as personal experience. Only a small fraction of planned work is worked as planned. I attribute this to the corrective maintenance process model. Failures command higher attention that other work. Large failures outrank routine work. Failures will outgun routine work under this system. The cycle is stable and self-perpetuating. There is no way out of reactive maintenance performance.

Maintenance people enjoy job autonomy. This has benefits and costs. Most plants don't have a maintenance performance improvement strategy. Few plants are committed to standardize their maintenance planning and performance. Standardization, in fact, is contrary to utility maintenance culture. Non-standard processes increase variation of outcomes. Processes that embed randomness cause forced outages. Process control is the subject of total quality management (TQM). TQM methods have only

[1] Electricite de France (EDF), 1999 EPRI O&M Conference Proceedings

mildly penetrated maintenance and plant maintenance cultures. A regulated environment can be held partly responsible.

Maintenance programs can fail to operationalize[2] predictive, PM and testing programs into integrated, "efficient" plans. Multiple, independent departments may perform tasks independently from each other. Performers lack specific standards to identify "failed". Too many techniques are used indiscriminately where no payback results. Too many scheduled maintenance programs lack resource loading based on available manpower, leading to overly optimistic PM program scopes.

RCM theory reconciles work, work planning and practice. The airline industry implements this model to a high degree today. Even regulated airlines, though, are occasionally cited for maintenance lapses. Where regulation is perceived to be absent, even regulated maintenance practices diverge from plans. Looking at airline maintenance lapses give some insights at the attitudes that most organizations face. Untrained or ill-informed staffers have cancelled critical life-limited parts replacements and key inspections on the basis they aren't necessary. No one who "understands" deletes essential activities – this is the attraction of a formal "basis". (The formal basis institutionalizes the understanding.) An overwhelmed, under-trained staff may trim work they perceive as unnecessary, though. Practices reflect maintenance processes. Strong processes are robust. Processes and culture change slowly, sometimes requiring cataclysmic events to change. Reflecting upon these events, we occasionally see bursts of learning. Older workers can remember significant events.

TQM credits process reliability with outcome predictability. Generation hasn't always been viewed as a manufacturing process producing a "product." Given this, how can manufacturing techniques that help manage randomness and deliver product consistency be applied? Consider a few numbers. A typical generating unit has upwards of thousands of coded equipment. This could vary from a low of 2000 tags/fossil unit to 50,000tags/nuclear unit. Multiple unit plants are worse. Some have unique units designed or built by different AE's, in addition more equipment and their tags. These numbers can be overwhelming. Any effective maintenance development process must cope with large numbers. Some strategies are:

- Standardization
- Templates
- Automation
- Integration

RCM has great potential to help manage large plant equipment numbers. RCM offers effective strategies to integrate, "deselect," and otherwise standardize the responses to the failures that these equipment items generate. Condition monitoring, for example, can roll-up predictive monitoring to a system level, but only using system function knowledge. People must understand more about the equipment to take and use roll-up indicators and standards.

RCM suggests that the greater part of scheduled maintenance work is condition monitoring. To be effective at maintenance, organizations must excel at condition monitoring. This requires

- Knowing failures (failure modes)
- Know effective ways to identify failure modes
- Having effective condition-directed work methods
- Knowing when to act

Airlines & their suppliers have been effective operationalizing failure data. Pass/fail criteria are explicit. Key parameters and criteria are well-defined in part because industry focus for thirty years has been to explicitly define performance standards. This effort includes suppliers, vendors, and users – the entire supply chain. Though nuclear plants have exacting technical specifications, their technical specifications are based on the best available license analysis before RCM concepts evolved. Many specifications were

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[2] By "operationalize" I mean developing objective measures for performance measuring "pass/fail"

based on "like-new" performance criteria. Nuclear balance-of-plant equipment and systems are only moderately better off than their fossil cousins for useful operational limits.

Experience developing RCM-based maintenance programs has been mixed. Some users rejected analysis because of its complex nature, arcane terminology, or counter-intuitive results. In fact, many of these RCM-analysis problems are better attributed to the academic character of traditional RCM, rather than RCM itself. RCM methods are new; specific processes that convert RCM analysis to useful results continue to evolve at a fast pace. Prepared simply, most engineering analysts see value in a prescribed set of equipment maintenance outcomes based on equipment purpose and service in the plant. "Operations", the group most able to assess real-time operating risk, support equipment maintenance plans based on risk. These strategies, in an organizational context, can be developed and maintained, accessible to all, with an evolutionary capacity. Like the experienced driver of a car, no matter what their technical knowledge level, the activity that comes first – engine or brakes, is intuitive. Practical RCM provides the opportunity to relate intuitive answers for equipment service organizationally in ways that weren't possible before. This improves everyone's effectiveness. The key to practical RCM is the simplification of dogmatic RCM formalism to its essential features. This is what effective RCM and RCM software tools should do.

Seamlessness

Companies will always struggle with maintenance, for "maintenance" is implemented organizationally. Large facilities with many components implement maintenance with computerized maintenance management systems (CMMS). These systems:

- Initiate (or allow others to initiate) maintenance requests
- Schedule and track maintenance performance
- Provide a home for scheduled maintenance
- Prioritize work activity

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success.

- Account for maintenance performance cost and time
- Retain maintenance history

CMMS systems are structured around equipment registries and established work flow models. For many plants, the CMMS equipment registry is the only equipment list. For others, it is simply the primary list. The CMMS registry structures maintenance activity. It also focuses maintenance activity around a maintenance model. For better or worse, maintenance performance processes from twenty years ago provided the CMMS maintenance model – corrective maintenance. Most CMMS software designs begin with a fundamentally corrective maintenance model. Although augmented with scheduled maintenance, the corrective maintenance model establishes the maintenance paradigm.

CMMS-based maintenance centers on work requests. Work requests are not equal in value, however, particularly corrective maintenance ones. Loading CMMS systems with effective PM tasks places the right work onto the plant schedule. (This, of course, is a CMMS objective!) We can then find common work tasks and standardize around them in common ways. Although planners develop the maintenance strategy, *effective PM* program development is not within an average planner's expertise. Few planners generate efficient scheduled maintenance plans without engineering assistance. Even engineers require a great deal of training to become efficient selecting "applicable and effective" PM tasks. Setting failure limits that trigger condition-directed maintenance is an engineering task, and a specialty. Many companies struggle with the preliminary step – defining performance criteria to initiate maintenance. It can be viewed from a traditional perspective as unnecessary fluff. Shop-floor craft don't necessarily see the value, nor do they have the skills to develop these tasks readily for PM development. Their practical work selection inputs are key, however, to program success. Traditionalist companies fail to see defining performance limits as strategically necessary to develop an efficient maintenance program. More than ever, though, companies are willing to expend effort developing performance criteria. Although the work can be contracted to specialists, the selection of actual performance criteria is a core business. You can farm development out, but only the facility's owners and operators can know and commit to operating limits.

Experienced, high-performing organizations are either already sold on planned maintenance, or know the value implicitly by commitment to their maintenance plan. For these organizations value comes by growing maintenance depth to realize "age exploration" on currently installed equipment, while incorporating new technology into under-performing equipment. In a nutshell, maintenance in an evolving world is not static, and patently not "maintenance". The best maintenance planning tools can

- Document maintenance strategy opportunities
- Identify and track useful or necessary design changes
- Interpret maintenance needs in documented failure modes

Performing these steps is beyond the capacity of most CMMS systems.[3] They require supplemental processes to develop the scheduled maintenance program, it's derived PM tasks, and basis. It then must pass these to the appropriate CMMS tables in a streamlined, efficient way.

Several scheduled maintenance task-development tools have been used. They include:

- Word-type documents
- Spreadsheets
- Relational databases
- Software applications

These tools can all generate tasks using RCM. The early analysis in the eighties was in document form; later analysis migrated towards LOTUS and EXCEL spreadsheets, then finally SAS mainframe relational databases. Finally with the arrival of PC-based databases such as ACCESS, development migrated into PC-based relational database products. Many commercially database applications use this format. Analysis results can be entered into the CMMS scheduled maintenance tables as keystrokes, uploaded

[3] Dofasco Steel remains an exciting exception. They've developed a fully-integrated RCM-based CMMS.

tables that are loaded into scheduled maintenance task tables by an import process, or a combination. Most CMMS systems support processes to upload appropriate PM tables.

Companies have invested millions in CMMS systems, only to revert to simple failure management techniques because they lacked the means to identify, install, and implement efficient scheduled maintenance tasks using their CMMS. Knowing RCM provides a technically efficient answer, the means to an efficient PM program is known. Whether a company sees the value developing the best tasks for their CMMS and scheduled maintenance process remains symptomatic.

Partly, this dichotomy stems from the intense effort needed to perform specific RCM analysis. Not many plants perceive they can afford detailed analysis, and many couldn't at the cost levels of the first RCM studies. Fortunately, there's good news. Analysis cost is dropping, partly based on learning, partly improved analytical tools. Performers are discovering that results are surprisingly transportable from one plant to another. A feedwater system for a supercritical fossil boiler is very similar to that at even a non-critical or nuclear plant. This similarity allows acceleration of the study when the performer is already familiar with, or has an available model of a similar system study. Component templates offer another streamlining technique, though stretching the limits of traditional RCM.

Another exciting development is new software that can generate upload tables, in effect removing the middleman in RCM analysis studies. The upload table approach offers a faster way to load results onto the CMMS, taking down another implementation barrier. While not for every organization, these applications bridge the gap between developer and planners more efficiently than ever before.

Even with analysis done, and tasks loaded in the CMMS, there's no guarantee the right work gets implemented. A discouraging outcome for some studies and their analysts has been seeing results representing work-years casually falling by the wayside because the organization's users hadn't seen the value or purpose in the analysis in the first place. When push came to shove, the planners failed to replace the legacy tasks, re-plan the work, or otherwise perform the steps needed to give birth to the RCM recommendations as revised CMMS work orders. Management's objectives exceeded the plant's capacity to implement change. Studies and stories in maintenance circles abound about organizations that discounted the final strategy of their hard-bought effort. Reflecting, what competitive industry has the luxury to invest in a similar vein? How can companies pay hard dollars for new methods and designs, only to throw them away? Where non-implementation gets accepted, a strong signal supporting "practice as usual" results. Failed efforts reflect an environment that rejects change. Though hard to accept, they exist, occasionally prevail, and when present, are hard to overcome.

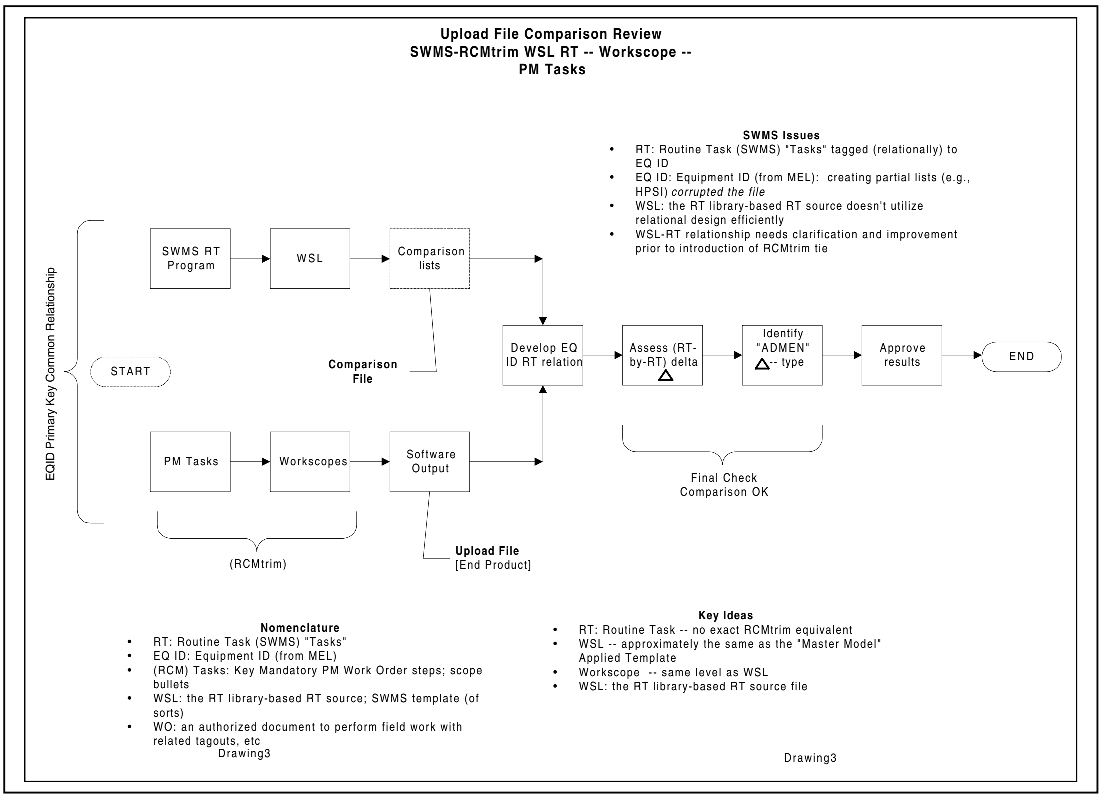

Figure 1: Upload Process

To realize benefits we must place useful analytical tools in the hands of end-users -- mechanics, technicians, and engineers who make daily decisions. They must intelligently question any aspect of the maintenance strategy for any piece of equipment quickly.

This suggests a failure data database with an RCM-based structure. A relational database using RCM principles offers several inherent advantages. It can be efficient – like RCM itself, providing a set of PM tanks around a core of dominant failure modes. It offers a way to document tasks that were once thought perhaps effective, but now aren't. It can support a formal program of "age exploration."

Finally, since regulated maintenance is presumed required, regulatory-based PM tasks – insurance, government, or codes should be documented. They should tie to their intended ""prevented-failure," or as close to it as can reasonably be identified. (Regulatory bodies prescribe tasks that are assumed to prevent intolerable failures affecting public welfare or safety. These failures should be easy to document, but in fact they often aren't.) Inability to identify regulatory-based failures points to the ineffectiveness of regulated PM tasks. Once discovered, the organization should petition their regulator for relief, in the public interest.

A process to improve the current state of maintenance must be

- Open (to users)
- Updateable
- Integratable with the CMMS
- Failure-based
- Efficient

These idealized goals should be evident. They're largely accepted in the industry today, with the possible exception of CMMS integration. This is unique, in that it's never been proposed as core requirement for useful RCM software. But less than ten-years ago such a list would have been provocative at a utility conference.

There's one last requirement. Complex equipment typically has multiple failure modes, and multiple PM tasks. As every auto mechanic knows, a last step to an efficient maintenance program is to package tasks into larger work groups for efficient performance. The scope of large work -- turbine, boiler, reactor, and so on must be well-defined. These major work activities constitute small projects. “Scope” defines overall work order content, and organizes tasks by craft, tagout, schedule, or other group. The last PM database requirement is to provide a means to efficiently group work for efficient performance.

Other factors

Many possible things (in principle) are impractical. The key to making theory possible is simplifying and streamlining application, reducing expense and simplifying performance. The last step applying RCM effectively is automation. A CMMS requires loading the solution – typically in the form of scheduled maintenance tasks and tables, into the CMMS. This is “uploading.” The set of tables with key scheduled maintenance attributes – tasks, intervals, units, limits, etc. must be loaded into the CMMS. In principal, automatic database-based software interfaced with the existing CMMS system could load the RCM-based CMMS program. Companies have invested millions in new third-generations CMMS products, installing and loading them to be “intelligent.” PM optimization software solution should integrate with existing tools and processes. It should minimize effort required to implement the analysis results. In a perfect world, the RCM applications results should upload to a CMMS system with little or no manual intervention.

Although this may at first seem an impossible request, most CMMS systems (certainly third generation ones) have modules to export and import table data. A subroutine to facilitate conversion of old legacy MMIS systems PM data tables was invariably provided. When available, it becomes relatively simple to import the new PM tasks in their respective tables that are logically constructed and mapped to the target CMMS system. Open CMMS systems facilitate upload of their predecessor’s MIS[4] tables. To be efficient and use existing resources well, an RCM system should integrate with the CMMS to perform automatic table upload.

[4] Maintenance Information System

Suppose then, you have a new third generation CMMS system, and you choose not to install the legacy PM program. How do you develop and install a new RCM-based PM program? Fortunately, the primary requirement is to develop the new program. The best PM development software available today can do this in formats that provide tables that transfer directly to the CMMS system. Several options and processes are available

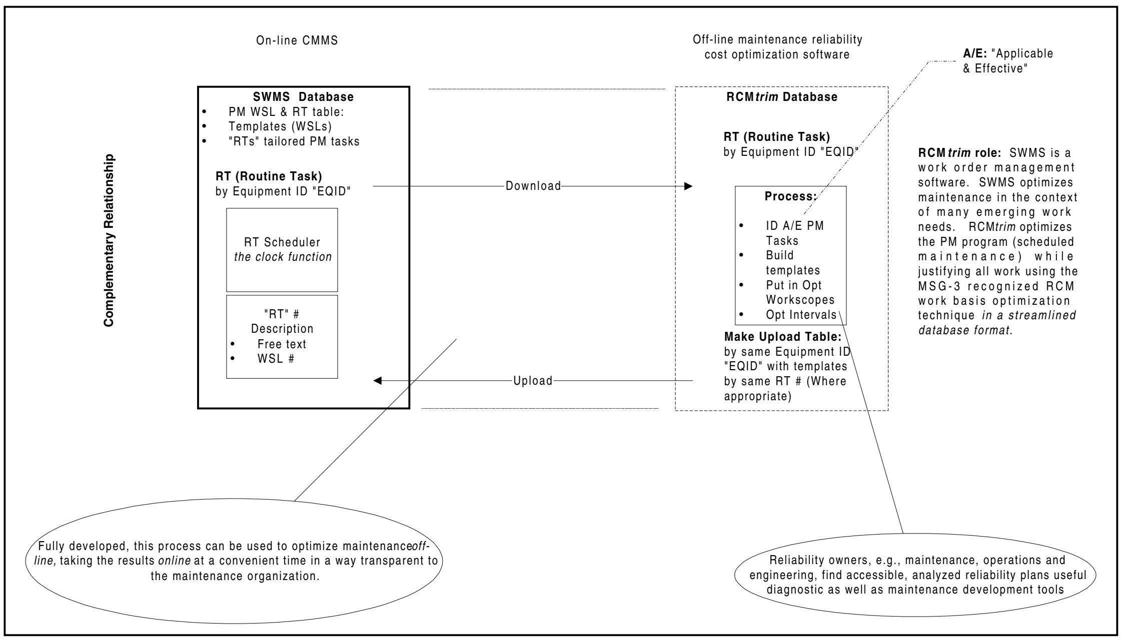

Figure 2: The CMMS Download/Upload Process

To summarize, an efficient CMMS PM data “front-end” must:

- Identify selected PM tasks
- Failure based format
- Be efficient
- Allow age exploration

- Document all requirements
- Facilitate grouping
- Integrate to the CMMS
- Be user friendly

No database is perfect. These design requirements however, provide specifications for a useful RCM tool. The company that provides the software best meeting these objectives should be given as much consideration --- if not more, for your next RCM database.

Strategy

Experience

The best operators, mechanics and engineers know equipment and its performance very well. Companies, however, may fail to operationalize their people's learning. Informal processes are institutionalized. By "informal" I mean non-rigorous, non-documented, non-trained processes. These must (of necessity) be shared informally by word-of-mouth on-the-job communications. Maintenance strategy communication is one-on-one. Outcomes vary. The results rely on individual knowledge, skills, and initiative.

Within the industry, low turnover has helped assure maintenance process consistency despite an aging workforce and limited training. Block retirements can change this state quickly. Some plants have lost effective maintenance capacity due to sudden turnover of large numbers of key people. The industry needs to integrate maintenance workforce experience into work processes more formally. Developing RCM-based work strategies won't replace the skills that retire, but it will maintain continuity of work plans through major workforce changes. The physical equipment usage and wear depends on the installation and its mission – not specific people operating or maintaining it.

Options

Once an RCM-based maintenance strategy is selected, how should we begin? Many approaches have been tried. New users should anticipate a learning curve that goes along with their RCM process development efforts. Time is required to learn, streamline and institutionalize methods that produce quality, useful RCM analysis. A deliverable product – like the logical list of plant equipment, their supported functions, importance and failure consequences, takes time to develop and learn. This list, which can be a spreadsheet, provides a basic worksheet for analysts to select "applicable and effective" scheduled maintenance tasks.

There are several fundamental RCM approaches. Each has strengths and limitations. Indeed, most organizations will want to adjust the process slightly. Alternatives include (1) traditional RCM, (2) streamlined RCM (SRCM), and (3) variations that feature innovative tools such as component-oriented templates and applications.

Traditional PM

Two alternatives have been used for traditional *scheduled maintenance* program development. They differ radically, from one extreme to the other.

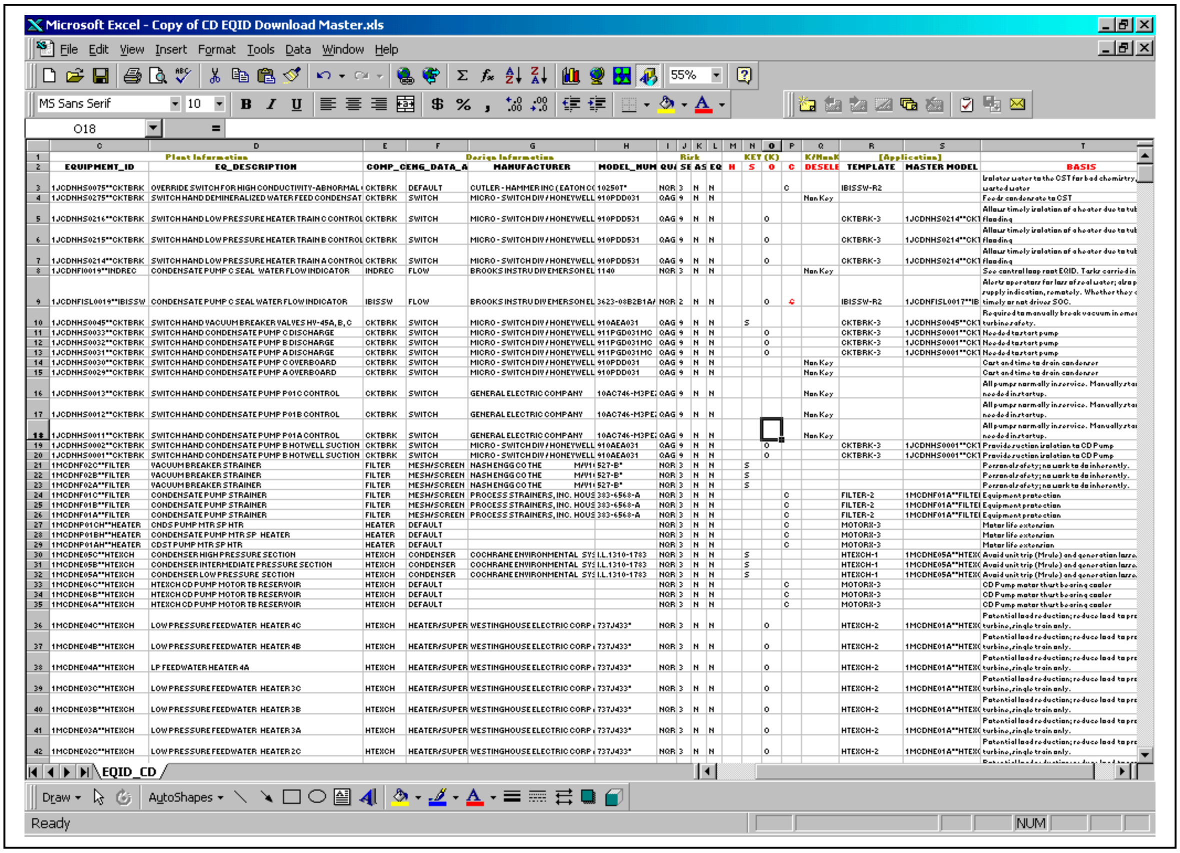

Figure 3 RCM Software Input Worksheet

Component

A component-oriented approach addresses component maintenance requirements as isolated elements. Component-based PM program development is the fastest *PM* methodology to perform. Reflecting the traditional method of going through the plant register asking, "what can be done on this piece of equipment?" it's farthest away from the RCM objective of identifying functions, their failures, and dominant failure modes. Analysis of equipment failures in the context of supported-system functionality, basing maintenance off failure consequences, is at the root of RCM methodology. Done by experienced analysts, it's fast, readily implemented, and produces good results. Its weakness is inability to understand analyses in an operating context and carry the results forward over time. The component-based analysis standardizes for repeatability and speed.

System-based

System-based analysis uses RCM ideas of partitioning, function identification, and failure effects categorization. It also requires understanding of the equipment's operating context and the systems supported (e.g., engineering context), in terms of system functionality. Theory looses its attraction for typical plant schedulers and planners (charged with development) at this stage. These people generally lack the operating contextual background and engineering expertise to perform analysis and sustain interest. A systems emphasis is engineering-oriented. Even component engineers occasionally lack the interest or depth to develop component system-based failure contexts for RCM analysis.

For a CMMS-based maintenance program, equipment partitioning breaks analysis down to a tangible level. This supports understanding the equipment's context, allowing growth and evolution of work over time, as more information becomes available. This is a legitimate CMMS supplier-claimed benefit. However, the processes embedded in most CMMS systems don't contain RCM process features. To the degree the outcome -- an efficient maintenance strategy, occurs, it's because workers already apply RCM principles. Because most RCM features are characteristics of the best fact-based maintenance programs, many plants have success on this level. Their processes, however, may reside within people, be informal, and not reflected in organizational processes.

Classical RCM

Classical RCM adheres rigorously to the seven steps of RCM recently formalized by a new SAE standard.[5] Classical RCM requires *operating goals* to assess functions and failures. Who better than operators can identify the intended purpose of a piece of hardware in the plant? Who better than maintainers can identify the dominant failure modes, and effective technologies to address these? RCM's rote process, technical jargon and theoretical flavor are distasteful to most maintenance people who, for the most part

- Like to "work"
- Aren't engineers or bean-counters
- Prefer tactics ("fix this") to strategy (make it go away)

[5] Standard JA 1011 Evaluation Criteria for Reliability-Centered Maintenance (RCM)Processes, SAE, 1999

Plant maintenance people want to *do* work. RCM success hinges on making analysis relevant and useful to these performers in the course of their daily objectives. Plant maintenance staffs want to work smarter. Techniques that allow them to do this, in my opinion, have always been well received, and find support.

SRCM

Streamlining techniques appeal with their promise of getting results while avoiding pain. However, the dictum, "No pain no gain" should be considered. The weightlifter's motto could apply as well to RCM field application. Those who've been through the complete RCM process gain significant insights into failures, their classification, and treatment that serve them well in later daily work. But is this depth necessary for basic maintenance competence and success? Despite all good intentions and process certification standards, a program that isn't implemented has little value. SRCM helps bridge the practical gap towards implementation. Processes that fail to gain practical implementation have little merit. An efficient process should be useful on many levels, and without requiring every user to be an expert.

Processes are adaptations and simplifications of ideal methods, but some are better than others. Selecting the RCM process that can achieve practical implementation, while retaining the key function ideas, helps greatly. There has been so much information on SRCM variations that you might think selection of one method was easy. It's not. Rather than bog down in theoretical process analysis, if you've decided upon RCM, you may as well select a process and get on with it. Experience has shown you'll want to rethink your selection as you gain experience.

If you select an SRCM approach, check the standards such as MSG-3 or JA1011. You want to be sure that your process adequately meets your expectation for an RCM-based program. Some SRCM methods won't. The literature discussing the pros and cons of streamlined RCM is as old as RCM application in the utility power industry. In my opinion, SRCM methods that retain the essence of RCM are valid useful improvements on traditional RCM. Because power plants differ from aerospace in both hardware complexity and application usage, use of streamlining methods is compelling. Some streamline methods, though, lead to superficial analysis. Newcomers won't necessarily be able to discern the differences. To summarize, legitimate RCM (1) is failure based, (2) identifies system-supporting functionality, and (3) classifies failures by outcomes.

Use of templates is a streamlining feature employed by many software applications. Templates are used because they are efficient, and legitimate experience generalizations. Their downside risk is to miss the 2nd and 3rd essential RCM steps above. This leads to classical – not RCM-based PM analysis. Appropriate methods or software starts with templates as source material, and then amplifies upon them in system contexts.

Results

A goal of an RCM-based PM optimization effort should be a living maintenance program. There are no static programs in a dynamic world. The maintenance program that changes as new materials, methods, and experience are developed is a living program. RCM techniques should ultimately support a living maintenance program.

This suggests the need for an RCM application based around a relational database. Applications can live and grow, identifying trends and changes as circumstances change. A great many processes and products are single-use applications. They will have no further value beyond a project because their use is so complex, or the results so cryptic. A company that will gain an RCM application license through a project will benefit by asking, "How suitable is the application to support living maintenance after the project ends?" A negative answer may cast doubt on the validity of the project itself as a stepping stone towards a living maintenance program.

Conclusions

What is your vision of your future maintenance program? Strategic? Automated? Standardized? Complete? Effective? The present state of some programs suggests that substantial changes may be needed to move from tactical to strategic maintenance. RCM provides a tool to help make this transition. As you consider RCM in your toolbag, ask the following:

- Which RCM variation best suits your needs?
- What analysis methods best support your effort?
- What will be your end product?
- How will you migrate results to your CMMS?
- How will you capture learning?
- How will you grow the results into a living maintenance program?

Many technologies and their advocates are available. Before you commit to one, seek out the ones that offer the best overall value in the context of your situation.

RCM will not leave us. It is a technology. Its tools will improve. But in its most complete form, RCM is a maintenance approach. Organizations that pursue RCM from the "flavor of the month" club perspective will be disappointed. It's just not that easy. However, don't also be surprised to find your organization engaging in a new path towards maintenance excellence, with goals you don't completely understand, but stimulating excitement and a growing conviction that you've finally found the best way to select and perform maintenance – the right way!

BOILER AUTOMATED WELDING SYSTEM®

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Abstract

In cyclone boilers, the coal, molten slag, and molten iron combined with high temperature result in erosion and corrosion of the boiler tubes. The common failure and neglect of protective refractory systems expose the steel boiler tubes to this severe environment, limiting the life of a typical cyclone to 20 years. Replacement of an entire cyclone burner is expensive.

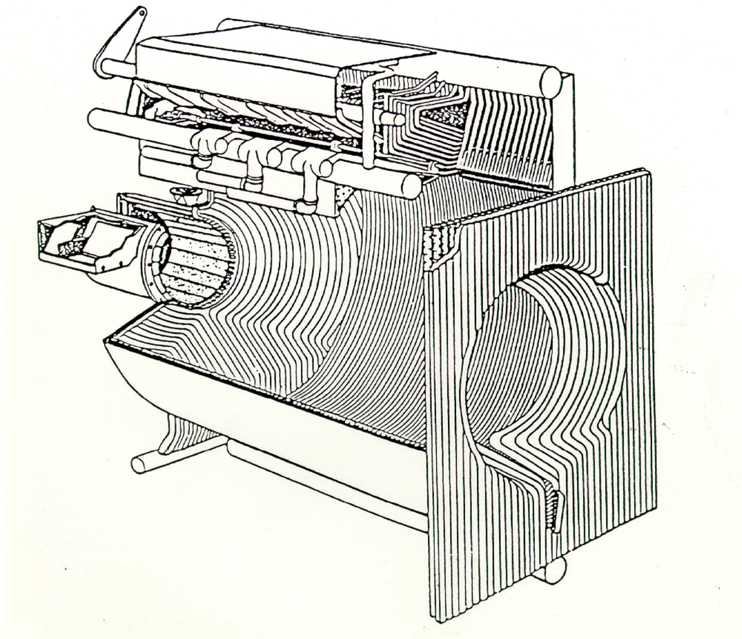
To extend the life of a cyclone boiler, sacrificial weld metal is applied over the eroded/corroded tubing. Restoring and increasing the wall thickness of the tube on the fireside allows for installation of new studs and reinstatement of the protective refractory system.

There are several challenges to be overcome to accomplish the task of overlaying the damaged tubing. The erosion of the tube wall and the remnants of the studs leave an irregular surface. The older cyclone boiler tubes are individual tangent tubes, which are usually out of plane and distorted. The tubes must be repaired in place requiring welding that continually changes position. And all of this must be completed rapidly to meet the outage schedule.

The Boiler Automated Welding System® uses a unique and innovative combination of welding systems, computer systems, robotic systems, and sensing technologies to accomplish the job.

Background

The Boiler Automated Welding System® was designed specifically to repair and extend the life of coal-fired boilers using cyclone burners. The cyclone burner is a horizontal cylinder fabricated of boiler tubing, which is part of the boiler's waterwall circuit. Coal sized to ¼" is introduced into the cyclone through the burner end of the cyclone. Combustion air enters the cyclone tangent to its cylindrical axis, blowing the coal in a path that follows the cylindrical shape of the cyclone. The coal particles burn as they orbit the center line of the cylinder. As the coal particle burns up, it becomes hot gas which travels into the furnace and slag (the non-combustible component of the coal), which is deposited on the walls of the cyclone.



The tubing that makes up the cyclone has a protective layer of refractory. This refractory is held to the tubing by studs, which are welded to the tubing. There have been many types of refractory made for this purpose. Protecting the cyclone tubes is the key to a long cyclone life. The coal and molten slag swirling against the cyclone walls combined with high temperature results in erosion and cracking of the protective layer of refractory. During operation, some of the refractory is lost. This exposes the steel boiler tubes to a very aggressive corrosion/erosion environment.

As slag, which is deposited on the walls of the cyclone builds up, it is pulled down the wall by gravity and leaves the cycle through an opening between tubes and flows to the floor of the furnace. This flow of slag corrodes and erodes any unprotected tubes that it comes in contact with.

The reducing atmosphere in the cyclone aids in the smelting of iron-including smelting of the exposed tubing. If the coal has an iron content, the iron, moving with the slag, will flow through the cyclone. When the unit is shut down, the iron solidifies on the bottom of the cylinder in a thick layer. It must be manually removed. This removal results in damage to tubes and the removal of any studs in contact with the iron, leaving no anchor for new refractory unless the studs are replaced.

These various attacks on the cyclone tubes reduce their wall thickness until the remaining strength of the tube wall can no longer contain the pressure resulting in a tube leak.

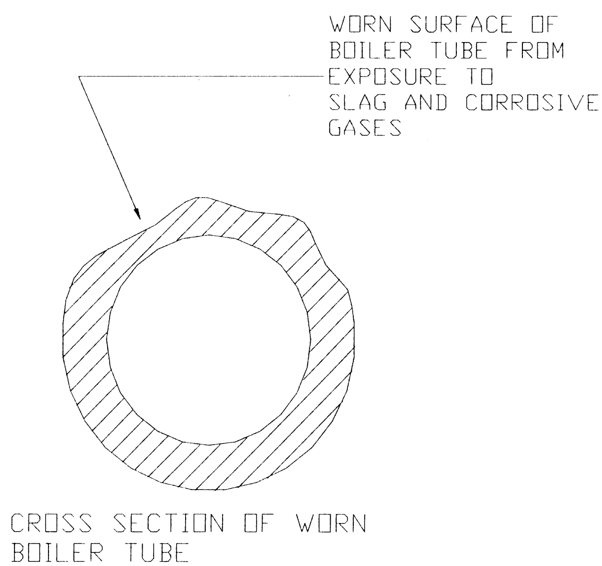
This process sequence limits the life of cyclone burners to approximately 20 years. At the end of life, it is necessary to replace the cyclones.

Exploration and Obstacles

To extend the life of the cyclone burners, the concept of putting weld overlay on the eroded areas of the boiler tubing was explored. The concept being that the overlay would restore the wall thickness of the eroded tube to at least the original wall thickness, allowing new studs to be applied and a protective refractory layer to be solidly anchored. The difficulties in applying weld overlays in a reliable manner are substantial.

Scheduled maintenance outages are held to minimal time to maximize revenues. These outages are too short in duration to utilize manual welding techniques.

The erosion/corrosion of the tube wall is irregular. This creates a wall thickness that varies in an unknown manner along the length of the tube. In addition, the remnants of studs (which are removed) add to this irregular surface. The irregular surface and irregular wall thickness significantly affect welding parameters.



The boiler tubes are distorted. This results from years of use and previous repair work. This distortion eliminates the possibility of calculating a standard weld path in advance. A frame of reference for measuring tube position must be created. The weld path must be measured for each tube just prior to welding.

The boiler tubes must be repaired in place. Access to the tubes is obtainable only through a 34-inch access manhole. There are no flat surfaces in the cyclone to work from as equipment staging areas.

Several complex tube geometries exist in a cyclone boiler. The interior is a horizontal cylinder with a split wall at the top (secondary air inlet) of the cylinder.

The burner end of the cyclone is a shallow cone made of boiler tubes each bent on a different diameter with panhandle on each end. The furnace end of the cyclone has a flat wall with vertical tubes. A large cone of tubes (re-entrant throat) protrudes into the cyclone from the furnace, creating a formidable obstacle to accessing other tubes.

Finite Element Analysis

When all of the obstacles were overcome, would the overlaid material cause other problems? The first concern was would the buildup of weld metal cause a fatigue crack at the end of the weld? Taking that concern further, would additional sacrificial material in a high wear area make that condition worse? And finally, would welding the tangent tubes together on the ID of the cyclone cylinder cause any stress-related cracks?

To resolve these issues at the outset, a finite element analysis was performed.

The cyclic stresses were determined by means of a model simulating five tubes in the approximate center of the weld area. The study simulated "worst case" conditions where the cyclone environment was considered at 3000^{o}F and the water temperature inside the tubes was taken as 700^{o}F. Two cases were run.

On the single layer of weld metal 0.080" thick, the stress at the transition area from weld metal to bare tube was 33.5 KSI, corresponding to a life of 15,000 cycles or 41 years before a crack was initiated. This was assuming a daily cycle off-line. The stress at the transition for the double layer of weld metal 0.160" thick was essentially the same.

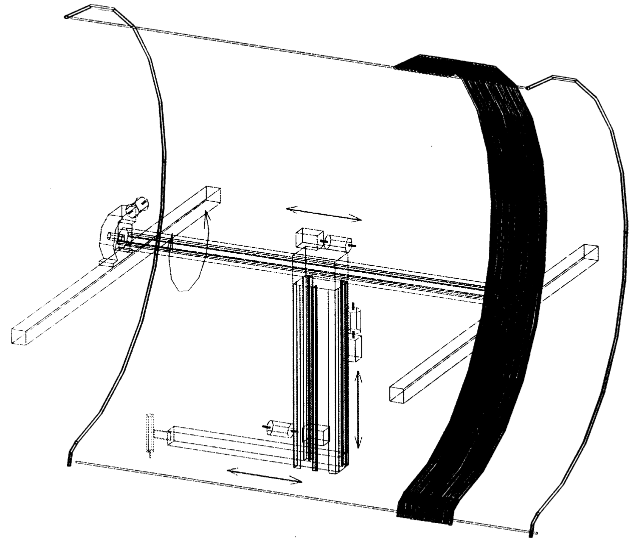
As part of the model geometry, each tube was tangent to its neighbor and welded to fill the space between the tangent line and the tops of the tubes. Stresses in this area were very low.

Boiler Automated Welding System®

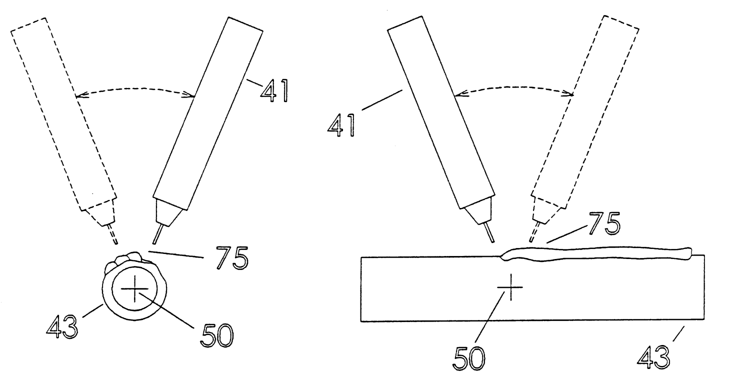
To rebuild the boiler tube's wall thickness using weld overlay required a very innovative system. This system called the Boiler Automated Welding System® (BAWS®), uses a unique and innovative combination of state-of-the-art sending technology, welding systems, computer systems, and computer-controlled robotic system.

Robotics

The four-axis positioner is comprised of four independent motion axes. Three of these axes form the cylindrical coordinate system. These are the rotational axis, the radial axis, and the axial axis. The fourth axis extends the reach of the axial axis. This allows access for automated welding to any part of the cyclone.



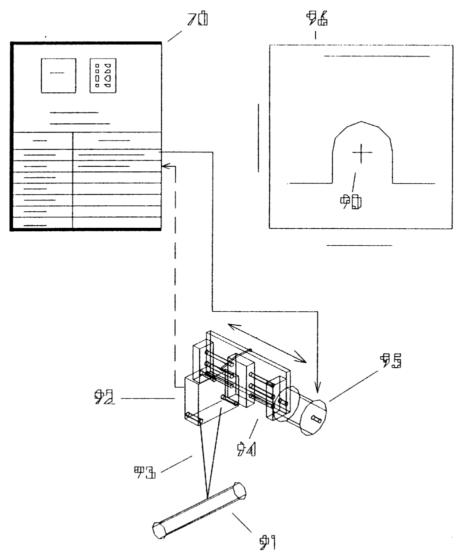
The two axis tool point positions allow the torch head to be revolved around a point in space. This ensures proper rod (wire) position for any weld. When the torch head tool point is located at the centerline of the boiler tube, multiple weld passes can be laid side by side. This is accomplished by repeating the weld path of the four-axis positioner and changing the gimbal axis position of the tool point positioner.



Tube Tracking

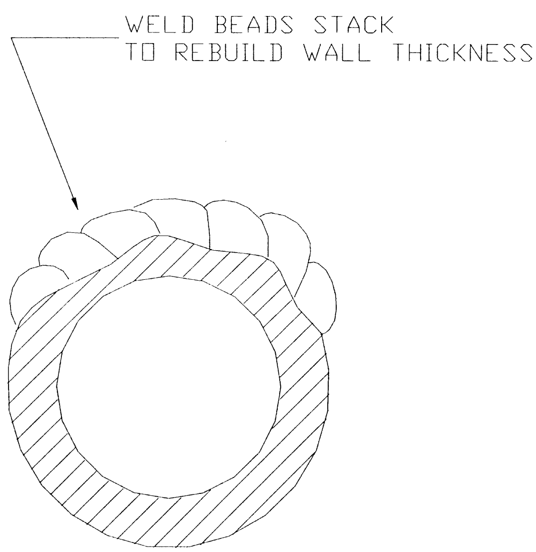
A laser distance gage emits a laser beam. The laser beam is reflected off of the surface of the boiler tube. The reflected laser beam is sensed by the laser distance gage. An analog voltage is generated by the laser distance gage that is proportional to the distance between the boiler tube and the laser distance gage. The last distance gage is mounted to a tube-tracking slide.

The tube tracking system is attached to the four-axis positioner. The four-axis positioner moves the tube tracking system over the boiler tube to be welded. The BAWS® uses its own coordinate system as the coordinate space in the cyclone boiler. The distance measurement from the laser distance gage and the position of the tube-tracking slide form a profile of the tube at the measured location in the cyclone.



Welding

The welding is GMAW automatic using pulsating arc as a transfer mode. The computer controller is connected to the constant voltage power supply. The computer controller uses converters to create DC voltage signals to control the arc voltage and wire feed speed.



CROSS SECTION OF REPAIRED
BOILER TUBE

Operation

The separate components of BAWS® are designed to perform specific tasks. These tasks must be integrated to accomplish the overall function of applying a weld overlay. This integration is accomplished by the computer controller. The computer controller provides command and control of the process through software developed specifically for this purpose.

The operator has completed control from the computer controller. Using mouse, keyboard, and video input, the operator can start, stop, and change the process from outside the cyclone. For teaching the computer the parameters for each new cyclone, a pendant that has full computer and video display capabilities can be taken in the cyclone for initial setup.

Project Speed

After removal of refractory (by waterblasting) in the cyclones is complete, stud removal, touchup grinding, grit blasting, and UT testing of the selected area can be accomplished in six shifts. Machine setup, assembly, testing, welding, and removal can be accomplished in eight shifts. The cyclone is now ready for restudding and installation of new refractory.

Conclusion

The BAWS® provides an automated system to restore cyclone tubes using weld overlay. The system performs automatically using a multi axis robot positioner, a system to provide automatic tube tracking, and a system that provides torch head position control.

Most cyclones can be restored with as little as 50 square feet of weld overlay.

Tubes can be restored to original wall thickness or built up with additional sacrificial metal. Installation of new studs and refractory return the cyclone to excellent condition, suitable for continued service.

AUTOMATIC MOTOR WINDING DRY-OUT MACHINE

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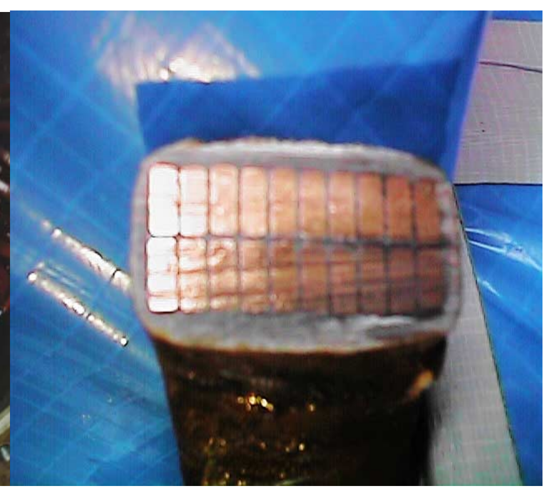
Abstract

Large motor windings (>250 hp and >480 Volts) are made of individual coils which are comprised of copper conductors, multi-layers of mica tapes, and a binding or outer layer of glass or dacron tape. The coils are treated or coated with polyester or epoxy resins to provide structural strength as well protection from moisture and abrasion. See photos below:

COILS WOUND IN STATOR FOR A REACTOR COOLANT PUMP MOTOR



CROSS SECTION OF ONE OF THE COILS SHOWING THE COPPER CONDUCTORS AND LAYERS OF INSULATION TAPES

As motor insulation systems age, small cracks will form within the resins due to winding movement, thermal degradation, radiation (nuclear only), and time in service. Because of this characteristic of motor insulation, the windings become more susceptible to moisture intrusion over time. This usually is only a concern when the motors are removed from service for an outage. Although motor heaters (available on some motor designs) help prevent the windings from dropping below dew point, moisture intrusion has still been a problem and has resulted in many motor failures on start-up after being de-energized for an extended period of time. The moisture within a winding will provide a current path between the copper conductors and ground. Because a motor winding experiences 6 to 8 times running current during starting, a failure due to moisture is most likely to occur on start-up.

Moisture can also be introduced into a motor winding from steam cleaning to remove oil and dirt which accumulates over time on the windings. If the dirt and oil is not removed, ventilation can be reduced and winding overheating and/or failure may occur. Regardless of the reason that the insulation materials become wet, drying of the winding is essential to help prevent premature motor winding failures.

Removal of this moisture has always been a problem in the field because of the lack of an oven (as used in motor repair shops) to heat the windings and the physical problems associated with removal of the motor from many plant locations. This problem has been resolved with the introduction of the **A**utomatic Motor Winding **D**ry-Out **M**achine (**ADM**).

Introduction

Most of the utilities in the U.S. are operating with motors that were designed in the 1960s. Many of these motors have the original insulation system still installed. Some operate in an indoor controlled environment, many operate in a dirty environment, some are outside, and some operate near salt water. All are susceptible to moisture being absorbed into their insulation materials, especially those that are in an uncontrolled or outside environment.

To determine if a winding has absorbed moisture, an insulation resistance test is usually performed for ten minutes. A reading is recorded at one minute and ten minutes (in megohms). The one minute reading is then divided into the ten minute reading. This is called the Polarization Index (PI) and is required to have a value of >2.0 unless the one minute reading is >5000 megohms in which case the PI is ignored (ref. IEEE 43). If the PI is <2.0, there is a strong possibility that the insulation has absorbed moisture or is contaminated with oil and/or dirt which is creating excessive surface leakage current. If moisture is the problem, a dry-out is required; if the winding is contaminated with oil and dirt, a steam cleaning may be in order. In either case, the winding will require drying.

The methods available in the field for motor winding drying are limited. They consist of the following:

1. Use of hot air blowers while tenting the motor stator
2. Use of heater elements while tenting the motor stator
3. Circulating DC current through the copper conductors and using the I^2R losses of the copper to heat the winding from the inside out.

The preferred method is Number 3. Although this method provides the quickest dry-out, there are several problems using welding machines for this purpose:

1. Welding machines are not designed for continuous duty (winding dry-out by this method usually takes 60 hours of continuous operation).
2. Because motors have three phases and welding machines have one positive and one negative output, the current has to be divided by two of the phases and one phase carries full current. This will make the winding heat uneven, therefore the phase connections to the welding machine output leads have to be rotated regularly to maintain some attempt at even heating. This can be labor intensive.
3. If the winding temperature is raised too rapidly, damage to the winding can occur due to formation of moisture turning to vapor within the layers of mica tape. To prevent this, the winding temperature is raised at 9°F/hour (ref. IEEE 43). This requires constant monitoring of the winding temperature (usually not available at the breaker where the welding machine is connected) and constant adjustment of the welder output (as copper heats, its resistance changes therefore changing the current required for a given temperature). This is labor intensive.
4. Once dry-out temperature is obtained (usually 220°F.) and maximum current is achieved ($\leq$ 75% of full load amps), constant welder output adjustment is required to maintain the required temperature. Requires manpower around the clock.

The Challenge

The challenge was to develop a machine that would dry-out a motor winding using the same method as the welding machines but have it perform all of the functions automatically. The development requirements of the machine were:

- Capable of automatically ramping up the temperature of the winding at an operator's choice of temperature (normally 9°F/hour) without exceeding the current limit that was decided on during the initial program setup for a particular motor. This function must be performed without any operator assistance other than initial setup.

- Must provide temperature stability within 5°F of maximum set point temperature (this would be determined from the insulation systems' Class Rating (ref. NEMA MG-1). Usually the maximum temperature for dry-out will be around 220°F.

- The machine will have the capability of automatically switching the current between the 3 phases at a specified interval (determined by the operator - usually between 1-4 hours) to provide even heating of the winding.

- Real time winding temperature monitoring must be capable both at the motor and at the machine (usually connected to the breaker) using embedded temperature elements that are built in the winding.

- Must be capable of monitoring real time winding temperature if embedded temperature elements are not designed in the motor winding. (The back iron of the stator core usually represents winding temperature within 10-20°F. once stable core temperature is reached.) A special magnetic base with a spring loaded thermocouple was developed for back iron temperature monitoring. Infrared sensors were also developed to provide non-intrusive monitoring of winding temperature if the rotor is removed.

- Must be capable of allowing local hookup at the motor or remote hookup from a power supply breaker.

- The machine must be able to hold the dry-out temperature for a specified length of time without operator assistance.

- Automatic shutdown is required in the event of an anomaly during the dry-out process.

- The controls for the machine must be user friendly, capable of storing the dry-out process, and allowing down loading of the data for reports.

- The machine must be transportable by rolling (without damaging the painted floors of the plant) by use of a fork lift or by lifting with a crane.

- The power supply cable, the output cables, and all auxiliaries must be stored onboard to provide ease of transport.

- Visual indication must be designed into the machine to allow easy verification of proper operation even from a distance.

- Internal protection is required to protect the plant's supply as well as the machine for 60 amps (most 480 volts outlets) and 200 amps (connected directly to a board).

- Program lock was required to prevent unauthorized tampering.

- A touch sensitive computer was required to prevent having to have an external keyboard.

- All components must be industrial grade. The internal design of the wiring must be secured to withstand transport and slight abuse.

- Output of the machine must be capable of 0 to 1200 amps DC max.

- Output was required to have automatic phase switching or be controlled manually without switching.

- Output voltage control with current limiting was required to use the machine as a DC voltage source instead of a current source if needed.

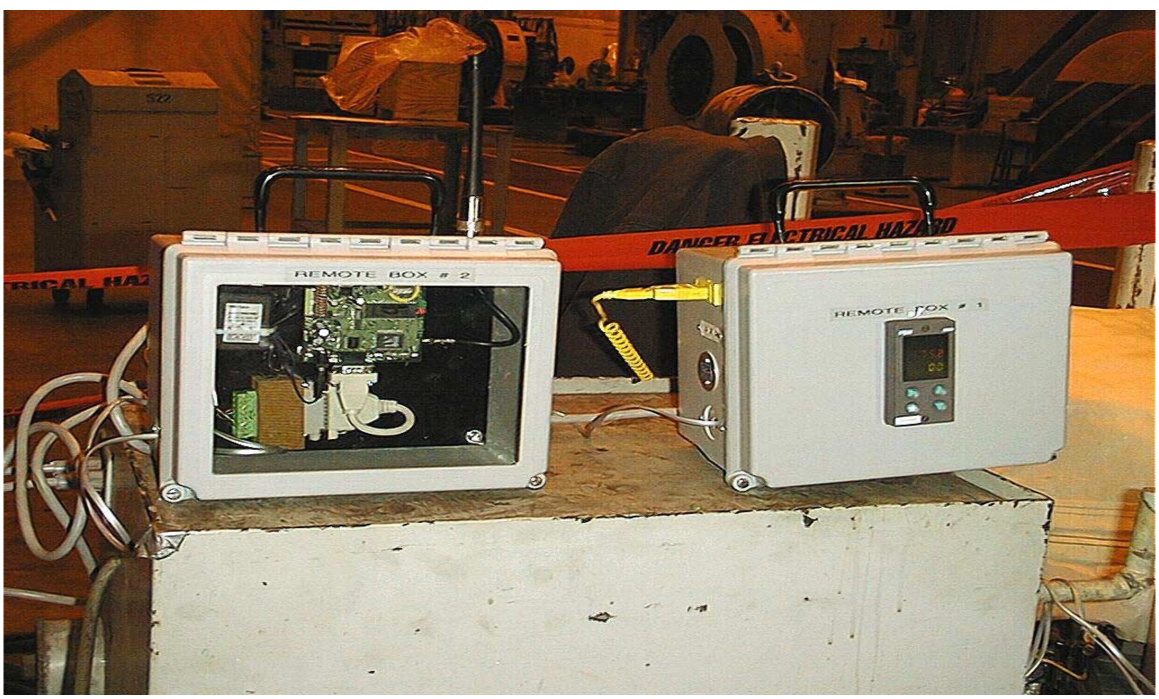
Meeting the Challenge

TVA worked with EPRI to identify a company that had the understanding and expertise to build a machine that met all of the requirements listed above. The company that was given the contract was Mannings, USA. A prototype of the machine was built and first tested during TVA's Sequoyah Nuclear Plant's Unit 1 Cycle 10 refueling outage on two motors that were in the basement of the turbine building. Both motors had dirty/oily windings and required steam cleaning. After steam cleaning the stator windings in place, the ADM was connected to the supply breaker which was approximately 800 feet away from the motors as well as 4 stories up. Radio modems (designed with the unit) were used to provide local hookup of the embedded thermocouples of the stator windings. The radio modem not only gave local winding temperature, but also transmitted this temperature back to the ADM as a feedback signal for the ADM to control the winding temperature. During the dry-out of one motor, the supply breaker that was providing power to the ADM failed. The machine tripped its internal breaker and protected itself and the motor. On that same motor, the ADM was accidentally unplugged 23 hours into the dry-out cycle. Again, the machine tripped its internal breaker and protected itself and the motor. On one occasion, the "B" phase on the power supply was lost to the ADM. The machine drove the output to zero and went into a hold status. The radio modem signal was also lost during this first field test. The ADM drove the output current to zero and went into a hold status as designed.

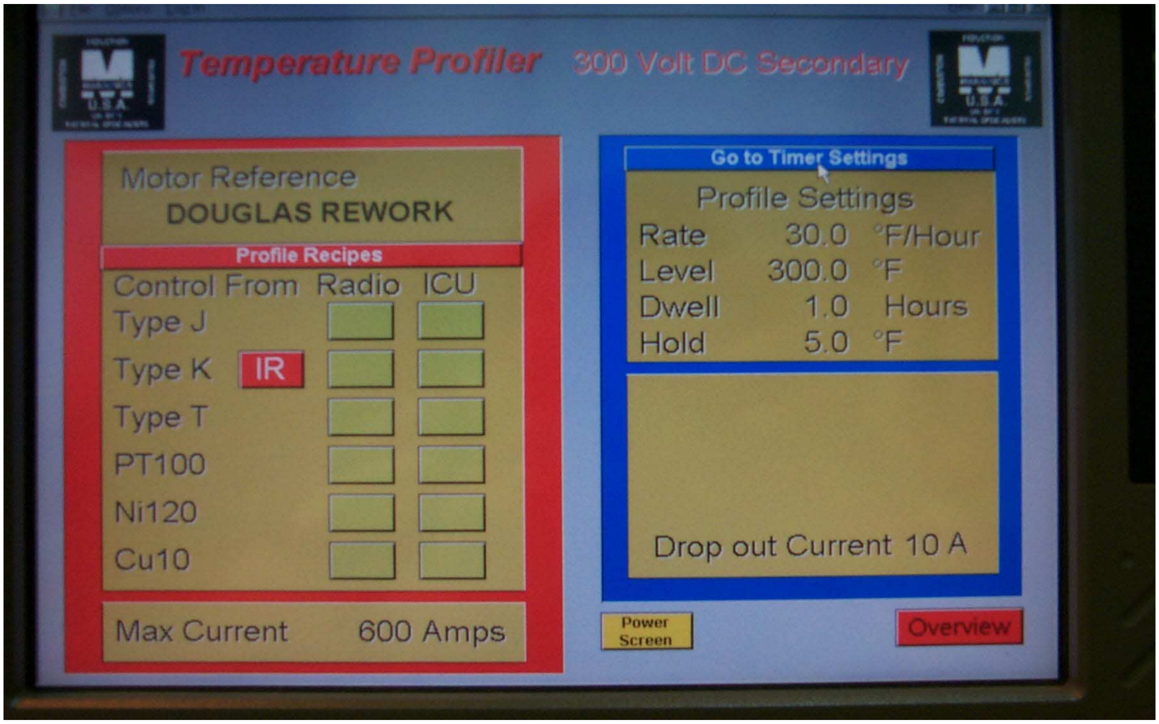
Not only was the ADM used to dry-out two stator windings that were steam cleaned, it was also used to reduce the cure time of a winding re-treatment resin used on both motors from 24 hours per motor to 4 hours per motor. The dry-out of each stator was accomplished in 30 hours instead of 60 hours. Both of these time reductions were significant during the refueling outage as well as eliminating the need to have a manpower resource overseeing welding machine operation. Overall, the first field test of the prototype ADM was very successful.

PHOTO SHOWING THE DIRT/OIL ON THE STATOR WINDING
(BEFORE CLEANING)

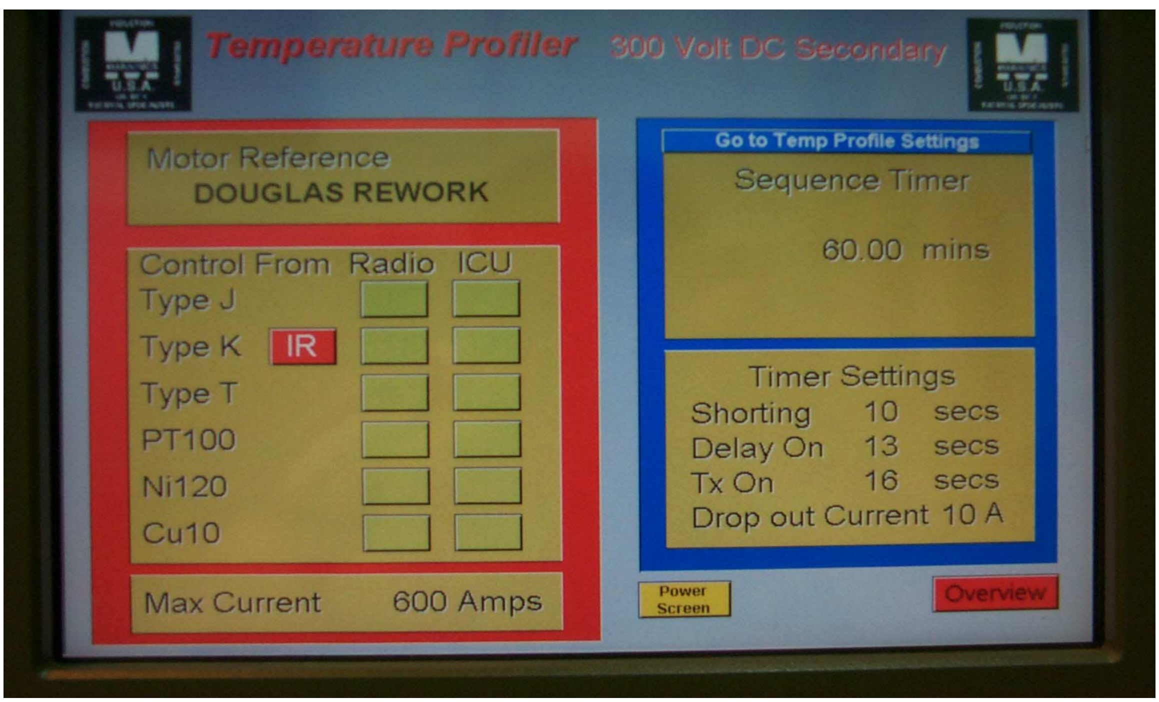
PHOTO SHOWING THE ADM AND RADIO MODEM IN USE
AT TVA's POWER SERVICE SHOPS



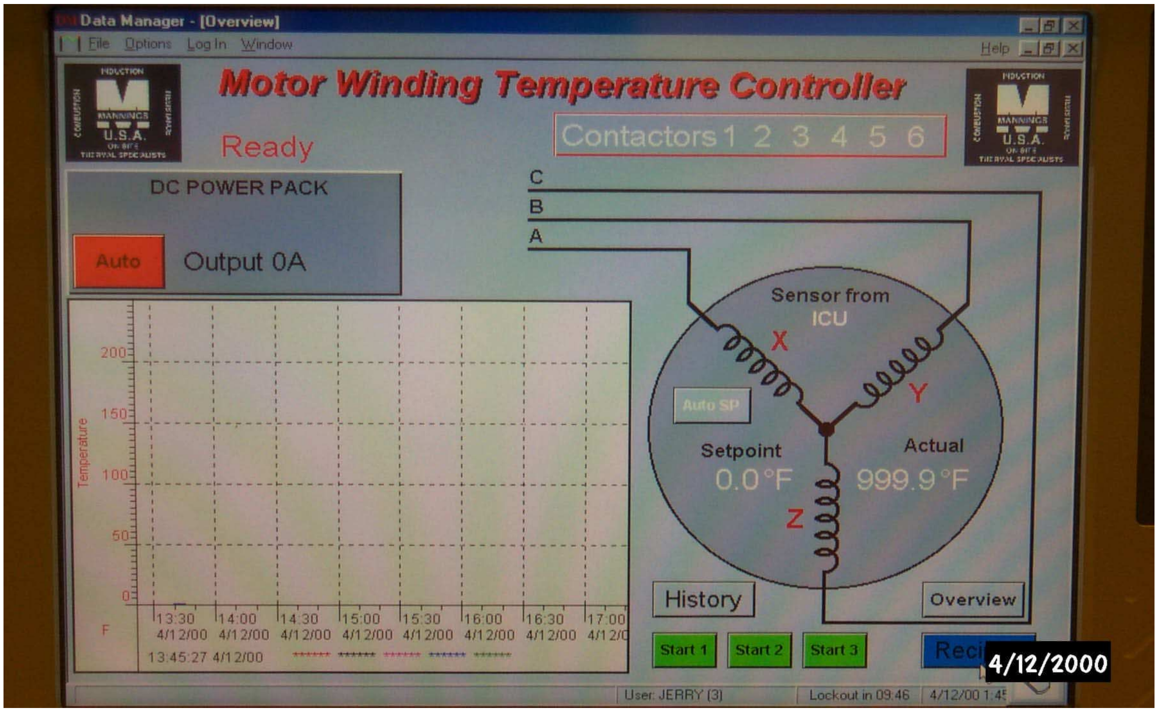
RADIO MODEM BEING USED DURING INITIAL ADM TESTING



INITIAL SETUP SCREEN ON THE ADM
ALL PARAMETERS CAN BE SET BY THE OPERATOR



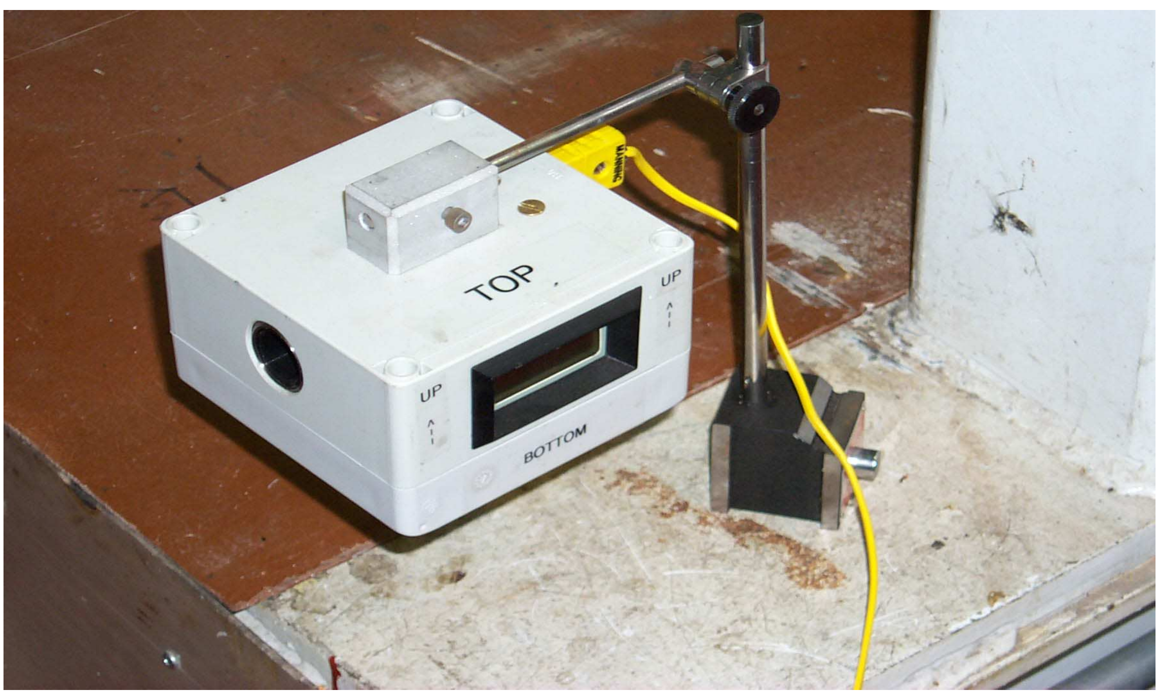
SECOND SCREEN DISPLAYED ON INITIAL SETUP
SEQUENCE TIMER REPRESENTS THE PHASE SWAPPING TIME TO
MAINTAIN EVEN HEATING



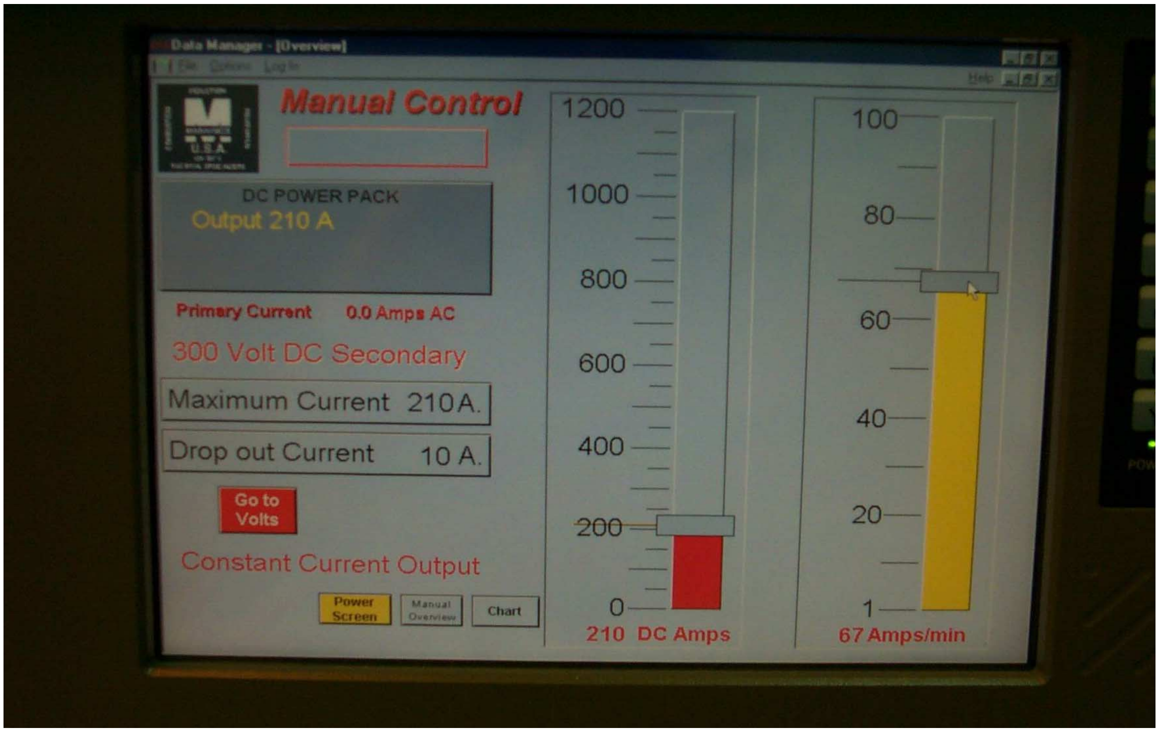
MAIN SCREEN DISPLAY AFTER SETUP - THIS SCREEN WILL BE DISPLAYED FOR THE ENTIRE DRY-OUT OR CURE PROCESS

DISPLAY OF ADM DURING OPERATION
NOTICE TOUCH SENSITIVE SCREEN

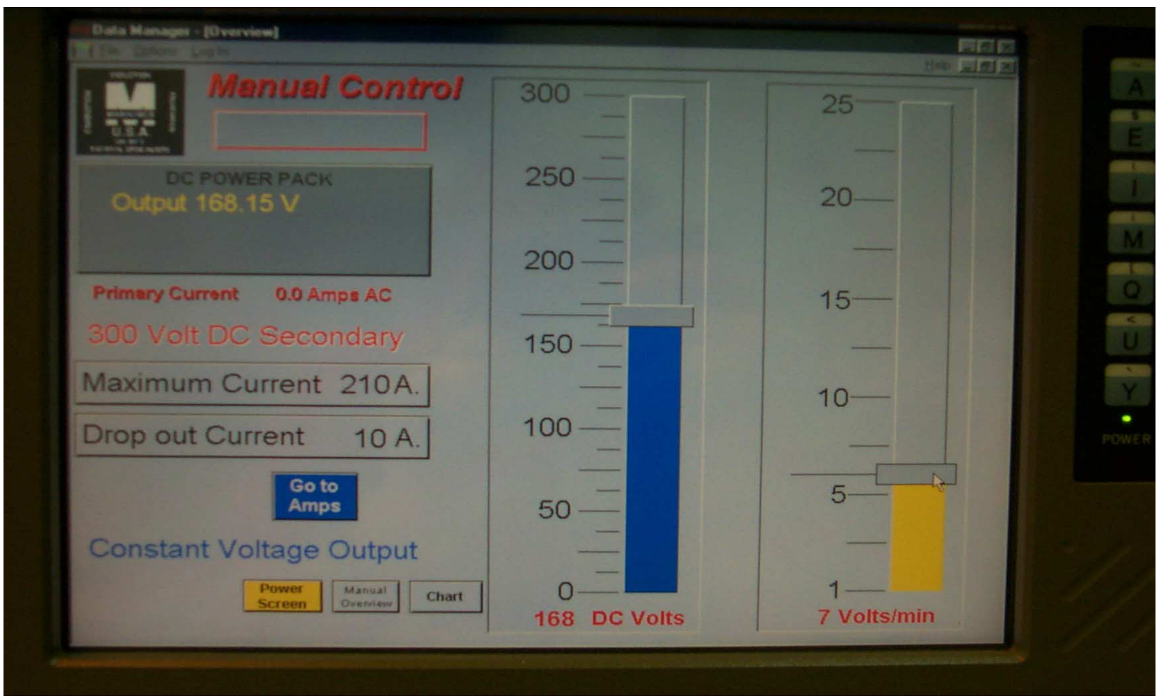
SPECIAL MAGNETIC BASE AND SPRING LOADED THERMOCOUPLE BEING USED ON MOTOR BACK IRON - THIS MOTOR DID NOT HAVE EMBEDDED TEMPERATURE ELEMENTS



INFRARED SENSORS USED FOR NON-INTRUSIVE TEMPERATURE MONITORING - USED FOR HYDRO GENERATOR POLE PIECE CURING PROCESS AFTER RE-INSULATION



MANUAL NON-SEQUENCING CURRENT OUTPUT CONTROL SCREEN
USED TO DRY OR CURE GENERATOR ROTORS



MANUAL NON-SEQUENCING VOLTAGE OUTPUT SCREEN
CAN BE USED TO POWER DC MOTORS OR OTHER DC LOADS

CONCLUSION

The prototype ADM performed extremely well for its first field test. The time saved on just two motors during the Sequoyah outage assisted in shortening the outage. The system is totally automatic except for hookup and programming, is very user friendly, and is easy to learn to operate. TVA has purchased a second commercial machine and has successfully used it for:

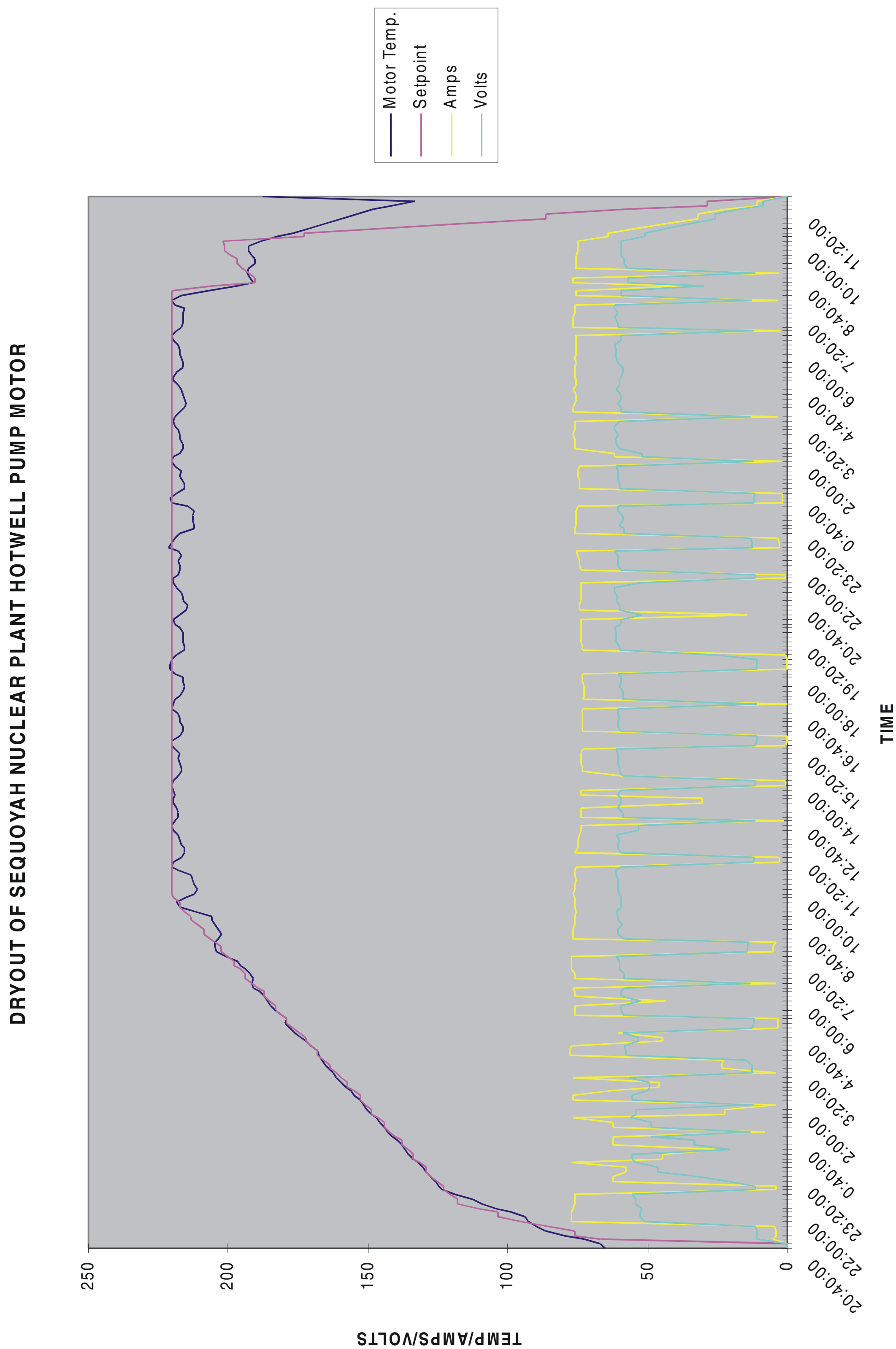
- Curing of a main generator rotor after re-insulation.
- Curing of hydro-electric generator pole pieces after re-insulation.
- Drying out a main generator winding.
- Drying of a main generator rotor.
- Drying of several cooling tower fan motors at the same time connected in parallel.

There are many other uses for the ADMs that TVA has not tried yet. A few near term applications are:

- Curing a motor winding after a VPI resin dip.
- Provide temperature controlled portable ovens (hot boxes) made from modular resistance heat panels.
- Running DC motors.
- Taking the place of a battery bank in emergency situations.

The ADMs are being used to support Nuclear, Fossil, and Hydro for both motors and generators. They are becoming routine onsite equipment for outage support and are being used in the shop and field environments.

The raw data generated from the dry-out of one motor at Sequoyah is attached. This data generates the chart shown on the next page which provides a visual understanding of how the machine works. The chart shown on the next page is displayed on the ADM computer screen during the ADM's operation to allow the operator to easily and continually view the operating parameters that are used for the dry-out or cure processes.


DRYOUT OF SEQUOYAH NUCLEAR PLANT HOTWELL PUMP MOTOR
Motor Temp.
Setpoint
Amps
Volts
TEMP/AMPS/VOLTS
250
200
150
100
50
0
TIME
20:40:00
22:00:00
23:20:00
0:40:00
2:00:00
3:20:00
4:40:00
6:00:00
7:20:00
8:40:00
10:00:00
11:20:00
12:40:00
14:00:00
15:20:00
16:40:00
18:00:00
19:20:00
20:40:00
22:00:00
23:20:00
0:40:00
2:00:00
3:20:00
4:40:00
6:00:00
7:20:00
8:40:00
10:00:00
11:20:00

Time	Motor Temp.	Setpoint	Amps	Volts
20:40:00	65.4	0	0.1	0.1
20:50:00	66.8	0	0.1	0.1
21:00:00	72.8	67.2	5.1	11
21:10:00	79.7	76.2	4	11
21:20:00	86.1	76.2	4	11
21:30:00	90	86	4.5	11.5
21:40:00	92.4	95.7	77.4	50.8
21:50:00	93.9	103.6	77.1	52.9
22:00:00	99	103.6	77.1	52.9
22:10:00	104.2	110.6	76.8	52.2
22:20:00	109.1	118.1	76.3	54.2
22:30:00	112.8	118.1	76.3	54.2
22:40:00	119.1	120.7	76.3	55.4
22:50:00	123.8	122.9	3.8	11.6
23:00:00	124.7	122.9	3.8	11.6
23:10:00	126	125.1	62.4	20.6
23:20:00	127.6	127.3	62.2	31.6
23:30:00	129.2	129.3	57.6	46.5
23:40:00	130.5	129.3	57.6	46.5
23:50:00	132	131.5	77.3	54.5
0:00:00	133.8	133.7	44.7	55.4
0:10:00	135.4	133.7	44.7	55.4
0:20:00	136.7	135.8	23.6	20.5
0:30:00	138.1	137.9	62.5	33.3
0:40:00	139.6	137.9	62.5	33.3
0:50:00	141.2	140.1	62.4	48.7
1:00:00	142.8	142.3	7.9	13.3
1:10:00	144.3	144.4	62.3	48.7
1:20:00	145.7	144.4	62.3	48.7
1:30:00	147.1	146.6	76.9	56.1
1:40:00	148.7	148.8	22.4	54.3
1:50:00	150.5	148.8	22.4	54.3
2:00:00	151.5	150.8	3.9	12.1
2:10:00	152.6	153	76.8	55.3
2:20:00	154.9	153	76.8	55.3
2:30:00	156.4	155.2	62.3	50
2:40:00	157.8	157.4	46	49.1
2:50:00	159.4	157.4	46	49.1
3:00:00	161.1	159.4	76.6	56.8
3:10:00	162.6	161.6	3.9	12.3
3:20:00	164	163.8	23.3	12.5
3:30:00	165.4	163.8	23.3	12.5
3:40:00	166.6	165.8	23	14.7
3:50:00	167.7	168	77.6	57.9
4:00:00	168.4	168	77.6	57.9
4:10:00	170.4	170.2	77.4	58.6

Time	Motor Temp.	Setpoint	Amps	Volts
4:20:00	172.4	172.3	44.4	53
4:30:00	173.9	172.3	44.4	53
4:40:00	176.1	174.5	60.6	58.7
4:50:00	178.1	176.7	3.4	12.3
5:00:00	179.5	178.8	3.2	12.2
5:10:00	179.1	178.8	3.2	12.2
5:20:00	180.6	180.9	76.2	58.1
5:30:00	183	183.1	76	59.4
5:40:00	184.6	183.1	76	59.4
5:50:00	185.7	185.3	43.7	52.9
6:00:00	187.1	187.3	76.3	59.7
6:10:00	188.9	187.3	76.3	59.7
6:20:00	191.1	189.5	76.7	58.3
6:30:00	191.8	191.7	3.8	12.9
6:40:00	191.1	193.9	76.3	58.3
6:50:00	192.3	193.9	76.3	58.3
7:00:00	194	195.9	77.3	60.2
7:10:00	195.8	198.1	77.4	59.8
7:20:00	196.7	198.1	77.4	59.8
7:30:00	200.6	200.3	77.5	61.1
7:40:00	204	202.4	4.9	14.1
7:50:00	205	202.4	4.9	14.1
8:00:00	204.7	204.6	4.2	13.5
8:10:00	203.9	206.7	76.7	58.6
8:20:00	202.8	208.8	76.8	60.4
8:30:00	203.6	208.8	76.8	60.4
8:40:00	204.7	211	76.1	59.2
8:50:00	205.8	213.2	76.2	60.8
9:00:00	205.8	213.2	76.2	60.8
9:10:00	211.6	215.4	75.8	61.1
9:20:00	217.4	217.4	76.1	59.7
9:30:00	218.6	217.4	76.1	59.7
9:40:00	215	219.6	75.9	59.4
9:50:00	212.2	220	76.4	60.2
10:00:00	211.2	220	76	60.9
10:10:00	212.4	220	76	60.9
10:20:00	212.7	220	75.8	60.5
10:30:00	213.2	220	75.9	61.2
10:40:00	218.1	220	75.9	61.2
10:50:00	220	220	75.6	59.7
11:00:00	219.7	220	2.8	12
11:10:00	216.7	220	2.8	12
11:20:00	215.6	220	76.1	59.7
11:30:00	215.7	220	74.9	60.8
11:40:00	216.9	220	74.9	60.8
11:50:00	217.3	220	74.9	60.2
12:00:00	218.2	220	74.6	61.3
12:10:00	219.5	220	73.6	53.1

Time	Motor Temp.	Setpoint	Amps	Volts
12:20:00	220	220	73.6	53.1
12:30:00	219.2	220	1.1	11.7
12:40:00	218.2	220	74	59.2
12:50:00	217.9	220	74	59.2
13:00:00	218.8	220	73.9	60.8
13:10:00	219.5	220	30.6	59.4
13:20:00	219.5	220	30.6	59.4
13:30:00	219.3	220	74	60.9
13:40:00	219.5	220	73.7	59.7
13:50:00	220.1	220	0.8	11.7
14:00:00	219.6	220	0.8	11.7
14:10:00	218.1	220	59.3	58.8
14:20:00	216.6	220	73.5	60
14:30:00	216.7	220	73.5	60
14:40:00	217.4	220	73.6	60.9
14:50:00	217.8	220	73.6	60.6
15:00:00	217.5	220	73.6	60.6
15:10:00	219	220	73.4	61.2
15:20:00	220.1	220	0.4	11.2
15:30:00	220.3	220	0.2	11
15:40:00	217.6	220	0.2	11
15:50:00	216.3	220	73.1	59.4
16:00:00	216.3	220	73	60.4
16:10:00	217.2	220	73	60.4
16:20:00	217.2	220	73.1	60.1
16:30:00	217.8	220	73.2	60.9
16:40:00	220.1	220	73.2	60.9
16:50:00	219.8	220	0.2	10.9
17:00:00	218.9	220	73	58.7
17:10:00	217.6	220	72.9	58.7
17:20:00	216	220	72.9	58.7
17:30:00	215.7	220	72.9	60.1
17:40:00	216.3	220	73	59.4
17:50:00	216.5	220	73	59.4
18:00:00	219	220	73	60.7
18:10:00	221.1	220	0.1	10.8
18:20:00	220.6	220	0.1	10.8
18:30:00	220.2	220	0.2	11
18:40:00	218.7	220	0.6	26.3
18:50:00	215.7	220	73.5	60
19:00:00	215.8	220	73.5	60
19:10:00	216.1	220	73.7	61.2
19:20:00	216.5	220	73.6	61
19:30:00	216	220	73.6	61
19:40:00	217.6	220	73.7	61.7
19:50:00	219.3	220	73.9	59.7
20:00:00	219.6	220	73.9	59.7
20:10:00	217.2	220	14.2	52

Time	Motor Temp.	Setpoint	Amps	Volts
20:20:00	215.3	220	74.1	60.3
20:30:00	214.7	220	74.1	60.3
20:40:00	216	220	73.8	61.1
20:50:00	216.5	220	73.9	60.7
21:00:00	216.7	220	73.9	61.6
21:10:00	218.7	220	73.9	61.6
21:20:00	219.7	220	74	52.5
21:30:00	219.7	220	0.8	11.6
21:40:00	217.8	220	0.8	11.6
21:50:00	217.2	220	73.8	59.5
22:00:00	217.2	220	74.3	60.8
22:10:00	217.8	220	74.3	60.8
22:20:00	216.6	220	75.1	60.6
22:30:00	218	220	75.6	61.6
22:40:00	221.2	220	2.7	12.7
22:50:00	220.4	220	2.7	12.7
23:00:00	219.3	220	3.4	12.9
23:10:00	217.2	220	76.3	58.6
23:20:00	212.3	220	76.3	58.6
23:30:00	212	220	75.7	60
23:40:00	212.6	220	75.6	59
23:50:00	212.8	220	75.6	59
0:00:00	212.1	220	75.3	60.4
0:10:00	214.8	220	74.9	60.9
0:20:00	220.4	220	1.8	11.9
0:30:00	220.7	220	1.8	11.9
0:40:00	218.3	220	1.7	11.7
0:50:00	215.4	220	74.6	60
1:00:00	215.5	220	74.6	60
1:10:00	216.6	220	74.4	60.9
1:20:00	217.3	220	74.7	60.6
1:30:00	216.8	220	74.7	60.6
1:40:00	219.2	220	74.4	61.4
1:50:00	220.2	220	1.8	11.9
2:00:00	219.4	220	61.7	52.3
2:10:00	217.3	220	61.7	52.3
2:20:00	216.4	220	76	60.2
2:30:00	216.4	220	76.2	61.2
2:40:00	217.2	220	76.2	61.2
2:50:00	217.4	220	76.4	60.7
3:00:00	217.8	220	76.3	61.6
3:10:00	219.1	220	76.3	61.6
3:20:00	219.8	220	76.2	59.9
3:30:00	219.3	220	3.6	13.1
3:40:00	217.4	220	76.5	59.3
3:50:00	215.7	220	76.5	59.3
4:00:00	215.2	220	75.9	60.7
4:10:00	215.7	220	75.6	59.7

Time	Motor Temp.	Setpoint	Amps	Volts
4:20:00	216.3	220	75.6	59.7
4:30:00	217	220	76.4	61.2
4:40:00	217.9	220	75.7	60
4:50:00	219.4	220	75.7	60
5:00:00	219.4	220	75.9	59.6
5:10:00	218.3	220	75.9	59.1
5:20:00	216.1	220	75.9	59.1
5:30:00	216.4	220	75.8	60.5
5:40:00	216.9	220	75.9	61.3
5:50:00	217.3	220	75.6	61
6:00:00	217.2	220	75.6	61
6:10:00	218.2	220	75.8	61.8
6:20:00	219.5	220	75.4	59.7
6:30:00	220.4	220	75.4	59.7
6:40:00	218.6	220	2.2	11.9
6:50:00	216.9	220	76.5	60.6
7:00:00	216.1	220	76.5	60.6
7:10:00	216.5	220	76.9	61.8
7:20:00	216.2	220	76.1	60.9
7:30:00	215.5	220	75.9	61.6
7:40:00	219.3	220	75.9	61.6
7:50:00	220	220	3.2	12.4
8:00:00	216.9	220	75.7	59.6
8:10:00	206.9	220	75.7	59.6
8:20:00	196.6	205.3	37.9	29.9
8:30:00	190.8	190.6	76.4	57.3
8:40:00	192.5	190.6	76.4	57.3
8:50:00	193.6	192.6	2.9	11.7
9:00:00	192.8	194.8	75.7	57.3
9:10:00	190.4	197	75.7	58.5
9:20:00	190.4	197	75.7	58.5
9:30:00	191.4	199.1	75.7	59.6
9:40:00	192.7	201.3	75.1	59.5
9:50:00	192.8	201.3	75.1	59.5
10:00:00	188.4	201.9	75	59.7
10:10:00	182.7	173	64.3	51.2
10:20:00	176.9	173	64.3	51.2
10:30:00	171.2	144.2	53.6	42.7
10:40:00	165.4	115.3	42.9	34.2
10:50:00	159.7	86.5	32.2	25.7
11:00:00	154	86.5	32.2	25.7
11:10:00	148.2	57.6	21.5	17.2
11:20:00	142	28.8	10.8	8.7
11:30:00	133.4	28.8	10.8	8.7
11:40:00	187.7	0	0.2	0.2

Condition-based maintenance of reactor coolant pumps

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Abstract

Deregulation of the European electricity market makes optimisation of nuclear maintenance an essential challenge for Electricité de France (EDF). Together with reliability-centred maintenance, condition-based maintenance is considered a powerful way to reduce maintenance costs.

In this context, a project devoted to condition-based maintenance of reactor coolant pumps (RCP) began in 1998. It aims to develop knowledge, methodology and tools for maintenance decision support.

Setting up degradation models constitutes the key point of the maintenance optimisation approach.

Critical components have been identified by RCM studies on RCP 900, 1300 and 1450 MW Pressurised Water Reactor series. For each critical component, an optimal degradation model (statistical, numerical, tests . ..) is evaluated in order to estimate life duration.

The knowledge as a whole has been integrated into a tool for RCP condition-based maintenance in order to allow access, in exploitable form, to different information relevant to activities related to RCP condition-based maintenance, to carry out a health assessment of RCP, to carry out a diagnosis of faults in the event of a negative health assessment result. EDF has decided to industrialise a diagnosis expert system called DIAPO and to propose several decision support tools making it possible, before an outage or an overhaul, to assess the impact of different maintenance scenarios with respect to maintenance costs and unit availability.

The first goal of this service is to assist the user in assessing the feasibility of deferring an inspection scheduled by the Basic Preventive Maintenance Program (BPMP).

An initial prototype of this maintenance support tool was developed in 1999, so that future users can validate the principles of RCP condition-based maintenance. A more advanced tool will integrate maintenance optimisation functions by the end of the year 2000.

1. Introduction

Reducing the maintenance costs of the nuclear park is an essential consideration for Electricité de France (EDF) just as the electricity market in Europe is being deregulated. EDF actually operates 58 nuclear units (34 x 900 MW, 20 x 1300 MW and 4 x 1450 MW). The nuclear-source electricity share represents more than 80% of the electricity produced in France.

Optimising maintenance through reliability and condition-based maintenance constitute two important levers enabling maintenance costs to be reduced whilst controlling the two essential considerations of safety and availability of the industrial tool.

This requirement to optimise maintenance applies in particular for the reactor [main] coolant pumps, which are vital equipment for nuclear power plants.

In this context, a condition-based maintenance project began in 1998 with the aim of offering knowledge, a methodology and support tools to assist the maintenance decision regarding the RCPs.

The aim of this paper is to present this methodology and its associated tools in order to help draw up a health assessment of the RCPs and to optimise the maintenance inspections.

2. Maintenance of reactor coolant pumps (RCPs)

The reactor coolant pumps are one of the most important components as far as the availability and safety of nuclear power plants are concerned. They provide for circulation of the primary fluid between the reactor and the steam generator. The RCP is a vertical axis rotating machine, about 10 metres high, several MW in power with a flow rate that can reach 7 m3/s. The RCP consists of three main functional units: the motor, pump and shaft line. A system of controlled-leak shaft seals [gaskets] ensures the pump is leak-tight in relation to the hot cave.

Maintenance of the reactor coolant pumps is structured by systematic operations recorded in a basic preventive maintenance programme (BPMP). The aim of the study is to decrease in the future the periodicity of seal inspections.

This strategy is in the hope of significant potential savings in terms of seal maintenance.

Currently, the possibilities of deciding on-site to defer a seal inspection are very limited. The analysis of the operating parameters is very simplified and there are no decision criteria. This analysis in most cases results in the application of the BPMP. Furthermore, it is very difficult to get it changed. In fact, applying a maintenance programme based on seal periodicity presupposes that one can guarantee the reliability of the Park's 198 seals over the chosen periodicity.

The study presented here aims to include the knowledge as a whole and to develop a tool giving the sites the possibility of scheduling the seal inspections at a suitable time

3. The response to the requirement : the RCPCM tool

The RCPCM condition-based maintenance tool, developed within the context of this study, is aimed at capitalising knowledge of the degradation involved and more specifically at providing the following services:

- access, in an exploitable form, to different information relevant to the activities associated with condition-based maintenance (FMECA, experience feedback, etc.);
- the drawing up of a RCP “health assessment” on an operating cycle on the basis of operating data (leakage flow rate from the seals, temperature of the bearings, vibrations),
- a diagnosis support facility (DIAPO) making it possible, in the event of the health assessment detecting an anomaly, to search for the fault behind the anomaly;
- different aids [support facilities] based on a reliability analysis of the pump's different components (in particular, joints and bearings), making it possible, before a shutdown or inspection, to assess the impact of the different maintenance scenarios in question on the maintenance costs and availability of the unit.

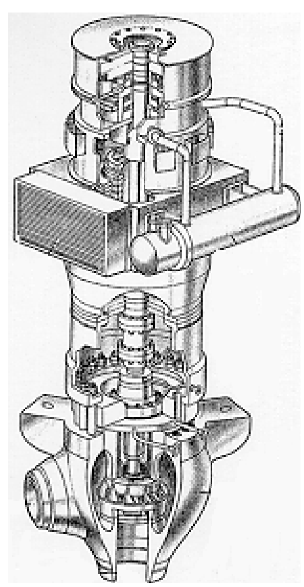

Figure 1: Outline of a reactor coolant pump

4. Condition-based maintenance procedure adopted

A FMECA analysis was initially developed to identify the degradation as a whole in the pump:

- The degradation detectable through in-service monitoring. [3],
- The degradation not detectable through ordinary monitoring but which can be highlighted by non-intrusive checks (e.g. ultrasound checks),
- The so-called hidden degradation which can only be quantified by an intrusive inspection.

Optimising the maintenance involves a delicate mix of analysis of the monitoring data, regular non-intrusive checks and expert appraisals of the components during the inspections.

There is another problem for the RCPs. Some faults can be detected by monitoring, especially shaft seal faults, but only belatedly. So the pre-failure time is short in respect of an operating cycle (18 months for the long cycles).

4.1. Global reliability analysis

The first step in the condition-based maintenance procedure which we have implemented corresponds to an RCM-type optimisation. This analysis is based on breaking down the machine into a technological unit (e.g. motor, pump), technological sub-units (TSUs)(e.g.: seal 1, seal 2, etc.) and components (e.g.: O-ring for seal 1). The critical components, for which the modes of degradation or failure are critical in terms of availability, maintenance and safety, are identified. A level of criticality is assessed on the basis of significant experience feedback for 198 RCPs and gravity in terms of failure impact on the functions to be provided by the machine.

An optimal degradation model (statistical, determinist, tests, etc.) is adopted for each component in order to estimate its life. In most cases, a statistical model has been used, combined, in the event of inadequate experience feedback, with numerical models.

This study has been carried out in respect of all the critical components and particularly the shaft seals. It should be noted that a single intrusive inspection enables the state of degradation to be discovered as far as most of these components are concerned.

The component with the shortest life is the element which conditions the periodicity of the seal inspection (serial system). The solution most often adopted to compensate for the problem is modification of the technology. It is a means of extending the maintenance periodicity.

This stage makes it possible, for all the components on the basis of the feedback experience for the park as a whole, to estimate a rate of degradation and a rate of failure. The periodicity of the inspections is the result of the synthesis between the failure and degradation rates of the critical components and detectability of such degradation by the monitoring and non-intrusive checking methods.

A life threshold is estimated, by expert opinion, by using the survival curve (degradation) of the component and the survival curve (failure). This threshold will subsequently be used to analyse deferral of the component inspections.

4.2. Application to a specific machine

An analysis as to global reliability has been carried out on the whole population. Particular care was paid to excluding early life failure or failures not directly ascribable to the component. A health assessment prior to the reliability analysis then makes it possible to take account of the behaviour of the RCP in question and in respect of which the issue of inspection deferral arises.

The principle of the health assessment is not to do a specific analysis. It does not call for interpretations on the part of the user, but involves solely the application of predefined criteria, particularly as far as the vibratory and thermohydraulic data are concerned (bearings and seals).

The procedure adopted is as follows:

- if the health assessment is good, the possibility of inspection deferral is based on the global reliability criteria established for the park as a whole.

- if the health assessment is not good (one or a number of parameters are outside the criteria), the operator uses a diagnostic approach with a view to identifying the source of the divergence by using the DIAPO expert system available in the tool:

1. if the diagnosis makes it possible to identify the source of the divergence, a prognosis is given and a maintenance decision must enable the anomaly detected to be dealt with.
2. if the diagnosis does not make it possible to clearly identify the source of the divergence, the inspection deferral is not authorised. The basic preventive maintenance programme must be applied as a fallback solution.

An intrusive inspection will make it possible to demonstrate the absence of risk associated with the problem identified and, if necessary, to remedy the problem.

We adopted this "binary" approach since, apart from the cases of proven faults in the seals and shaft line, we were unable, at this stage in our study, to identify obvious links between the degradation discovered on opening the machine and any discrepancies with the operating data. However, our aim is to proceed in this area by characterising the laws of degradation to take simultaneous account of the operating conditions and/or observations. The use of proportional contingency models is being studied.

5. Health assessment

The aim of the health assessment is to determine, on the basis of available in-service information, whether the RCP elements are in sufficiently good repair to continue to function over a fairly long period (which may make it possible to envisage putting off certain maintenance operations) or whether it is likely to quickly become necessary to carry out maintenance operations on such or such a component.

The health assessment on the machine is based on an analysis of the behaviour under nominal working and during the phases of shutting down and restarting the RCP over the last production cycle. More specifically, it concerns the analysis of the vibrations, leakage flow rates from the seals, temperatures of the bearings, motor stator and seals and the analysis of the effect of operating variables on these parameters.

On the basis of information obtained from questions asked of the user, the system adopts the following approach:

- it assesses the presence of macro-symptoms of greater or lesser gravity.
- it appraises the technological sub-units (shaft lines and static parts, the seals and motor) via the location relationships between the macro-symptoms and the technological sub-units (TSUs).

A TSU can be brought up for several macro-symptoms of varying gravity. The gravity of the symptoms is transferred to the TSU using the combination rules between the macro-symptoms which aimed at the same TSU.

The levels of gravity used are condition-based maintenance indicators making it possible to provide recommendations as to the planning of the maintenance operations and the feasibility of deferring an inspection.

6. Expert diagnosis support facility

In the event of a TSU being called into question by the health assessment or of abnormal behaviour in a RCP, the user can call on an expert diagnosis support facility. This system, known as DIAPO [4], has been implemented in collaboration with the manufacturer Jeumont Industrie. Its purpose is, from observations reflecting the RCP's behaviour anomaly, to suggest an "explanation" for this in terms of failures of component (combined, if necessary). This system uses the data worked out by a monitoring system, which employs about 200 descriptors. Most of them concern the vibrations, the flow rates of seals and the temperatures of the bearings and injection and cooling circuits.

DIAPO can identify about a hundred component failures (electrical faults in the motor, degradation in the seals, recognised shaft line faults, etc.). It is based on a breakdown model linking the faults to the symptoms through which they manifest. These symptoms are classified into several types:

1. necessary to recognising the fault. The absence of even one of these symptoms means the fault is not recognised,
2. potential, in other words, the fault may manifest under certain conditions through these symptoms.

The result of the diagnosis operation is a set of faults or conjunctions in respect of which all the basic symptoms is confirmed. The final diagnosis associates these faults (or combination of faults) with a plausibility, depending on the presence or otherwise of additional symptoms and the likelihood of the faults occurring based on the experience feedback.

7. Models of degradation

A FMECA type analysis has enabled all the machine's critical components to be identified. As far as these components are concerned, the reliability analysis has made it possible simultaneously quantify the degradation detected during the expert appraisals but also the faults. The latter generate chance incidents, which manifest through production losses and maintenance costs induced by the severity of the fault.

Optimising the maintenance includes proper management of both the faults and the degradation in the equipment. It is a case of minimising the faults and scheduling maintenance inspections before the degradation turns into a fault.

For each component, the analysis of the experience feedback data for the park as a whole has made it possible to quantify the chance rate, that is, the number of events per operating hour leading to partial or complete unavailability of the machine).

The different types of degradation behind the rejecting of a component during the inspections have also been quantified. The following graph gives an example of the degradation in face plates capable of being produced on a seal (on certain components, several instances of degradation of different kinds can co-exist).

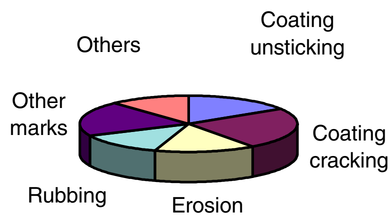

Figure n° 2: Example of degradation in glass plates

The histogram of the replacements of components also yields interesting information as to the percentage of components rejected and restored according to the number of hours' operation.

We give below an example of a histogram for the case of a face plate (number of rejected/restored components according to the number of hours' operation at the time of the inspection).

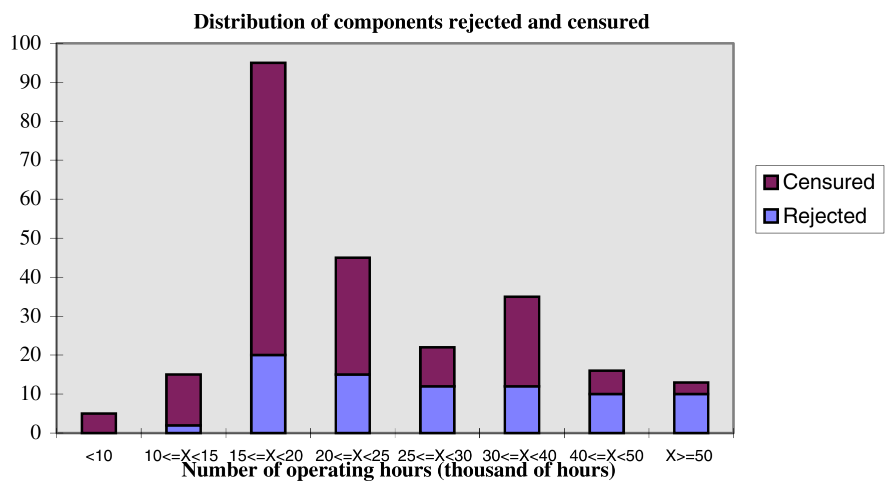

Figure n° 3 : Histogram of components rejected and censured

The general running thus gives indications of the type of model to be identified: exponential or Weibull (in the event of graphically detecting a rejuvenation or ageing effect in the component in question.

Before applying the conventional identification methods, we shown that these methods were applicable to the case of doubly censured data (left and right). The initial identifications showed that the most suitable model was the exponential one. No ageing phenomenon was able to be identified.

The degradation rates determined for each component gives "equivalent" degradation rates for the TSUs in the order of 100 times higher than the failure rates.

The following conclusions can be deduced from this initial analysis:

- the failure rate for the components in question is slight, in par linked to the fact that the maintenance operations are correctly carried out,
- the discrepancy between the degradation rate and the failure rate is too high,
- the components are changed preventatively (not as a result of ageing) and the criteria for rejecting the components during inspections are not optimised (precautionary rejection).

8. Analysis of inspections

The analysis of the inspections is aimed at providing the details making it possible to assess the possible influences on reliability and the on the costs of deferring an inspection scheduled by the PBMP. It may be a matter of deferring an inspection or of integrating a fuller inspection scheduled for later. An examination of a deferral inspection is only possible if the health assessment has been carried out and if it does not detect any anomaly in the machine.

The information necessary for this analysis concerns the type of inspection scheduled in the preventive maintenance programme, the value (in months) of the desired deferral and the age of the components.

The first criterion is compliance with the reliability threshold set during the analysis of the survival curve for the components (degradation and failure) (see paragraph 4.1).

The second criterion for the feasibility of an inspection deferral is that the machine should not show any anomaly following the health assessment in respect of the components covered in the inspection.

The third criterion concerns an analysis of the total costs (costs for maintenance and availability of the unit) as detailed below.

Three types of costs are calculated over the analysis period for both inspection scenarios:

1. the cost of the inspection without spare parts (labour, etc.) broken down by year,
2. the cost of replacing components during inspections weighted by the risk of rejection,
3. the cost associated with chance incidents.

The periodicity of the BPMP will eventually be optimised to have reliability analyses of all the RCP components. The initial simulations, which we have carried out, correspond to a deferral of one year in the systematic inspections carried out every three years. As the failure rate identified is constant (exponential law), we estimated that the cost of the chance incident is identical in both scenarios. In considering the cost of the inspection (parts and labour), the estimated saving is in the order of 15% of the total cost for a 3 to 4 year deferral. It can thus be deduced that the cost of the risk associated with degradation of the components corresponds to nearly 20% of the total inspection cost.

The analysis of the experience feedback shows that the models of failure (chance) are of the exponential type. It is therefore pointless to take them into account within a context of optimising costs since they remain constant.

Nevertheless, to illustrate the possibilities of the tool, we give below a simulation example where the probability of a failure is assumed to follow a Weibull law.

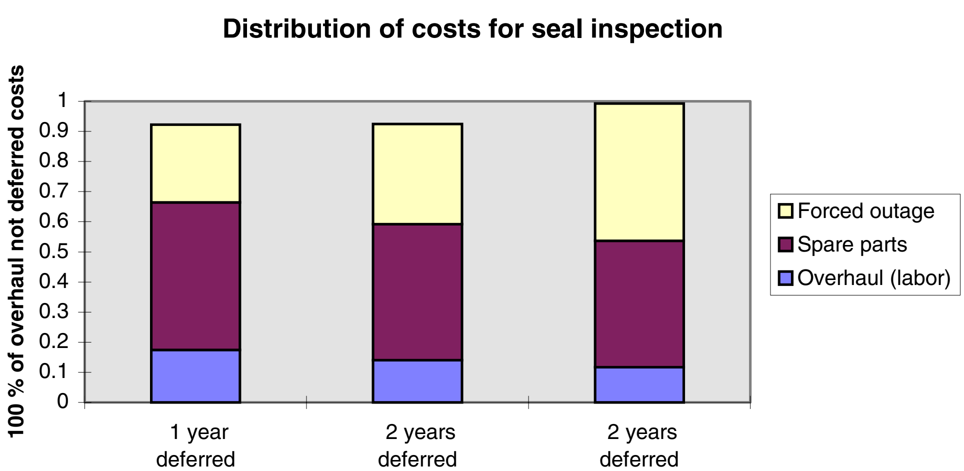

Figure n° 4: Distribution of costs according to the value of the inspection deferral (simulation)

9. Presentation of information

The decision to defer an inspection of a RCP must be taken by the maintenance engineer. He does not have experience feedback from all the sites in terms of the power plant.

To facilitate his request, the tool offers access, in exploitable form, to different information relevant for the activities associated with condition-based maintenance:

- the complete FMECA analyses,
- the plans of the main components,
- the experience feedback data (failure rates, degradation rates, expert appraisal data),
- a non-exhaustive list of the maintenance and expert documents, etc.

10. The tool

The potential customers for the RCPCM tool are not solely the nuclear power plants but also the experts responsible for attending the sites during the diagnosis and maintenance operations for the installations. In order to make updating the knowledge and managing the computing upgrades easier, we opted for an Intranet solution, with integration into a DIALOG software environment for capitalising diagnosis and maintenance knowledge of different equipment. This environment ensures the permanence of the knowledge, enables it to be consulted and exploited, and assists the user in designing and creating specific products (guides, collection, diagnosis support facility systems, etc.).

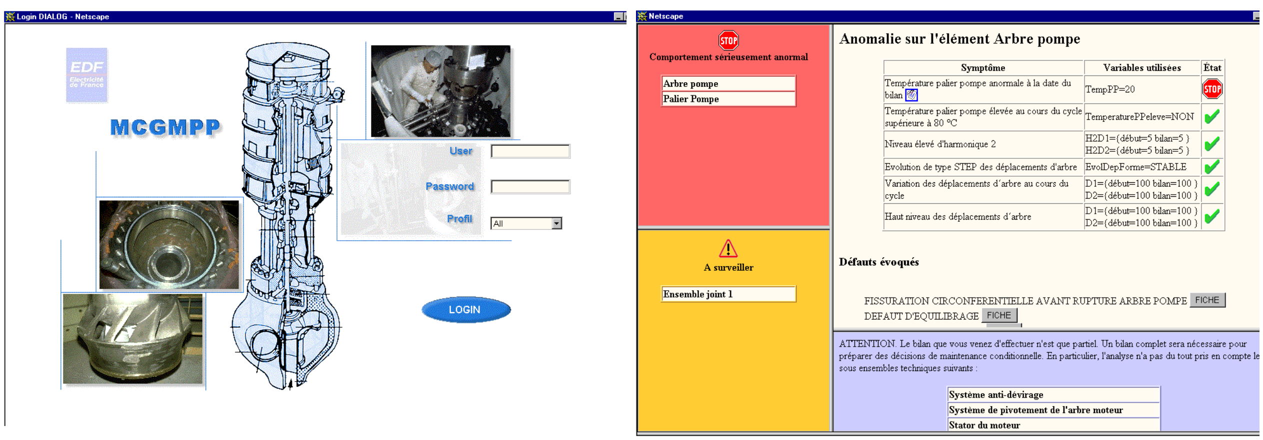

Figure n° 5: Health assessment service

11. Conclusions

A prototype of this maintenance support tool was developed during 1999 for assessment during 2000. This study does not only result in the creation of a tool, but also in the capitalisation of diagnosis and maintenance knowledge. The condition-based maintenance concepts employed for this tool are applicable to other vital equipment in nuclear and conventional power plants.

It must always be kept in mind, however, that the success of the condition-based maintenance projects is heavily dependent on proper management of the experience feedback data and particularly the expert appraisal and operating anomaly files.

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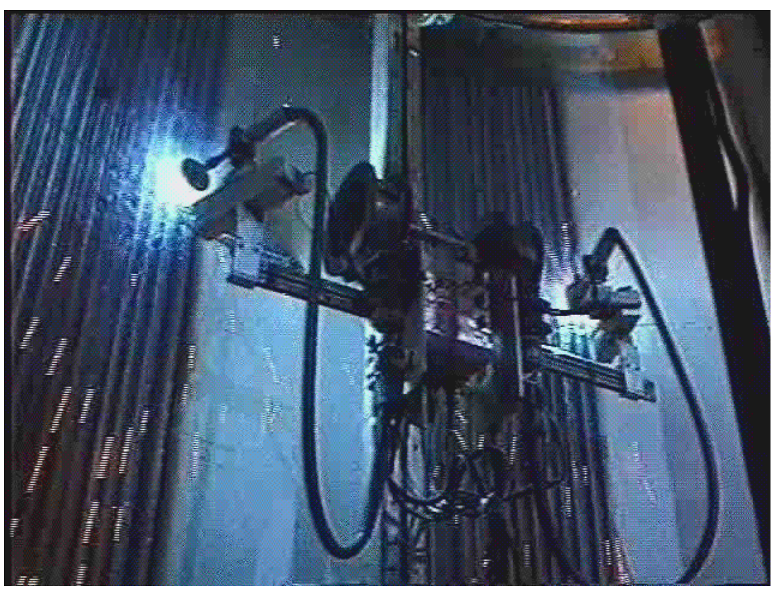
RELIABLE PLANT PERFORMANCE: LABOR SOLUTIONS FOR THE 21ST CENTURY

With an evolving society in mature North American, European, and Asian economies, more and more people entering job markets are focused on “white collar” versus “blue collar” careers. The reduced levels of craft labor personnel entering versus retiring from industrial boilermaker, pipefitter, etc. disciplines reflects this trend.

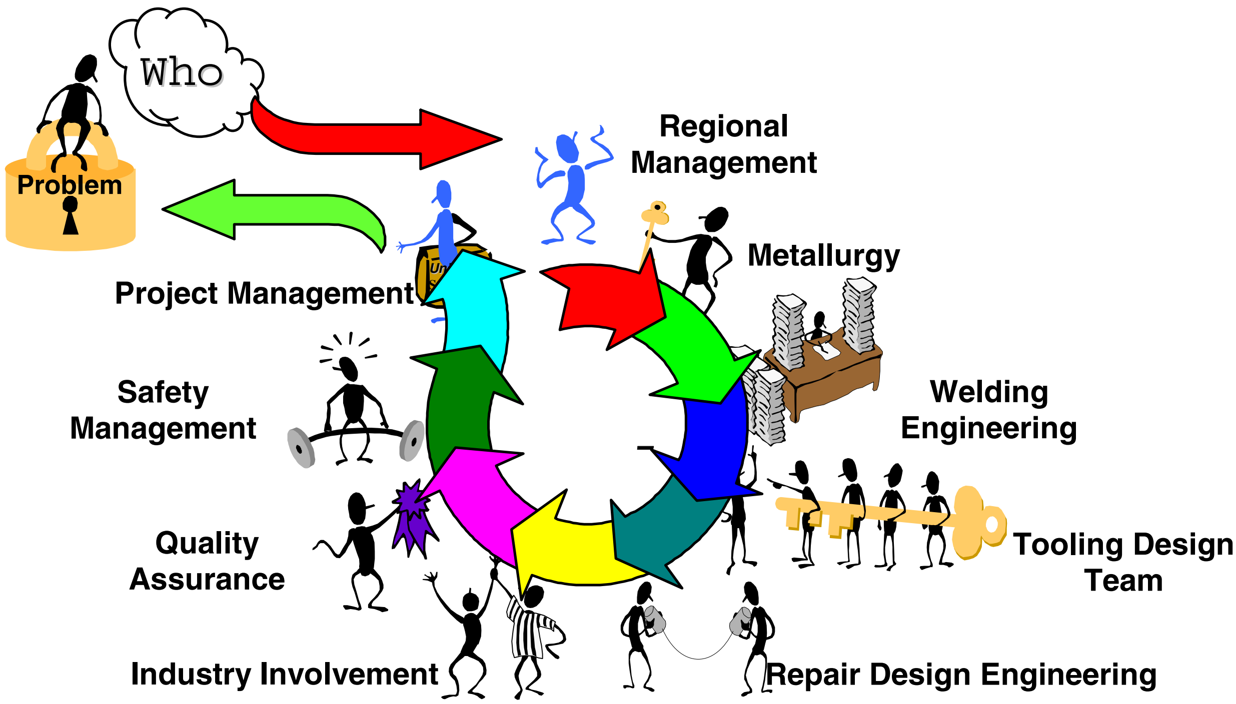
Another key trend associated with growing economics and populations is an expanded need for industrial capacity (i.e., power generation). The construction demands coupled with a consistent maintenance and modifications need for existing power plant operations, significantly increases the demand for qualified craft labor resources.

These two trends are creating a significant challenge for power plant operators to perform peak season outages with the quantity and quality of craft resources needed to meet reliability and downtime objectives.

Welding Services Inc. (WSI) offers a model of the future on how automation and advanced technologies can support plant operators with maintenance and modification solutions that reduce labor demands, while delivering innovative cost and schedule improvements. Several examples of how automation has been deployed to address boiler, turbine, and high energy piping maintenance and modifications with significant cost, schedule, and reliability improvements over conventional methods are presented herein.



Engineered Solution Approach: The key to identifying and developing opportunities for utilizing advanced repair technologies to reduce manpower requirements and deliver innovative solutions is proactive planning. It is critical to integrate strategic “technology” resources into your conventional outage planning in a timely manner to identify schedule, quality, and/or cost critical project demands that are "automation" candidates. The following "solution development" cycle is reflective of the typical problem to concept to solution evolution.



The following examples are reflective of a cooperative problem solving initiative between utility management and an "automation" partner:

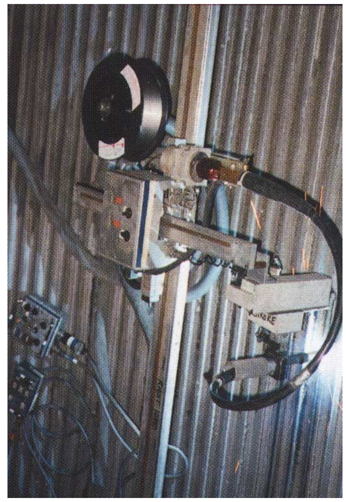
Automation Example #1

Coal-Fired Boiler – Low No_x Fireside Corrosion Degradation

Fireside boiler repairs and boiler tube replacements have always been a major cost, schedule, and manpower investment for coal-fired boiler operators. The conventional degradation of boiler tubes due to coal-ash erosion, sulfidation corrosion, and thermal fatigue cracking has inherently been dealt with through manual repairs and replacement techniques. The acceleration of tube wastage and associated repair and replacement requirements has been greatly accentuated with the addition of Low No_x burners throughout the 1990's.

In cooperation with WSI coal-fired boiler operators and EPRI, a comprehensive "automation" solution has been developed and deployed on over 150+ coal-fired boilers and 250,000+ square feet of damaged surface area. The automated weld metal overlay solution involved:

- Root cause analysis
- Metallurgy selection
- Boiler design assessment (distortion analysis, etc.)
- Automated weld overlay tooling technologies
- Personnel training program
- Comprehensive QA/QC Program



Automated Waterwall Tooling
(4-6 times manual production)

Automated Weld Overlay Program offers maintenance management the resulting benefits

<u>Technical Benefits:</u>

↳ **<u>Restore Pressure Boundary</u>**: Ability to restore existing tubes to full original strength on tubes as low as 0.100" thickness versus replacement alternatives.

↳ **<u>Optimum Erosion/Corrosion Life Expectancy</u>**: Due to automation and the improved metallurgy selection, significant life improvements versus exist versus replacement with original materials of construction.

***Unifuse*® after 10-year service in supercritical low waterwall environment**

<u>Economic/Manpower Benefits:</u> *2,000 SF waterwall corrosion damage*

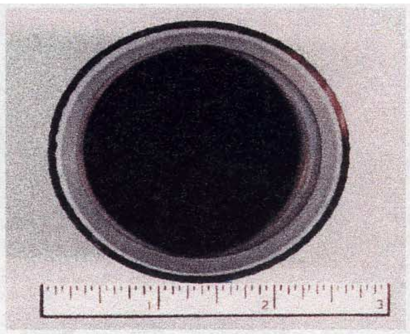
	Cost	Schedule	Number of manhours
Replacement	\$800,000 - \$1,000,000	8 days	2,500+
***Unifuse*® Insitu Automation**	\$400,000 - \$600,000	5 days	1,200

➻ ***Unifuse*® 360° for Superheater/Reheater:** An automated patented 360° weld overlay technology also offers manpower and cost savings in high wear areas of superheater, reheater, and economizer sections where shielding is typically employed. By installing a fully fused, super alloy metallurgy versus mechanically attached clips on shields, the downstream maintenance and inspection requirements reduce dramatically:

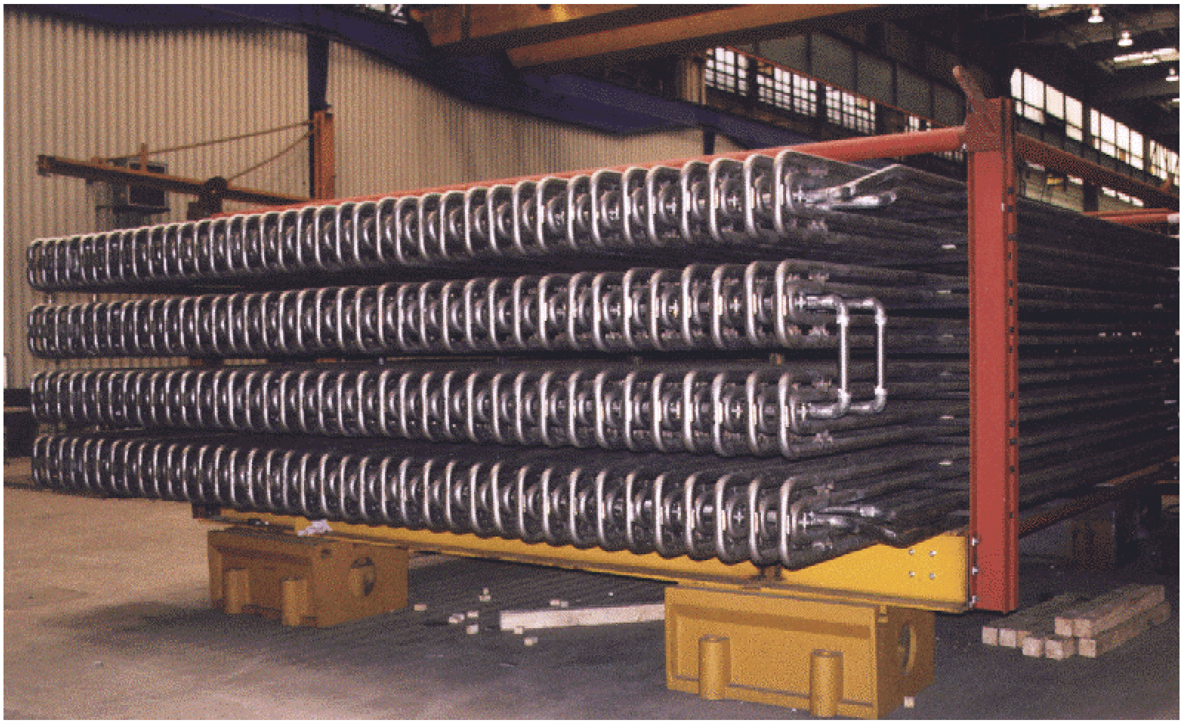
Economic Analysis

Assumptions: Leading Row Dutchmen

- 73 tubes x 20'/tube = 1460 linear feet
- Installation cost = $65,000
- Tube Failure on 250MW Unit = 2 days x $100,00/day = $200,000/failure


	Installation Cost	Annual Maintenance	Heat Transfer	# Tube Failures over 5 years
Shielding 309SS	$81,000 ($65,000)	$27,613	Poor	1
Unifuse 309SS	$123,400 ($65,000)	0	Excellent	0
5 Year Snapshot	**Shielding Cost = $391,452** **Unifuse ® Cost = $123,400**			



***Unifuse*® Superheater**

In addition, the ability to ensure no tube failures during long run times between outages via the reliability factor of a full fusion versus mechanically attached technique, greatly enhances plant risk management value.

Automation Example #2

↳ **Boiler Tube Replacement Orbital Welding Technology:** For areas of the boiler that cannot be restored in place due to access constraints (superheater/reheater/economizer), tremendous manhour and quality challenges exist executing manual butt welds that inherently require RT quality. The automated orbital welding program is geared to deliver the following:

- 100% repeatable RT quality
- Ability to work within access constraints as low as 1" radial clearance
- 50% manpower reduction for welding operations
- High alloy welding improvements due to improved process controls

Background

- 1969 B&W Supercritical Boiler
- Secondary Reheater Outlet Header
- 785 T22 to T9 DMW's

General Contractor

- 2.5 Week Outage Window
- 73 Welds Successfully Completed

Automated Orbital Welding

- 3 Week Outage Window
- 385 Welds Completed April
- 100% RT Quality

Automation Example # 3

P91 New Construction and/or Existing Plant Main Steam, Hot/Cold Reheat, Heavy Wall Piping Replacements:

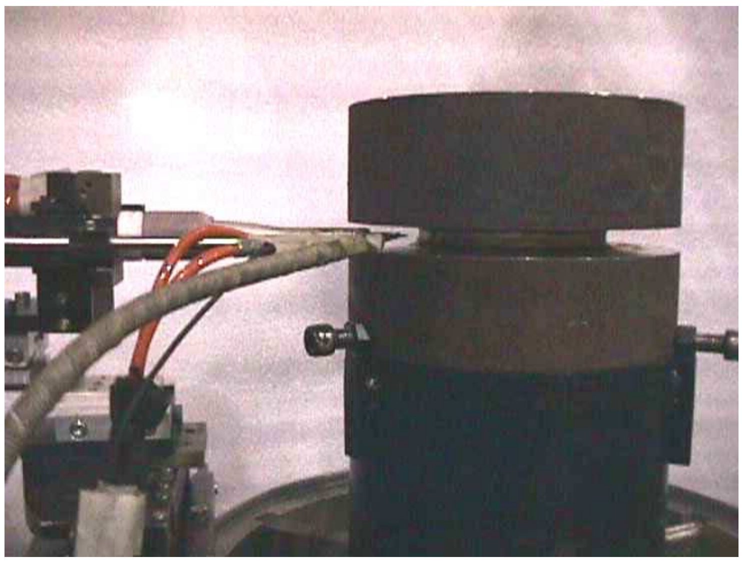
Our automatic orbital welding program also has significant benefits for high alloy, heavy wall piping replacements for new combined cycle construction and existing plant replacement requirements. Two major areas are targeted to deliver improvements over manual techniques:

A. Improved first-time quality and long-term material performance, and
B. Reduced manpower and overall cost requirements

In order to accomplish these objectives, the automated orbital welding program improves the long-term material performance on P91 materials due to the following approach:

The manpower and cost improvements are achieved via 100% first-time quality that eliminates costly repair cycles and automation that reduces the initial labor requirements versus manual techniques. The following chart indicates a prototypical saving potential on a P91 new construction installation.

100-5G/6G 24" Joints			
Weld Reject %	**Manual Hours**	**Quikarc® Hours***	**Manhour Savings**
5%	8,200	6,900	1,300 (18%)
10%	8,600	6,900	1,700 (24%)
15%	9,000	6,900	2,100 (30%)
*** 0 Rejects/100% RT Quality**			



Conclusion:

The automation technologies described herein offer a brief overview of proven manpower and reliability solutions that were cooperatively developed with utility maintenance management.

The key to the past successes of automation deployment and a critical formula for expanded utilization in the future, is an integration of technology partners with plant management in the formal outage planning and execution processes. Given the current and future trends facing us, proactive initiatives in this area are critical to cooperatively develop and refine automation approaches to key plant manpower demands. A parallel commitment to evolve automation and support manual craft resources will ensure an ability to maintain and potentially improve current cost and productivity benchmarks well into the future.

Field Experience of a Novel Monitoring System for Improved Control of Power Plant Steam-Water Chemistry

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ABSTRACT

As power plants compete in the new electricity markets, companies are facing the challenge to reduce their operating costs whilst operating in a more flexible regime. This financial pressure results in reductions being made to the number of technical staff being employed in the power station and a consequential reduction in the capacity of the station to maintain their previous levels of condition monitoring. One of the critical areas being affected is "Power Plant chemistry", an area technically understood, but where future poor monitoring combined with new flexible operating regimes could have a potentially significant impact on future operating and maintenance costs. Unión Fenosa is addressing this issue with the innovative development of an on-line monitoring system that follows directly the corrosion rate of the various materials employed in the steam water circuit in real time. This cost effective system allows for more simplified monitoring of the steam water chemistry through its bespoke user interface and more importantly provides a tool that can potentially be used to monitor, and subsequently optimise, the effect of flexible operation on the tube lives from a steam-water chemistry perspective. This paper will discuss the technical development of the product and present various results from the development phase and operating experience of the product after more than two years installation in a power station of Unión Fenosa.

INTRODUCTION

Due to the current demands of the electric market, the operation of the thermoelectric plants is forced to adapt its production levels to the electric network demand, which implies continuous load oscillations and, more concretely, continuous changes in the conditions of service of the SWC (Steam-Water Cycle).

In this situation the concepts are inverted from stationary to transitory, since load rises and decreases become the habitual operation regime. These operation conditions, far from the original conditions of design, implies an alteration of materials life forecast, and therefore their behavior.

The traditional control and management instrumentation of SWC in the chemical laboratories performs their mission correctly, but under the stationary operation conditions they were designed for. It is necessary to say that this instrumentation type provides an insufficient information under the current market conditions.

In order to reestablish capacity of the CL (chemical laboratorie) to control indirectly the structural integrity of the SWC components, it is necessary to endow this laboratory with monitoring tools to satisfy current production demands.

This tool must satisfy next necessities:

- Reduccing SWC costs of O&M.
- Quick response in transitory.
- Providing an estimation of effectiveness the chemical treatments have on the materials in contact with the SWC.
- Facilitating chemist responsible to design his own CT (chemical treatment).
- Evaluating installation structural integrity based on approaches of components life remainder.
- Detecting in a precocious way the contamination moment and the SWC entrance point.

The steam-water cycle monitoring system (SVC) satisfies all and each one of the previously outlined necessities. The proposed solution is based in a change in the concept of the structural integrity control (installation pipes and equipement).

While in the classic methodology this control is made indirectly through the process water, the SVC watches over the evolution and manages the materials life under its conditions of service, that is to say, it attends directly to these materials.

The use of this tool can derive in a reduction of costs in the SWC different systems:

Short term:

- Reducing the number of laboratory manual analysis.
- Reducing the number of 'in continuous' analyzers.
- Replacing laboratory current panel by a virtual panel in which all the information is visualized in a centralized way.
- Easy handling database and quick information access.
- Local and remote access to database.
- Reducing turbopump filter maintenance operations.
- Reducing turbopump dirtying.

Long term:

- Desmineralization water plant: Optimizing contribution water chemical quality.
- Chemical treatment: Optimizing and even changing the base of the treatment, since the system provides a tool able to evaluate it.
- Economic and chemist approach to control purges flows (drum, deaireator).
- Reducing boiler chemical cleaning.

BACKGROUND. THE STEAM-WATER CYCLE.

Now we expose two important concepts in relation to the steam- water cycles (SWC) of electric power plants. These plants use the energy contained in a thermodynamic cycle:

1. The first function of water in a SWC is to transform thermal energy to mechanical work expanding steam in a turbine. Any element or compound that, in its phase change, produces a comparable volumetric expansion, could be equally used. Nevertheless, the use of water as transformer element has a series of important advantages:

- It is cheap and abundant.
- Leakages don't produce environmental contamination.
- Manipulation doesn't require special cautions.
- It is not explosive neither deflagrante.

2. The usual thermodynamic cycle pressures and temperatures require the confinement of the energy transporter element. To achieve this, structural elements (pipes and pressure equipement) are needed.

Keeping in mind the two previous concepts, SWC can be defined as content + continent. The content is the process water or steam and the continent the installation pipes and equipements.

The operation experience in plant demonstrates that the practical problems like damages, shortcomings in service and unavailabilities of the plant, always come from the continent, that is, the structural element that suffers the service conditions:

- The material (manufacturing failures, assembly, etc.)
- Interaction with the content:

  Formation of deposits, which produce capacity loss of heat transfer and, therefore, reduce the installation efficiency. Moreover, they can produce structural damages due to overheating and to originate some types of located corrosion.

  Corrosion, which produces loss of structural integrity (loss of thickness) and, even, serious problems of acumulation of deposits originated by the removed material that can be transported along the SWC.

Usually to solve the problems caused by the interaction of the structural element with the content (flowing steam-water) next methods are used:

Demineralization of the gross water, to avoid deposits.

Adding chemical reagents in SWC, to minimize the material loss due to corrosion phenomenons.

The two previous actions have as objective to modify the fluid chemically to minimize interactions on the structural material. The Chemical Laboratory (CL) must control these actions.

Before continuing, we should remark that:

"The CL carries out the control of installation pipes and equipements (continent) structural integrity indirectly by means of the process water (content) control."

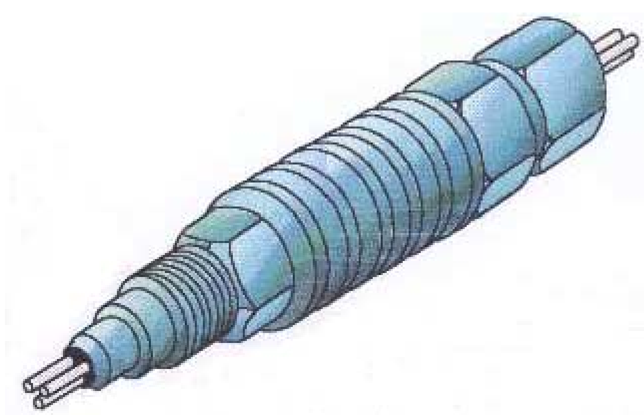
This empiric and indirect control of the continent, is based on years of experience in operation, and supported by international organisms. The approach is to maintain certain chemical values of the content, between some preset limits.

It is necessary to highlight that this way to control the structural integrity through chemical parameters of the process has shown good results along the years, but this control way has been designed for some operation plant stationary conditions.

SVC FUNDAMENTS

The SVC is based in a double focussing when approaching the problems of the steam-water cycle (SWC):

According to the quality of the water of process: Using in-situ chemical probes to substitute ex-situ commercial analyzers. The idea consists of taking the in-situ probes to the process lines instead of taking a sample of these process lines to the Chemical Laboratory ex-situ analyzers.



During our work, we have developed two types of in-situ chemical probes: pH / conductivity and dissolved oxygen. The reasons of choosing these probes is that both parameters define, in accordance with the Diagrams of Pourbaix, the thermodynamically stables zones or areas of metallic species.

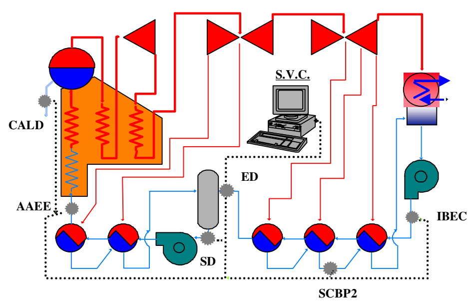
Relying on thermodinamyc studies (the way in which the chemical treatments habitually used in the SWC facilities are defined) we try to locate the metals in contact with the fluid within areas where a passive, stable and protector layer is formed. This film reduces the contribution to the fluid of metallic ions to the minimum, that is to say, it tries to minimize corrosion.

According to the response of the materials in contact with the fluids: Electrochemical probes of those materials and alloys have been used to carry out their service in contact with the SWC liquid phase.

It is necessary to remember now that thermodynamic stability areas of Pourbaix Diagrams don't say anything about the speed of corrosion (kinetics), that is to say, we can know if a certain phase is stable or not under the chemical conditions of the electrolyte that surrounds it, but we don't have any information about the speed of the process (formation or destruction of protector layers).

Current prototype developed for Anllares power plant uses metallic threads of existent typical materials in SWC (brasses, steel, stainless, etc) as measure electrodes, being introduced into the process pipes by means of accessories developed ‘ad hoc’.

Until this moment our interest has preferably been centered in measuring qualitative changes in the corrosion response of these alloys. For this reason, it is valid any commercial electrochemical technique that can be applied in field. According to our experience it is more interesting to have an approximate knowledge of corrosion in many points of SWC, instead of a very exact knowledge (quantitative) in some few points.



Measure points on field

DESCRIPTION OF SVC.

The system denominated SVC (system for monitoring chemical treatment effectiveness of the steam-water cycle by probes in-situ) is designed to determine the best operation plants procedures, from the point of view of pipes and equipement corrosion.

The system consists of a set of in-situ chemical probe. We measure temperature and specific conductivity and determine pH by means of an indirect method, obtaining the concentration of the majority ionic species.

It also consists of in-situ electrochemical probes. The sensitive part of these probes measures corrosion intensity of the sample threads that are usually made of the material that forms the e steam-water cycle pipes of the electric power stations.

The probes in-situ are inserted in cells made of an immune material to the corrosion and are located in lines ' side-stream ' to the pressure and temperature of the installation elected point.

These cells contemplate:
Termopars or RTD's for the temperature.
Pressure transducers.
Electrochemical probes to measure corrosion intensity.
Probes of specific conductivity and temperature to obtain the pH.

An interactive data adquisition and presentation of results graphical software provides the system with a great potential. The information coming from each sampling point, as well as the calculations, evaluation of parameters, storage and handling of the generated information allow to establish an approach to modify the cycle chemistry.

RESULTS

These results were obtained from the work carried out at Anllares thermal power plant, of Union Fenosa Generación. In this power station we installed the probes in diverse points of the steam-water cycle. This way we have a general and simultaneous vision of diverse metals behavior under different conditions of service in the cycle liquid phase.

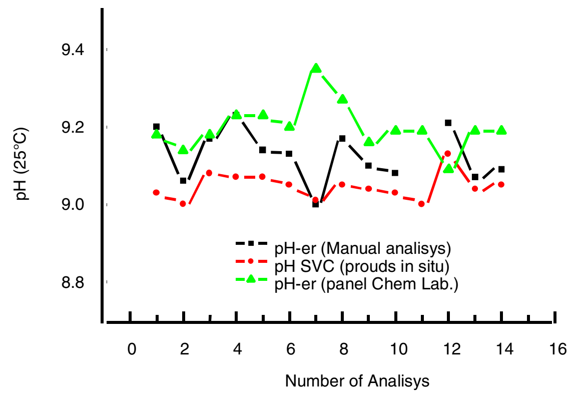
The location points of the in-situ probes are::

Hot well (20º-30º C and vacuun)
Extraction condensate pump (20º-50º C and 18-22kg/cm2)
Entrance in deaireator (90º-130º C and 4-8 kg/cm2)
Exit in deaireator (130º-170º C and 4-8 kg/cm2)
Feeding water in economizer (170º-260º C and 140-180 kg/cm2)
Drum purge (260º-350º C and 150-190 kg/cm2)

Thanks to our experience in real and pilot plants, we have picked up a series of results that we expose next.

- **Chemical and electrochemical probes measurements.**

In-situ probe pH / conductivity



Comparative of pH got by manuals analisys, comercial pH-meter and in-situ prouds

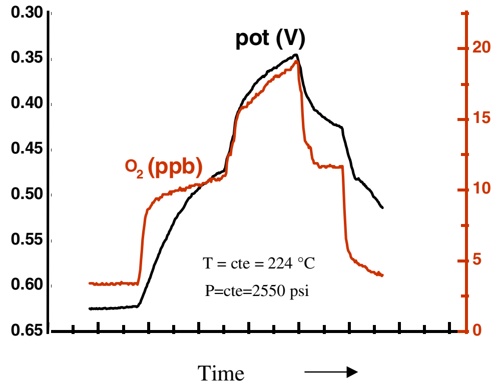
The graph shows a comparision between the concentration of ammonia obtained from the calculation of the sensor, the on-line commercial pH-meter of the chemical panel of the laboratory and measures carried out manually in Anllares power station Chemical Laboratory. A great agreement is appreciated in the results, except during a hard transitory, where all the chemical values of the cycle change. The dispersion of obtained results of the pH probe is smaller than anyone of the other two series.

Conclusions:

-The measures obtained from the probe and the estimate procedure have been sufficiently contrasted.
-Sensibility in the range of one pH tenth.
-The response of the probe is quicker than the conventional pH-meters
-It can be applied in any point of the cycle where liquid phase exists.

Probe of Oxygen

In this graph the measure variation of the sensor is shown versus the concentration of soluted oxygen given by the laboratory analyzer. The response of the sensor is perfectly comparable to the commercial analyzer's measure. The oxygen addition during the trial was carried out in four stages; two stages in the phase of oxygen concentration raising and two in that of decreasing. The response of the probe demonstrates to be at least comparable to that of the analyzer in the stages of concentration raising, even in the second stage the response is a little bit quicker than that of the commercial analyzer. The scale of times is about a couple of minutes.

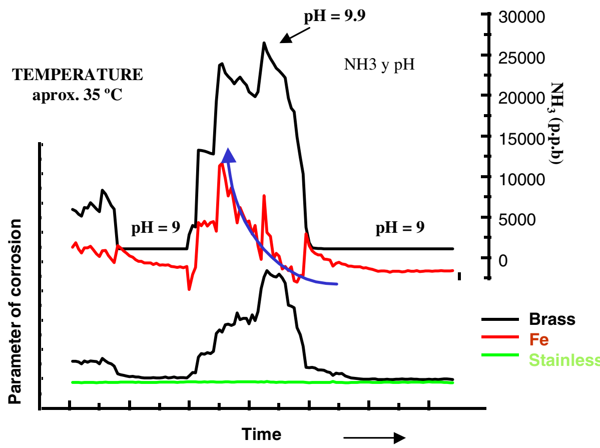


Response got with the in-situ proud O_2

Conclusions:
-Excellent replication measures.
-High sensitivity (range ppb).
-Low time of response in the concentration of O2 rise (Comparable to the commercial analyser).
-Slower response in the decreasing of O2 concentration.

Intensity of corrosion probe.

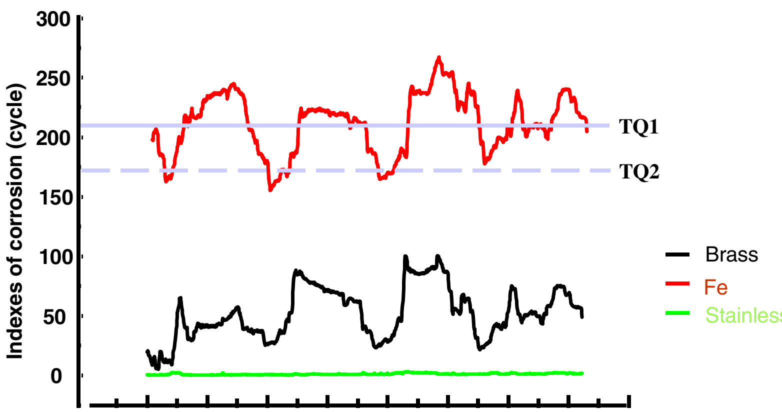
Increment of pH by means of addition of ammonia. It was proven that the biggest alkalinity in the water, alters the existent commitment among iron base alloys and cuper base alloys.
It is seen that the steel after an increment of the corrosion, suffers a descent of corrosion below the original value (pH=9). The brass suffer a continuous increment of the corrosion that doesn't diminish until ceasing the addition of ammonia again, being then when the values of corrosion return, approximately, to initial values. For the stainless steel it is practically invaluable in the whole trial.



Comparative of corrosion of three alloys Vs of the addition of NH_3

- **Measures obtained with the system**

- Comparison of behavior among alloys at the same point (temperature of service)
- Comparison of behavior of the same alloy at different points (different temperatures of service)
- Reference values for a chemical treatment



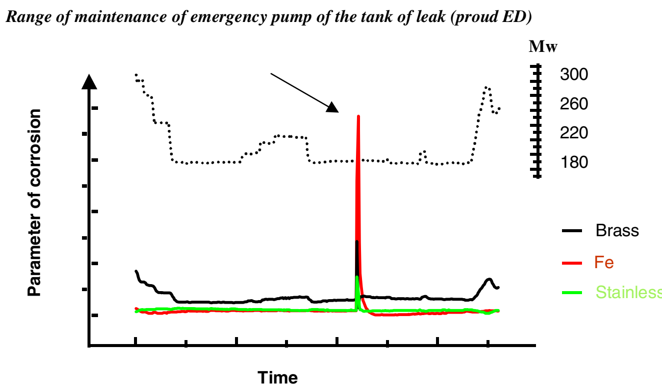
Influence of chemical treatment on three alloys at several points of the steam-water cycle

So we can compare the effectiveness of both treatments, observing for example, the indexes of corrosion of the alloys.

- Trials in plant to check the correlation among the electrochemical measures and the gravimetrical loss suffered by an alloy subjected to quick corrosion.

- Detection of entrance of contamination to the SWC.

A brief episode of accused contamination was produced by a pump maintenance operation at Anllares power plant. This pump discharges in the main pipe of condensate, some meters before its entrance in the deaireator. This means that the SVC can detect the position, more or less exact, where the contamination enters to the cycle.



Detection of contamination entrance to cycle

CONCLUSIONS AND FUTURE PERSPECTIVES

The system of monitoring of the Steam-Water Cycle (SVC) provides on-line continuous supervision of the intensity of corrosion of process pipes and equipements in contact with **the steam-water cycle** and of the parameters associated with this phenomenon.
In the classic approaches, this corrosion is minimized adjusting the Chemistry of the Cycle between some values predetermined by the experience. In a more innovative focus, the corrosion is controlled by use of corrosion in-situ probes that allow us an immediate readjustment of the applied chemical treatment, in function of the real corrosion of this in-situ probes.

- The proposed system is based on signals coming from in-situ probes instead of signals proceeding from exsitu commercial analyzers, and it has the following advantages.

    -Low cost
    -Low maintenance
    -Quick responses

- Besides having chemical signals (classic focus), the system analize the state of the metal (new focus), which allows us to have a direct vision of the effectiveness of the chemical treatment used.

- Quick detection of transitory

- Use of in-situ probe as electrochemical "switches" to detect the entrance of contamination to the SWC.

- The benefits provided by the installation of the SVC can be summarized in:

  Decrease of the maintenance SWC costs.
  Increment of the availability and the installation life.

The future works are guided to the improvement of the different components of the SVC with the purpose of getting a better integration and to obtaining a product that gathers the biggest possible benefits for the user.

ACKNOWLEDGMENTS

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EMI Diagnostics Provides Condition Based Information For Triggered Maintenance In The Nuclear Environment

Presented at the EPRI 2001
International Maintenance Conference
Maintaining Reliable Electric Generation
August 14-16, Houston, Texas

J. E. Timperley
American Electric Power Pro Serv
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Abstract:

EMI (electromagnetic interference) Diagnostics has been utilized to provide information for the condition based maintenance of large machines since 1980. Application of this technique to assist maintenance planning at Nuclear power plants has recently been implemented. The advantages of totally non-intrusive data collection, in real time, while a motor or generator remains in service has a great economic and safety benefit at BWR and PWR Nuclear facilities. Design modifications are not necessary to collect data and there are no connections made to energized circuits. EMI Diagnostics will detect a variety of system and machine related problems during the first evaluation. Trending data over weeks or months is not required for accurate condition assessment. EMI Diagnostics can be applied to all machines and systems operating at 440 volts and above. This paper provides examples of trouble free systems, as well as defects uncovered during EMI Diagnostics.

INTRODUCTION

EMI stands for Electromagnetic Interference and is a term used by communications engineers to describe unwanted radio frequency signals generated by electrical devices. EMI Diagnostic of rotating machines and associated electrical power systems is an extension of the methods and test standards applied since the 1920's to measure and identify various radio frequencies generated by defects in power equipment. The application of EMI Diagnostic techniques for the in-service evaluation of large generators began in 1980; by 1985 large generators as well as 13 kV and 4 kV motors were routinely evaluated. During the past 20 years there have been over 4,000 tests conducted on some 500-machine designs.

The radio frequency (RF) spectrum of interest ranges from 10 kHz to about 1 GHz. Defects in motors, generators, cables and transformers generate radio frequency signals or EMI when defects develop in insulation or conductors. The resulting signatures are classified as arcing, corona, partial discharges or random noise. There are a wide variety of defects that may develop and numerous combinations of EMI signatures that can result. Ambient signals such as a utility power line carriers (PLC), AM, FM and TV stations are also present. These transmitters serve as valuable benchmarks for verifying data and trending future data.

GENERATION OF EMI SIGNALS

Partial Discharge Analysis (PDA) is a time domain technique that relies on accurate measurement of each discharge event. Amplitude, polarity, power frequency phase relationship, apparent charge transfer and event count rate are important characteristics for accurate analysis. When a PD occurs there is also an electromagnetic (EM) wave produced that travels away from the discharge location.

EMI Diagnostics is a frequency domain analysis of the damped oscillations that result from each PD impulse. EMI can also be generated by low voltage, high current defects such as loose connections. Every EMI signature is unique for each type of defect. EMI can be either radiated or conducted from the defect location. That part of the energy that is conducted can be measured with a radio frequency current transformer (RFCT). Data are presented on a logarithmic scale to better represent both low and high values on one chart. Amplitudes from 0.1 microvolts to 100 millivolts with frequencies ranging from 10 kHz to 100 MHz on one spectrum plot are not unusual.

Since only a single point is needed for EMI data collection with an RFCT, it can be located at the stator neutral or other low voltage location, thus avoiding the numerous high voltage connections required with PDA techniques.

REQUIRED EQUIPMENT

The precision RF voltmeter used to measure EMI is NIST traceable and in full compliance with CISPR #16 and ANSI C63.2 standards, with a variety of detector time constants and intermediate frequency bandwidths. It is capable of displaying activity from 10 kHz to 1 GHz with a dynamic range of 150 dB. A simple RF receiver or spectrum analyzer will not accurately capture EMI Signatures.

Data is collected from the temporary placement of a split core RFCT around the power feed to the motor, the generator neutral lead or a machine safety ground.

It is basic that the act of measuring does not change the quantity being monitored. All successful diagnostic techniques must be non-intrusive. The current probe method of obtaining an EMI signature satisfies this requirement.

EMI Diagnostics is essentially the capture and classification of all signals present at a given measurement location. EMI patterns are evaluated in the frequency domain as well as visually (what does the discharge look like) and audio (what does the discharge sound like). A typical survey will require 30 minutes to one hour to complete at each location.

EMI PRODUCING DISCHARGES

Power system defects have been found to generate five fundamental types of EMI. These EMI signatures are:

1) Arcing
2) Corona
3) Random Noise
4) Gap Discharges
5) Microsparking

ARCING

Arcing is a low voltage electrical discharge involving current several orders of magnitude greater than that produced by partial discharges. Arcing is rich in low frequency harmonics extending throughout a wide range of the EMI spectrum. Arcing results from loss of continuity in conductors, loose bolted or crimp joints or broken conductors. Broken rotor bars in induction motors, an oil seal rub, wiped bearings or sparking shaft grounding brushes are frequent sources of arcing EMI.

CORONA

Corona is a partial discharge in air or hydrogen. Corona is usually found on conductors operating above 2000 volts and at frequencies below 10 MHz. Wet power cables and dirty, contaminated machine windings often produce corona even at 4 kV.

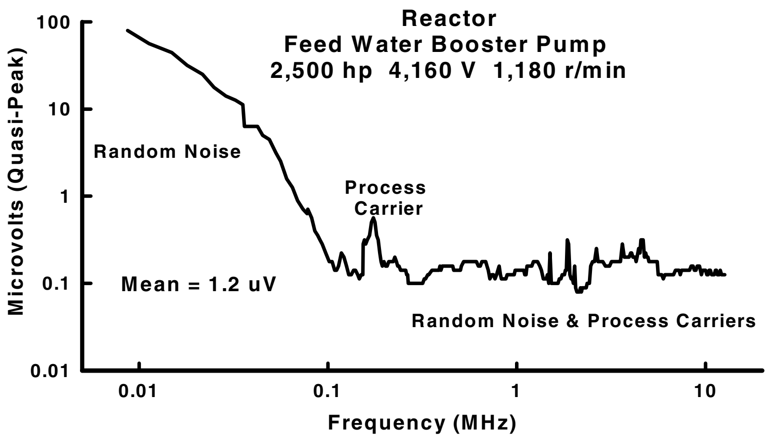

FIGURE 1: This location has a high EMI ambient level. Above 100 kHz the motor related signature indicates no motor maintenance is required.

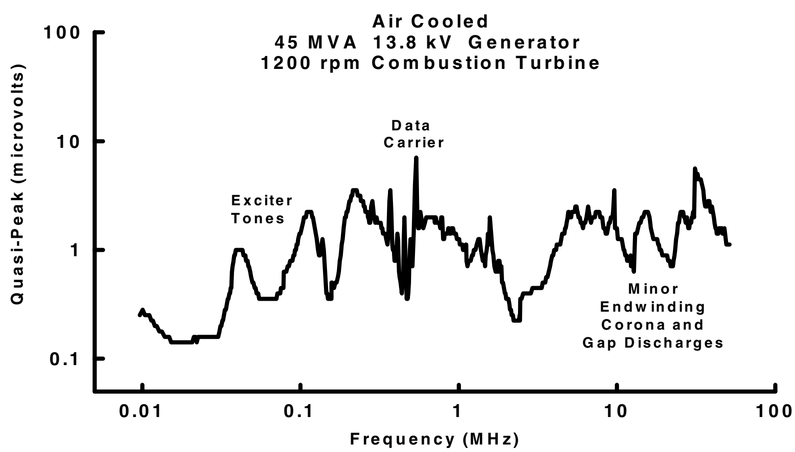

FIGURE 2: This combustion turbine generator is part of the off site emergency power for a nuclear facility. There is minor accumulation of dirt on the endwindings but no major maintenance is indicated.

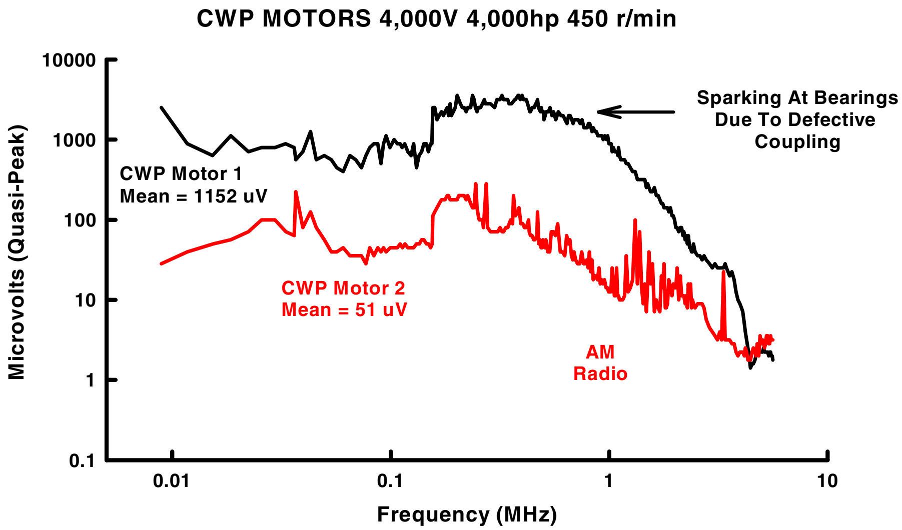

FIGURE 3: Circulating water pump motor 2 with little EMI activity has no major problems. CWP motor 1 however has severe shaft currents through the bearings due to defective insulation in the pump couplings.

GAP DISCHARGES

A gap discharge or partial discharge is produced when two surfaces, separated by a gap, are at different electrical potentials sufficient to spark over the gap and generate EMI. The rise and fall time of each discharge is extremely fast. The EMI generated by gap discharges is rich in broadband harmonics that are measurable at many frequencies throughout the RF spectrum, depending on the physical location of each PD. Loose stator windings are a common source of gap discharges.

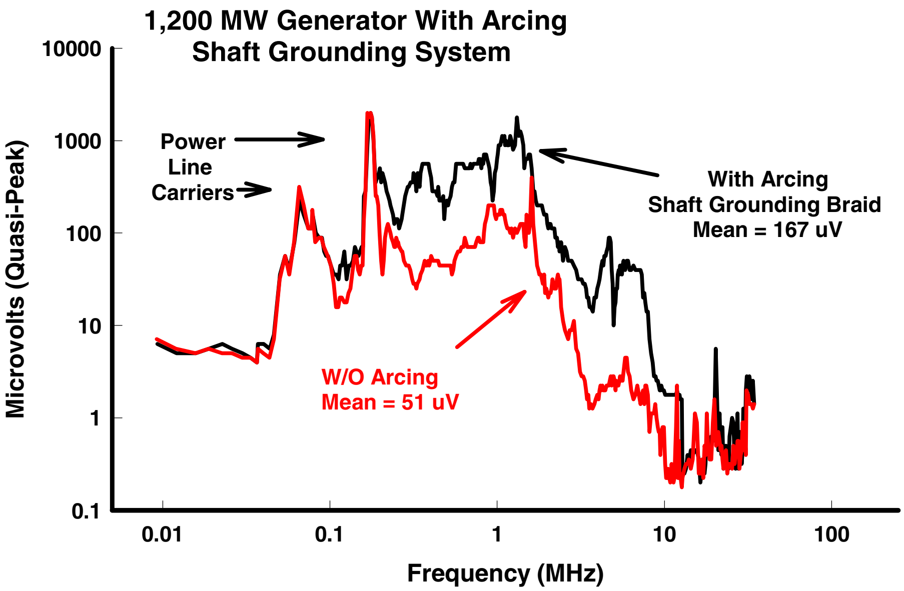

FIGURE 4: This large machine has the common problem of severe sparking at the shaft grounding brush.

MICROSPARKING

Microsparking is a type of gap discharge where the gap is extremely thin, usually less than 0.4 mm. There may be 15 to 30 discharges during each power frequency half cycle as opposed to gap discharges where there are only 1 to 15 discharges each half cycle. The EMI produced is usually found above 20 MHz. Defective isolated phase bus hardware is a common source of microsparking in generator power systems.

RANDOM NOISE

Random noise results when the surface of high voltage insulation is contaminated with conductive material, such as dirt. Contamination inside the insulation, i.e., wet stator bars also produces random noise. This "white" noise can be broadband or centered around specific frequencies with a spectrum response similar to an RF transmitter, but with a much wider bandwidth. If surface contamination is involved, ambient humidity changes often influence discharge activity.

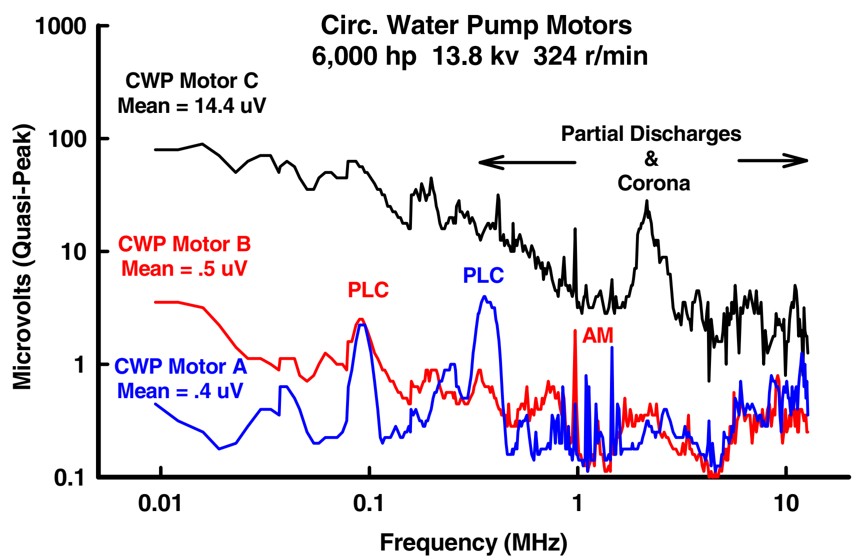

FIGURE 5: Circulating water pump motors A & B are in good condition. Motor C was found to have loose stator coils with corona damage and heavy dirt accumulation.

COMBINATIONS

Most EMI signatures are a combination of the five basic types, and they are always combined with a variety of man-made EMI sources. Gross problems such as dirty windings, broken conductors, slot discharges, arcing slip rings, and broken insulators are obvious and easy to detect. Other problems such as loose wedging, contamination and internal corona are more difficult to isolate, particularly if the deterioration is an early stage of development.

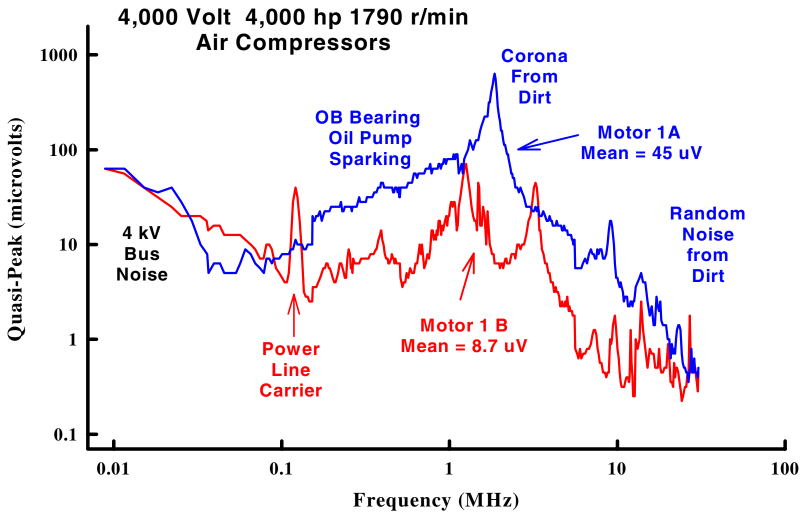

FIGURE 6: Both air compressors 1A & 1B have dirty stator windings. The 1A motor should be scheduled for cleaning. 1A also has shaft currents through the outboard oil pump piping than should be corrected.

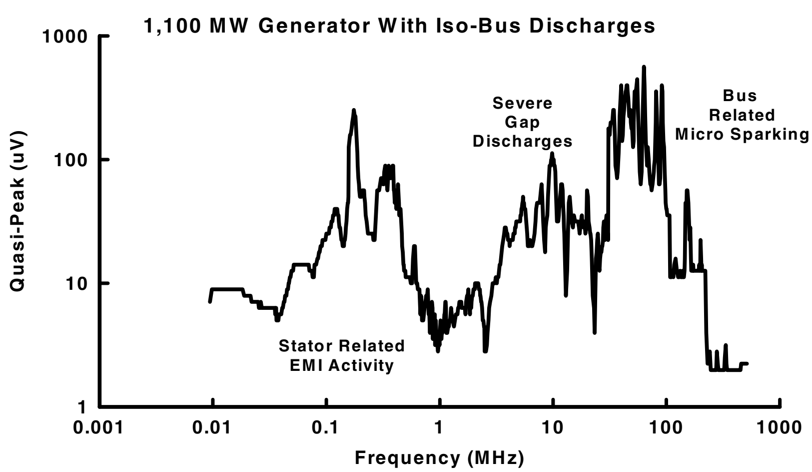

FIGURE: 7 This generator at a nuclear facility has stator related discharges as well as very serious high level gap discharges and microsparking related to defective internal and external isolated phase bus hardware.

SUMMARY

EMI Diagnostics has been able to detect and classify 55 patterns generated by defects in low voltage and high voltage systems, motor and generator rotors, stators and associated electrical equipment. This information is used for condition based maintenance focused on only those system components where deterioration is indicated. Maintenance for those systems without indications can then be deferred to a future refueling cycle with a minimum risk of service failure.

ACKNOWLEDGEMENT

The author wishes to express the major contributions to this paper provided by, John Allen and Dave Klinect without whose help this work would not have been possible.

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PlantView An Automation Tool for Maintenance Optimization

Presenter:
Richard Colsher, Product Manager

ABSTRACT

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

BACKGROUND

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

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

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

PREDICTIVE MAINTENANCE

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

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

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

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

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

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

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

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

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

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

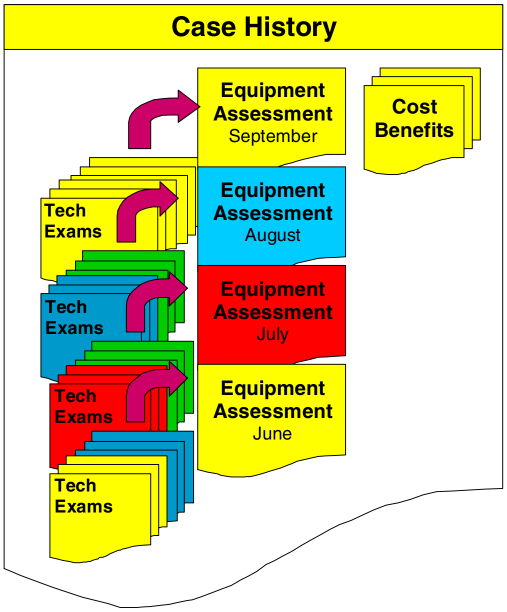
PLANTVIEW PdM AUTOMATION

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

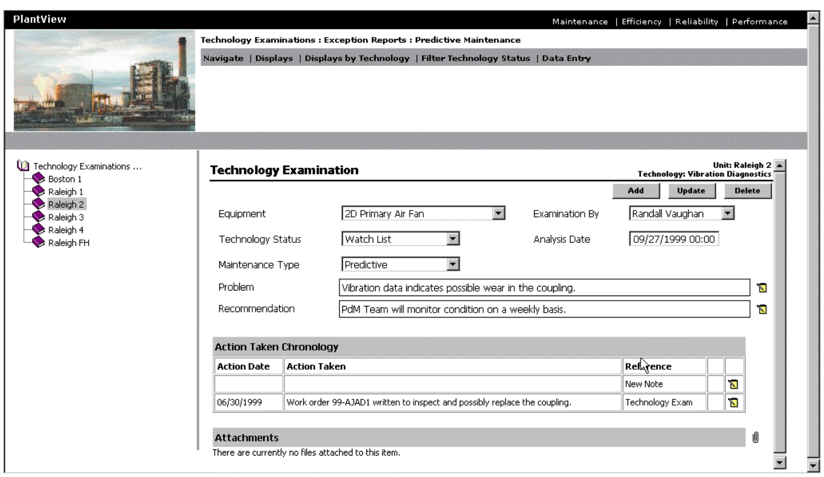
By presenting information in the same way to every computer, an Intranet can do what computer and software makers have frequently promised, but never actually delivered: put all the computers, software and databases that dot the Department landscape into a single system that enables employees to find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

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

The PdM Module automates the reporting process of a PdM program by dividing the process into 4 functional sections: Technology Examinations, Equipment Assessments, Case Histories and Cost Benefits. Multiple technology examinations form the basis for an equipment assessment. A Case History consists of any number of equipment assessments and can include multiple cost benefits.



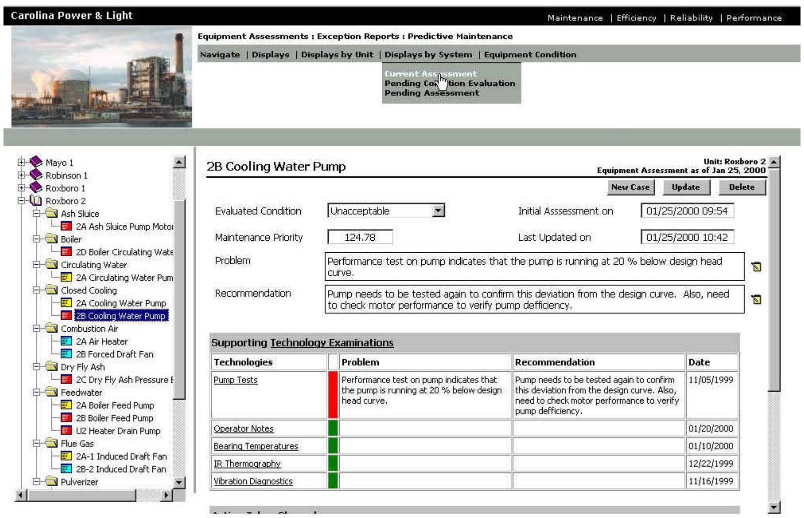
To aid users in visualizing status of equipment a consistent color coding is applied throughout the program. Technology exams and equipment assessments can be assigned a severity status of satisfactory (green), watch list (blue), marginal (yellow) or unacceptable (red).



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

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

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

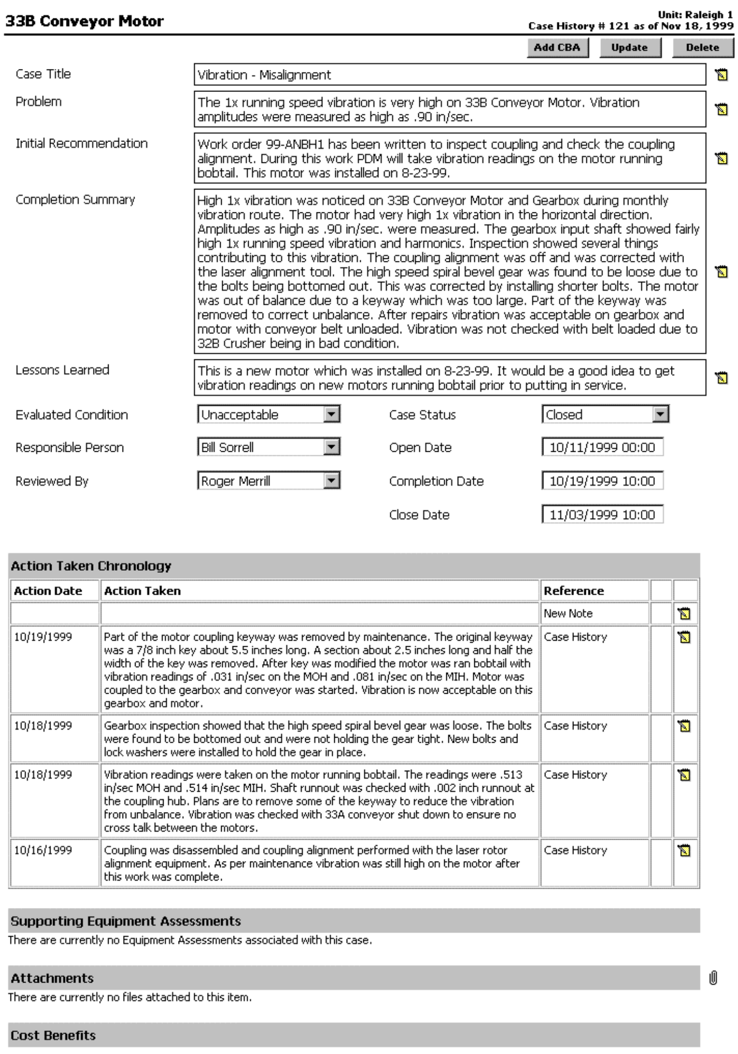


At regular intervals the system or equipment owners perform the component assessments combining the plant knowledge and engineering experience of the PdM team. PlantView will assign a condition status to the equipment following the simple rule: if all technologies within the assessment are acceptable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

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

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

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



33B Conveyor Motor

Unit: Raleigh 1
Case History # 121 as of Nov 18, 1999

Add CBA | Update | Delete

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

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

Action Taken Chronology

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

Supporting Equipment Assessments

There are currently no Equipment Assessments associated with this case.

Attachments

There are currently no files attached to this item.

Cost Benefits

There are currently no Cost Benefits associated with this case.

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

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

The relational database capabilities within PlantView, enables the overall cost totals to be displayed for Equipment, Units, Plants, and even rollup for Departmental totals. These totals can be used to support the success metrics associated with the overall PdM Program.

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

SUMMARY

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

A NEW STAINLESS STEEL FOR EROSION-CORROSION CONTROL IN POWER PLANTS

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Abstract

Maintenance departments in many industries are continually battling the daily fires that run costs up and productivity down. Many plants have equipment that must operate under wet sliding conditions, which can lead to accelerated, wear of the equipment. Electric power generating plants, for example, have ongoing maintenance concerns for piping, chutes, hoppers, heat exchangers, and valves. Pulp and paper plants have heavy maintenance on: plate screens, conical bottoms of blow tanks, chutes, and augers.

Coal handling equipment is often subjected to wet sliding conditions. Utility and coal prep plants can have serious flow problems if an improper structural or wear material is selected. Vibrating screens, chutes, surge bin feeders, conical distributors, screw conveyors and cyclones are some of the components that must resist the ravages of corrosion and wear.

This paper will address many of the issues that affect the life of plant components under wet sliding conditions. Environmental effects and material effects will be examined. Since the material of construction is most times the easier to change, the paper will concentrate on this subject. Such factors as: hardness, surface roughness, corrodent, and material of construction will be explored. Both controlled laboratory studies and real world service evaluations will be presented.

Introduction

The mining industry encounters many problems due to the combined effects of corrosion and abrasion. The coal industry, in particular, has many components such as chutes, liners, screening, conveyor belts, and hoppers that are subjected to wet sliding abrasion. In many locations, austenitic stainless steels have been specified because of their good corrosion resistance, durability, ease of fabrication, and maintenance free performance. AISI 304 is popular because of the improved "slideability" it offers over AR (abrasion resistant) steels (1). The AR steels rust causing build-up of material which lowers the flow rate, but stainless steels polish clean, providing smooth and continuous transport of material.

Although initial installation costs will be higher for stainless compared to AR steels, Swan (2) records several coal preparation plant trials that substantiate the cost effectiveness of stainless steels. He also reports on other effective measures such as corrosion inhibitors and design changes to better control corrosive wear in these plants. This paper is a continuation of work presented previously (3).

Experimental Program

Materials

Two classes of wrought alloys were studied in this program - alloy steels and- stainless steels. A few typical alloy steels were selected including: AISI 4340, Hadfield Mn, and Astralloy V. The compositions and heat treated conditions of all materials are listed in Table 1. All these steels had different levels of alloying elements to give a wide range of corrosion resistance.

Table I - Chemical Analysis, Heat Treatment and Hardness of Tested Alloys

	Weight %							
Alloy	**C**	**Mn**	**Si**	**Cr**	**Ni**	**Others**	**Heat Treatments**	**Hardness (HR)**
AISI 4340	.34	0.69	0.30	0.63	1.92	.27 Mo	150OF-20 min-O.Q. + 40OF-2 hrs-A.C.	C48
Astralloy V	.25	1.00	0.30	1.60	3.60	.35 Mo	1650F-15 min-A.C.	C45
Hadfield Mn	.79	13.20	-	0.16	0.07	.99 Mo	1850F-15 min-W.Q.	B93
AISI409	.01	0.25	0.57	10.89	0.16	.39 Ti	1350F-I hr-W.Q.	B82
17-4 PH	.04	0.60	0.51	15.72	4.45	3.26 Cu, .27 Cb	190OF-15 min-W.Q. +90OF-I hr-A.C.	C44
NITRONIC 30*	.04	7.39	0.38	16.73	2.31	.19 N, .75 Cu	1950F-15 min-W.Q.	B89
NITRONIC 30**	.08	7.81	0.55	16.22	2.31	.18 N, .64 Cu	1925F-15 min-W.Q.	B90
AIS1304	.07	1.66	0.48	18.45	8.90		1925F-15 min-W.Q.	B75
AIS1316	.06	1.77	0.56	17.46	12.93	2.2 Mo, .3 8 Cu	1950F-30 min-W.Q.	B73

*Series 1,2
**Series 3

AISI 409, a ferritic stainless grade, was evaluated because the South Africans use a modified version extensively in their mines to minimize their serious corrosion problems at reasonable cost (4). The martensitic class was represented by 17-4 PH heat treated to its highest hardness, HRC 44. Three austenitic alloys were tested with different degrees of strain hardening capacity. AK Steel NITRONIC 30, with the highest strain hardening rate, was included to compare with the popular AISI 304, which has an intermediate work hardening rate, and AISI 316, which has a low rate. The latter alloy also has significantly better corrosion resistance than the first two austenitic alloys.

Test Method

A 5.3 liter steel-backed porcelain jar was used as a ball mill to produce corrosive wear to the specimens. The Canadians have done extensive work in studying corrosion effects in grinding media using such ball mill techniques (5,6,7,8). The United Stated Bureau of Mines also uses a similar test method to conduct corrosive wear studies (9). An overall view of the equipment is shown in Figure 1.

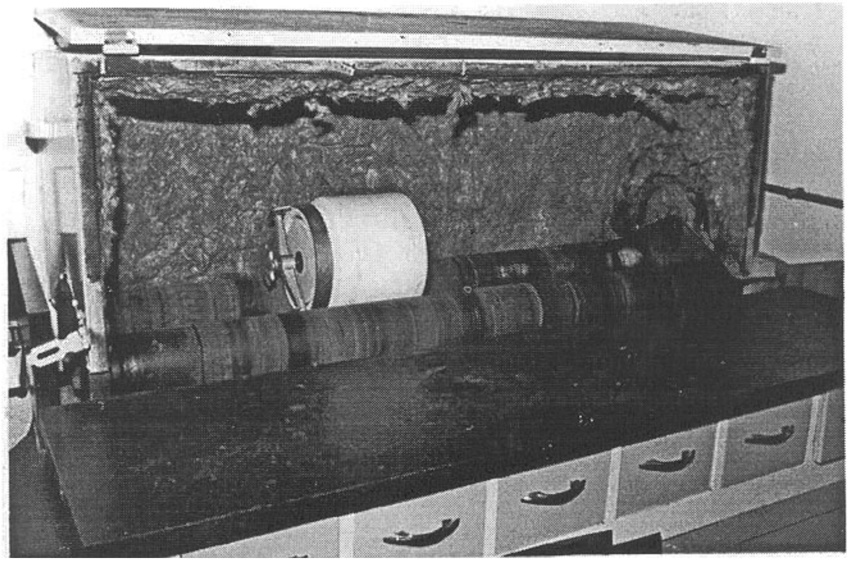


Figure 1 - Overall view of ball mill test equipment. Noise suppression box encloses the rotating porcelain jar

The specimens were prepared from sheet stock and measured 2.5 mm x 12.7 mm x 43.2 mm, (0.1 in. x .5 in. x 1. 7 in.) and were allowed to tumble freely in the ball mill in contact with the abrasive and liquid. Pea gravel was used as the abrasive. A total of 200 ml of gravel was used at -6.4 mm, + 3.2 mm (-1/4 in. + 1/8 in.) size in a liquid volume of 2 L. Some typical specimens and abrasives are shown in Figure 2.

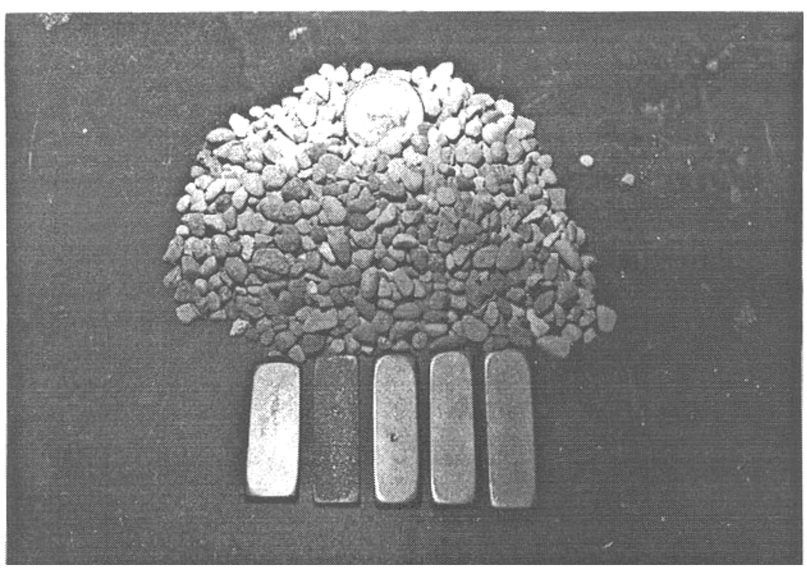


Figure 2 - Typical specimens and pea gravel abrasive used in ball mill corrosive wear studies.

Two types of mine water were used. In the first test series, actual coal mine water effluent was used and in the second series, a synthetic Ni-Cu sulfide mine water was used. More details of these solutions are listed in Table II.

All tests were run for 16-hour periods with fresh slurry (solution + abrasive) used each period. Weight losses were measured to the nearest 0. 1 mg after each period and converted to volume loss by dividing by the density. Duplicate specimens of each alloy were tested and all alloys were tested at the same time for a particular series. There was no evidence of sufficient metal-to-metal contact to cause either wear or galvanic corrosion. The peripheral sliding speed of the ball mill was .64 m/s (126 ft/min), or about 86% of the critical speed.

Table II - Mine Water Analyses

Series 1 - Coal Mine Effluent
pH - 8.00
Alkalinity - 140
Total Dissolved Solids - 685
Hardness - 170
Specific Conductance - 950
Cl ion -35 mg/l
$S0_4$ ion - 302 mg/l
Series 2 and 3 - Synthetic Ni-Cu Mine Water
pH - 9.1-9.6
NaS04 - 2 g/l ion concentration
NaCl - 0.2 g/l ion concentration

Results

Two preliminary series were conducted to study the combined effects of corrosion and abrasion to make certain the test parameters were satisfactory. Once confidence was gained, more detailed experiments were run to establish the individual contributions of corrosion and abrasion relative to the synergy of the combined effects. The results of the first series using coal mine water are shown in Table III and Figure 3.

Table III - Corrosive Wear of Alloy and Stainless Steels - Series 1 Ball Mill

Coal Mine Water, .64 m/s (126 ft/min), room temperature, 16-hr periods, pH - 8.7 after tests, 2 L of liquid, 0.2 L - 6.4 mm + 3.2 mm (-1/4" + 1/8") pea gravel, duplicates.

	Cumulative Volume Loss (mm^3)						
Hard. (HR)	**AISI 4340 C48**	**Astralloy C45**	**V AISI 409 B82**	**17-4 PH C44**	**NITRONIC 30 B89**	**AISI 304 B75**	**AISI 316 B73**
Period							
1	4.25	3.59	1.80	1.51	1.31	1.58	2.08
2	8.57	7.32	3.62	2.97	2.77	3.23	4.62
3	12.76	11.45	5.46	4.55	4.27	4.98	7.39
4	17.16	15.63	7.14	6.00	5.71	6.70	9.97
5	21.75	20.17	8.98	7.39	7.13	8.38	12.56
Relative Rank	3.05	2.83	1.26	1.04	1.00	118	176

All the stainless steels outperformed the two alloy steels despite their higher hardness, but only by about half of the amount of that found earlier in reference (3). This was due to the large increase in surface roughness of the alloy steels caused by corrosion in this more aggressive slurry. There was some retention of the corrosion products on the alloy steel specimens that could not be removed completely by cleaning with a short bristle brush, resulting in lower volume loss readings than could be expected from fully cleaned specimens. The change in surface finish is shown below.

Surface Roughness (micro-in. AA)

	Astralloy V	**AISI 4340**	**AISI 409 17-4 PH**
Before Testing	32	37	31 30
After Testing	217	172	27 18
	NITRONIC 30	**AISI 304**	**AISI 316**
Before Testing	32	37	32
After Testing	22	22	20

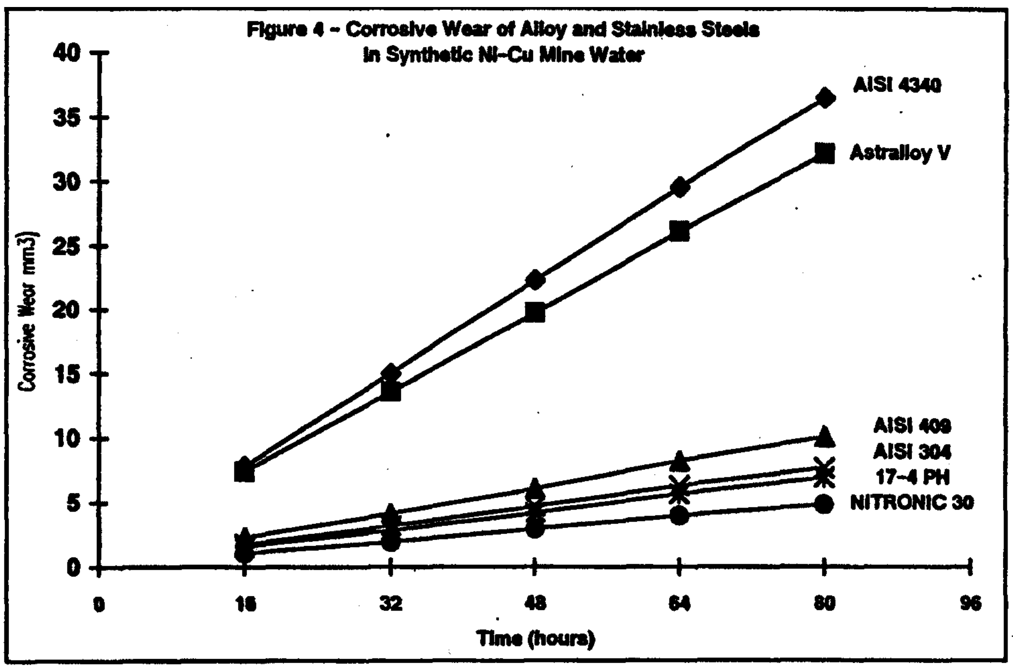
All the stainless steels became smoother due to polishing, while the alloy steels became pitted and rougher due to corrosion. A smoother wearing surface is much preferred in coal handling to facilitate sliding of the coal without clogging.

In the second preliminary series, a synthetic Ni-Cu mine water was used similar to that in the Canadian work. The same alloys, except for AISI 316, were evaluated. The results in Table IV and Figure 4 ranked the alloys exactly as in the first series.

Table IV - Corrosive Wear of Alloy and Stainless Steels - Series 2 Ball Mill

Synthetic Ni-Cu Mine Water, .64m/s (126 ft/min), room temperature, 16-hr periods, pH - 9.1-9.6, 2 L of liquid, 0.2L - 6.4 mm + 3.2 nun (1/4" + 1/8") pea gravel, duplicates.

	Cumulative Volume Loss (mm^3)					
Period	**AISI 4340**	**Astralloy V**	**AISI 409**	**17-4 PH**	**NITRONIC 30**	**AISI 304**
1	7.87	7.44	2.28	1.56	1.09	1.75
2	15.04	13.64	4.15	2.85	1.97	3.22
3	22.35	19.73	6.14	4.22	2.96	4.74
4	29.54	26.13	8.27	5.72	3.98	6.35
5	36.54	32.14	10.15	7.00	4.89	7.76
Relative Rank	7.47	6.57	2.08	1.43	1.00	1.59



The two alloy steels were far inferior to the stainless steels by a factor of 3 to 9 times. The highly metastable NITRONIC 30 again was the best of the stainless steels tested.

The individual contributions of corrosion and abrasion were studied in a final series of tests using the synthetic mine water. The first attempt to evaluate abrasion alone in dry tests was unsuccessful. The specimens became coated with a very fine, whitish powder. This powder was tightly adherent and obstructed the metal-to-abrasive contact. X-ray diffraction revealed the powder to be dolomite, which had come from the pea gravel.
An attempt was then made to isolate the effects of abrasion by conducting the wear tests in water adjusted to a pH 10.5-11.0 with sodium nitrite. Since static room temperature corrosion tests of the alloy steels showed no weight loss in this inhibited solution, the weight change for the alloy steels in the ball mill test was taken as being due to abrasion only.

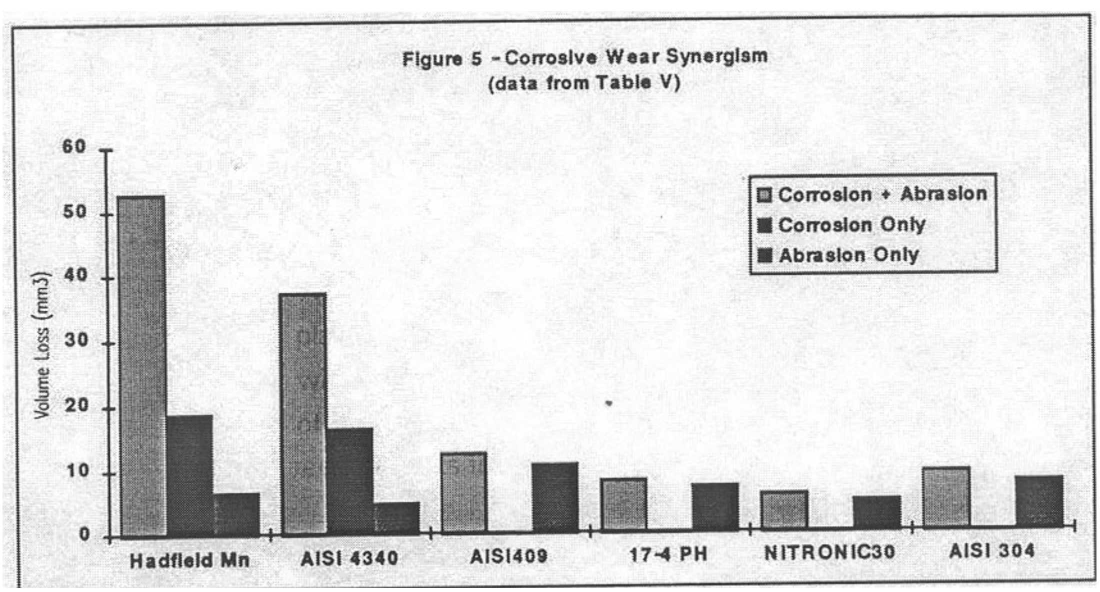
The total results for corrosion only, abrasion only, and the synergistic corrosion + wear tests are recorded in Table V. None of the stainless alloys exhibited any weight loss in the corrosion tests, but corrosion was pronounced for the two alloy steels. A summary plot is shown in Figure 5 depicting the contribution of each component - corrosion, abrasion, and corrosion + abrasion.

Table V - Corrosive Wear Synergism - Series 3 Ball Mill

Synthetic Ni-Cu Mine Water, .64 m/s (126 ft/min), room temperature, 16-hr periods, pH 9.1-9.6, 2 L of Liquid, 0.2 L - 6.4 mm + 3.2 min (4/4" + 1/8") pea gravel, duplicates

Cumulative Volume Loss (mm^3)						
	AISI 4340	**Hadfield Mn**	**AISI 409**	**17-4 PH**	**NITRONIC 30**	**AISI 304**
Corrosion only 5-16 hr periods	16.49	18.72	0	0	0	0
Abrasion only: tap water inhibited to pH 10.5-11.0 with sodium nitrite.						
5-16 hr periods	4.83	6.63	10.67	7.13	4.91	7.88
Corrosion + abrasion 5-16 hr periods	37.13	52.71	12.45	8.18	5.90	9.32
Relative Rank	6.29	8.93	2.11	1.39	1.00	1.58

It is clear that corrosion in this solution played a minor role to the wear of the stainless steels. In contrast, the alloy steels were much more affected. Although corrosion was only three times higher than abrasion, the synergism of the two caused the rate to be eight times greater than abrasion alone.



Discussion

The excellent corrosive wear resistance of the austenitic stainless steels compared to alloy steels has been documented previously (2,10,11,12,13). Hoey and Bednar (10) showed that de-aeration had a significant effect in reducing the wear of AISI 1020 and 1065 carbon steels. The erosion corrosion of these alloys is controlled by the oxygen reduction reaction; varying the hardness of 1065 from HRC 21 to HRC 65 did not affect its volume loss in either aerated or de-aerated coal slurries. Alloys like Ni-Hard and AISI 440C with intermediate corrosion resistance exhibited dramatic increases in wear rates in aerated slurries. In sharp contrast, austenitic stainless steels were not affected by aeration and were about equivalent to AISI 440C (HRC 55-60) and much better than Ni-Hard (HRC 65).

Postlethwaite, et al. (14,15,16) in electrochemical studies, demonstrated the greatly increased effect of corrosion in the presence of solid particles in slurry handling pipelines made of steel. They attributed the synergistic effect to the removal of surface rust and salt films by the flowing abrasives, which permitted much easier access of dissolved oxygen to the corroding surface. Thomas (4) arrived at the same conclusion in his work for the South African Mining Industry.

Noel and Ball (12) have shed much light on the complex subject of corrosive wear. They found that the corrosive component of wear of mild steels was practically constant from I to 5-Kg load; even lightly loaded systems had severely deformed surface layers. This layer would eventually reach a critical strain that would cause microfracture and result in wear debris. They also showed wear grooves caused by the abrasive with much corrosion product adjacent to the groove. The high density of dislocations with its high energy acted as an anode in a galvanic cell. Subsequent sliding action removed these corrosion products and the wear rate accelerated.

Noel and Ball also found that the frequency of abrasion in the presence of corrosion was important. Since volume loss increases proportionately as load increases and since volume loss due to corrosion is constant, the percent volume loss due to corrosion decreases with load. Under highly loaded systems in a corrosive environment, the contribution by corrosion is small. However, where low loads are found and infrequent abrasion occurs in a corrosive medium, the contribution due to corrosion can be quite high. They concluded that stainless steels are ideal for ore conveyors because of the light loads and intermittent corrosion exposure, while for crushing equipment a material with superior abrasion resistance and not corrosion resistance should be selected.

The stainless steels have a more stable passive film than alloy steels in most corrosive media. Even when disrupted by sharp abrasives, they have rapid healing qualities. However, in the present work, the inherent corrosion resistance of the stainless alloys is only one factor that contributes to their good performance. If corrosion were the dominant factor, AISI 316 would have performed the best in series 1, but it was actually the poorest. The high work hardening alloys, AISI 304 and NITRONIC 30, were better than AISI 316 despite the latter's inherently better corrosion resistance. Once the corrosion component of wear is controlled by high chromium levels, high strain hardening capacity is dominant in resisting the abrasion under these sliding conditions.

The metastable austenitic stainless steels have strain hardening capacity exceeded only by the Hadfield Mn type alloy. However, this alloy did very poorly under corrosive wear conditions as noted in Table V. It did not have the corrosion component under control. For crushing or gouging applications where high stress abrasion is produced, Hadfield Mn steel would fare much better.

Popov and Brykov (17) found that the transformation from austenite to martensite during abrasion also induced compressive stresses at the surface and caused a fine second phase to precipitate in this region to help resist further wear. In metal-to-metal wear studies, Korshunov and Mints (18) attributed the relatively high wear resistance of the metastable austenitic stainless steels to the deformation martensite produced in the surface layers which inhibited the onset of seizing.

In a more recent study, Ball (19) developed a model based on the stress-strain behavior of a material. He concluded, like de Gee (20), that the superior wear resistance of face centered cubic (austenitic) alloys compared to body center cubic (ferritic, martensitic) alloys at equivalent hardness levels was due to their higher work hardening coefficient. Such alloys dissipate energy over wide strains without cracking and spalling. AK Steel NITRONIC 30 was developed specifically for its ability to rapidly work harden even under low stress abrasive conditions - impact is not necessary; hardness has been measured up to HRC 50 at worn surfaces. It is the combination of good corrosion resistance and high strain hardening capacity of NITRONIC 30 that made it the best performer of the alloys studied in this investigation.

Conclusions

1 . Corrosion plays a dominant role in metal loss of alloy steels under low stress abrasion in wet environments.

2. Stainless steels have better corrosive wear resistance than alloy steels to varying degrees tested in two mining waters.

3. AK Steel NITRONIC 30 outperformed all steels evaluated in corrosive wear due to its combination of good corrosion resistance and high strain hardening capacity.

Acknowledgement

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Deep Cryogenic Tempering

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300 Below, Inc.

Introduction

The demands on today's power plants are significantly different than the original designers and builders anticipated. Deregulation and the accompanying industry consolidation and nationwide power marketing has created service requirements and capacity demands that were not dreamed of as recently as ten years ago. One of the newer nuclear power stations was designed in the seventies with planned capacity factors of 70% annually and the expectation of 10 shutdowns per calendar year. This station, along with many others, is not being run at those original design values. In fact, if those original assumptions were representative of current operation, the station would be shutdown because of inefficiencies. Capacity factors of 95% or more and 18 or 24 month continuous runs are expected for nuclear plants and fossil stations are required to run at comparable or higher levels. Many stations that were originally intended as peaking units are now being run at base load levels.

This places a much higher priority on component reliability and reduced downtime for planned or corrective maintenance along with increased emphasis on cost control and profitability. In most cases, it is not the cost of the replacement part that is of concern, but the requirement to take the equipment or the unit out of service for the maintenance or repair that is the largest impact to the bottom line. Our goal at 300 Below is to extend the service time of installed equipment to reduce planned and corrective maintenance and the subsequent loss of generation that can occur.

Cryogenic processing creates significant savings for the power generating industry in three unique areas. Primarily we realize savings on replacement parts with a cost of $.20 on the dollar, or better stated, a 500% return on investment. Additionally and even more significantly for the utility industry, reduced downtime and the savings recognized from newly increased throughput exceed the parts savings. By reducing downtime and replacement costs, millions of dollars are both saved in cost and also created by additional throughput generation allowing the company to efficiently produce energy at industry standards. Years of application testing of deep cryogenic processing at 300 Below has repeatedly saved hundreds of thousands of dollars.

History of Deep Cryogenic Treatment

Cryogenic treatment of metals to improve their properties is not a new process. A hundred years ago, Swiss watchmakers stored the high wear parts for precision watches in high altitude caves over the winter to improve the wear characteristics of the material. Tool manufacturers have used the process in some applications for greater than 50 years, and NASA has specified cryogenic treatment for some parts since the early days of the space program. There has been an equal amount of acceptance and skepticism associated with the process and it's effects. Early treatments used a variety of techniques to achieve a variety of results. Commonly, a temperature of -110°F was used, as that is approximately the temperature of dry ice. The rate of cooling, the time at the low temperature and the subsequent warm-up rate all were variable or uncontrolled. As a consequence, the results were unpredictable and, generally discounted. Serious research into the metallurgical phenomenon associated with deep cryogenic processing was conducted by just a few individuals during the late 60s and early 70s. This involved strict scientific methods and achieved predictable, repeatable results, thus validating the process as a useful tool in improving the physical properties of materials.

As the founder of the cryogenic processing industry in 1966, 300 Below processes over a million pounds of steels and iron per year. Equipment is in use at Lawrence Livermore National Laboratory, NASA, the Naval Nuclear Retrofit Facility, and many other recognized sites. In fact 300 Below developed the patented application of deep cryogenic treatment involving computer controlled temperature change rates, extended soak periods, and a dry cooling process utilizing liquid nitrogen as a cooling medium, thereby reaching temperatures below -300°F. The current era of deep cryogenic treatment has begun and a new industry is being formed.

Explanation of the process

Cryogenic treatment is an extension of, but not a replacement for, proper heat treatment of metals to improve their physical properties. The process involves a controlled cooling of the material to -300°F, a prolonged soak at that temperature and a controlled heat-up to 375°F for stabilization. Critical components of this process are the rate of change of temperature and the length of time the material is held at –300°F. The process involves the use of liquid nitrogen as a cooling medium, but the liquid does not come in direct contact with the treated components, thus avoiding thermal shock and potential damage. The cryogenic portion of the process is performed in specialty cryo-processors, cooled by liquid nitrogen. As the temperature is increased and passes through ambient, the material is transferred to a natural gas fired furnace for the heating cycle. The temperature ramp rates are computer controlled, with programming specific to the material being treated.

Metallurgy

To more clearly understand the metallurgical properties we want to improve, we need to discuss the principles of wear. There are four main types of wear; adhesive, abrasive, fatigue, and corrosive. The type of wear most common in industry is abrasive wear, which on a microscopic level is the penetration and gouging of material from one surface by another material. Two body abrasive wear involves only the two direct surfaces. Three body wear involves a free abrasive grit particle from an external source, or an internally generated wear particle. Reduction or prevention of this wear is a fundamental principle in design.

Deep Cryogenic treatment improves the ability of material to withstand abrasive wear by causing distinct changes in the microscopic structure of the material. The most significant change is the transition of retained austenite to the harder and more durable martensite. In 52100 carbon steel, normal heat treating results in the transformation of approximately 89% of austenite to martensite. Deep Cryogenic treatment increases that percentage to approximately 99%, providing a higher concentration of more durable material that is inherently more wear resistant.

In addition, the creation of more and smaller carbide particles and the improvement of their dispersion in the material provides a denser and more uniform crystalline structure. "We use cryogenic processing because it develops a more uniform refined microstructure with greater density and releases internal stresses" (NASA consultant). Much as sand added to concrete improves its durability and strength, the carbides provide a 'binder' to the individual crystals in the material, improving their resistance to tear out and reducing microscopic voids in the surface. These changes provide a denser, more uniform wear surface. As the quality of the surface improves, especially on a microscopic level, the effect is the same as providing additional surface area. More wear area directly provides more resistance to wear.

Although the wear resistance alone is a significant improvement in the material properties, the reduction in internal stress can also be a major benefit of the process. One major computer manufacturer uses a component retaining clip made of non-ferrous metal, approximately the size of a dime. The problem was breakage of the part, apparently due to stress points created in the stamping process, with the subsequent effect of a small metal part loose in a computer system. The cost of the part is insignificant, however, the impact to the installed computer equipment was catastrophic. The stress relief inherent in the cryogenic process has eliminated the failures of this part, at practically zero cost per unit.

Unlike many other processes, the effects of cryogenic treatment are permanent and homogenous. Subsequent machining or tooling operations do not change the improved properties of the treated material. This is readily apparent with machine tooling, with life extension and increased time between sharpening. Subsequent sharpening of treated tooling does not require additional treatment to maintain the improved performance. In fact, the major applications of cryogenic treatment over the last ten years have been in tooling.

Conclusion

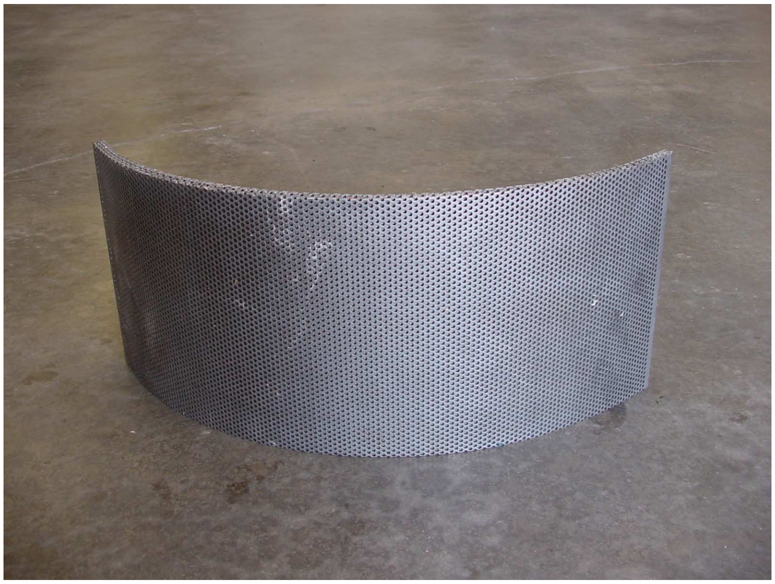
The benefits of the Cryogenic tempering offered by 300 Below are well documented. These benefits are achieved in hundreds of industries worldwide and the multi-tiered savings associated with Cryogenic tempering is allowing thousands of businesses to boost efficiency and ultimately increase profitability.

Examples and Applications

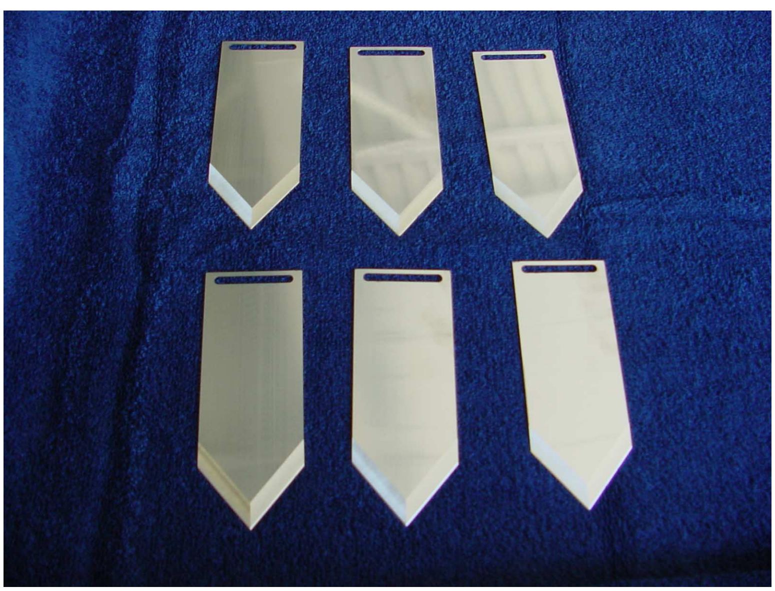
Golf clubs, Guns, Tooling, Musical instruments, Baseball bats, Brakes, Rotors, Computer parts, Race car engines, Race car frames, Heavy machinery, Pyrite plows, Pumps/Impellers, Bearings, Flighting, Electric motors, Coal handling equipment.

Shredder Rings
400% Gains

Hammer Mill Hammers
200% Gains



Screens
275% Gains



Blades
325% Gains

Machine Shaft
350% Gains

Mine Roofing Bits
200% Gains

Fitness for Service Program and Local Thin Area Repair Component for Pressure Retaining Items

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ABSTRACT

Erosion/corrosion in pressure vessels often requires pressure boundary repair to prevent failure. The nuclear power industry has recently experienced shell wall failures in feedwater heaters. Flow accelerated corrosion (FAC) monitoring programs have been expanded to include feedwater heaters. Minimum wall thickness acceptance criteria used for pressure vessel inspections is often derived from ASME Section VIII, Division 1 Code rules and Code Case 2243 for internal design pressure. These rules, applicable to original construction, form the acceptance basis for abbreviated "Fitness For Service" (FFS) evaluations of localized thin wall in determining if vessels should be repaired or can return to service. This approach often overlooks many considerations that encompass FFS evaluations.

Use of a single "go", "no-go" wall thickness value for acceptance determination can result in non-conservative decision-making or unnecessary repairs. For example, pressure vessels that have vacuum design or applied nozzle loads from large bore piping systems may not be governed by internal pressure thickness requirements. Shell or head wall at locations remote from nozzle loading or adjacent to stiffening rings may have an acceptable wall thickness that differs from other locations due to the reinforcement of the surrounding shell.

Asta Engineering, Inc. has developed a FFS evaluation for the power industry that uses a comprehensive approach to determining acceptable wall thickness at unique vessel locations based on application of ASME Code design rules. These rules form the basis of a proprietary software tool that evaluates the entire vessel, including shell, heads and nozzles, to determine the impact localized metal loss has on continued service. Results have demonstrated that based on the size and location of a local thin area, wall thickness less than that defined by Code rules and Code Case 2243 for internal design pressure can satisfy Code requirements and be returned to service without repair.

A common method of pressure boundary repair involves cutting out the affected section and replacing it with new material of equivalent or better erosion/corrosion resistance. New sections are installed using full penetration welds. This type of repair is generally referred to as a "flush patch repair". A "weld build-up" repair can also be performed to restore areas of localized metal loss. In this type of repair, weld metal is deposited on the thin area to restore the profile and thickness to original supplied condition. Asta Engineering, Inc. has developed an alternative to the flush patch and weld overlay repair methods. This alternative, entitled "**Local Thin Area Repair and Restoration Component for Pressure Retaining Items** (Patent Pending) ", hereinafter referred to as the "AstaCap", encapsulates the defect area and forms a new pressure boundary. The "AstaCap" is attached to the vessel outside surface using a full penetration weld. It satisfies original construction code requirements and meets NBIC rules for vessel alterations.

FITNESS FOR SERVICE PROGRAM

BACKGROUND

The Asta Engineering FFS evaluation is based on utilizing margin available in the original design to generate acceptance criteria for use in evaluating local thin areas. Usually, acceptance criteria is generated in advance of actual scheduled inspections. This provides owners with an indication of vessel margin that can be compared to existing historical inspection data. From this comparison, repairs can be planned and scheduled in advance and inspection frequencies adjusted to remaining life.

Wall thickness acceptance criteri for local thin areas is graphed as a function of adjacent wall thickness for various vessel regions. This provides a convenient tool that can be used in the field for rapid determination of as-found wall thickness for acceptability and returned to service.

APPROACH

The Asta Engineering FFS software program approach is based on application of ASME and NBIC Code rules to:

- Define available margin in an existing vessel design and apply it towards reinforcing localized thin wall areas;
- Define code requirements for reinforcing a localized thin area by treating it as an opening, in an existing vessel, whose size is equal to the size (diameter) of the localized thin area;
- Define minimum wall thickness requirements of a local thin area to maintain pressure integrity of vessel; and,
- Define acceptability of stress in localized thin area region due to nozzle, support, wind, or earthquake loadings.

<u>Available Margin</u>

Available margin is defined as the difference between the bounding minimum required wall thickness and actual measured wall thickness.

The FFS software performs simultaneous calculations for minimum required wall thickness to satisfy ASME code requirements and industry standard approaches for:

1. internal design pressure,
2. external design pressure,
3. nozzle reinforcement for internal and external design pressure,
4. piping system nozzle loadings,
5. support loadings
6. wind and earthquake loadings
7. application of remaining life corrosion allowance.

The final determination of minimum acceptable wall thickness is the bounding calculated value that satisfies these seven requirements.

Wall thickness required for nozzle and support loadings is based on Welding Research Council Bulletins (WRC) 107 and 297 methodologies and standard industry practice for determining material allowable stress acceptance criteria.

<u>Minimum Wall Thickness</u>

Before a corrosion allowance is determined, the minimum bounding wall thickness is calculated.

Minimum wall thickness values are calculated for design pressure requirements per:

- UG-27, "Thickness of Shells Under Internal Pressure",
- UG-28, "Thickness of Shells Under External Pressure",
- UG-32, "Formed Heads, Sections, Pressure on Concave Side
- UG-33, "Formed Heads, Pressure on Convex Side

Additionally, the required minimum wall thickness in the local vicinity of nozzles and supports, as applicable, is calculated to satisfy the area replacement and stress requirements per:

- UG-37, "Reinforcement Required for Openings in Shells and Formed Heads"
- WRC Bulletin 107, "Local Stresses in Spherical and Cylindrical Shells Due to External Loadings on Nozzles, Revision 1"
- WRC 297, "Local Stresses in Spherical and Cylindrical Shells Due to External Loadings on Nozzles, Supplement to WRC Bulletin 107: Revision 1

Also, the minimum thickness required to satisfy support, wind, and earthquake loadings is calculated.

<u>Erosion/Corrosion Allowance (CA)</u>

An erosion/corrosion allowance (CA) that would result in pressure boundary wall eroding/corroding to the minimum code required thickness over the specified operating period is calculated. Bounding wall thickness values are selected for defined regions by adding this erosion/corrosion allowance to the minimum required wall thickness.

The FFS software assumes that the erosion/corrosion mechanism responsible for localized metal loss will remain constant. However, changes to the rate of erosion/corrosion can be factored into the program. Erosion/corrosion allowances resulting in both the local thin area and adjacent shell wall eroding/corroding to the minimum required code thickness in a specified operating period are calculated and added to the minimum thickness values required for the local thin area and adjacent wall.

The approach use in the FFS software to calculate corrosion allowance follows the process outlined in the National Board Inspection Code (NBIC) as defined in Part RB-3236, Remaining Life Calculation, and Section (l) of Part RB-3238, Conditions That Affect Remaining Life Calculations. The corrosion allowance is calculated by first calculating the maximum allowable corrosion <u>rate</u> that can be tolerated before minimum code thickness is reached. The corrosion allowance is calculated by multiplying the corrosion rate by the specified service period.

Bounding Wall Thickness

The Bounding Wall Thickness of a vessel is calculated by adding the applicable erosion/corrosion allowance to the thickest wall required to support the design conditions at any vessel location wherein local thin areas are to be evaluated.

Local Thin Area Acceptance Criteria

Code compliance is maintained provided as-found wall thickness values are greater than the bounding wall thickness. If localized metal loss results in a wall thickness less than this bounding value, code compliance may still be shown. The Asta FFS program generates acceptance criteria, including full code compliance documentation, that allows for local thin areas. The FFS acceptance criteria optimizes available margin based on the size and location of the local thin area with respect to the surrounding metal. It is based on Code rules for vessel openings. Local thin areas are treated as openings of equivalent size with the wall surrounding the thin area used as reinforcement. For convenience, and as an aid during vessel wall thickness inspection, wall thickness acceptance criteri for local thin areas are graphically depicted on charts. The acceptance criteria charts (ACCs) are generated for the required operating period before next inspection.

Minimum Required Local Thin Area Thickness

The FFS program determines the required thickness of a local thin area based on thin area diameter and vessel design pressures, temperatures, and rate of erosion/corrosion.

Any additional wall material required for satisfaction of ASME code area replacement requirements, nozzle loadings, wind, earthquake, and support loadings is also required to be available in either the thin area or in vessel wall material surrounding the local thin area.

The minimum required local thin area thickness values are calculated as follows:

1. Shell Thin Areas – Internal Pressure – The minimum of the following two calculated values is selected as the required thickness for internal pressure. a) Considering the thin area to be a flat plate, the thickness is calculated based on ASME Section UG-34, “Unstayed Flat Heads and Covers”, b) Considering the entire shell to be a thin area, the thickness is calculated based on ASME Section UG-27 “Thickness of Shells Under Internal Pressure”).
2. Shell Thin Areas – External Pressure –The required thickness is calculated based on ASME Section UG-28, “Thickness of Shells Under External Pressure”, and setting shell length equal to thin area diameter.
3. Head Thin Areas – Internal and External Pressure – The required thickness is calculated based on ASME Appendix 1, Section 1-6, “Spherically Dished Covers

The largest of the values calculated for internal and external pressure is the **minimum required thickness of a local thin area.** To this thickness value is added the required erosion/corrosion allowance.

Minimum Required Thickness of Vessel Wall Adjacent to Local Thin Area.

The margin in vessel wall adjacent to the local thin area provides reinforcement. The ASME rules contained in code Section UG-37, Reinforcement Required for Openings in Shells and Formed Heads, are followed to determine the required thickness of shell adjacent to a local thin area. The required reinforcement thickness is a function of local thin area thickness and diameter. The available adjacent shell reinforcement (i.e. margin) is wall thickness not required for pressure and other loadings.

Other Considerations

If a local thin are occurs in a vessel section that contains a weld, the code required joint efficiency, based on original construction weld examination performed, is factored into the acceptance criteria development.

If a local thin area is located close to a nozzle or support, the nozzle area replacement and local stresses due to nozzle or support loadings are evaluated after available wall thickness is reduced for the local thin area and it's required reinforcement.

The program also provides criteria for protection against possible Pin Hole Leaks. A minimum single thickness value is provided to assure that pinhole leads will not occur during the required operating period.

Generating Acceptance Criteria Charts (ACCs)

Development of local thin area acceptance criteria is performed using an iterative process that varies the thin area diameter, thickness and adjacent wall thickness. Additionally, acceptance criteria are generated separately for areas of the vessel that could contain a weld within the local thin area. A set of bounding acceptance criteria is determined by selecting the maximum local thin area diameter with the thinnest local thin area wall, reinforced to the maximum extent by the margin available in the adjacent wall thickness. If local thin area diameter is remains fixed, the adjacent wall thickness can decrease when the local thin area wall thickness increases. If thin area diameter decreases, there is a corresponding increase in both thin area thickness and adjacent wall thickness. Accordingly, a range of acceptable thin area diameters, thin area wall thickness, and adjacent wall thickness can be generated. The relationship between acceptable local thin area wall thickness and minimum required adjacent wall thickness for various thin area diameters for different vessel regions is graphed for used during vessel inspection.

The FFS software generates a family of graphs of acceptable local thin area wall thickness as a function of adjacent wall thickness for a specified diameter for different vessel regions. A sample Acceptance Criteria Chart (ACC) is depicted in Figure 1

ACC USAGE

The ACCs are simple to use. The user need only determine thin area diameter and average thickness, and adjacent shell average thickness and plot these values on the ACC chart appropriate for the thin area diameter and vessel region. Values plotted above the chart acceptance line indicate acceptance of thin area for continued vessel operation, whereas values below the acceptance line indicate a need for further evaluation or repair before returning the vessel to service. Based on the location of plotted values, (i.e. near the line or significantly above or below the line) the user can quickly determine if the vessel would be acceptable for a least a shorter operating period or if the time period to the next inspection interval can be increased.

Wall thickness plot locations are indicative of corrosion rates. As described above, the corrosion allowance is derived from a maximum allowable corrosion rate based available margin and service hours to date. As additional service hours are logged, the maximum allowable erosion/corrosion rate is reduced because available margin is divided by a greater number of service hours. The actual corrosion allowance required to support the specified service period is less than the one used in generating the charts. The existing ACCs therefore become more conservative as additional service hours are accumulated. Wall thickness values plotted above the line indicate that erosion/corrosion rates are less than maximum allowable rates. Conversely, plotted values below the line indicate that erosion/corrosion rates are greater than maximum allowable rates for the specified operating period..

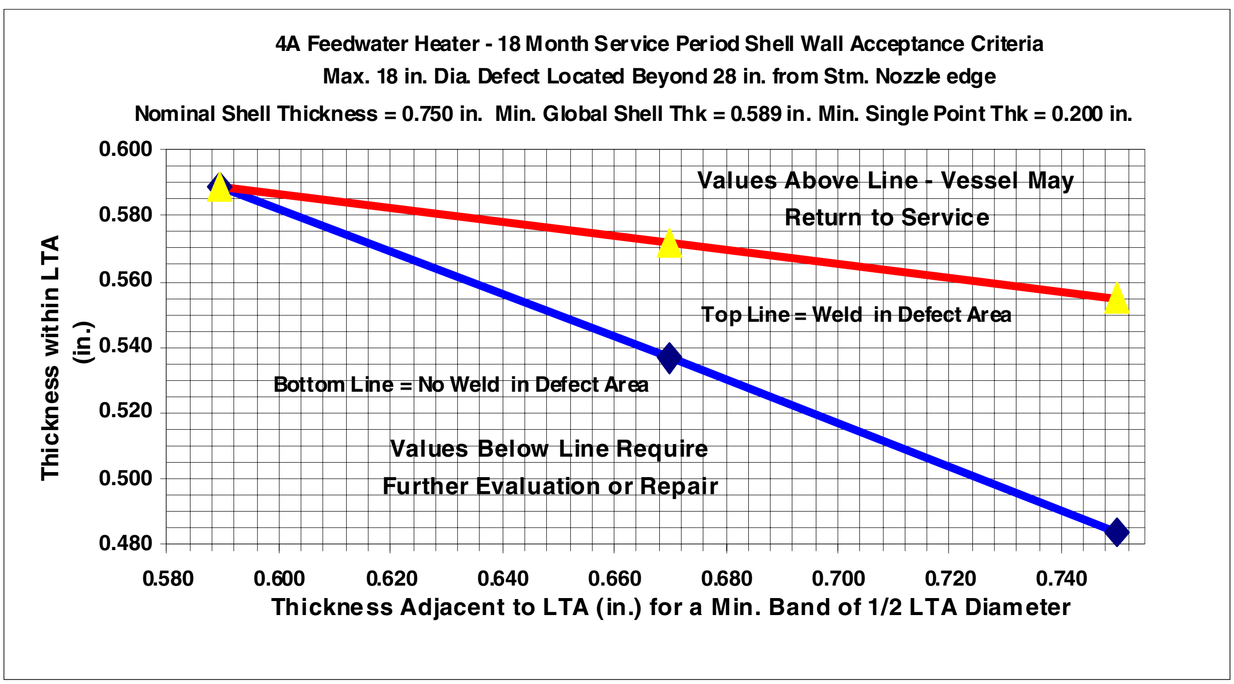
FFS PROGRAM LIMITATIONS

Limitations on the size of local thin area covered by the FFS program parallel the rules outlined in the National Board Inspection Code as defined in Part RB-3238 (g.)(1.), and (2.), and the ASME Code as defined in Section UG-36 (b), and are depicted below in terms of defect diameter:

Local thin areas in shells

- The lesser of one-half the vessel diameter, or 20 inch for vessels with inside diameters of 60 inch or less, or
- The lesser of one-third the pressure vessel diameter, or 40 inch, for vessels with inside diameters greater than 60 inch.

The FFS program has no limitations on the size of local thin areas in heads.



Fitness For Service Acceptance Criteria Chart
FIGURE 1

LOCAL THIN AREA REPAIR COMPONENT

BACKGROUND

The "flush patch " and cavity "weld build-up " repair methods are allowed by the National Board Inspection Code (NBIC) and are accepted by jurisdictional authorities. The "flush patch" repair involves removal of degraded vessel wall and replacement with new material. The "weld build-up" repair method restores wall profile and thickness to original supplied condition by depositing weld metal to a local thin area. These material replacement repair methods can provide a factor of safety and erosion/corrosion protection equal to original construction. To maintain the original design factor of safety, nondestructive examination of the new weld, using the same or equivalent NDE method as that used during original construction, is required. For most pressure vessel repairs, ultrasonic examination of the new welds is performed as an alternative to the radiographic examination originally specified. Additionally, the jurisdictional authority may require a hydrostatic test of the vessel after completion of the repair.

Material replacement repair methods have several other limitations including:

1. Requires removal and isolation of vessel from service.
2. Requires removal of defective vessel wall.
3. Creates personnel risk of exposure to hazardous vessel contents.
4. Creates environmental risks associated with disposal of vessel contents and job materials.
5. Creates risk of damage to vessel internals.
6. Creates risk of foreign material intrusion.
7. Requires cutting vessel wall for new "flush patch".
8. Requires exact fit-up of new flush patch replacement plate into vessel cutout with edge weld joint preparation.
9. May require use of weld joint backing strips to achieve full penetration weld. Note: *Backing strips left in place may result in a reduction in weld joint efficiency factor. Also, in high flow regions, backing strips may separate and become loose parts or create new flow turbulence thus accelerates local erosion.*
10. Requires welder access inside vessel for "weld build-up" repair.
11. May expose welder to radiological hazards.
12. Requires equipment downtime to implement repairs.
13. Labor and time intensive repair.

ALTERNATIVE REPAIR METHOD

Asta Engineering, Inc. has developed an alternative repair method that satisfies code requirements without the limitations identified above. This alternative uses a custom designed component that encapsulates defective pressure boundary areas. The component is entitled "**Local Thin Area Repair and Restoration Component for Pressure Retaining Items** (Patent Pending) ", hereinafter referred to as the "AstaCap".

The "AstaCap" is a pre-fabricated component that can be installed as a vessel alteration. It restores pressure vessels with local thin areas, cracks or pitting to original design capability. It is welded to the outside pressure boundary surface using a full penetration weld. It encapsulates the defective area and becomes a new extension to the original pressure boundary.

Repairs can be made without removing defects. Degraded wall areas are totally encapsulated by the "AstaCap". The "AstaCap" is constructed to satisfy all original code and jurisdictional requirements including material, certified design calculations, examination, inspection, testing, stamping, and partial data reports. "AstaCap"s allow for quick repairs and rapid return to service with minimal risk by eliminating cutting of the pressure boundary, foreign matter intrusion, and exposing vessel internals or contents to the environment.

"AstaCap"s can be designed to encapsulate shell, head, or nozzle regions in any shape but are commonly supplied as round or obround. The "AstaCap" can be used to repair pressure boundaries in pressure vessels, piping, and tanks. They will restore the structural, pressure retaining integrity, and erosion/corrosion capability to an original or enhanced design condition. "AstaCap's include a corrosion allowance adequate for the remaining item life or can be supplied with an optional corrosion resistant liner.

Design

"AstaCap"s can be designed to various codes or standards, using the ASME Section VIII, Division 1 code as the primary code of construction. Details on designing an "AstaCap" for compliance with the ASME code are provide below.

"AstaCap"s are designed for vessel internal and external design pressures, including pressurization of the cavity should the encapsulated wall be breeched. These loadings cause both membrane and bending stresses in the skirt and flat head portion of the "AstaCap". The "AstaCap" is designed to satisfy these loadings per ASME code rules and stress acceptance criteria. Thickness determination is based on design pressure and area replacement criteria. As a minimum, code criteria, contained in Sections UG-27, "Thickness of Shells Under Internal Pressure", UG-28, "Thickness of Shells Under External Pressure", UG-34, Unstayed Flat Heads and Covers, and Appendix 13, Vessels of noncircular Cross Section are followed as applicable. Additionally, Code rules contained in Appendix 1, Supplementary Design Formulas, and Appendix 4, Integral Flat heads with a Large, Single, Circular, Centrally Located Opening, as applicable, are considered.

The "AstaCap" is designed to integrally reinforce the shell to improve structural and pressure retention integrity. Code rules contained in Section UG-37, Reinforcement Required for Openings in Shells and Formed Heads, are followed to determine the thickness of the flat head portion of the "AstaCap" required for reinforcement of the local thin area. Generally, vessel wall encapsulated by the "AstaCap" is not included in strength or reinforcement design. However, this wall provides an erosion/corrosion barrier that may be used in determining remaining service life.

Corrosion allowances for remaining design life are calculated and added to thickness requirements governed by code stress and reinforcement rules. Alternatively, the "AstaCap" can be provided with an erosion/corrosion resistant liner. No strength or reinforcement credit is taken for the encapsulated area or material provided solely for erosion/corrosion protection.
Vessels, with "AstaCap" alterations, meet or exceed original design and have improved erosion/corrosion resistance at the installed location.

Fabrication

The AstaCap is usually round but can be square, rectangular, obround, oval, triangular, or any combination of these shapes. They can be constructed to various codes and standards but are generally constructed in compliance with ASME code requirements. Fabrication discussions provide herein are based on ASME code construction. "AstaCap"s are fabricated from a single piece of material or by welding composite pieces. They are rolled, machined, formed, forged, or cast to fit the contour of the outer surface of the pressure boundary they are to be attached to. All internal machined radii are designed to reduce stress concentrations. For fabricated "AstaCap"s, the reinforcement plate head weld can be shop pressure tested. "AstaCap"s can be supplied as either ASME code "material" or ASME code-stamped components. They can be pre-staged for future repairs and rolled to fit prior to installation. An "AstaCap" package includes hardware, partial data reports, shop fabrication drawings, material, examination, inspection, testing documentation, and certified calculations. A detail of a round configuration "AstaCap" is shown in Figure 1, General Arrangement Machined and Fabricated Round "AstaCap".

Installation

The "AstaCap" is attached by a full penetration weld to the pressure boundary outer surface. The internal cavity between the pressure boundary surface and the inner surface of the "AstaCap" allows for volumetric examination of the attachment weld. If pressure testing of the attachment weld is required, the "AstaCap" can be supplied with pressure taps for use in pressurizing the cavity (note: the encapsulated area thickness will need to support hydrostatic testing as well). Alternatively, a small hole can be drilled into the existing pressure boundary for complete vessel hydro or in-service pressure testing. An installed "AstaCap" picture is shown in Figure 2.

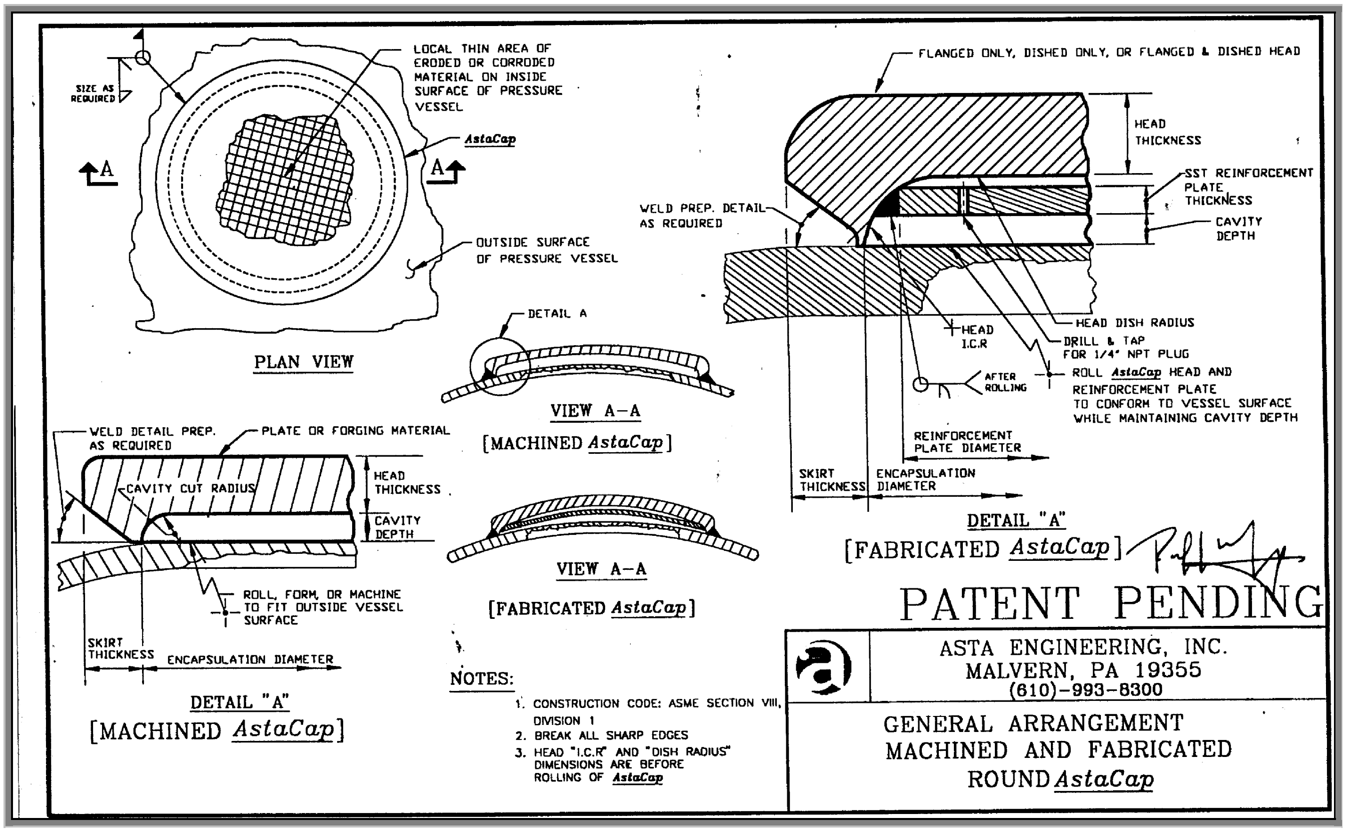
DESIGN OBJECTIVES AND ADVANTAGES OVER CURRENT REPAIR METHODS

The objectives in designing the "AstaCap" were to provide a simple, safe, cost effective method of repairing pressure boundaries in compliance with original design codes. An additional design objective was to provide a repair method that alleviated or eliminated many if not all of the negative aspects of the current common methods of repair using the "flush patch " or "weld build-up" type repairs. Various national codes, including but not limited to, the American Society of Mechanical Engineers (ASME), American National Standards Institute (ANSI), Tubular Exchanger Manufacturers Association (TEMA), American Petroleum Institute (API), and National Board Inspection Code (NBIC) govern construction, operation, and in-service inspection. Local jurisdictional authorities may specify combinations of these governing codes for construction, operation, and inspection.

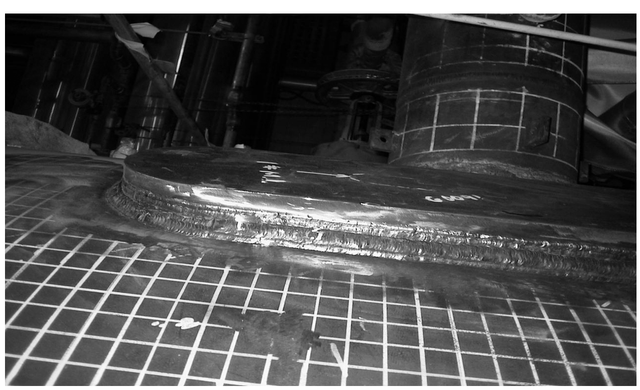
The "AstaCap" solves many of the negative aspects of current common methods of repair and offers several advantages. These include but are not limited to:

1. May not require removal of the pressure retaining item from service.
2. Does not require removal of defective section from vessel wall.
3. Does not require vessel shell preparation for "AstaCap" weld attachment.
4. Does not require weld joint backing strips.
5. Eliminates risk of personnel exposure to lethal or hazardous vessel contents.
6. Eliminates environmental risks associated with release of contents.
7. Eliminates risk of damage to vessel internals.
8. Eliminates risk of intrusion of foreign materials.
9. Eliminates need to breech pressure boundary for repairs.

10. Eliminates need for personnel to access inside of vessel.
11. Eliminates contaminated material disposal costs.
12. Allows for hydrostatic or pneumatic testing after repairs.
13. No geometric shape limitations.
14. Quick and simple to install thus reducing costs associated with repair or equipment downtime.



Round "AstaCap"
Figure 2



Installed Obround "AstaCap"
Figure 3

COST EFFECTIVE REPAIRS OF A LOOP STOP ISOLATION VALVE A UNIQUE APPROACH

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ABSTRACT

This paper summarizes the results of a project that employs remote robotic end effectors to repair a loop stop isolation valve (LSIV) at Exelon's Byron Nuclear Station. Specifically, it addresses the internal guide valve repair. Byron Station has two identical units with a total generation capacity of 2250 megawatts. It is a four-loop Westinghouse designed pressurized water reactor located in Byron, Illinois. Each loop contains two LSIV's that allows the steam generator to be isolated from the remainder of the system for maintenance activities. The loop stop isolation valves were experiencing guide rail problems, specifically if the guide rail had become loose and if miss-positioned, it could lead to the valve not closing and damaging the guide rail and valve disk. In order to rectify the situation the valve guides needed to be secured to the valve body eliminating the chance that the guide would become miss-positioned. The original equipment manufacturer (OEM) recommended modifying the valve body guide rail slots to eliminate the problem. In order to perform this modification, the valve would have to be disassembled and repaired, an intensive manpower and dose process. To eliminate the need to disassemble and reassemble the valve an alternative approach was utilized. Custom tooling was designed and fabricated to allow the modification to be performed through an eight-inch by-pass line downstream of the valve. The key results will be summarized in this paper along with the experience of using remote tooling to provide cost-effective solutions.

INTRODUCTION

Byron Nuclear Station Unit Two is a four-loop pressurized water system providing steam for the 1175 MW electrical turbine generator system. Each loop contains two LSIV's. The valves are located between the reactor coolant pump and reactor vessel and between the steam generator and reactor vessel. The LSIV's are closed during outages to allow the refueling activities and steam generator maintenance/inspection services to be performed concurrently.

Each LSIV weighs fifteen tons, is thirteen feet tall and is approximately six feet wide. There are a total of eight LSIV's per unit, or two per loop. They were installed during the construction phase and would require seven and one-half feet overhead clearance for disassembly. In addition, in order to disassemble and remove the bonnet and valve disks numerous beams, conduits, cables, piping and instrument piping would need to be removed. The environment could best be described as a very congested area with very little floor space in the near vicinity for disassembly. Figure 1 shows a cutaway of a LSIV.

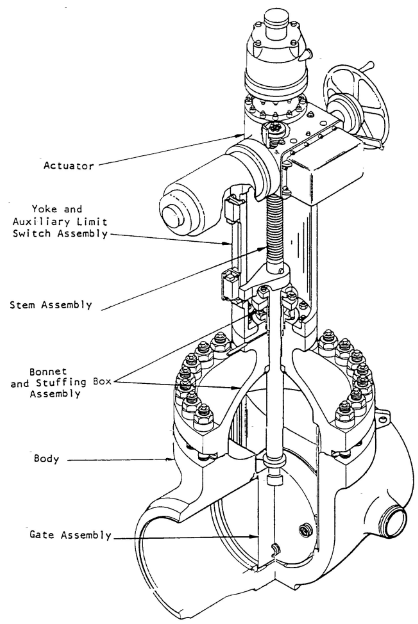

Figure 1 - Loop Stop Isolation Valve

HISTORY

Each LSIV has two 410 stainless steel guide rails that fit into milled out pockets in the casted valve body. Their purpose is to act as a guide during the opening and closing of the gate valve disk. The guides are held in place using a three pin design; two pins at the top and one at the bottom with the pins being spiral wound 302 stainless steel.

In February 1985 one of Exelon's sister plants had a cold leg LSIV fail[1]. After disassembling the valve, broken guide pins were discovered in the valve. Metallurgical examinations of the broken pins from the valve show a susceptibility to stress corrosion cracking. This susceptibility confirmed the matter of pin shear, and subsequent isolation valve binding and failure.

During a past outage the motor operator valve (MOV) failed during the closure of the 1RC8002A LSIV located on the cold leg. The utility's investigation of this failure identified probable degradation and failure of the valve guide retention pins due to stress corrosion cracking. They concluded that Byron's Unit 1 LSIV's will continue to pose problems during future cycles. They concluded that there was a strong potential that these valves will ultimately fail to stroke as a direct result of valve guide failure. Such a failure would disable refueling outage loop isolation and could pose an even larger problem of a dislodged guide (loose parts) should a complete failure of the guide pins occur. These results could cause a forced outage, damage to other plant equipment, damage to fuel, scheduling problems, outage delays and added costs. Figure 2 shows an exploded view of the valve body including the guide rails and rolled pins.

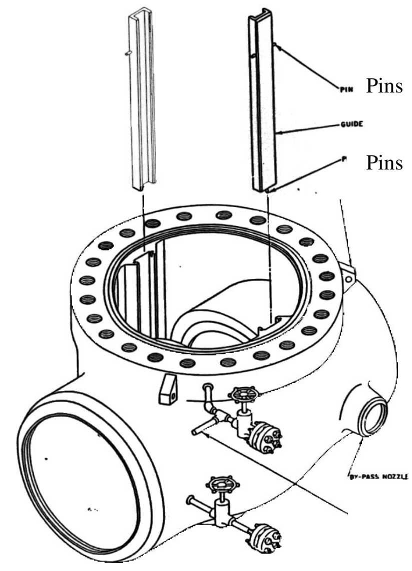

Figure 2 – LSIV in Exploded View

The investigation also concluded the hot leg LSIV's guide rails are not as susceptible to fail based on industry experience. The OEM stated that all known failures have been on the cold leg LSIV's. It is believed that due to the close proximity of these valves to pump discharge, the guides are subjected to more turbulence and flow dynamics. As part of the investigation, the utility reviewed previous LSIV motor current strip charts for hot leg MOV's 1RC8001A, B, C, D, and cold leg MOV's 1RC8002A, B, C, D. Based on these strip charts, the hot leg MOV's appear to indicate subtle indications of guide problems. However, the cold leg MOV's exhibit severe guide problems, the worst of which are 1RC8002A & B. The signature traces taken during closing strokes of the valves show drastic increases in motor current in the 40 to 50% areas of the close stroke. This is indicating that the valve guide lower pin is missing and the guide is "kicking out" at the bottom. When the valve is cycled closed, the guide is being wedged against the valve body. This has stopped valve travel by causing the torque switch to open. When the valve is then cycled open, this has pulled the guide up enough to pop it back onto its guide support. The valve has then been able to electrically cycle closed completely. If the two upper pins supporting the guide would fail, the guide could fall off the guide ledge and travel downstream in the reactor cooling (RC) system. There is also the potential that if the MOV was to fail, other valve internal components and Limitorque™ actuator components could also fail, requiring more involved maintenance.

The hot leg 1RC8001A, B, C, and D do not show severe indications of motor current increases during the closing stroke. This reinforces data from previous LSIV failures indicating that failure is more prone to cold leg LSIV's. The 1RC8002A failed to fully close on 2/9/93. The valve went approximately 80% closed and then stopped due to the torque switch opening. The valve was then cycled open and closed successfully. The failure was attributed to crud buildup on the valve guides, which is highly suspect for the RC system. The utility concluded that the valve guide popped back into position, because if the guide had actually fallen off its support ledge, the valve would not have traveled as far as the 80% closed position.

The 1RC8002B motor current strip chart from 9/15/94 shows an increase in current from about 6 amps to greater than 25 amps, at the 80% closed area. The motor current instantly drops back down to about 6 amps and maintains this value until the valve is fully close. This instantaneous drop indicates the valve guide either popped back into position, or separated into two pieces. The 1RC8002C & D do not show as severe changes in motor current, but both do show slight indications of motor current change in the 40 to 50% closed areas. This is indicating mechanical problems due to the motor current changes, although the current change is very slight.

A comparison of the motor amperage verifies that there appears to be problems with the cold leg LSIV's as Figure 3 indicates.

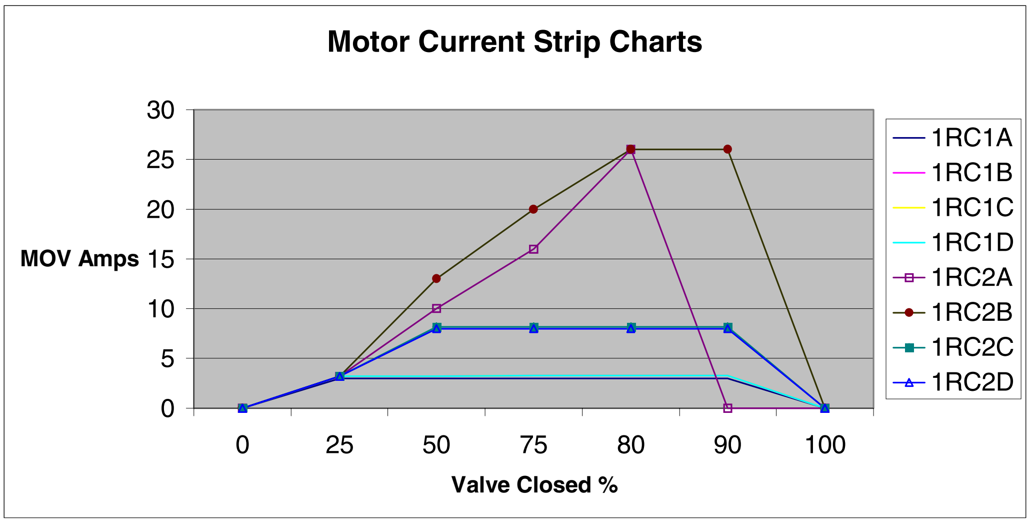

Figure 3 – Summary of MOV Motor Data

During B1RO9 (April 1999) the " A " valve did not close and required disassembly to determine the extent of the problems. Upon disassembly and inspection, significant damage to the valve guide and valve body was observed. It appeared that the guide became wrapped around the valve gate disk and as the gate was being lowered into the closed position became bound and was forced out of position. In order to repair the valve, the valve guides were replaced and welded into place. An inspection of the MOV motor trends shown that the "B" valve experienced motor current trends similar to that of the " A " valve, however, during B1RO9 the valve closed on the first attempt. The "C" valve did not close on the first try during B1RO9 but did close acceptably on the subsequent attempts. The loads applied to the "C" valve were less than applied to the " A" valve and acceptable closure of the valves indicates that the guides were in place and not significantly damaged. The "D" valve is considered to be in the best shape of the four valves. There are no indications of loose parts from any of the LSIV's indicating that the guides are intact.

REPAIR OPTIONS

The new guide design by the OEM is the preferred rather than installing the old designed guide because the failure mechanism of stress corrosion cracking of the retention pins is removed.

The capture mechanism of the new guide design is tabs (ears) on both sides of the top of the guide and a tab at the bottom of the guide. These tabs are machined (integral) with the guide and are not susceptible to stress corrosion cracking. These tabs prevent the bottom of the guide from kicking out toward the valve discs and the top two tabs prevent the guide from falling completely off their guide slots and dropping into the flow stream. Although this new guide design is difficult to implement, it assures positive retention of the guide for the design life of the valve. A second repair option utilized by the utility prior to the unit going critical consisted of placing small stopping clips in front of the guide rail as figure 4 illustrates. These clips would keep the guide rail in place even if the retaining pins failed. They were installed by either disassembling the valve or by crawling through the twenty-eight inch pipe to implement the repair. Both options utilized a manual welding process.

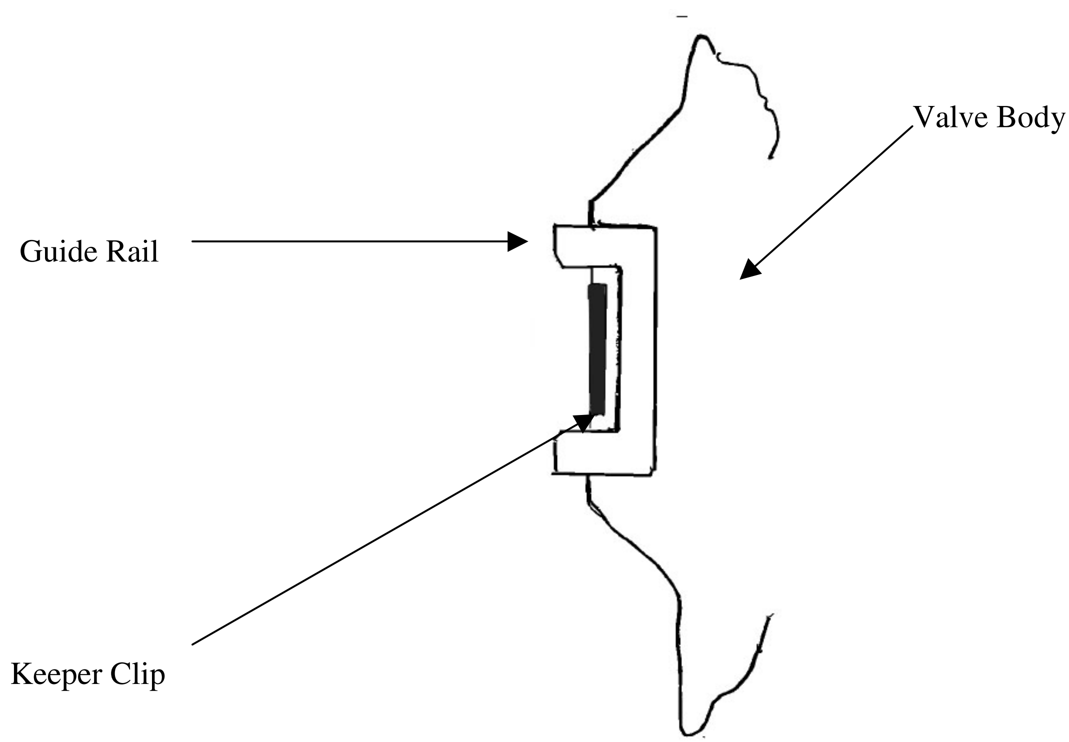

Figure 4 – Guide Rail with Keeper Clip in Place

In September 1998 a team was formed between the customer and the OEM to identify ways of repairing the LSIV's. The teams charter was; 1) To evaluate options to effectively (schedule, cost, dose, risk, etc.) provide reliable LSIV operation for Byron. The team was to review, develop and recommend repair options including; 1) Remotely welding a stop at the base of the LSIV guide where needed; 2) Conventional LSIV disassembly and replacement of valve guide where needed; 3) Drill through the LSIV body to secure the valve guides where needed; 4) Identify methods to remotely assess the valve guide condition and make repairs.

After several months of meetings, the team came up with the following recommendations to management; 1) Do nothing; 2) Repair through conventional disassembly; 3) Repair through eight inch by-pass line using the same modification performed to similar plants before they went critical.

Management reviewed the options and in February of 2000 issued a contract to repair three LSIV's using robotics and working through the eight inch by-pass line. The work was to be performed during the next outage scheduled for the fall of 2000. The contract was to supply two sets of equipment and personnel to repair the LSIV internals within thirty-six hours.

REPAIR METHODOLOGY

Since this was a first of a kind repair, most of the tooling had to be designed, manufactured, tested, mocked up and qualified. Table 1 describes the internal LSIV repair tooling:

General Area Camera and Lights (inserted in the valve to allow the operator to position the arm and effectors).	For operator use, FME concerns and video taping purposes
Control Center	To control all cameras inside the valve
Shield Plug for 8" Nozzle	To be installed whenever the manipulator arm was out of the valve
Nozzle Flange with Setup Fixture	The point where the tooling is attached
Loading Cradle	The staging cradle for the manipulator arm
Spreader Tool	Inserted into the valve to reposition the guide rails in their proper location
Spreader Delivery Tool	End effector to deliver the spreader tool
Manipulator Arm	Used to perform all internal mods
Pneumatic Control Box	Used to control the manipulator arm
Installation and Tack Weld Tool	Clip placement and weld end effector
Weld Buildup Tool	Weld end effector
Seal Weld Tool	Weld end effector
Drying and Cleaning Tool	End effector used to clean the welding area
Jack Delivery End Effector	End effector used to deliver jack tool
Jack Tool	Used to reposition the guide rail if needed
Gripper and Video Tool	Contingency tool used to pick any FME items
Vertical Weld Tool	Contingency tool used to repair any damaged guide rails

Table 1 - LSIV Guide Rail Repair Tooling

The conceptual design for the manipulator arm is illustrated in figure 5.

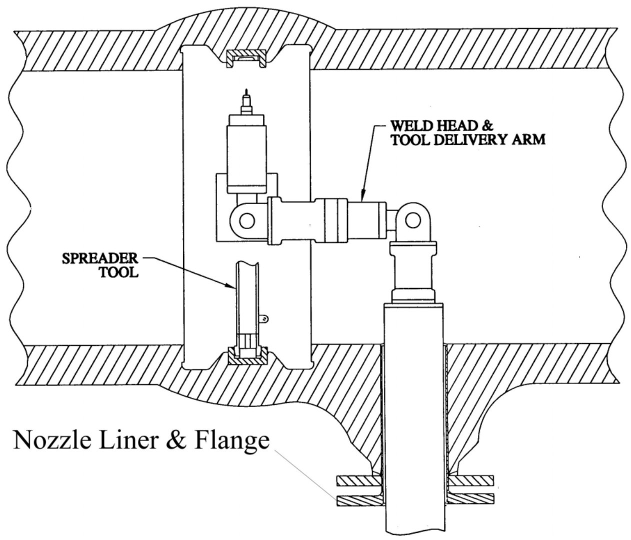

Figure 5 – Manipulator Arm in LSIV

In order to perform the guide rail modification, a number of steps were required. The work methodology is outlined below.

Remove a section of the 8 inch by-pass line to allow approximately 6 linear feet of clearance and 12" of radial clearance at the valve nozzle. Once the pipe spool piece is removed, insert the by-pass pipe nozzle pipe liner into the pipe to eliminate any nozzle damage on future repair operations.

Working through the nozzle liner, install the remote camera and inspect the general condition of the valve internals and current condition of the existing guide rails. This information is recorded using a conventional VCR for future reference.

Once the as found condition is documented, a temporary mounting / location flange is tack welded to the by-pass nozzle. Once the flange is in place a loading cradle will be attached to the mounting flange. This cradle will serve as the holding / alignment device for the manipulator arm.

The next phase would be to assemble and load the manipulator arm onto the cradle and attach the cleaning and drying end effector onto the arm. The arm is inserted into the valve through the nozzle liner and is positioned to the proper guide rail ledge. With the aid of two cameras the guide rail ledge is cleaned and dried using the end effector. Any radiological contamination concerns are addressed by a local collection hood attached to the end effector that is connected to a high-efficiency particulate air (HEPA) filter. Once the area is cleaned and passes inspection the end effector is removed for the next operation.

The next step is to deliver, align and install the guide rail-retaining blocks. The same manipulator arm used to deliver the cleaning end effector will deliver and position the retaining block. This end effector is configured to perform two functions, the first is to deliver the retaining clip to the guide block area and second is to perform the tack welding that secures the clip in place. Once the guide rail clip is tack welded into place the manipulator arm is withdrawn from the valve and the end effector is removed.

The final step of the repair is to perform a fillet weld on the interior of the guide rail clip. This is accomplished using another end effector designed to meet the weld geometry and access restrictions. On board video cameras provide visual verification of delivery position and weld quality.

Once the first side of the repair is complete, the manipulator arm is withdrawn and is configured to repair the opposite side. The repair is performed using the same steps as outlined above. After the internal valve work is complete, the arm is withdrawn. The internal area video camera inspects the valve internals for the final foreign material exclusion (FME) procedure and is documented. The final step would be to remove the internal camera, remove the nozzle liner and mounting flange and reinstall the by-pass line.

All of these operations were performed during the mock-up phase of the project. The utility provided an exact duplicate LSIV for training purposes which was quite useful and very handy.

SITE EFFORT

Once all of the tooling was complete, tested and qualified, the crew traveled to site to perform one week of just in-time-training. The training was set up to allow all personnel involved with the project to go through all the evolutions. The spare LSIV was set up in the training building and the all phases of the repair project were demonstrated. Figure 6 shows the training being performed.

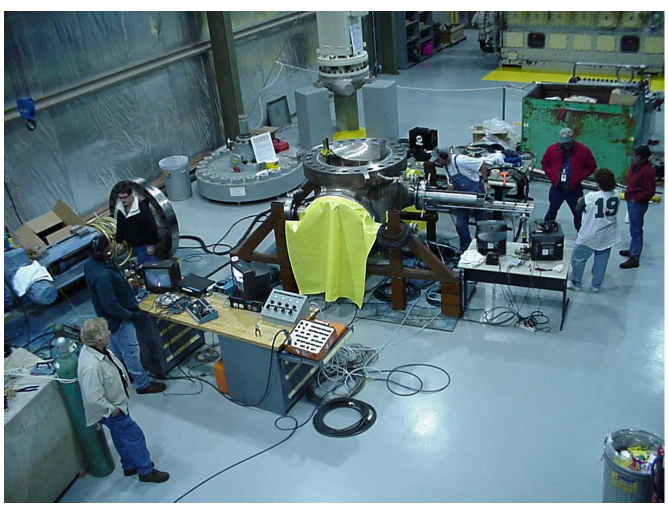

Figure 6 – Just in Time Training

Once the training was complete, the tooling was transported into containment and the project was performed.

The original schedule for the internal repairs to the LSIV's was thirty-six hours. After mocking up the project and timing the internal activities the schedule was further reduced to twenty-four hours. The actual on-site duration for the activities was twenty hours.

CONCLUSIONS

The objective of providing a solution that allows Byron to have reliable LSIV's at a reduced impact to outage schedule was achieved. As the data below indicates (figure 7), the time required to repair three LSIV's was over ten times less that the previous two repairs (repairing one LSIV).

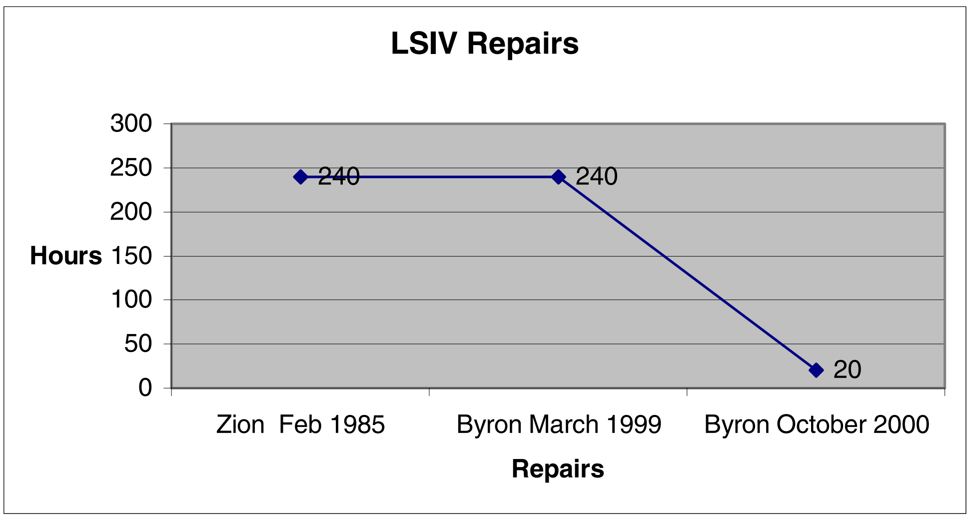

Figure 7 – Hours Required to Repair LSIV's

REFERENCES

1. Exelon internal report dated November 21, 1997, Loop Stoop Isolation Valve Repair SCRF.

CONTROL OF SUSPENDED SEDIMENT CONCENTRATION OF INTAKE CHANNEL AT YONGKWANG NUCLEAR POWER PLANT, KOREA

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Abstract

Two methods to reduce the suspended sediment concentration of the seawater coming into the cooling water system of Yongkwang Nuclear Power Station, Korea, were examined by using an existing numerical model system, KU-2DVFS-00. Main cause of the high concentration of suspended sediment at the site is believed to be strong wave attacks rather than tidal flows, judging from the analysis of previous data sets of hydodynamic forces and the suspended sediment concentrations. The model results show that the first scheme of dredging a trench at a part of the intake channel increases the suspended sediment concentration at the downstream area. The second scheme of constructing a vertical wall in the intake channel reduces the suspended sediment concentration at the downstream area. The second scheme is considered to be more effective to reduce the suspended sediment concentration of the seawater passing through the pumps.

Introduction

Yongkwang Nuclear Power Plant is situated on the west coast of Korea, see Figure 1. Six generators are planned at Yongkwang Nuclear Power Plant altogether, and four generators have been installed up to the present. Generators 1, 2 were completed in 1986, and generators 3, 4 were completed in 1992. The tidal range at the site is quite large (mean spring tidal range is 3.4 m), and the tidal currents are non-negligible, although the tidal currents are relatively weak near the coastline. According to measurements, when strong waves attack the site, the suspended sediment concentration around the plant including intake channel becomes very high. The movement of suspended sediment concentration at the site should be explained by the waves, wave-induced currents, as well as tidal currents.

The distance from the breakwater tips to the intake channel is about 700 m, and the distance from the intake channel entrance to the fourth intake point is about 1200 m. The average suspended sediment concentration at the intake entrance is about 70 mg/L, and that at the outfall is about 60 mg/L, see Huh (1980). Coarse sediment grains (median grain diameter, $d_{50} > 0.125$ mm) at the site are known to move as the bed load, while fine sediment grains move more likely as suspended load. The high suspended sediment concentration causes fast abrasion of several parts of the circulation system, especially the pump impellers. That results in frequent exchange of the parts, and abnormal operations of the whole plant. Since the generators 3, and 4 were constructed the depth-average current velocity of the fluid in the intake channel has increased, and the median diameter of the suspended sediment concentration has increased, too. Silt is included in the whole suspended sediment coming into the circulation system in addition to silty clay. The trend will continue when generators 5 and 6 are constructed in the near future.

Strong North-West waves often develop in winter season between December and March at the site. Advection and diffusion of the suspended sediment concentration due to the wave-induced current at the site was described by a horizontal two-dimensional numerical model system, KU-WIBATH-99, see Kim (1999). The model system successfully reproduced the high suspended sediment concentration at the intake channel for a storm period. A dredging scheme was proposed by Kim (1999) as a counter-plan to reduce the high suspended sediment concentration at the site. However, the counter-plan has not yet been examined by any laboratory or numerical model test which can resolve the distribution of fluid velocities and suspended sediment concentration in the vertical plane. Another possible counter-plan of constructing a barrier in the intake channel can be considered to reduce the suspended sediment intrusion into the cooling water circulation system. This additional structure may reduce the conveyance section, but it could generate a calm zone after the wall structure.

The effectiveness of those counter-plans can be examined by a numerical method. Existing flow

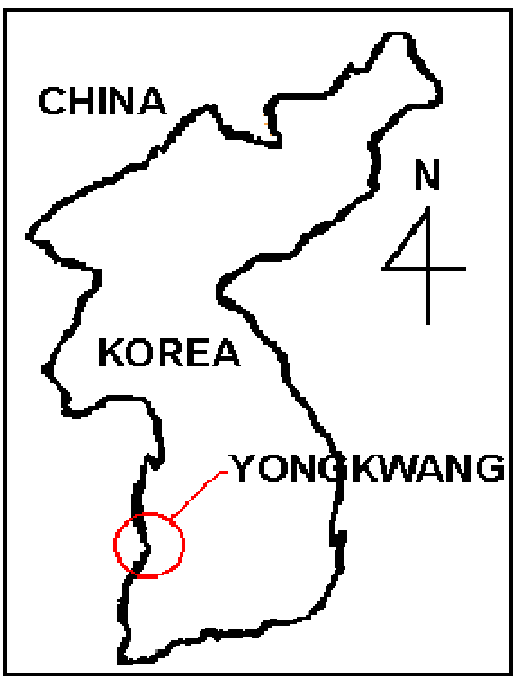

Figure 1a: Study area (large map).

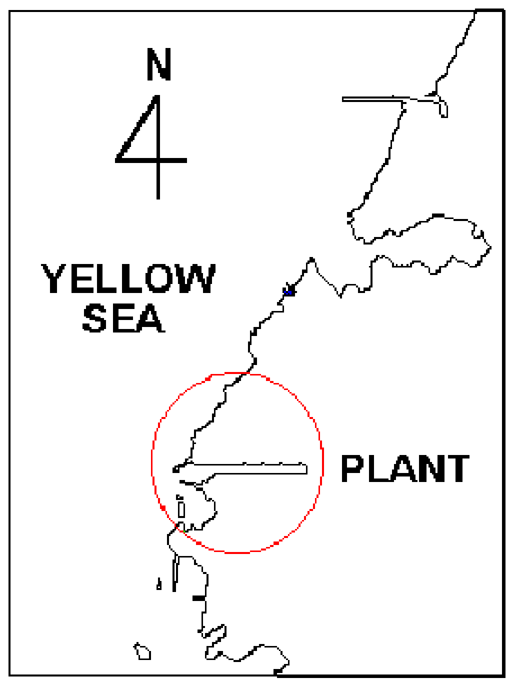

Figure 1b: Study area (small map).

and suspended sediment transport models in the vertical plane include Hansen et al. (1994), Van Rijn (1993), and Kim et al. (1994, 2000). The models were compared to laboratory measurements, see Longuet-Higgins (1981), Du Toit and Sleath (1982), Vongvisessomjai (1986), and Blondeaux and Vittori (1990). In order to compare the two possible counter-plans to reduce the suspended sediment concentration around and in the intake channel of Yongkwang Nuclear Power Plant, an existing numerical model system, KU-2DVFS-00, was selected. The system is composed of flow and suspended sediment transport parts, and solves in the two-dimensional vertical domain.

Numerical Model System

Kim et al. (2000) proposed a numerical model system, KU-2DVFS-00, composed of a flow model (KU-2DVF-94; Kim et al., 1994) and a suspended sediment transport model (KU-2DVS-00). The governing equations and numerical technique of splitting method of the sediment transport model was described by Kim (1993) in detail. The sediment model adopted Nielsen's (1992) pickup function with a modification coefficient. The model system was used to describe suspended sediment movement over ripples by Kim et al. (2000). Kim et al.'s (2000) model system was used for the present work as well.

The governing equations of the flow model are the turbulence-average continuity equation in the vertical plane (*x-z*) and the two Euler momentum equations in the *x*, and *z* directions, turbulence-averaged from the Navier-Stokes equations. These are:

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}+0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\partial (u')^2}{\partial x}+\frac{\partial u'v'}{\partial z}+\nu\nabla^2 u$$

(2)

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\partial u'w'}{\partial x}+\frac{\partial (w')^2}{\partial z}-g+\nu\nabla^2 w$$

where *u,w* are the turbulence-averaged horizontal, and vertical velocities in the *x, z* directions, respectively; *x, z* are horizontal and vertical Cartesian coordinates, respectively; *p* is the pressure; ρ is the density; *g* is the acceleration due to gravity; ν is the eddy viscosity; the prime means the turbulence portion of the velocity, and the over-bar means turbulence-averaged value.

The Reynolds stresses were described by a mixing length hypothesis which is a simple level of closure adopting the eddy viscosity concept. The mixing length was assumed as the distance from the fluid particle to the bed boundary.

At the top boundary line a zero vertical flux condition was applied. At the two side boundary lines uniform flow condition was applied. At the bed boundary a zero-flux condition in the normal direction to the solid bed, and a slip boundary condition in the tangential direction were used. The latter slip boundary condition may not be exact for the real flows, especially near the bed, but way be acceptable when the form drag forces are dominant compared to the skin friction like the present situation.

The driving force, pressure gradient in the horizontal direction was provided by trial and error to produce a given depth-average current velocity at the side boundary lines for the convenience of computation instead of a fixed flux condition.

The governing equation of the suspended sediment transport model is the two-dimensional vertical advection-diffusion equation with regard to the suspended sediment concentration. The equation expresses mass conservation of suspended sediment material. At the top boundary line a no flux condition was applied. At the bed boundary line an empirical pick-up function of Nielsen (1992), and a free settling condition of suspended sediment were applied.

Application of Model System

A part of the intake channel (length of 50 m) was selected as the computation domain for the model application, see Figure 2. The spatial increments in the x, z directions were chosen as 0.2 m, 0.2 m, respectively, for the model execution. The model grid points were 150x50 for the whole computation domain. The time increment for the model execution was chosen from the CFL condition. A possible additional restriction of the time increment is from the diffusion, but the restriction is not as serious as the advection in this case. The horizontal pressure gradient was adjusted to produce the depth-mean current velocity of about 0.5 m/s which is for the case when all six generators are operating in the near future.

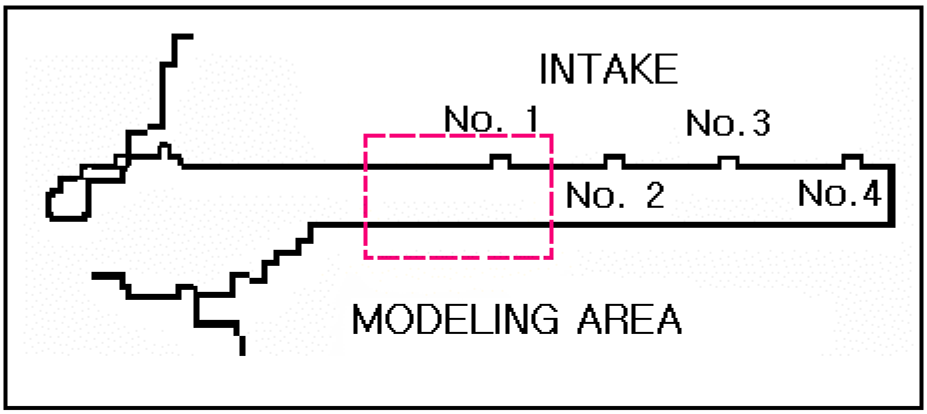

Figure 2: Modeling area.

The model system was applied to three cases. These are (a) the present status, (b) a counter-plan of dredging a trench, and (c) a counter-plan of constructing a vertical wall. There were some undulations on the present bed surface. The trench counter-plan of case (b) was about 10 m long, and 2.5 m deep. The vertical wall counter-plan of case (c) was 2 m wide, and 2 m high. At the top of the wall of case (c) a no deposition/erosion condition was applied.

Model Results

The computed flow vector field for the present status is shown in Figure 3. The flow is a simple straight flow except around the undulations. The computed flow vector field for the trench case is shown in Figure 4. A large circulation cell occurs just after the downward step, and a small cell after the upward step. The flow is much congested over the tip of the upward step. The computed flow vector field for the wall case is shown in Figure 5. The flow is congested over the top of the wall for the wall case.

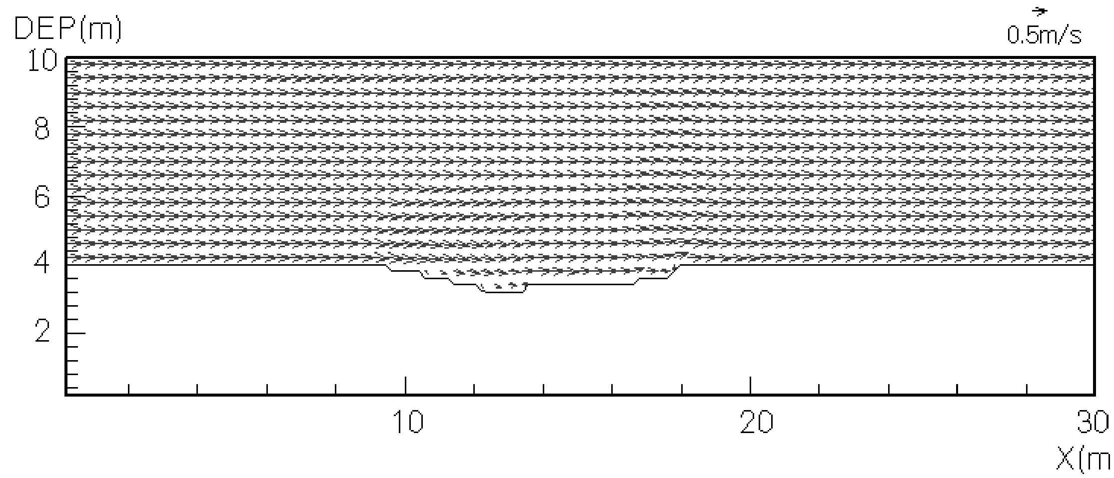

Figure 3: Calculated flow field for the present case.

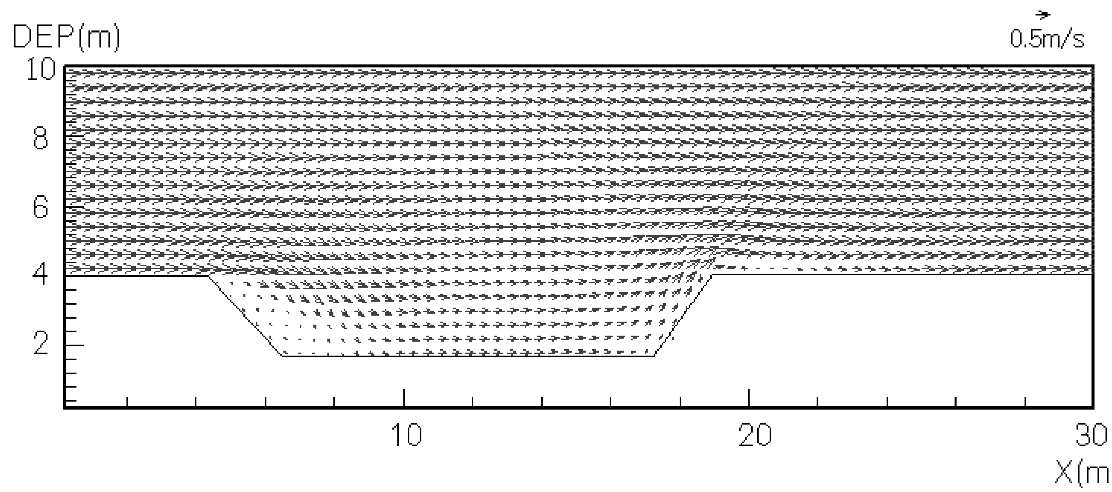

Figure 4: Calculated flow field for the trench case.

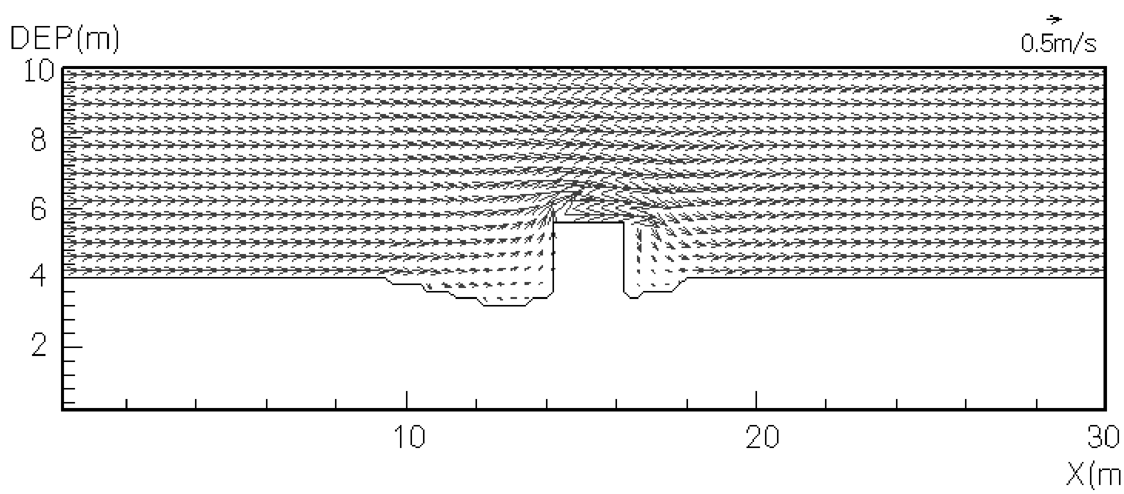

Figure 5: Calculated flow field for the wall case.

In order to compare the computed flow fields quantitatively two sections were chosen downstream of the computation domain, see Figure 6. Section A is the position just after the two counter-plans. Section B corresponds to the position of the Intake No. 1 for Generator No. 1. At Section A the horizontal velocity at an elevation of 5 m from zero level for the trench case increases by about 0.04 m/s compared to the present state case, see Figure 7. The computed horizontal velocity at the same elevation for the wall case decreases by about 0.2 m/s due to the hidden zone after the wall, see Figure 7. The flow velocities for the trench and the wall cases are recovered to the uniform flows at around Section B. The slight differences in the depth-mean current velocities at Section B between the three cases are originated from the differences in the drag forces of the three cases.

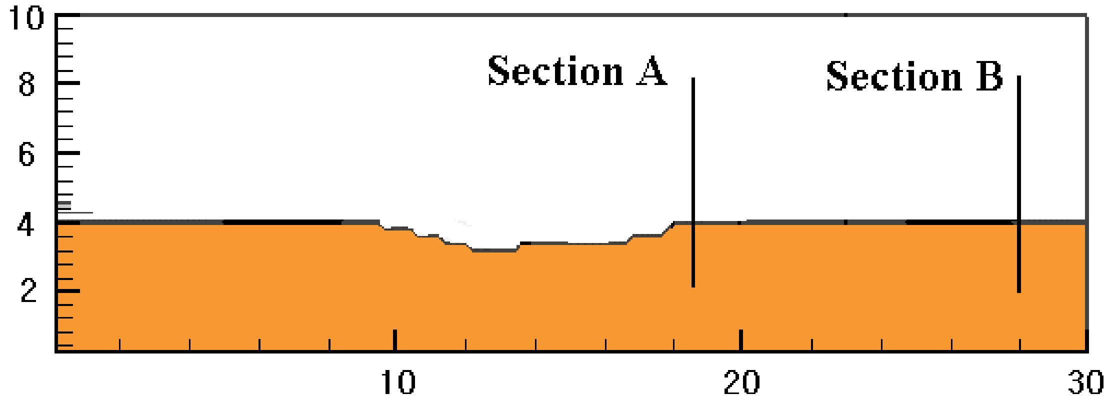

Figure 6: Positions for comparison.

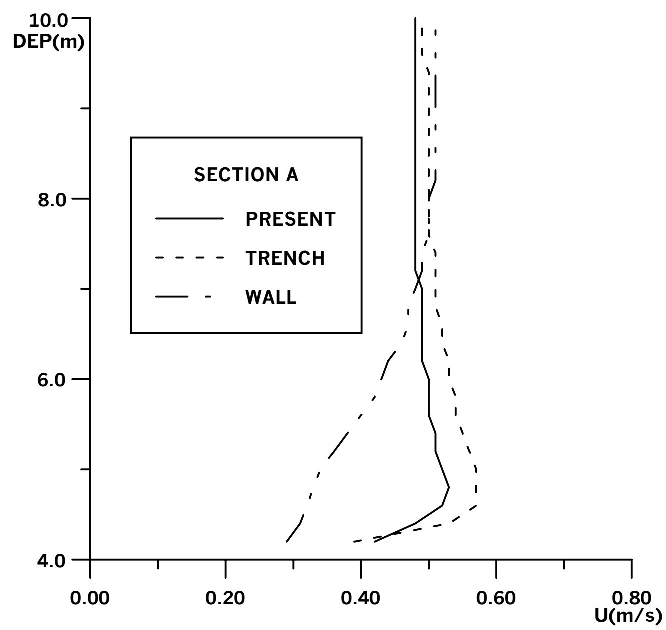

Figure 7: Comparison of calculated current profiles at Section A.

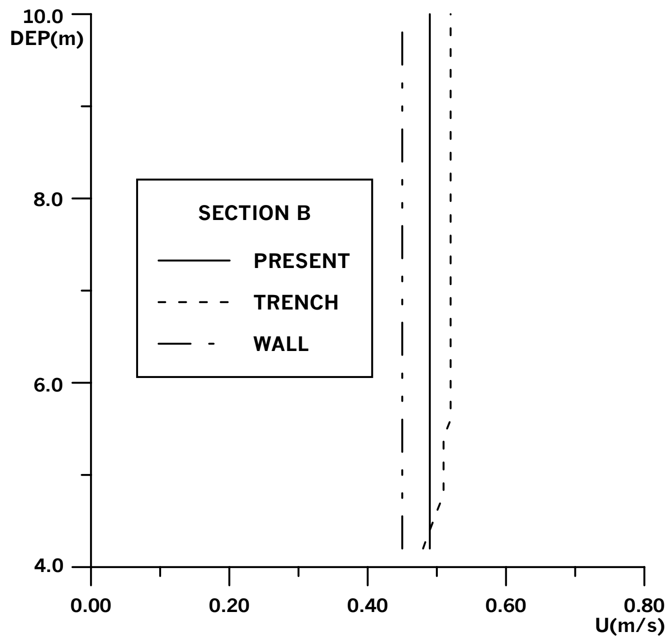

Figure 8: Comparison of calculated current profiles at Section B.

The computed suspended sediment concentration fields for the present status is shown in Figure 9. The computed suspended sediment concentration for the present status is higher around the undulations. The computed suspended sediment concentration fields for the trench case is shown in Figure 10. The computed suspended sediment concentration over the tip of the upward step for the trench case is very high due to the high erosion rate on the bed protruded surface. The computed suspended sediment concentration for the wall case is shown in Figure 11. In contrast to the trench case the computed suspended sediment concentration for the wall case is relatively low for the wall case in general. Over the top of the vertical wall the suspended sediment concentration does not increase much since the wall surface was treated as no deposition/erosion boundary, in other words, bypassing zone. This treatment may be reasonable if the wall structure is made of concrete or other hard material.

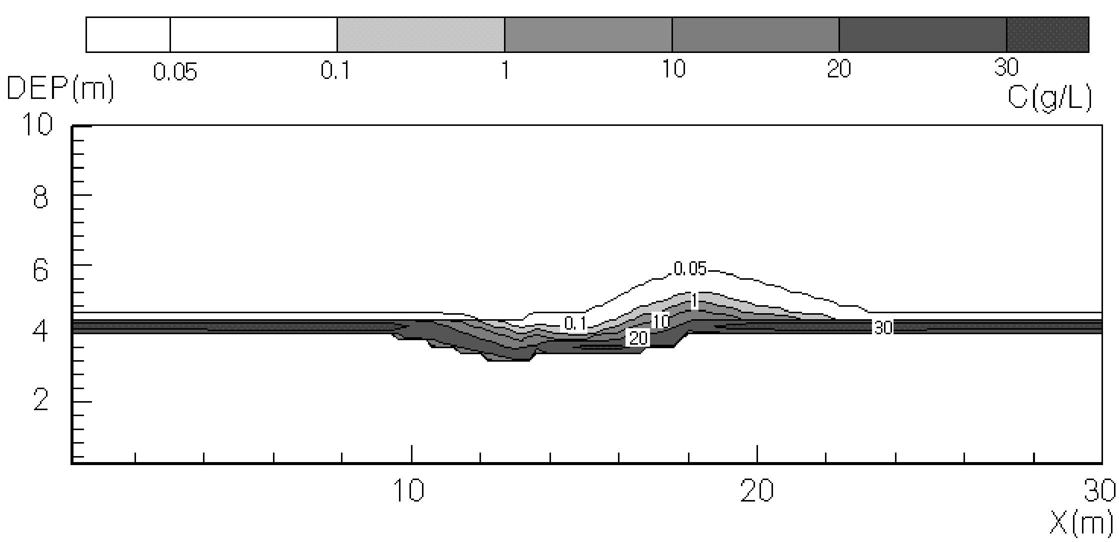

Figure 9: Calculated suspended sediment concentration field for the present case.

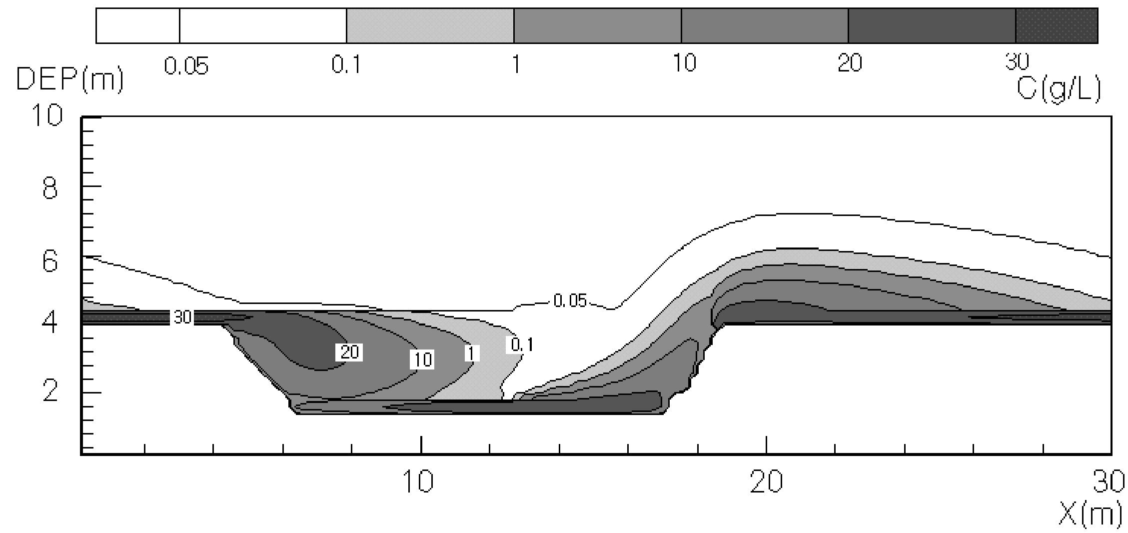

Figure 10: Calculated suspended sediment concentration for the trench case.

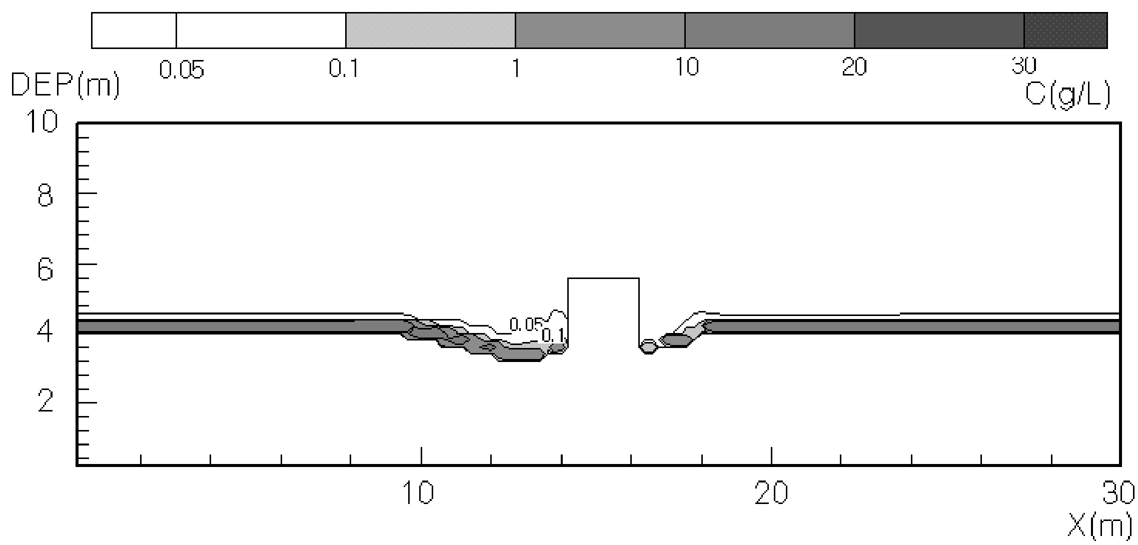

Figure 11: Calculated suspended sediment concentration for the wall case.

At Section A the computed near-bed suspended sediment concentrations for the three cases are of similar order of magnitude. However, the computed gradients of the suspended sediment concentration in the vertical direction differs from each other, see Figure 12. The decreasing gradient of the suspended sediment concentration for the trench case is small due to the high eddy viscosity around the upward step. At Section B where the effect of the structures on the flow is not significant, the computed suspended sediment concentrations decrease compared to those at Section A. However, the suspended sediment concentrations still differ from each other due to the advection of the suspended sediment from the upstream.

The suspended sediment concentration at an elevation of 5 m at Section B which corresponds the first intake position will increase by about 42 % for the trench counter-plan, and decrease by about 2.5 % for the wall counter-plan compared to the present state.

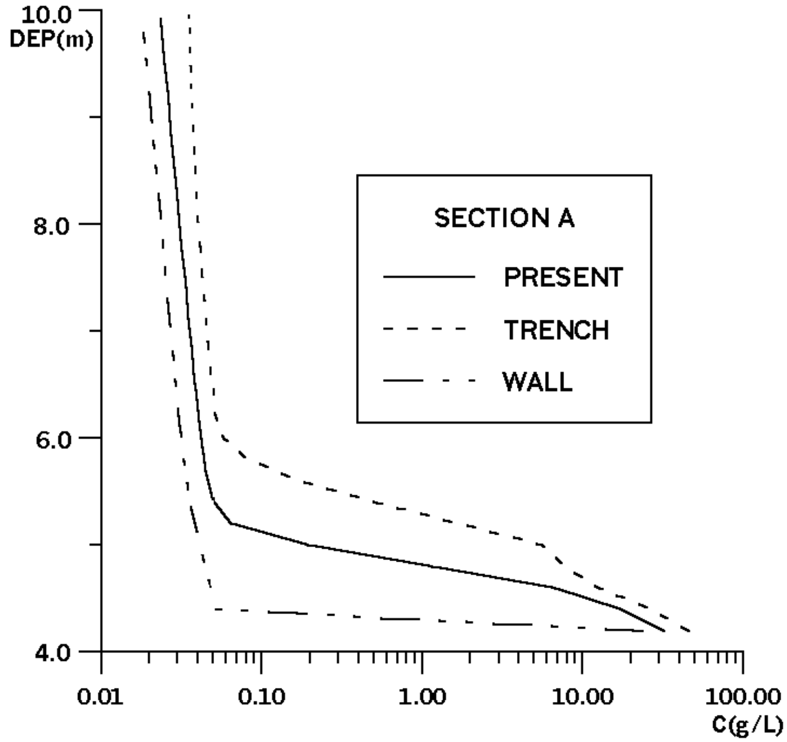

Figure 12: Comparison of suspended sediment concentration profiles at Section A.

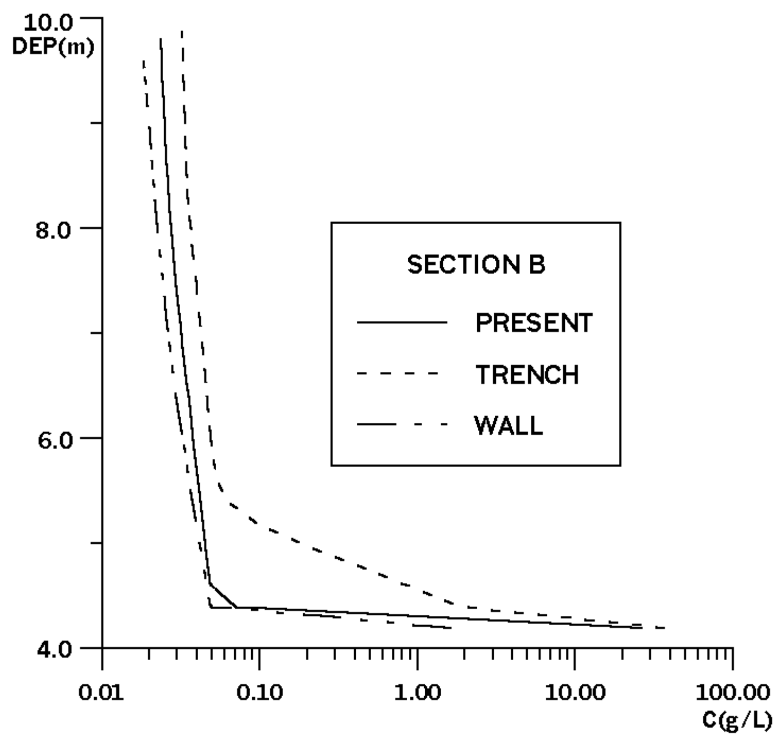

Figure 13: Comparison of suspended sediment concentration profiles at Section B.

Conculsions

Two counter-plans to reduce the suspended sediment concentration of the incoming sea-water at Yongkwang Nuclear Power Plant were examined by using an existing numerical model system. The model system results suggest that the counter-plan of constructing a vertical wall is more effective at the site than the counter-plan of dredging a trench in the intake channel.

The present model system was not verified to the present field measurements, although the model system was previously verified at several other field situations. The verification of the model system for this particular site will justify the model system results more soundly. The present tests of counter-plans were for two particular geometries only. If an optimum counter-plan for the Power Plant is needed, additional tests should be followed.

Acknowledgement

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TROUBLESHOOTING A CENTRIFUGAL CHARGING PUMP - A ROTORDYNAMICS ANALYSIS APPROACH

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ABSTRACT

Multi-stage centrifugal pumps, used in power generation applications, are complex components with very tight functional clearances. Changes in internal geometry due to wear, corrosion, and mechanical defects can adversely affect the performance and reliability of the component.

Research has shown that the radial gap between the impeller vane exit, and the diffuser or volute inlet, contributes to high dynamic loads causing many pump failures. Failures have also been associated with pump bearings, mechanical seals, stuffing box packing, breakdown bushings, the annular seal wearing rings, the axial thrust balancing device, and coupling gear teeth.

It is shown in this work that radial clearances in pump internals control not only pump performance but also the vibration response and shaft deflection. Excessive shaft deflection is generally the root cause for the failure of shafts, mechanical seals, balancing device and journal bearings.

Due to complexities in pump design and the unavailability of robust sensors, practically no instrumentation is used to monitor pump internals directly. Traditionally, these pumps are equipped with a very limited number of sensors for condition monitoring. No dedicated vibration sensors are typically used. A thermometer located at the oil exit on the outboard bearing accomplishes monitoring of the thrust bearing temperature. A balance line differential pressure has been recently used successfully as an indicator for pump internal wear.

This paper shows that rotordynamics modeling can provide sensor placement effectiveness to enhance sensor development and virtual sensing for use with advanced monitoring technologies based on intelligent diagnostic algorithms.

1 INTRODUCTION

High-energy centrifugal charging pumps are complex components, composed of many rotating elements having very tight functional clearances. Changes in internal geometry due to wear, erosion, corrosion or mechanical defects can adversely affect the performance of the component. Research has shown that the radial gap between the impeller vane exit, and the diffuser or volute inlet, contributes to high dynamic loads causing many pump failures.

Due to complexities in multi-stage centrifugal charging pump (CCP) design and the unavailability of robust sensors, practically no sensors are used to monitor pump internals directly. A balance line differential pressure has been used recently as an indicator for pump internal wear. Modeling techniques such as rotordynamics and computational fluid dynamics can provide sensor placement effectiveness to enhance sensor development and virtual sensing for use with advanced monitoring technologies based on intelligent diagnostic algorithms.

Recent developments in vibration pattern recognition, expert systems, and Bayesian Belief networks **[1,2]** are being investigated for applicability in machinery health monitoring in addition to the traditional trending methods. The key to reliable diagnostics is being able to correlate the degradation mechanisms with the symptoms. Data can be trended, analyzed, and compared to information from design, testing, analytical model calculations, and predictions.

Continued developments in information technology and advanced electronics have made it possible not only to provide early-failure warnings, but also to assist in diagnostics through extensive analysis of dynamic systems and monitored signals. Using this technology, the urgency of a sensed or inferred component condition can then be determined, necessary actions can be taken over an appropriate time frame, and condition-based rather than time-based maintenance can be scheduled.

1.1 Description

Traditionally, centrifugal charging pumps are equipped with a very limited number of sensors for condition monitoring. No dedicated vibration sensors are typically used. A thermometer located at the oil exit on the outboard bearing monitors temperatures at the thrust bearing. In general, OEM provided pump instrumentation is very limited. The centrifugal charging pump is an 11-stage horizontal, centerline mounted, diffuser type, barrel pump as shown in ***Figure 1***. The pump is used to fulfill three primary functions:

- Provide makeup water flow to the reactor coolant system during normal operation
- Provide seal injection flow to the reactor coolant pumps
- Deliver high-head safety injection flow to the reactor coolant system during emergency conditions; such as a loss of cooling accident (LOCA)

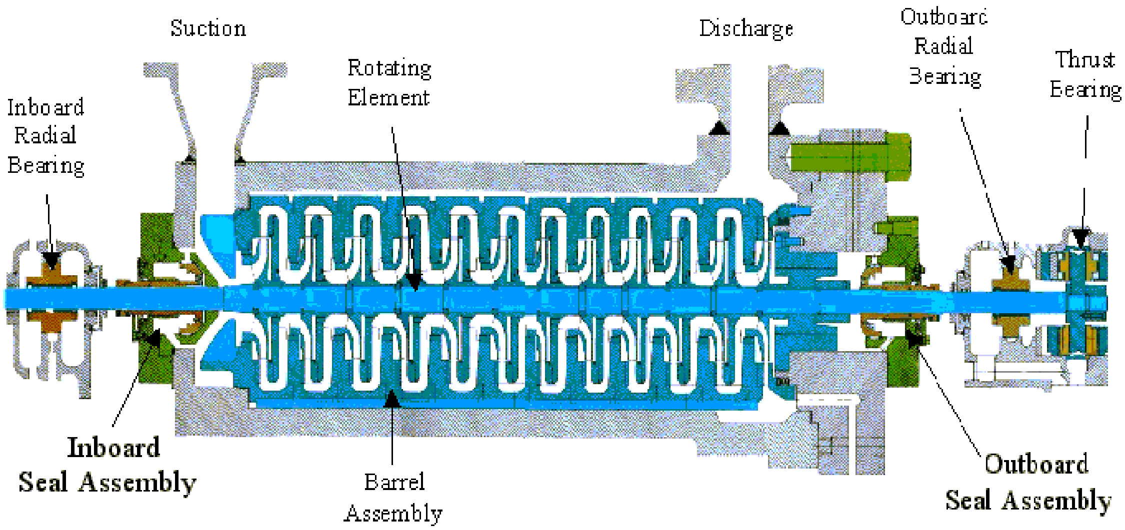


Figure 1: Pump Sectional View

During normal charging service, this pump operates continuously at 5800 feet of developed head and 150-gpm nominal flow rate at the operating speed of 4850 rpm. The motor meets the equipment qualification requirements for a nuclear safety "active" component.

The pump impellers are arranged in series with a single suction. A stationary multi-vane diffuser is fitted around the periphery of each impeller. The casing is equipped with a removable head at the discharge end. The seal housings are removable. The pump shaft is supported at each end by self-aligning split sleeve bearings and a six-pad Kingsbury thrust bearing on the discharge end of the pump carries the axial load. The bearings are pressure lubricated by an integral gear type oil pump, driven by a worm gear on the main shaft. A motor driven gear type auxiliary oil pump is furnished for starting and for emergency service.

Inboard and outboard radial bearings provide vertical and horizontal support for the rotating assembly. The thrust bearing is located near the outboard radial bearing and provides axial support for loads generated by the pump. The gear type lube oil pump takes oil from the oil reservoir and supplies it to the thrust bearing and each radial bearing. The total flow to the bearings is about seven gallons per minute.

The motor is a 600 horsepower squirrel cage induction type. The air circulation system is totally enclosed, cooled by component cooling. The motor rotor is supported at each end by split sleeve bearings. A gear drive transfers torque from the motor to the pump. The drive increases the speed of the motor (1780-rpm) to the proper speed for the pump (4850-rpm).

The rotor includes the pump shaft, bearings, seals, coupling, impellers, balance drum, and channel rings. The impeller may have many vanes, depending on the pump design. The coupling interconnects the pump and driver rotating assemblies and transfers rotational motive power to the pump. The rotating pump shaft spins the impellers at the required angular velocity and provides a bearing surface (journal) to support the rotating assembly.

Pump shaft diameters are usually larger than would be required to simply transmit the driving torque to account for the maximum permissible shaft deflection. The wet shaft bearing assembly is designed to operate below the rotors first critical speed. Shafts are usually protected from erosion, corrosion, and wear by renewable sleeves at the stuffing boxes, leakage joints, and in the waterways.

Babbitted sleeve bearings are reliable under adverse chemical or moisture conditions. Commercial Babbitt material is made of antimony, copper, tin, and lead. The base metal can be either tin or lead counting for 65-85% of the total material weight. A Babbitt sleeve can sustain a maximum allowable temperature of 150^{o}F. When load conditions and operating temperatures are high, bronze sleeves are used. Bronze sleeves are harder than Babbitt sleeves and can sustain temperatures up to 300^{o}F. In this case, the bearing lubrication must be adequate to avoid damage of the shaft journal. Thrust bearings consist of a collar mounted on the shaft revolving between one or more sets of Babbitted-faced and pivoted pads.

A flow control valve maintains an oil supply pressure to the bearings. Oil is pressure fed to the bearings then is passed through the heat exchanger where it is split. Some oil is delivered to the inboard radial bearing and the remainder delivered to the outboard thrust/radial bearing set, which operates in an oil bath. Oil is returned from the inboard bearing by gravity feed to the reservoir and is returned from the thrust bearing via a tangential drain.

The lubricant is required to support loads transmitted by the rotor in radial and axial directions. The radial bearings can support load because the shaft assumes a slightly eccentric position in the bearing. A positive pressure is developed when the shaft pulls supply oil, via rotation, into the wedge shaped cavity between it and the bearing (hydrodynamic effect). This integrated pressure represents the load required to balance the rotor weight and any other radial loads. The thrust bearing, using the same general principles generates axial loads in each of the tilting pads to counter axial loads developed in each of the pump stages. The lubricant must support the developed loads and maintain adequate clearances between the rotating and stationary components.

The radial, fluid-film bearings play a significant role in controlling rotor vibration characteristics, particularly in thin shaft, multistage pumps at dry operating conditions. The fluid-film provides stiffness and damping characteristics that can affect the location and response of rotor critical speeds. Analytical models of the rotor/bearing dynamic system have been exercised to determine the effect of variations in radial bearing film stiffness and damping caused by the water in the lubrication.

Although mechanical seals do not contribute a lot to the rotordynamics of the pump, they have been a major contributor in pump failures. The purpose of the mechanical seal is to control the leakage of process fluid to the atmosphere along the rotating shaft and in-leakage of contaminants. Mechanical seals operate under dynamic, not static conditions. As the pump rotates, the pressure in the impeller housing becomes higher than the pressure in the stuffing boxes. This pressure difference tends to force the liquid toward the low-pressure side. All mechanical seals are designed for controlled leakage; however, the leakage is not typically visible because it evaporates due to heat generation as fluid passes between the seal faces.

Wear rings with tight clearances are used in pumps primarily to prevent leakage between regions of different pressure within the pump. Differences are in the design type, materials used, lengths, radii, pressure drops across the ring, and velocity conditions of the fluid at the entrance.

There are three types of wear rings in a pump (***Figure 2***). The impeller neck wear-ring is located at the suction region of the impeller and is used to reduce leakage between the impeller shroud and casing into the impeller inlet. The impeller hub (interstage seal) wear-ring in multistage pumps is located at the back of the impeller and reduces leakage from an impeller inlet along the shaft to the backside of the preceding impeller. Finally, there is the balance drum or pressure-reducing device used primarily to balance the thrust created by the action of the impellers.

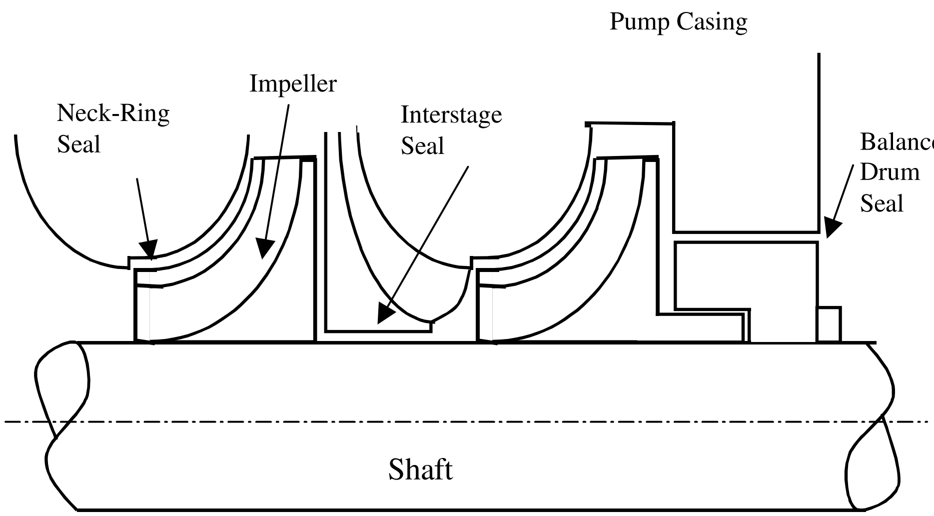


Figure 2: Multi-Stage Centrifugal Pump Wear Rings

Typically pumps have had very limited sensor coverage. The best-instrumented pumps have been retrofitted and have two displacement probes at each radial bearing, an accelerometer at the bearing casing, a thrust position indicator, and an oil temperature indicator.

Vibration measurements are usually made in a plane that is perpendicular to the rotating shaft. This measurement direction is effective for measuring most standard machine conditions such as rotor unbalance; hydraulically induced motion, and potentially critical speeds determination.

1.2 Centrifugal Charging Pump Failures

Many failures have occurred in these pumps, with an approximate failure distribution as given by ***Figure 3***.

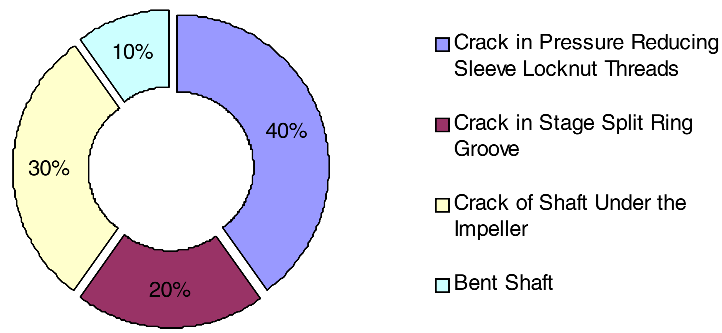


Figure 3: Centrifugal Charging Pump Shaft Failures

Figure 3 shows that about 40% of the shaft failures occurred in the area behind the hydraulic thrust balance piston and about 30% are shaft cracks under the impeller. Regardless of the location of failure, all failures have been attributed to low-stress high-cycle fatigue.

Some pumps have ingested large bubbles of hydrogen gas, some have operated with suction or discharge (or both) valves closed, some operated at large flows and others at low flows. Independent of any design deficiencies, several charging pump failures have been attributed to specific system operational conditions. The presence of free gas in the flow may subject the rotor to very high axial and radial loads. It is also the cause for the loss of the Lomakin effect provided by the wear rings resulting in metal-to-metal contact leading to severe degradation and eventually to pump failure.

CCP failures at Duke Power's Catawba Nuclear Station (CNS) and other nuclear power plants have been investigated. Results have pointed to shaft material, design sensitivity to concentrated bending moments, gas entrainment, insufficient venting and misalignment as leading cause candidates.

Failure of one of the elements at CNS showed that significant fretting developed on the shaft under the ninth stage impeller. A crack initiated in that location had propagated sufficiently through the shaft to result in a loss of required rotating geometry and clearance for pump performance as shown in ***Figure 4*** **[3]**.

Failures have been associated with pump bearings, mechanical seals, stuffing box packing, breakdown bushings, the annular seal wearing rings, the axial thrust balancing device, and coupling gear teeth. Radial clearances in pump internals controls not only pump performance but also largely the vibration response and shaft deflection. Excessive shaft deflection is generally the root cause for the failure of mechanical seals, balancing device and journal bearings.

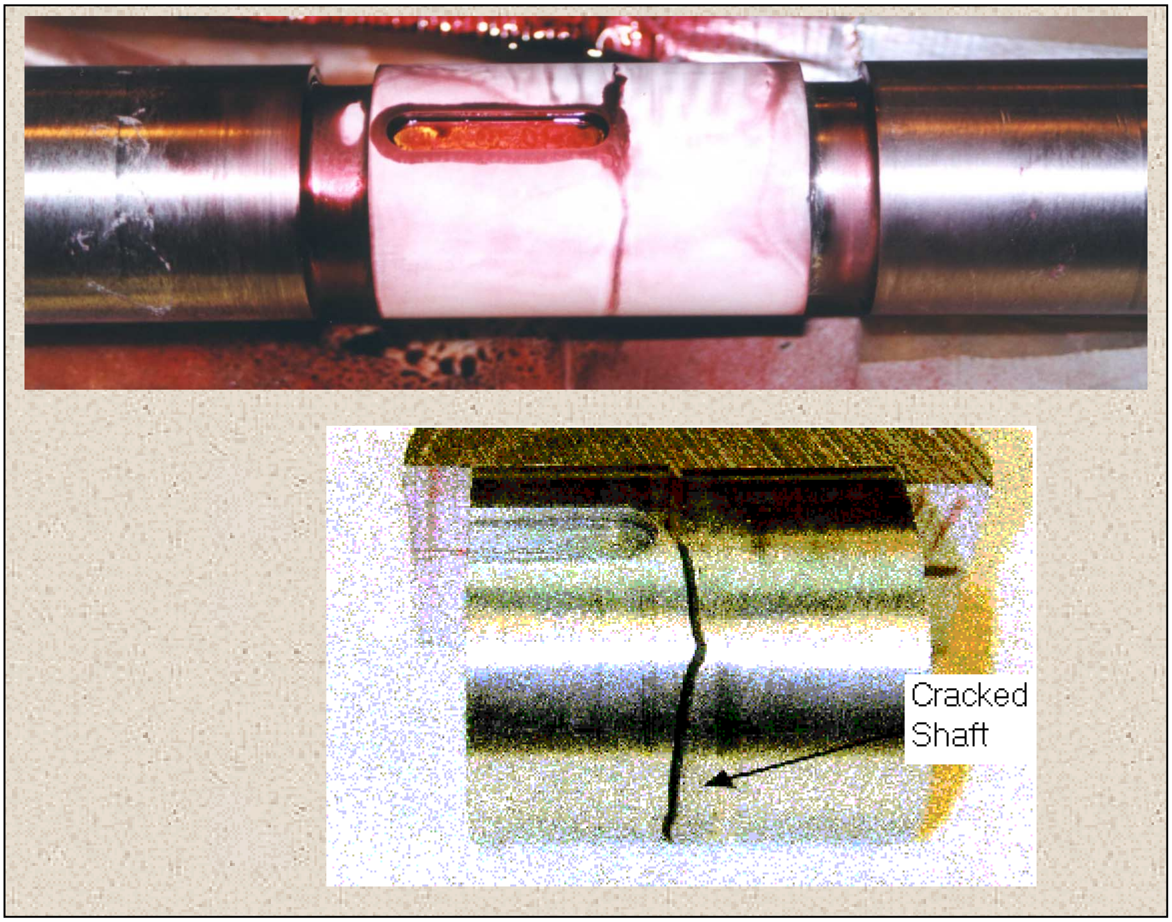


Figure 4: Failed Shaft at Catawba Nuclear Station]

Recent CCP failures have been investigated by the owners and the OEM. The process may include an in-situ as well as thorough shop investigation. Typical disassembly results include:

- Loose inter-stage cover fits
- Loose split rings
- Loose impeller fits
- Misalignment of impeller/diffuser hydraulic channels
- Fretting under the impellers
- Wear ring clearance openings
- Improper hydraulic geometry
- Sharp radii
- Inadequacy of impeller hardness

1.3 Industry Analysis Efforts

The results of several in-depth failure analyses performed by the OEM and individual owners concluded that the combination of shear, torsional, axial and bending stresses are not severe enough to cause classic low-stress high-cycle fatigue failures. Further, the failures seem to occur randomly.

Although sophisticated stress analysis consistently indicates the shafts to be reliable, the OEM has introduced various changes to solve the problem. Over the years, the shaft design evolved resulting in two sizes of radii at impeller retaining split ring grooves and two sizes of thread root radii. There are three pressure-reducing sleeve retaining nut designs and two heat treatments for the shaft material. Recently, the OEM has proposed designs replacing the shaft's pressure-reducing sleeve retaining threads with a split ring and a third shaft material.

Design modifications were aimed at improving mechanical strength and fatigue endurance limit by decreasing stress levels and distributing loads evenly on various sections of shaft. Custom shaft materials have been specified to enhance shaft thread loading and provide higher strengths. Another design improvement is the use of spherical contact threads that would decrease the stress riser at this weak location.

Design modifications investigated include:

- Changes in heat treatment techniques
- Shaft material changes
- Manufacturing methods

2 ROTORDYNAMICS ANALYSIS

Various dynamic analysis techniques can be used to solve the centrifugal charging pump/support system problems identified to-date. These include finite-elements structural analysis, experimental modal analysis, computational fluid dynamics, and rotordynamics. These techniques are powerful analytical and experimental tools used throughout the industry to model complex dynamic systems for design of new machinery, as well as for diagnostics and evaluation of retrofits on existing machinery.

2.1 Rotor/Bearing Dynamic Modeling Overview

Rotordynamics analysis deals primarily with the calculation of characteristics that affect the vibration response of a machine to loading, system changes, and different operating conditions. Dynamic characteristics considered are:

- Undamped natural frequencies and mode shapes
- Assessment of forced response to unbalance excitation
- Stability analysis

The undamped natural frequency calculation provides a fast check on the potential for critical speeds within the operating speed range of the machine. No forces are included in the equations so the solution only takes into account system properties and resulting vibrations are said to be free or natural vibrations. A forced response analysis considers generally different distributions of unbalance excitations to assess the system sensitivity to such loading. Stability analysis is concerned with the solution of the damped eigenvalue problem to determine the potential for self-excited vibrations.

2.1.1 Critical Speed Analysis

Critical speeds are rotational speeds that correspond to rotor natural frequencies. Depending on the amount of damping available in a system, potentially severe vibration can occur is the machine is operated at or near a critical speed. Associated with natural frequency calculations, as a function of support stiffness is a mode shape indicating the relative deflection of the rotor stations if the rotor is excited at that natural frequency.

Critical speeds are evaluated with a program that calculates rotor/casing natural frequencies as function of support stiffness. Output consists of plot of rotor/casing mode shapes and associated natural frequencies. A critical speed map is also produced indicating the location of the rotor undamped critical speeds.

In multi-stage centrifugal pumps, shaft resonant critical speeds are rarely observed because of the tremendous amount of positive damping provided by the wear rings.

2.1.2 Synchronous Response Analysis

In a forced response analysis, damping is included and the vibration response of the rotor is predicted as a function of stipulated excitation usually an imbalance. This analysis allows prediction of shaft/casing vibration under various wear rings, shaft, imbalance, and rotor speed conditions.

2.2 Analyzed Cases and Scenarios

The purpose of the rotordynamics analysis is to produce a computational model capable of replicating the dynamic behavior of the rotor/bearing system under various loading and design scenarios. Furthermore, the model provides the analyst information impossible to get by today's sensor technology.

In addition to the calculation of the standard rotordynamic properties, various failure scenarios have been considered, most of which have been analyzed in this work. Some of the results are presented in this report.

- Thrust bearing analysis: Consideration of various axial thrust loads and analysis of various film and pad parameters such as film thickness, temperature distribution, pressure distribution, and mechanical deformation
- Analysis of the radial bearings and evaluation of the dynamic coefficients used in the rotordynamics model
- Evaluation of the dynamic coefficients associated with the pump internal clearances such as the impeller neck-ring annular seals, the impeller hub rings, and the pressure reducing sleeve
- Stipulation of a rotor unbalance distribution to serve as a base-reference case
- Evaluation of the dynamic characteristics such as critical speeds, mode shapes and steady-state unbalance response of a normal operating system
- Evaluation of the dynamic characteristics of a dry pump (no seals effect)
- Evaluation of the dynamic characteristics of the system as a function of wear-ring clearance openings

- Evaluation of the effect of bearing drop due to dissimilar stiffness in the horizontal and vertical directions
- Assessment of the unbalance response sensitivity of the system to balance shots at various accessible locations
- Evaluation of the dynamic characteristics of a cracked shaft **[4]**
- Evaluation of the effect of impeller/shaft shrink fit looseness on the dynamic characteristics of the system
- Effect of oil system failure such as oil cooler failures (oil temperature variation) on the dynamic characteristics
- Effect of lube system failure (less oil) on the dynamic characteristics
- Analysis of various shaft re-design scenarios (geometry and material variations)

2.3 Analyses Results

2.3.1 Thrust Bearing Analysis

A tilting pad type thrust bearing consists of a number of load carrying thrust pads retained within a base ring and incorporating a means of load equalization among the thrust pads. The bearing is designed to transmit rotor axial thrust from a collar to the machine casing. The collar may be either integral to the shaft or a separate piece. The thrust load is carried by and transmitted through a hydrodynamic oil film at the interface of rotating collar and stationary thrust pads. A double acting thrust bearing carries the load in either direction and provides control of rotor position. A common design is a thrust bearing with six pads but may be any number. Load equalization is achieved with various pivot or rocker designs including spherical and equalizing links.

In calculating the thrust load, only steady state, axial forces are considered. Fluctuating axial forces primarily due to pressure pulsation are not included. The steady axial force is calculated by multiplying the projected balance sleeve area by the pump's differential pressure. It is assumed that each stage contributes an equal share of the axial thrust.

The difference between the thrust towards the drive end of the shaft created by the impellers and the thrust towards the non-drive end of the shaft created by the balance sleeve is carried by the thrust bearing. While the actual thrust is unknown, it should not exceed the thrust capacity of the bearings. The centrifugal charging pump considered is fitted with a 7" JHJ Kingsbury type 6-pad bearing with a rated load capacity of about 9,300 lbf.

Thrust load calculations were based on published empirical data available from Kingsbury. Based on the data, the load carrying capability of the thrust bearing was determined to be approximately 9300 pounds. Thrust loads used in the calculations varied from 3600 pounds (light load) to 18000 pounds (heavy load = twice load capacity of the bearing).

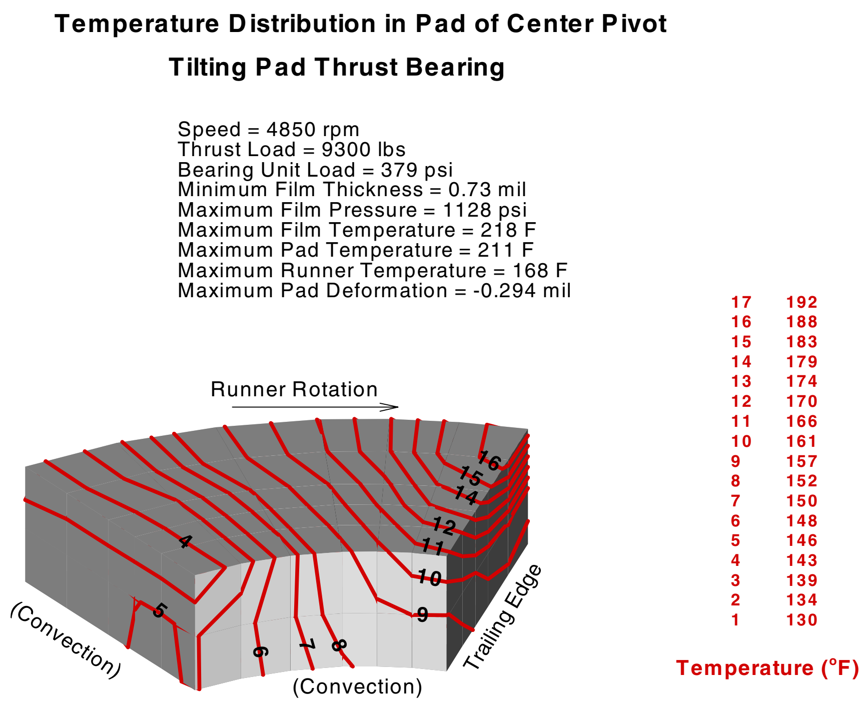


Figure 5: Temperature Distribution in Thrust Bearing Pad

The isotherms shown in ***Figures 5*** and ***6*** demonstrate the changing temperature patterns, which develop under various operating conditions.

Based on the maximum specified oil inlet temperature of 128 degrees F, the expected maximum oil temperature at nominal thrust is approximately198 Degrees F. The maximum thrust shoe temperature would be 191 Degrees F. The outlet temperature would be 135 degrees F (ambient temperature is assumed 140 degree F). A summary of the performance analysis of the thrust bearing is presented in ***Figure 7***.

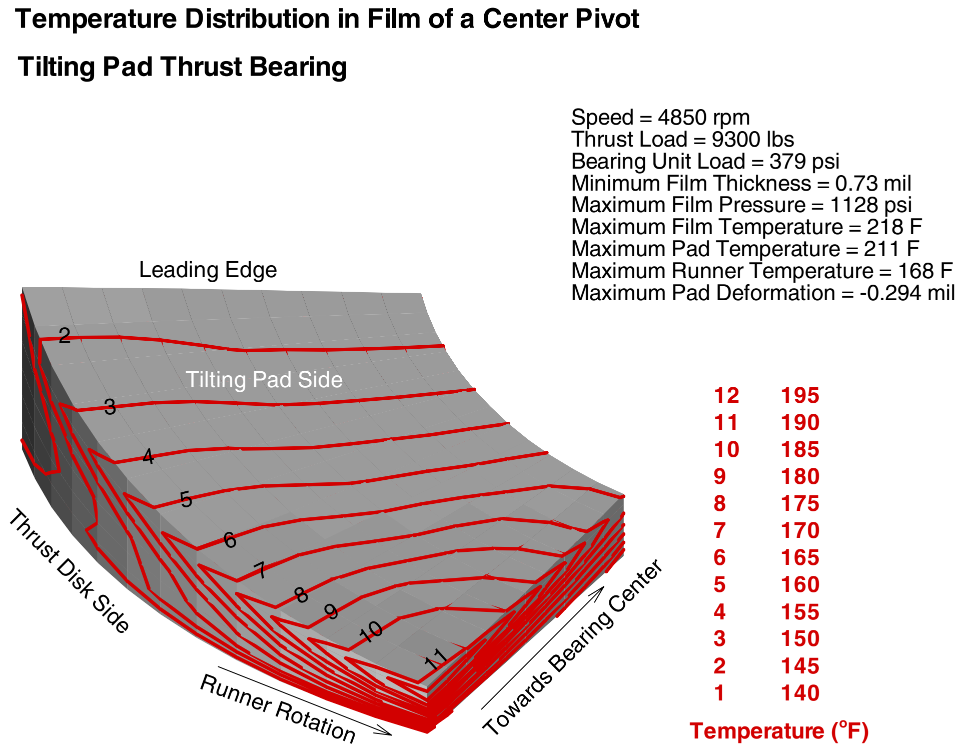


Figure 6: Temperature Distribution in Film

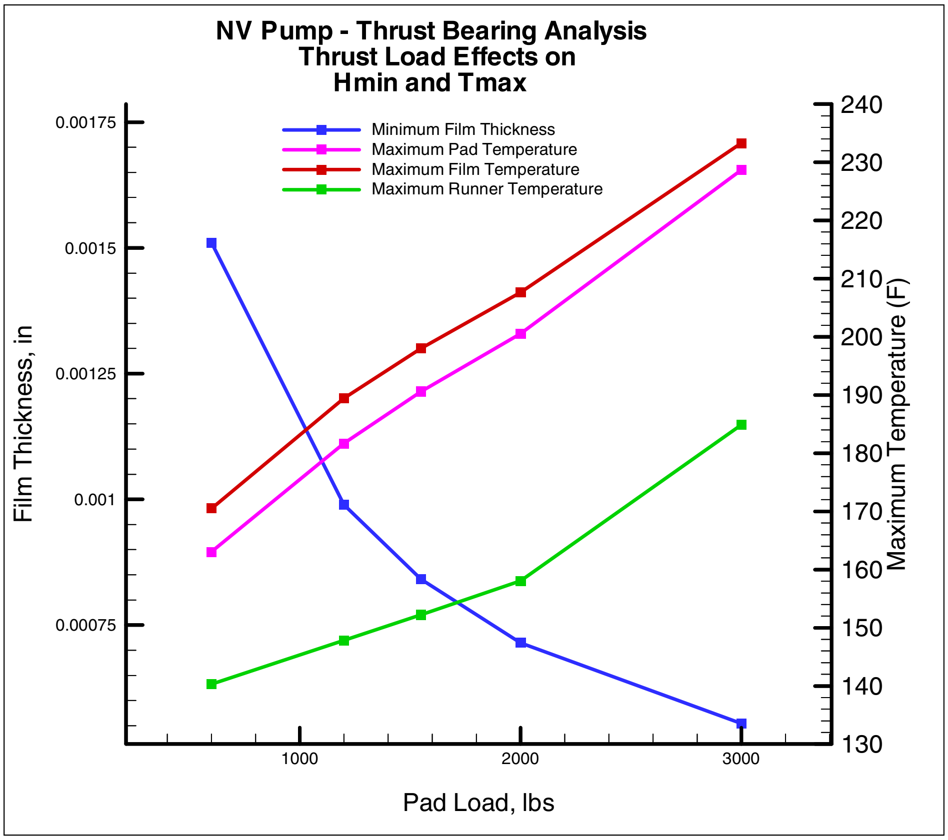


Figure 7: Performance Analysis of the Thrust Bearing

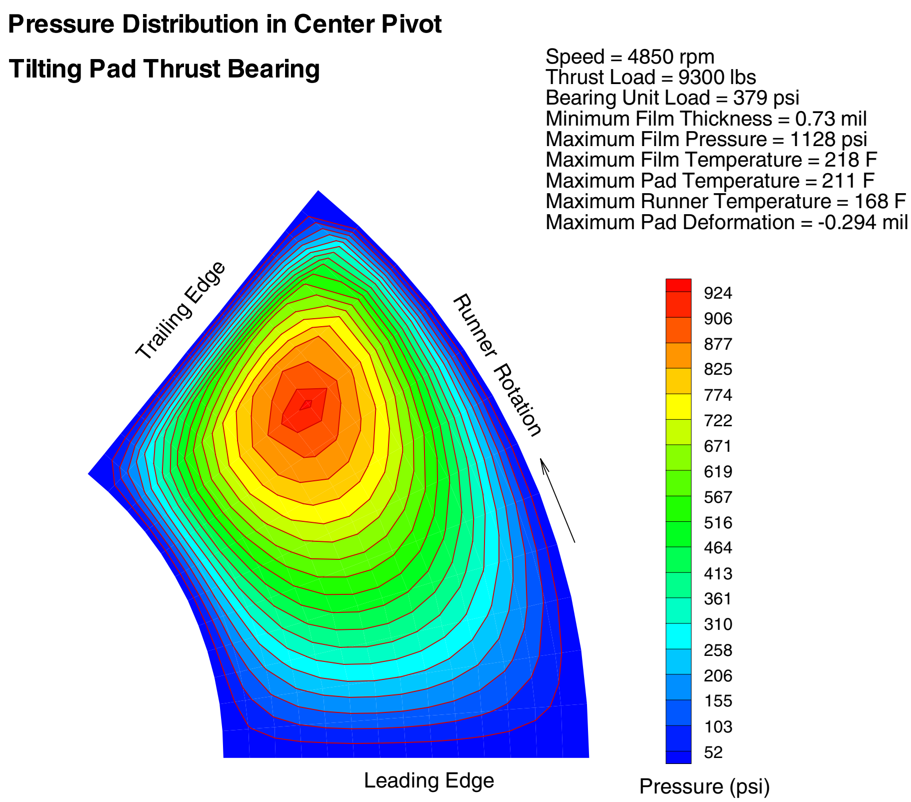


Figure 8: Pressure Distribution in Thrust Bearing Pad

In Summary, thrust bearing analysis results indicates that:

- Temperature distribution in both film and pad varies with thrust load
- Temperature sensor at oil exit is not a good indicator of highest temperature in pad
- Film thickness is very small at higher thrust loads requires lube oil monitoring for solid particles to guard against wear and metal-to-metal contact
- Pad and runner mechanical and thermal displacements are small (less than ½ a mil)

This pump has typically two sensors to monitor the axial position of the rotor and the oil outlet temperature. As seen by the previous figures, the changing pattern of the pad temperature cannot be monitored using one sensor. Depending on the operating conditions the pad temperature can be much higher than that indicated by a thermometer located at the oil exit.

The axial rotor position indicator cannot provide monitoring of the minimum film thickness, which depends also on the pad, runner, and rotor deformations as well as the hydrodynamic characteristics of the fluid film.

Thrust bearings may fail due to high operating temperatures resulting from high thrust loads or lubricant system failure. A sensor mounted at the 75/75 position (highest-pressure location see ***Figure 8***) can report the shoe temperature at that location, but cannot indicate the temperature pattern over the entire region as shown by the isotherms in ***Figure 5***.

Temperature sensors have been used extensively in shop testing at OEM locations for research and development purposes. Conventional monitoring of thrust bearings utilizes only one sensor indicating the oil temperature at the exit of the bearing. This may be an acceptable practice for a machine with normal operating conditions not requiring an overloading of the bearing. For varying operating conditions, producing higher than normal loads, more sensors may be required to monitor the performance of the bearing for reliable operation of the system. For instance, a temperature sensor placed in the pad at the maximum pad temperature, would provide an effective way to monitor the bearing overheating failure mode.

2.3.2 Radial Bearings Analysis

Bearings used in high-energy pumps vary with the pump design from simple cylindrical journal bearings to pivoted pad bearings. The centrifugal charging pump shaft is supported at each end by self-aligning split sleeve bearings and a six-pad Kingsbury thrust bearing on the discharge end of the pump carries the axial load. The bearings are pressure lubricated by an integral gear type oil pump driven by a worm gear on the main shaft. A motor driven gear type auxiliary oil pump is furnished for starting and for emergency service.

Inboard and outboard radial bearings provide vertical and horizontal support for the rotating assembly. The gear type lube oil pump takes oil from the oil reservoir and supplies it to the thrust bearing and each radial bearing. The total flow to the bearings is about seven gallons per minute.

Fluid-film bearing design is more completely understood than is seal design. Bearings and associated lubrication theory have been researched more thoroughly due to their importance to rotating machinery. A tremendous amount of literature has been developed in both analytical and experimental research of bearing characterization **[5,6,7]**. Software for modeling and analysis of all types of bearings is readily available from multiple vendors.

The standard fluid mechanics equations of continuity and momentum are applied to the lubricating film to produce a partial differential equation in terms of pressure. The energy equation is also considered to take into effect temperature variations. Once the pressure is calculated, integration yields the dynamic force acting on the shaft. Bearing dynamic coefficients are then evaluated and included in the rotordynamics analysis code.

2.3.3 Wear Rings Dynamics Analysis

Wear rings with tight clearances are used in pumps primarily to prevent leakage between regions of different pressure within the pump. Differences are in the design type, materials used, lengths, radii, pressure drops across the ring, and velocity conditions of the fluid at the entrance.

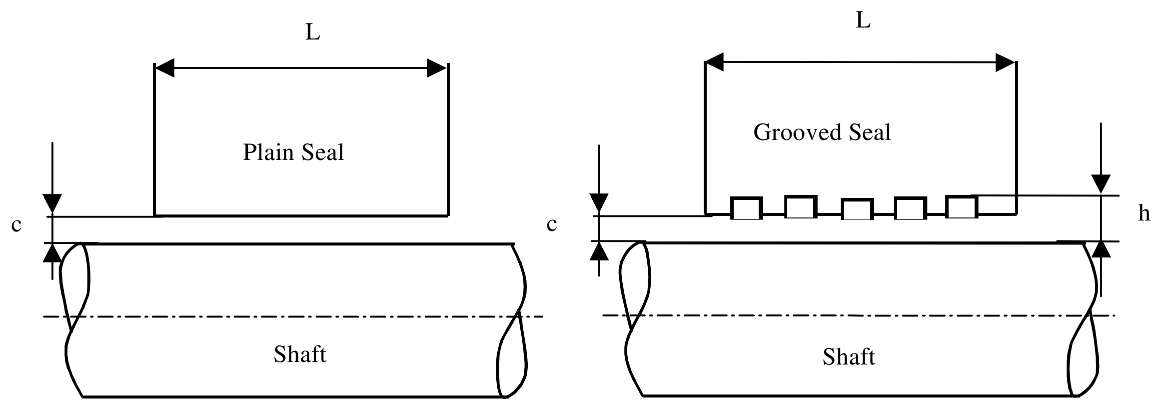


Figure 9: Various Seals Types

The static sag line of the CCP shaft presents a maximum deflection of about 10 mils below the alignment centerline when sitting in the bearings. The wear ring clearance is typically 15 mils leaving a few mils between the rotating and stationary components. If all the stationary components were aligned with respect to the axis of the bearings the wear rings would rub when the rotor is turned by hand and possibly seize during start up. When the pump starts up the Lomakin effect tries to center the rotating wear parts within their mating bores **[8,9].** Calculation of the dynamic characteristics of the wear rings necessitates the determination of differential pressure (DP) between the inlet and outlet of the wear ring **[10].**

There are no direct sensors used to monitor the wear ring clearances. Recently, the balance line pressure has been used as an indicator for monitoring pump internals wear. The axial rotor position is one of the parameters always monitored but has not been used efficiently to predict the loading on the thrust bearing.

Results of wear rings dynamic characterization are summarized below:

- Dynamic coefficients of wear rings were calculated for both plain and grooved designs for various speeds and differential pressures across wear rings
- Grooved wear ring design provides a better vibration control through higher direct stiffness and damping coefficients
- Wear ring radial clearance has a big effect on rotordynamics for both plain and grooved wear ring designs
- Wear ring eccentricity does not significantly affect the dynamic coefficients
- Wear rings clearances have a big effect on pump dynamic characteristics
- Pressure reducing sleeve has a much higher dynamic coefficients than impeller wear rings (about a 5:1 ratio)

Monitoring of pump internal clearances should be achieved using locally mounted sensors. Technological limitations may prevent application nowadays, but this is certainly an area to be researched and sensors developed.

2.3.3 Rotor/Bearing Dynamics Analysis

The rotor geometry is derived from the 600-hp model installed at Catawba Nuclear Station. The power applied ranges from 450 hp at low flow to 650 hp at large flows. For simplification, it is assumed that the input torque is equally distributed and each stage contributes one eleventh of the total power. There are alternating torsional stresses due to hydraulic pulsation, electric motor torsional excitation, gear mesh, and torsional critical frequencies that are not considered in this analysis.

In order to perform the rotordynamic analysis of the rotor-bearing system a mathematical model must be produced taking into account the geometry of the various components that make the machine as shown in ***Figure 10***. It is also necessary to supply the characteristics of the interconnections such as pedestals, bearings, and wear rings. For simplicity, the shaft is modeled as a discrete system of uniform beams of various sections. The actual shaft diameter under the fit area is increased to account for the additional stiffness provided by the tight fit.

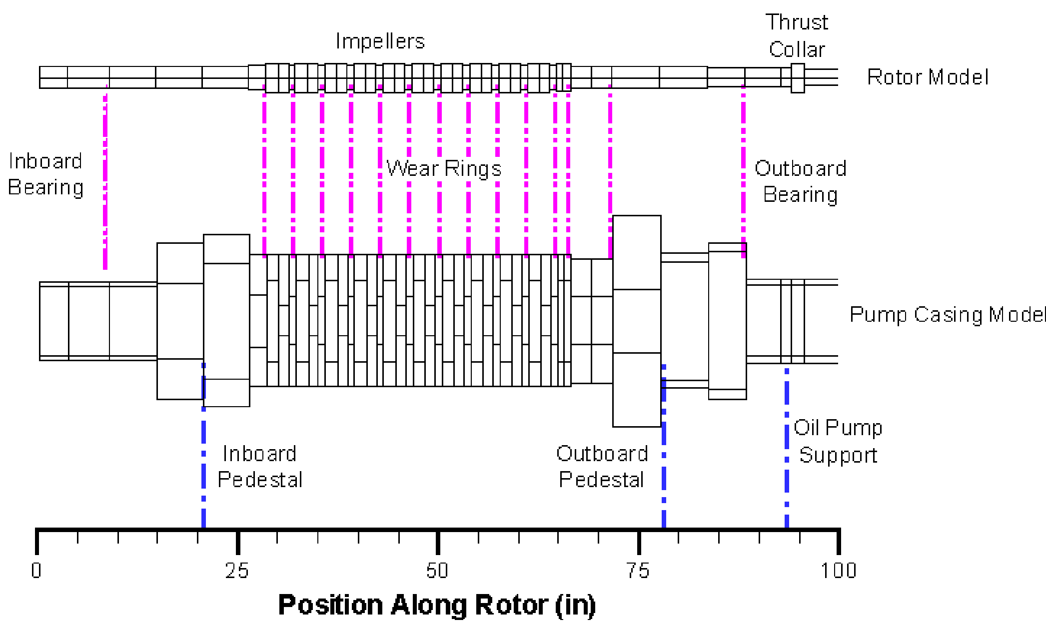


Figure 10: Centrifugal Charging Pump Rotordynamics Model

Evaluation of the dynamic characteristics of the bearings and wear rings depend on the operating parameters of the pump system and oil lube sub-system. When the pump is running it usually operates at extreme conditions of low or high flows. At low flow, the differential pressure and axial thrust are maximized and the input power is minimized.

Industry failure investigations have pointed to shaft material properties; design sensitivity to concentrated bending moments, bearing drop, gas entrainment, insufficient venting, and misalignment as leading cause candidates.

Hydrodynamic radial bearings provide stiffness and damping to the system under the action of the rotating shaft. During startup and shutdown operations, a lack of pressure may induce wear and bearing heat. For this reason, an auxiliary oil pump supplies pressurized oil to the bearings.

Under abnormal operating conditions, there exist a potential for shaft-bearing contact and wear to occur accompanied by high vibrations.

Wear of the wear rings is a major contributor to the failure of this pump. Clearance openings have an adverse effect on the dynamic characteristics of the rotor bearing system. Analysis shows that pump operation becomes supercritical as wear ring clearances open. The second mode of vibration falls short of operating speed thereby inducing stress cycling on the shaft element. With loss of damping and stiffness provided by good wear rings, the pump may fail due to high vibrations resulting from a very small imbalance distributed along the shaft. Flexible, multistage rotors such as the one analyzed here, requires strong centering forces produced by the fluid properties in the wear rings.

Rotordynamics modeling and analyses produced the following results:

- Critical Speeds and Mode Shapes: The second vibration mode gets closer to running speed as wear clearances open and relative vibration amplitudes become higher at pump internals inducing wear
- Forced Response: Vibration may reach very high levels as wear ring clearances open inducing wear and cycling stresses leading to failure
- Balance Sensitivity Analysis: Outboard seal ring may be used as a balance plane to reduce outboard bearing shaft and casing vibration
- Bearing Drop (effect of half circular channel): Half circular channel design provides reduced vertical stiffness at both ends of pump and does affect pump dynamic characteristics
- Effect of Wear Ring Clearance Openings: Wear ring clearances affect tremendously the dynamic characteristics of the pump
- Shaft Crack Investigation: It has been documented **[4]** that cracked shaft has little or no effect on rotor lateral response/critical speeds with normal running wear ring clearances
- Loose Fit: Simulation of loose fit as a distributed unbalance produces a non negligible response when accompanied by wear ring clearance opening
- Shaft material properties and shaft geometry variations have not been investigated in this work

Sensors such as displacement probes and accelerometers are readily available to monitor vibration levels at the bearings. They can be effective monitoring means as long as pump wear ring clearances are normal. They are however, totally ineffective to monitor pump internal degradation.

Monitoring of pump internal clearances can best be achieved using locally mounted sensors and performance testing data.

Bearings have been universally used as standard for sensor placement. They provide effective location for condition monitoring of rigid rotors but are not necessary the best placement for sensors on flexible rotors.

Vibration modes as depicted by ***Figure 11*** provide a straightforward answer to the effective location of sensors when available. The best location to monitor for the high amplitude associated with the first mode is at the center of the shaft (*stage 7*). Sensors located at stages 1 and 11 best achieve monitoring of the second vibration mode. Sensors located at stages 3 and 9 best achieve monitoring of the second vibration mode. For example, a synchronous response analysis provides information for any station included in the model. For instance, shaft relative position to the wear rings can be obtained and compared to available radial clearance.

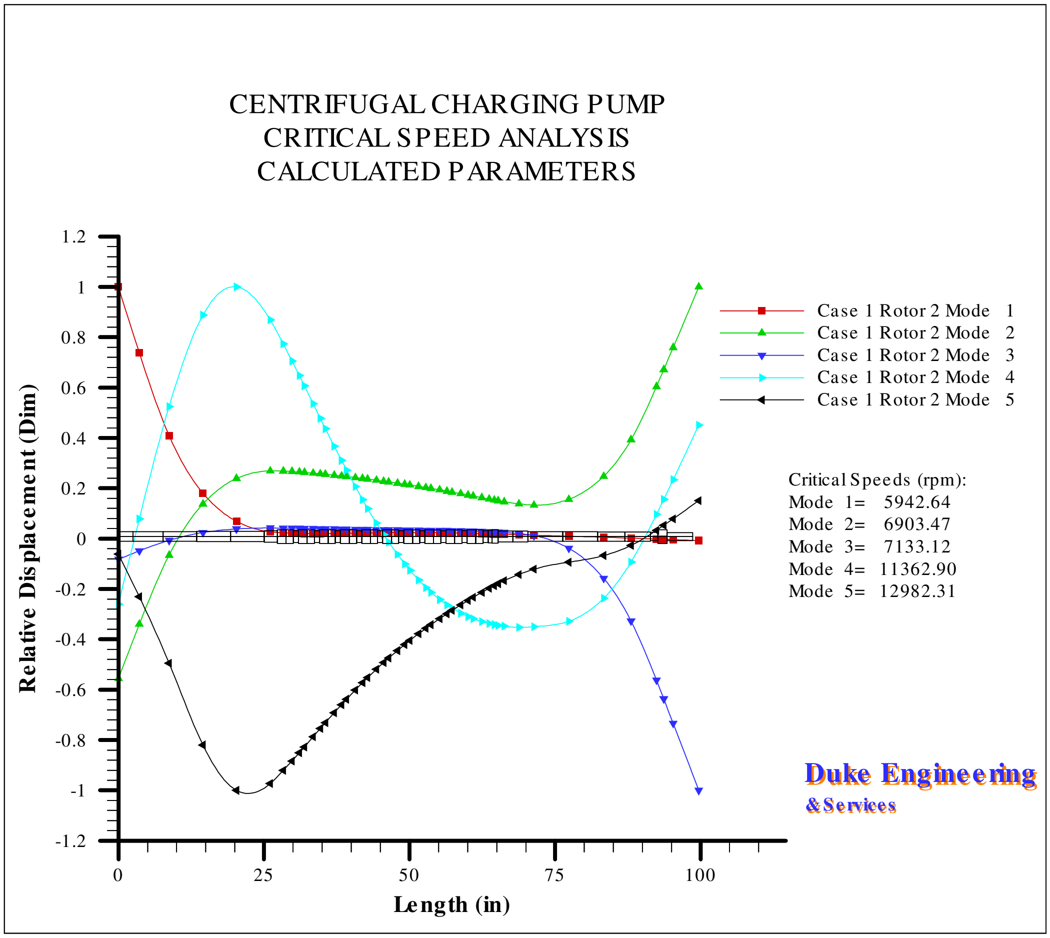


Figure 11: Centrifugal Charging Pump Critical Speeds Analysis (Normal)

Current technological limitations may prevent application of local sensors to monitor for wear ring clearance opening in high-energy pumps. The alternative would be to use computational models to predict the dynamic behavior and provide the necessary information for diagnostics. Additionally, rotordynamics calculations provide virtual sensors thus allowing checking on readings by actual sensors for vibration and other monitored parameters.

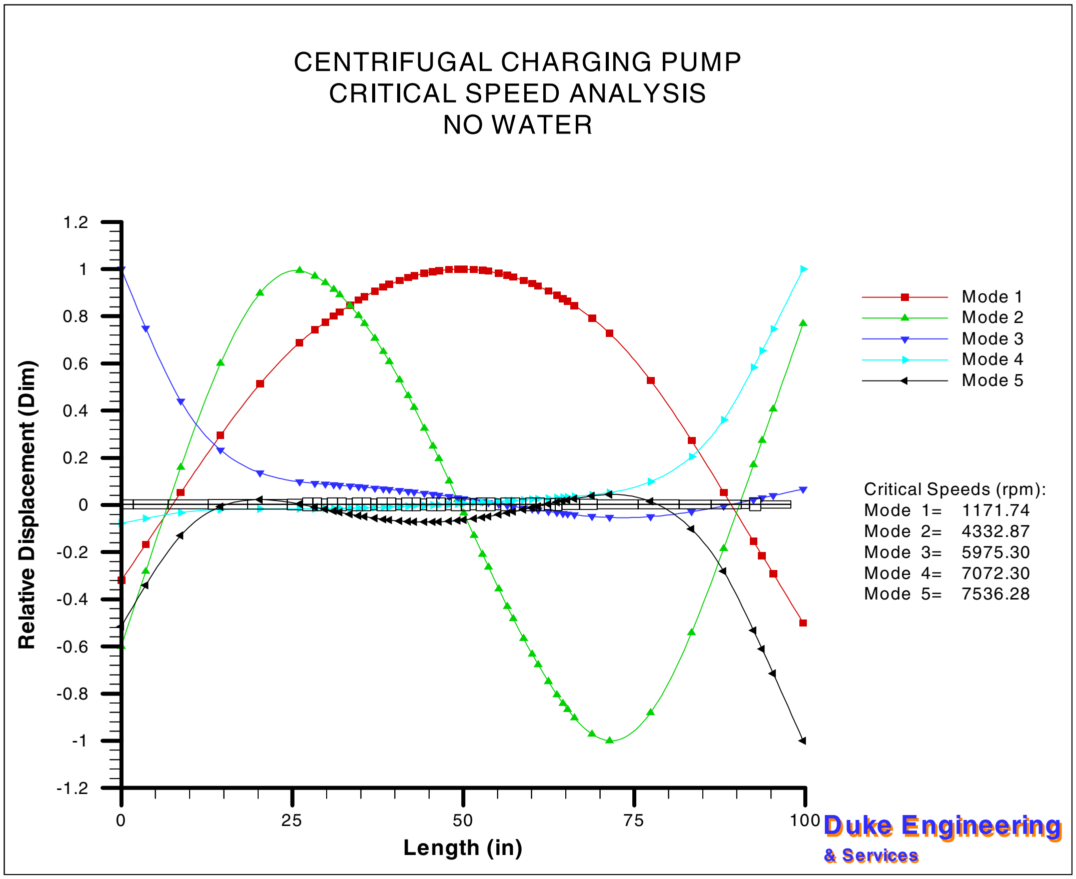
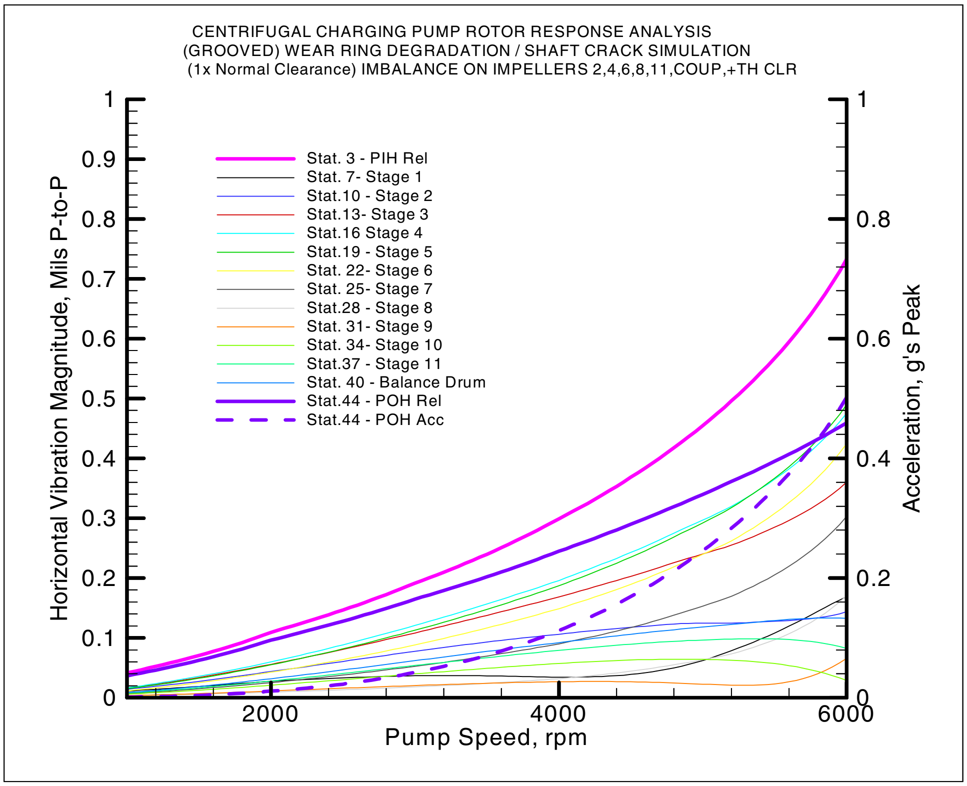


Figure 12: Centrifugal Charging Pump Critical Speeds Analysis (No Water)

Figure 13: Centrifugal Charging Pump Rotor Response Analysis (Normal)



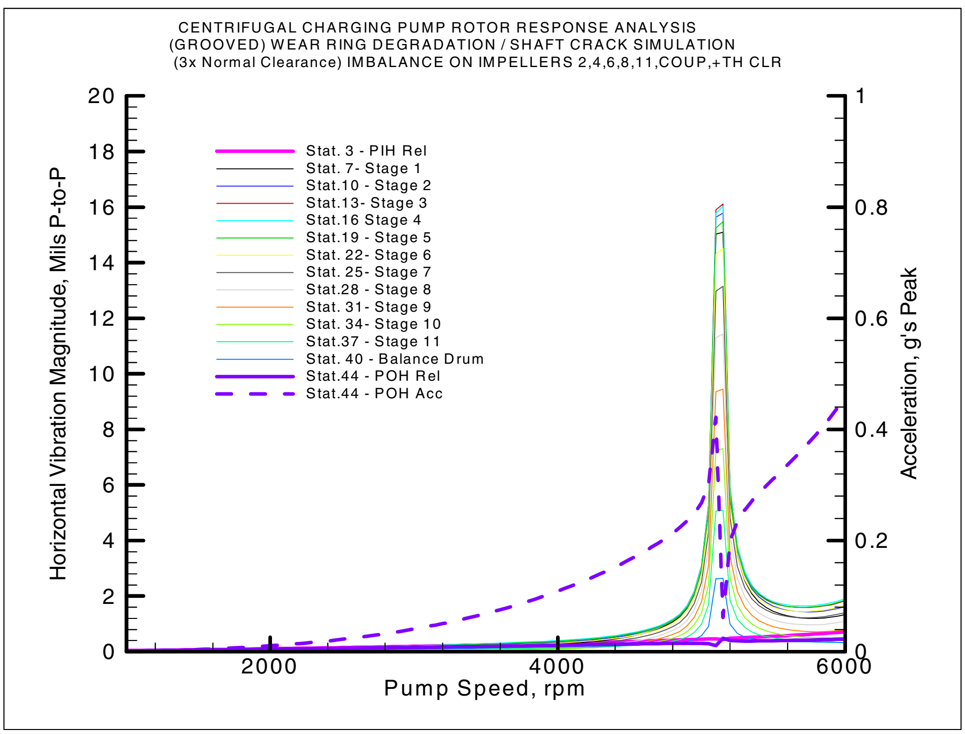
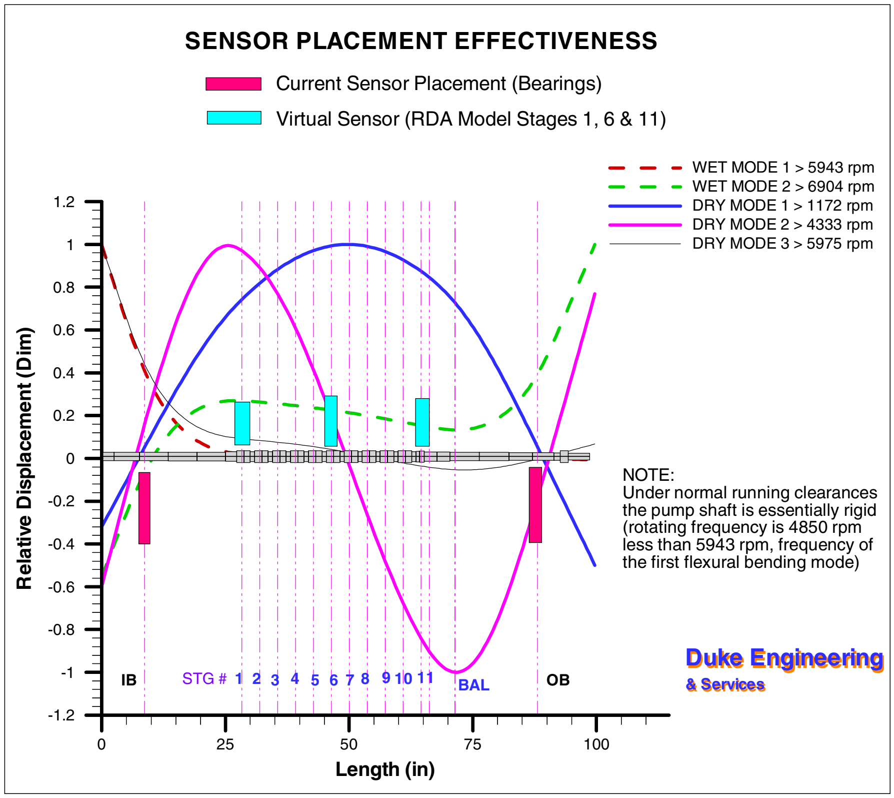


Figure 14: Centrifugal Charging Pump Rotor Response Analysis 3x Normal Clearance

Figure 15: Sensor Placement Effectiveness



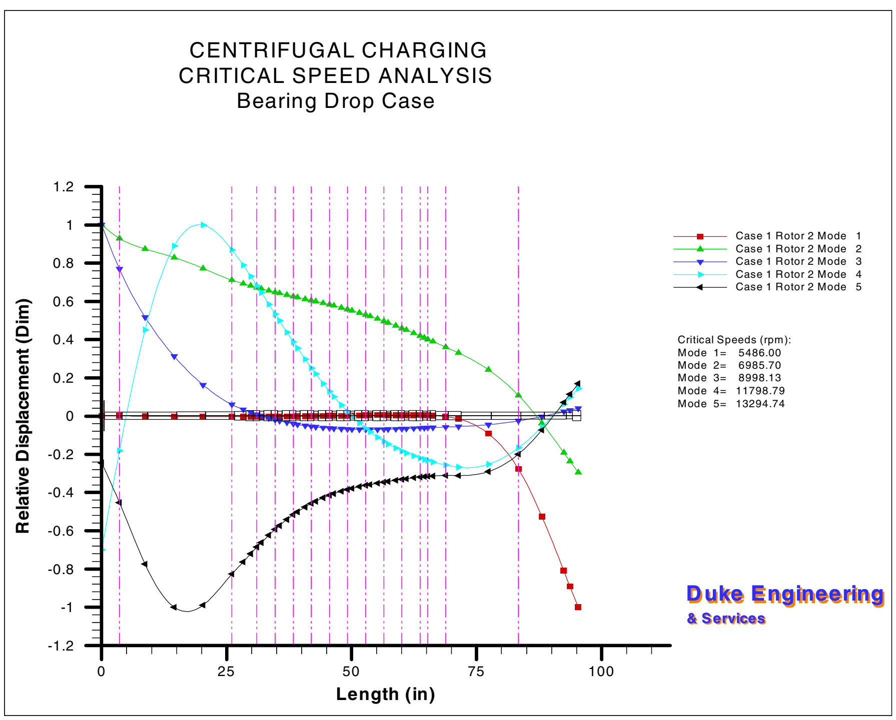
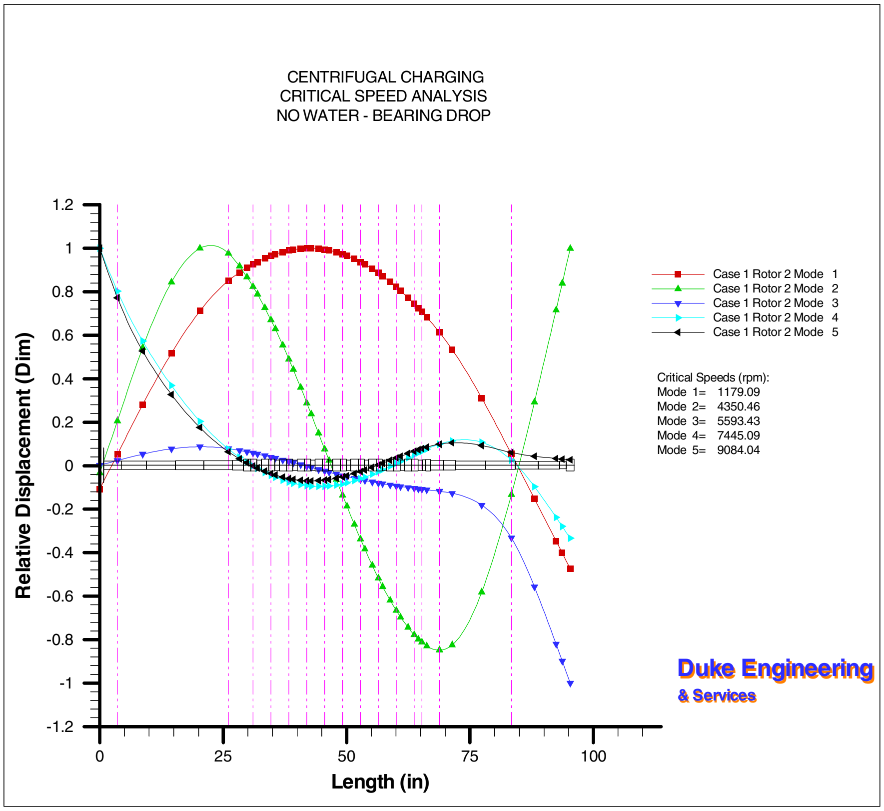


Figure 16: Centrifugal Charging Pump Critical Speeds Analysis - Bearing Drop – Normal Clearance

Figure 17: Centrifugal Charging Pump Critical Speeds Analysis - Bearing Drop – No Water



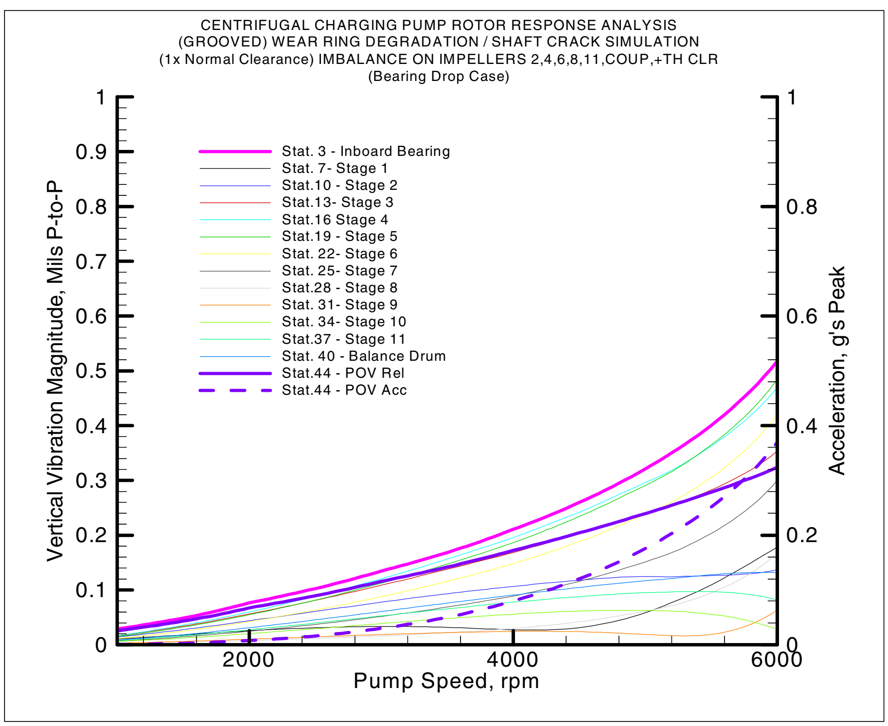


Figure 18: Centrifugal Charging Pump Rotor Response Analysis - Bearing Drop – Normal Clearance

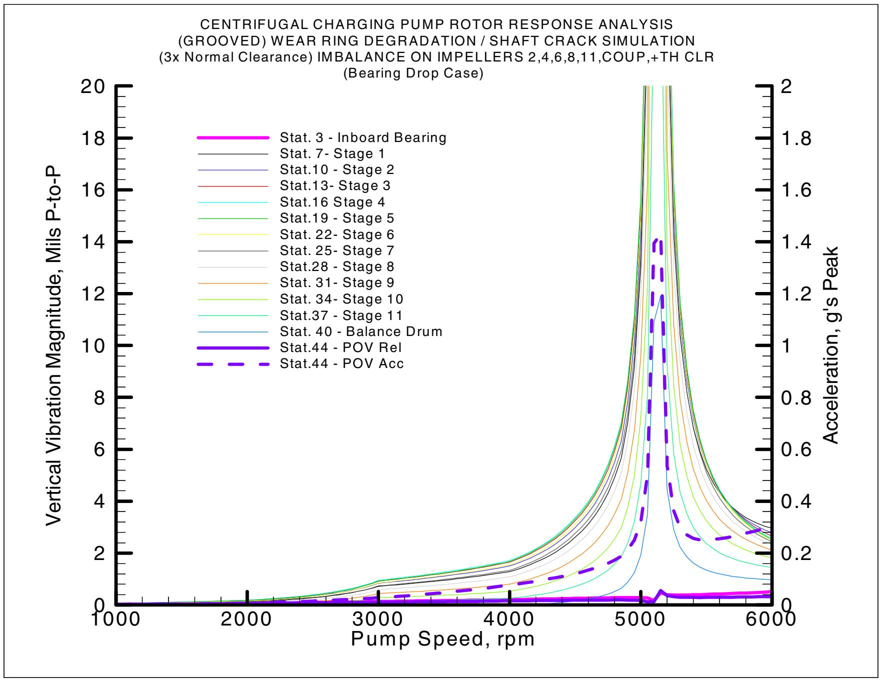


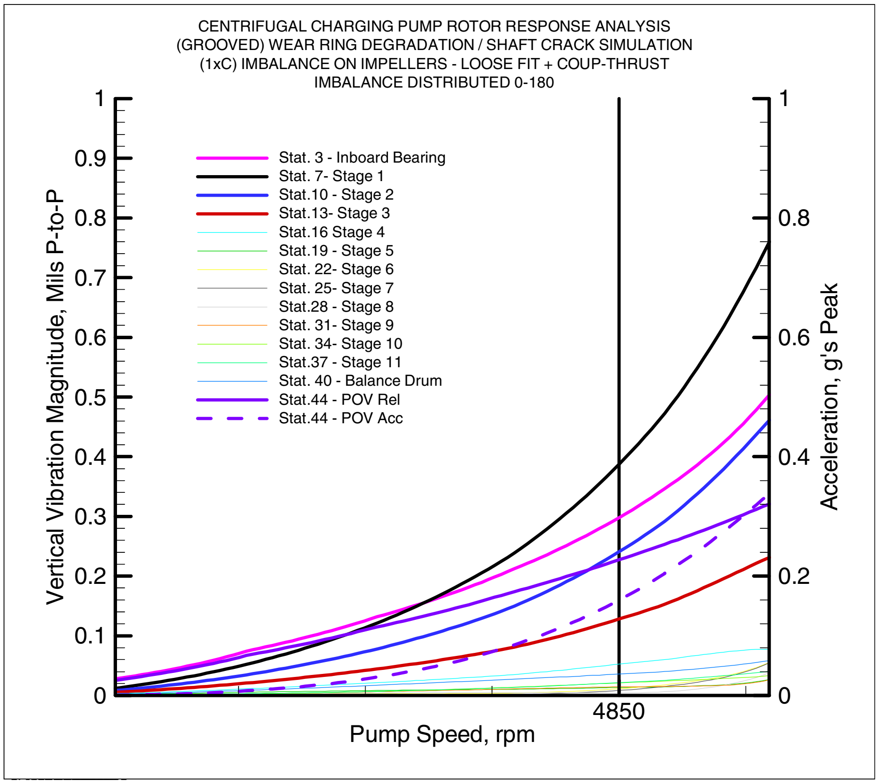
Figure 19: Centrifugal Charging Pump Rotor Response Analysis - Bearing Drop – 3x Normal Clearance

2.3.5 Loose Fit Effects Assuming a Loss of Lubricant Coolant

The initial fit between the impellers and shaft is usually tight. As the pump operates, the impeller shrink fit becomes loose. This condition may be simulated in the analysis in different ways. The first method is to reduce the shaft section to account for the stiffness loss at the location of the impeller. The second method is to simulate the shrink fit loss as an eccentricity of the impeller with respect to the rotating axis much like a mechanical imbalance condition. This latter method has been used in this analysis and the results obtained are shown in ***Figures 20*** to ***22***.

- With normal clearances, vibrations are low (impellers 1 & 2 have higher response than the other impellers due to higher stiffness and damping mainly provided by the balance device)
- As wear ring clearances open vertical response is much higher than horizontal response
- As wear ring clearances open the rotor second mode shape characterizes the dynamic behavior of the system (as shown by past failures investigations)
- Wear ring clearance control is necessary for vibration control

Figure 20: Rotor Response Assuming a Loss of Coolant and an Imbalance due to Loose Fit with Normal Wear Ring Clearances



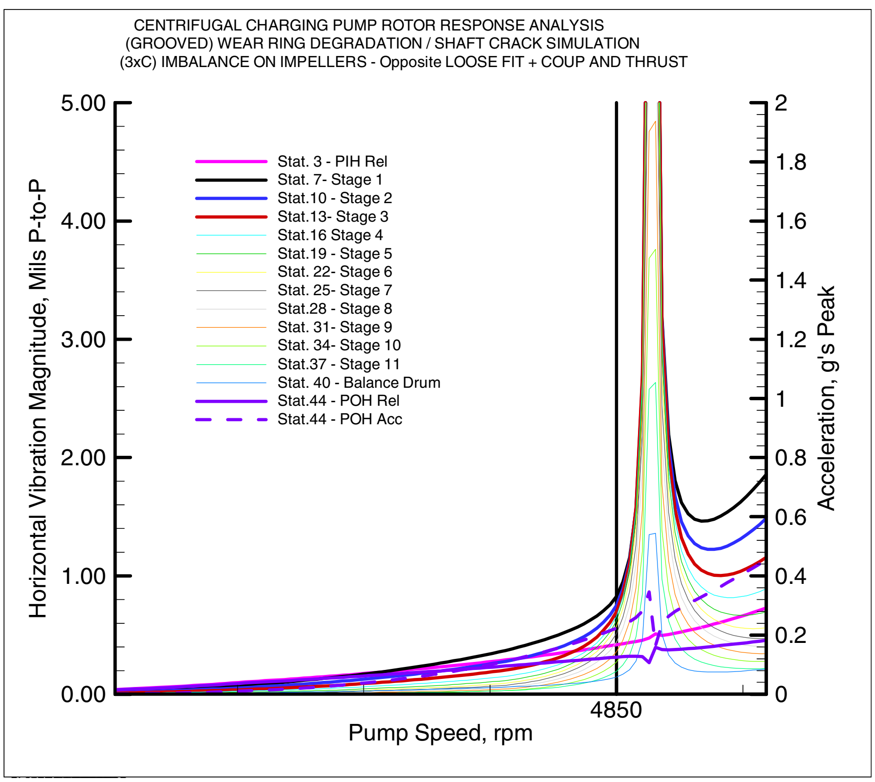


Figure 21: Horizontal Rotor Response Assuming a Loss of Coolant and an Imbalance due to Loose Fit and 3xClearance Opening at Wear Rings

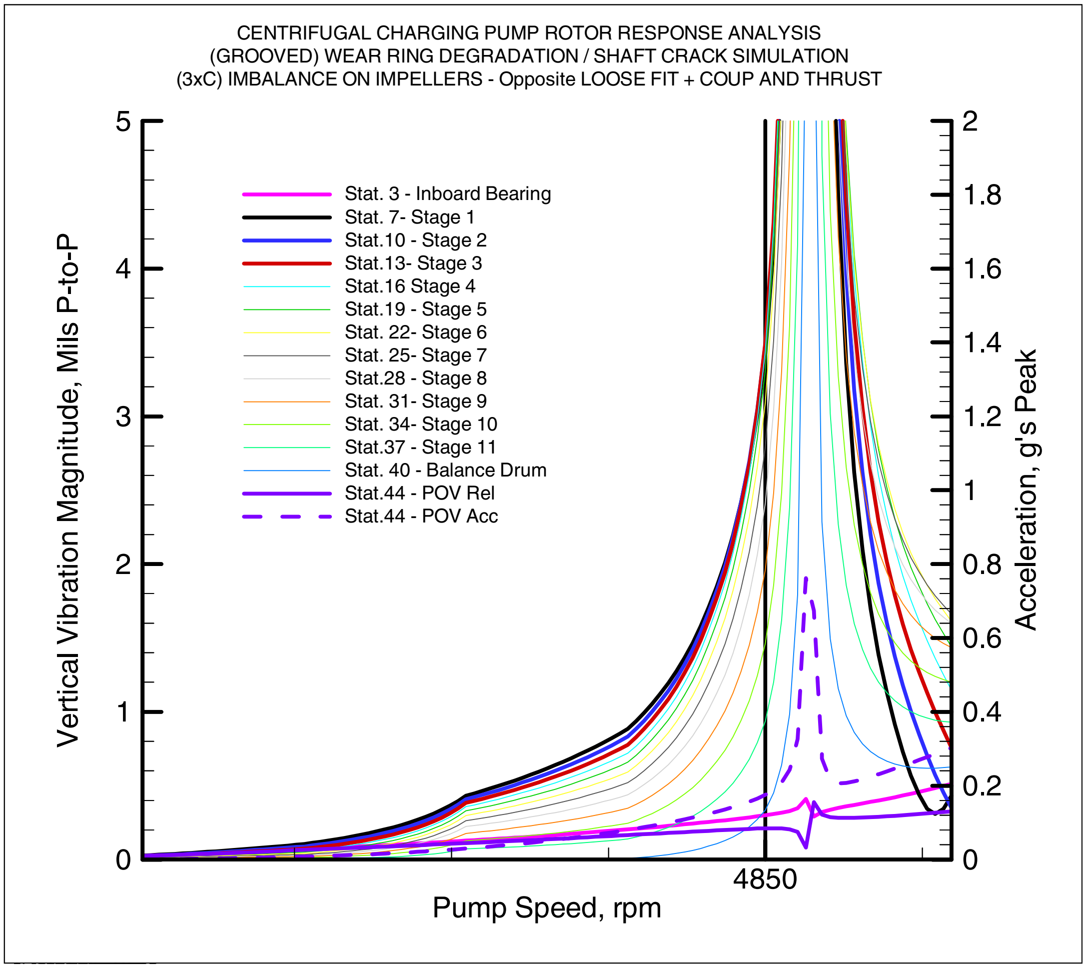


Figure 22: Vertical Rotor Response Assuming a Loss of Coolant and an Imbalance due to Loose Fit with 3xClearance Opening at Wear Rings

4 CONCLUSION

Analysis of the centrifugal charging pump has shown that:

- The pump typically operates at off its Best Efficiency Point (BEP)
- The pump has had recurring documented failures with unresolved issues
- Typical instrumentation is very limited on this component
- This pump provides enhancement opportunities of sensors, instrumentation, and diagnostic methods
- Rotordynamics modeling can be used as an off-line virtual machine for condition assessment and as an on-line diagnostic support tool

OEM and Industry Users Groups have devoted significant efforts toward resolving the issues. Proposed solutions included:

- Various re-Designs - Shaft Material and Geometry, Mechanical Seals Redesign
- Monitoring Methods - Pump internals monitored through Balance Line DP
- Potential Instrumentation Enhancement Locations

Primary results of the cases run indicate:

- The most significant factor in pump failures is wear ring radial clearance openings and its effect on rotordynamics. Process parameter trending can assist here.
- Another significant factor is the bearing support stiffness due to its effect on the rotors second natural frequency
- Temperature distribution in both film and pad varies strongly with thrust load and is not adequately assessed with bulk exit oil temperature measurement
- Oil film thickness are very small at higher thrust loads requires lube oil monitoring for solid particles
- Current sensors are inadequate (***Figure 23***). Wear ring clearances and thrust bearing pad temperatures are strong candidates for instrumentation upgrade. Pump starts and stops should be minimized as they represent high wear operating conditions.
- There is a need for smart on-line diagnostic tools - Integration of various technologies with decision algorithms (such as Bayesian Belief Networks):
  - Performance Monitoring
  - Rotordynamics Analysis & Computational Fluid Dynamics (CFD)
  - Standard Predictive Maintenance (PdM) Technologies

An analytical model of the thrust bearing may provide all the necessary information given the operating parameters to monitor the condition of the thrust bearing due to load changes and/or other changing operating parameters. Such a model is a discrete representation of the actual bearing that can provide virtual readings of pad temperatures, deformations, and stresses.

To best represent the mechanical condition of a machine, the types of sensors and mounting location should be investigated. Sensor placement should consider practicality, maintainability, and should not interfere with pump functional elements. The important dynamic effects provided by the wear rings suggest that sensors should be placed not only close to bearings but also close to wear rings as indicated in ***Figure 23*.**

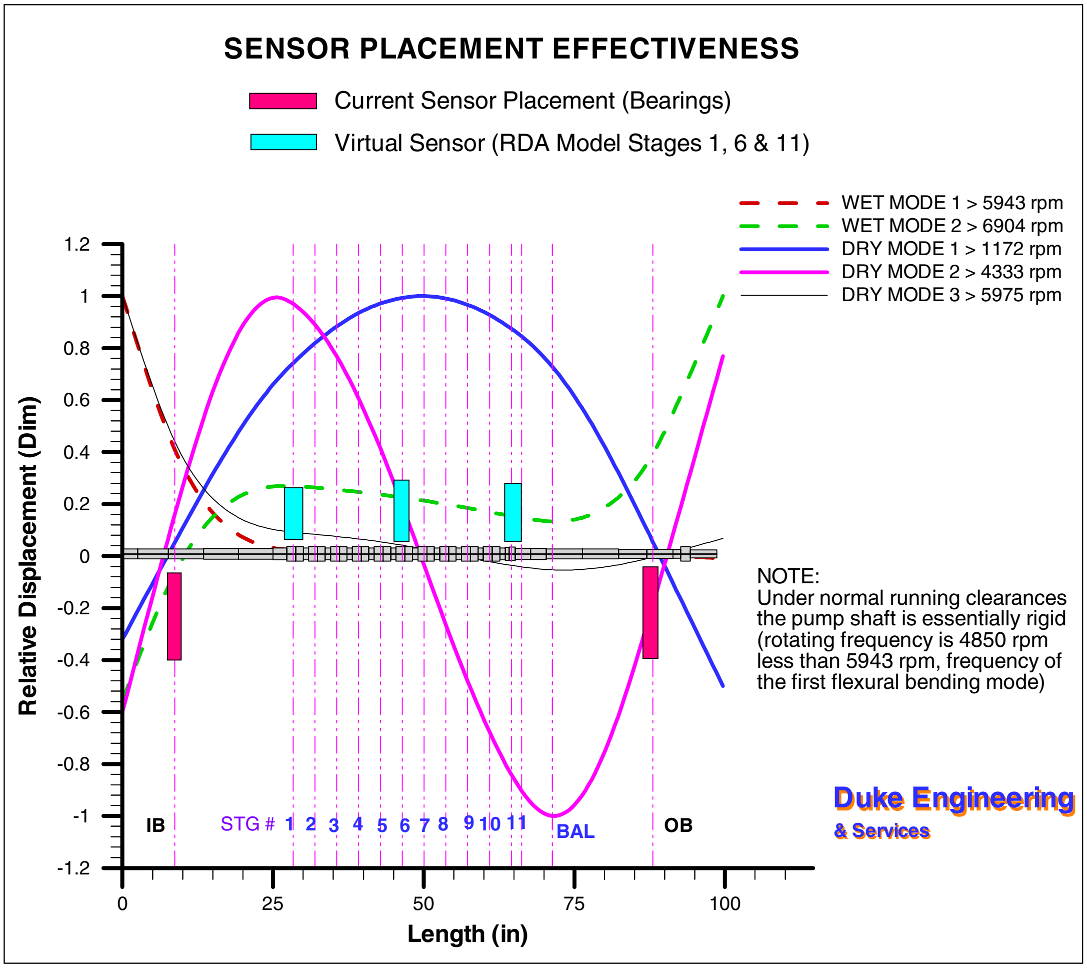


Figure 23: Current Sensor Ineffectiveness – Virtual Sensors Provided by RDA

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Infrared Thermography
Past, Present, and Future

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Introduction

Over the past decade, Infrared Thermography (IRT) has proven to be an effective tool for diagnosing the condition of many different types of equipment. The popularity of this diagnostic tool has expanded the utility industry's use from the Generation stations to the Transmission and Distribution lines. Engineering, Maintenance, and Operations use the results of infrared surveys to identify the health of an individual component, or an entire system. The increased popularity of this technology has stimulated new ideas that have provided investigations into many new areas over the past ten years. It has been demonstrated that infrared thermography has very broad boundaries. The visual effect, enhanced camera operation, and multiple applications have brought this diagnostic tool to the forefront of predictive maintenance.

This paper offers a glimpse of what has been accomplished over the past two decades of infrared use. Included is a discussion on the past and present status of infrared cameras, methods and techniques of detection, severity criteria that have been established, applications on use, report generation of findings, and training requirements of thermographers. In addition, some insights from manufacturers, teachers, and users on the future expectations of this technology are provided.

Background

Infrared Thermography (IRT) was first used commercially in the early 1970s in the building industry. During this time, IRT was used to locate thermal losses due to deteriorated roofing material. This type of investigation required a wet or humid sunny day for moisture to be absorbed by the deteriorated roofing material, and then be heated by the sun. At sunset, the cooler air chilled the roof, but the deteriorated areas holding the moisture would stay warmer longer than the good sections of the roof. The differences in temperatures are because water holds heat longer (has higher thermal resistance value) than the dry insulation material. It was these differences in temperatures that could be viewed thermally using an infrared camera.

After this initial use of infrared technology to the commercial roofing industry, the technology has found many diverse applications and has been expanded to many different industries; however, the focus of this paper concentrates primarily on utility applications.

For many novice IR thermographers in the early 1990s, electrical applications seemed to be their first area of interest. Electrical Motor Control Centers (MCCs) and 4160-volt cabinets were the most viewed components inside the plant. Electrical components outside the plant, in the switchyards and sub-stations, consisted of high-energy lines and connections, transformers, and circuit breakers. Some of the primary reasons for the electrical popularity were that: the components could be viewed on-line; there is an abundance of electrical components; electrical components require a substantial amount of man-hours to perform the Preventive Maintenance (PM) tasks; the PM tasks did not fully identify all the abnormal conditions; and, the deficiencies appear to be easily understood by the IR thermographer and the utility personnel.

Electrical MCC compartment deficiencies such as loose connections, deteriorated thermal overloads, defective fuses, stranded or overloaded conductors, internal breaker and contactor deficiencies, etc., are common anomalies found on electrical equipment and can be easily detected by using an IR camera. A typical electrical compartment PM task requires an electrician to disconnect the circuit breaker and contactor connections, clean the connections, and then properly reinstall and torque each screw per the manufacture's specification. Some PMs require resistance checks on the primary components (breaker, contactor, etc.) to determine if there are any internal deficiencies. This effort takes an extensive amount of time and the PM must be done offline. In some cases, disassembling and re-assembling the components can cause connection problems due to over-torquing. Occasionally, the moving of the conductors can cause crimping looseness, insulation cracks, and metal fatigue. Also, performing this type of maintenance does not fully protect a component from all types of failures. Some conditions such as stranded conductors, deteriorating thermal overloads and fuses, relay deficiencies, and internal breaker and contactor problems may go undetected.

IRT eliminates most electrical PMs and unnecessary component breakdowns by identifying only the connections and components that display an unhealthy condition. IRT is the only diagnostic tool that can identify many electrical conditions on-line, be cost effective, and complete the testing in a timely manner.

The success of using IRT in the electrical applications has heightened the awareness of this technology; however, during the late 1980s and into the early 1990s the use of infrared technology was thought to be exclusively for electrical diagnostics, which was actually to the detriment of the technology. Widespread use of IRT for many electrical applications somewhat labeled it as an electrical diagnostic tool, since the amount of electrical components compared to rotating equipment in the plant is at least 4 to 1. Therefore, it would be expected that the electrical findings would significantly outnumber the mechanical findings. This being the case, IR thermography technology had to re-establish the notation that IR was not just for electrical components only.

Methods and Techniques

Ever since IRT has been introduced to the utility industry, and to other industries for that matter, the data being collected were always compared to a component performing the same service. Many Industrial Power Plants throughout the country have systems with at least two operating components performing the same service at the same time. These similar service components allow an IR thermographer the advantage of comparing the thermal profile of one component versus the other. This process throughout the industry is referred to as **'Comparative Thermography'**. Depending on the nature of the component(s) being observed, comparative thermography can be used to obtain qualitative or quantitative data.

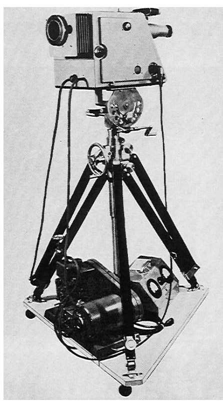
Qualitative data is used when a component **'does not require numerical data'** to determine the severity of a component's condition, for example an underground water main break. The water main break is the fault, and the recommended action would be to repair the piping. Recording an absolute temperature measurement or a temperature differential as compared to the surrounding area is not required to further diagnose the condition of the piping. Finding the area of the ground that displays a difference in temperature indicating the location of the leak is sufficient. Recording the temperature or temperature difference is irrelevant to locating and repairing the break.

Quantitative data is used when a component **'requires numerical data'** to determine the severity of a component's condition: For example, a 480VAC three-phase breaker where the breaker has one phase that is hotter than the other two phases. The hottest spot is located on the A-phase line side connection. The temperature at the A-phase connection is 85 degrees Fahrenheit; phases B and C are both indicating 75 degrees Fahrenheit. With this data, a 10-degree Fahrenheit temperature rise is calculated. Since this is a molded case breaker with a screwed connection, the 10-degree temperature rise would be considered a minor problem that can be repaired as part of routine maintenance. However, if the connection were 100 degrees Fahrenheit above the other two phases, the recommendation would be that it is a serious problem and should be repaired within one week. It is also recommended that the temperature be trended until it is repaired. Identifying the fault without providing the temperature rise for this application does not define the severity of the condition or what recommended action should be taken. Therefore, numerical data is essential in determining the condition of this component.

When there are no similar service components available to perform a comparative analysis, then recording **'Baseline'** data is recommended. Baseline data is a method in which a thermogram, or several thermograms, are taken of the component being observed. The baseline thermogram(s) are then compared to the data taken on subsequent surveys in the same fashion a similar service component would be analyzed, i.e., any changes from the original baseline data would be recorded as a temperature rise above normal.

IR Equipment

An infrared camera is a device that creates a visual display of thermal infrared energy coming from a scene. Initially qualitative, they have evolved to IR imaging plus non-contact temperature measurement capability. These cameras were based on thermal detectors called bolometers, which are to the thermal characteristics of the viewed scene. One of the first commercially available thermal detector imagers was the evaporagraph (Figure 1) manufactured by Baird Atomic from 1950 through 1968 (reference 1). The image was produced by oil condensing on a membrane, thicker where the membrane was cooler, thinner where warmer. The membrane temperature was driven by the infrared energy from a scene being focused on it. With a 30-second exposure time, skilled operators claimed to be able to distinguish less than 1 degree C temperature variations in the resulting qualitative image.



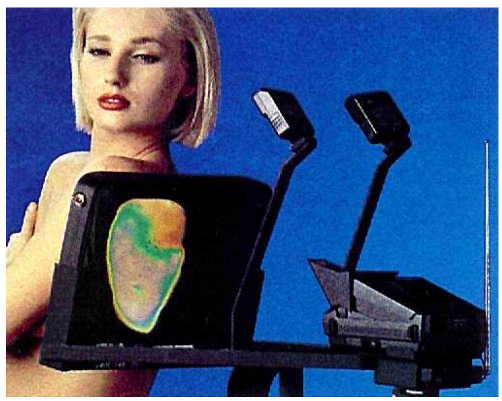


Figure 1. Evaporagraph **Figure 2. Liquid crystal thermal image used in contact mode.**

Liquid crystal imagers were the next big step. Certain cholesteric liquid crystals reflect light in a narrow spectral region by scattering light within the liquid crystal layer (reference 1). For some of these materials the visible wavelength of maximum reflection depends on liquid crystal temperature. Thus IR images could be viewed by focusing infrared energy on the liquid crystal, or in contact mode as shown in Figure 2. Imaging is once again slow with potentially good thermal resolution but poor dynamic range. These early devices showed the promise of IR imaging, but it was the advent of quantum detectors that gave IR cameras the image acquisition speed and sensitivity needed, first for military, then for commercial applications.

Quantum detectors are significantly different than thermal detectors. They are comprised of semiconductor materials with IR photons interacting on the atomic level transducing the IR energy into an electrical signal with nanosecond response times and excellent thermal resolution. Typical quantum detector elements include: Mercury-cadmium-telluride (HgCdTe), primarily used for long waveband (8-12 micrometer) cameras; and,

Platinum silicide (PtSi) and Indium Antimonide (InSb), used for short waveband (3-5 micrometer) cameras. Quantum detectors became efficient only at low temperatures. Typical detectors were cooled using liquid nitrogen. Imagine having a 5-liter container of liquid nitrogen in your thermographer toolkit! Later Stirling coolers replaced liquid nitrogen and were a significant advancement in the industry.

Initially, cameras were produced using single detector elements with various scanning schemes. The airborne line scanner used a rotating mirror to produce the x-axis of the image and the forward motion of the aircraft to produce the y-axis. For military purposes, this was often problematic as one must fly directly over the target to get a thermal image. Small wonder the acronym FLIR, Forward Looking InfraRed, came into being as it was a real life-saving advance in IR technology. Now one can see the target without having to fly directly over it.

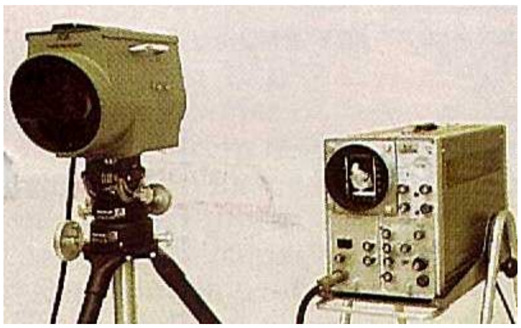


Figure 3. AGA Model 651 IR camera.

Figure 4. Inframetrics Model 600

AGA (later AGEMA, now part of FLIR Systems, Inc.) developed the first IR system, the Thermovision 651 (Figure 3), for commercial use. It was delivered to the Swedish Power board for electrical inspection of substations and power lines in 1965. It was a real-time imaging system with fast scanning. It used a 4-sided refractive prism for the horizontal scanning and an oscillating mirror for vertical scanning. The camera Field of View (FOV) was 5 degrees. The control unit was a Fairchild oscilloscope with AGA-designed plug-in units. It used a single element InSb detector with liquid nitrogen cooling.

For its IR thermography debut, Inframetrics (now part of FLIR Systems, Inc.) employed a single detector element with a free running galvanometer oscillating sinusoidally at 8 KHz for the horizontal scan and a framing mirror scanning in a sawtooth mode at 60 Hz with associated IR optics to produce an image. It was the first TV compatible IR camera. Quantitative measurements required reading graphs of the system output. Later a separate "hand-held" computer was added. In either case, getting a temperature was a time consuming process. Later the Inframetrics Model 600 (Figure 4) became the first microprocessor based IR imaging radiometer with temperature readout capability on the IR image.

Though IR camera size kept getting smaller, the Model 600 and its competitors were still large compared to today's market. The system had a separate camera head and electronics control unit. Typically, the thermographer used a two-wheel cart to provide mobility.

The advent of focal plane array (FPA) cameras in the early ‘90s was made possible by advances in microprocessor and array technology. The engineering challenge is to get over 60,000 individual detector elements all working in concert, with the same gain and offset characteristics. Each must also be read out to display the image at a 60 Hz rate. For the thermographer, it was worth the effort. Together with Stirling cycle coolers, the focal plane array camera reduced the weight and amount of support equipment required. True hand-held portability had been achieved (Figure 5).

Computer technology continued to play an important role with the advent of PCMCIA storage. Now many images could be stored on a small card inserted into the camera, and loaded into the computer by transferring the card to a reader. In just 25 years, IR technology went from big and slow to small and fast. They also went from qualitative, or troublesomely quantitative to readily quantitative.

The microbolometer was developed jointly for military and commercial applications with funding provided by both the public and private sectors. The term microbolometer, stems from the bolometer, which is physically a much larger single detector element. As discussed above, the bolometer was introduced years ago as the first radiometric IR device. Now we have come full circle from bolometers to quantum detectors and back to microbolometers.

The microbolometer’s individual micro-machined elements consist of a vanadium oxide film, supported on silicon nitride ‘legs’ of low thermal conductance. This collection of detector elements is integrated onto a substrate that is held at a stabilized temperature to minimize gain and to compensate for drift. Stabilization of the detector environment is necessary, because each 1/3000ºC change in detector temperature indicates a 0.1ºC change in scene temperature.

Now microbolometer arrays are routinely fabricated. Today’s IR cameras are on Gen III of these detectors. Figure 6 shows a modern microbolometer detector array IR camera. Image quality approaches that of cooled quantum detector arrays for IR cameras similarly priced. The good news: No more cryogenic cooling! This is a real bonus as Stirling coolers eventually wear out and need refurbishing. Camera ruggedness is improved. Operationally, the dynamic range of microbolometers is significantly greater than that of cooled FPAs. The IR camera in Figure 6 also has capability of recording a visual image, text comments and voice, all attached to the IR image file so tracking of data is ensured. And it has autofocus! The thermographer starts the 21st century right with IR cameras of this ilk. Not only is capturing quantitative thermal imagery orders of magnitude easier, but cataloging the data and generating reports has become much simpler. Today’s IR cameras give the thermographer a powerful tool for predictive maintenance plus a multitude of other applications

Figure 5 PtSi, Stirling cooled FPA camera

Figure 6 Microbolometer IR camera

Severity Criteria Considerations

How bad is bad? Do we really care? If a thermal anomaly is found, shouldn't we just report it and let the repair team sort it out? These are all questions thermographers have asked themselves or others when trying to decide the severity of a problem. On the other hand, the supervisor and/or operations wants to know how long a problematic component will last. Does it need immediate repair? Will it make it to the next scheduled outage? Until next weekend? You found 40 anomalies. We only have time to get to the top ten in the next two weeks. Which should we do first? These are questions the thermographer will definitely get asked.

Ranking an anomaly by its severity is a fair request for any diagnostic technology. In many cases it's a "no-brainer", especially in mature predictive maintenance (PdM) teams where everyone has agreed to specific criteria and procedures. In other cases it's a real "head-scratcher". For the latter, bringing in other diagnostics is often fruitful.

For IRT, problem severity is often categorized using temperature alone as the main criterion, but its not the only thing to consider. For the real bottom line on the severity of the problem ask yourself the question: "If this fails, what's it going to cost us?" Not cost just in dollars, but also safety. Most Pdm programs evaluate the criticality of the equipment and assign one or more diagnostic technologies where they make sense to protect that equipment. So, part of the cost issue is equipment criticality. Where does this problem equipment fit on my criticality list? Will anyone get injured or die if the equipment fails?

Temperature by itself can be misleading; and, to demonstrate this point several electrical examples have been selected. Variables affecting temperature reading of an electrical problem include: load, hot spot size to working distance ratio, wind speed, emissivity, ambient and background temperatures, solar effects, and how "direct" the reading is (reference 2). The last parameter considers the amount of thermal insulation between the actual problem spot and what the IR camera sees. Often, this is categorized as a direct reading for bare connections, or connections with thin layers of insulation, and indirect reading for heavily insulated components. Remember, good electrical insulation is good thermal insulation. Indirect examples include: Oil circuit breaker contacts, load tap changer contacts, insulated 4160 switchgear connections, internal connections in bus ducts (including iso-phase bus ducts), pad mount transformer connections, underground elbows, and so on. All these items need a separate temperature severity criteria from that of direct readings.

Few severity criteria address the direct/indirect issue. PG&E for example, has separate criteria for overhead and underground electrical distribution facilities. Their criteria state that for overhead, a 61° C temperature rise is a critical problem, for underground 11° C rise is critical. Corrective measures are required for 21° C rise for overhead and 5° C rise for underground.

Any published severity criteria that does not address direct/indirect ought to be revised. We know that a 5° C rise on an OCB often indicates a critical problem. Similar temperature rises on the above mentioned indirect targets can also be critical in nature. There is just too large a difference between directly read and indirectly read targets to ignore. We should also be doing research in this area to specify severity criteria for the various types of indirect targets. Failure of these devices can be extremely costly in both dollars and human life. For example, Bob Woyshner under an EPRI M&D project working with Rick Bjornson of Seabrook Nuclear Station found a warm iso-phase bus duct that resulted in $30,000,000 avoided cost for the station (reference 3).

Attempting to correct for load variations has resulted in simple equations that are incorrect. As shown by Perch-Nielsen (reference 4) and B. R. Lyon et al (reference 5) temperature rise does not follow a simple square of load change rule that is widely disseminated. Similarly, for wind effects Madding (reference 6) has shown that the wind speed correction factors historically used by thermographers are suspect.

These other variables are even more crucial for indirect targets. Small temperature rises that indicate big problems can be significantly influenced by other factors such as wind and solar insulation, simply because they are small (reference 2).

All of these variables can appear daunting to the PdM team responsible for establishing severity criteria; but it is possible to write reasonable severity guidelines with caveats for the variables, letting the thermographer have some leeway in making the call. It is strongly recommended that severity criteria with temperature rise as one of the key parameters, and separating direct criteria from indirect criteria, be written.

Applications

In 1998, the EPRI M&D Center performed a survey to determine the nature of IRT findings. The survey consisted of 35 utilities totaling 1592 IRT findings over a 3-year period. The EPRI M&D Center personnel provided the IRT surveys for the 35 utilities of which the data was extracted. The surveys were performed at fossil fuel plants as part of an overall Predictive Maintenance (PDM) program. Generally speaking, most utilities are using IRT as a tool to provide data for an overall PDM program; therefore, it is felt that the following results are a good representative sample of what is being surveyed in the fossil fuel utility industry. Figure 7 contains a summary of the findings of the surveys.

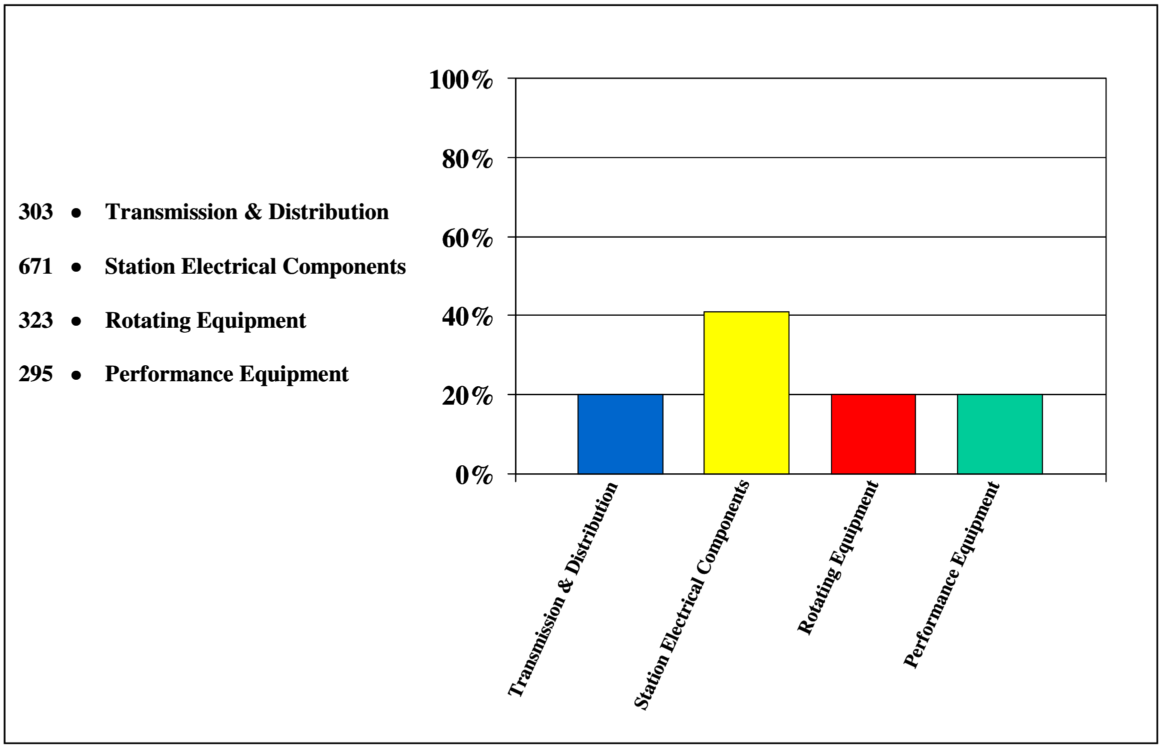


Figure 7: IRT Summary of Findings

A breakdown of the types of findings for each equipment category is included in the following figures: Figure 8: Transmission and Distribution; Figure 9: Station Electrical Components; Figure 10: Rotating Equipment; and, Figure 11: Performance Equipment.

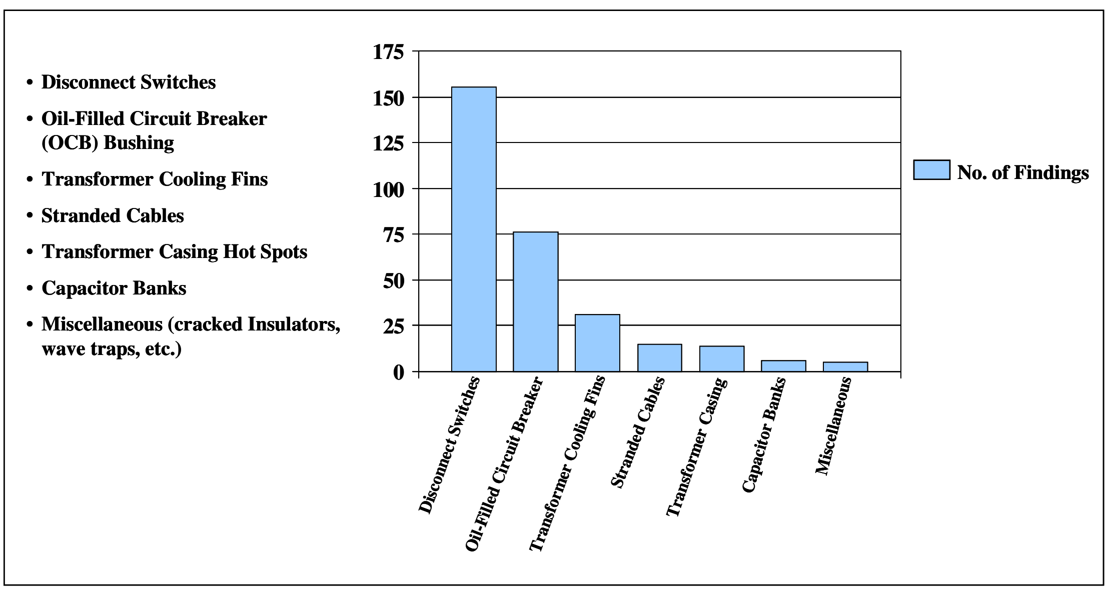


Figure 8: Transmission & Distribution – Number of Findings

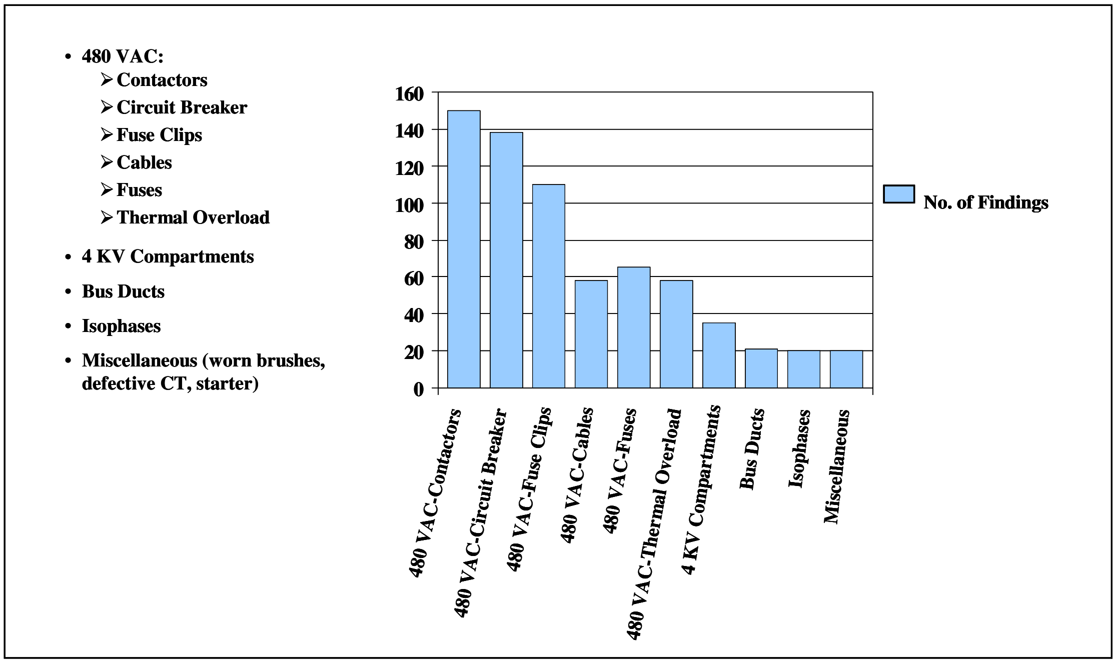


Figure 9: Station Electrical Components – Number of Findings

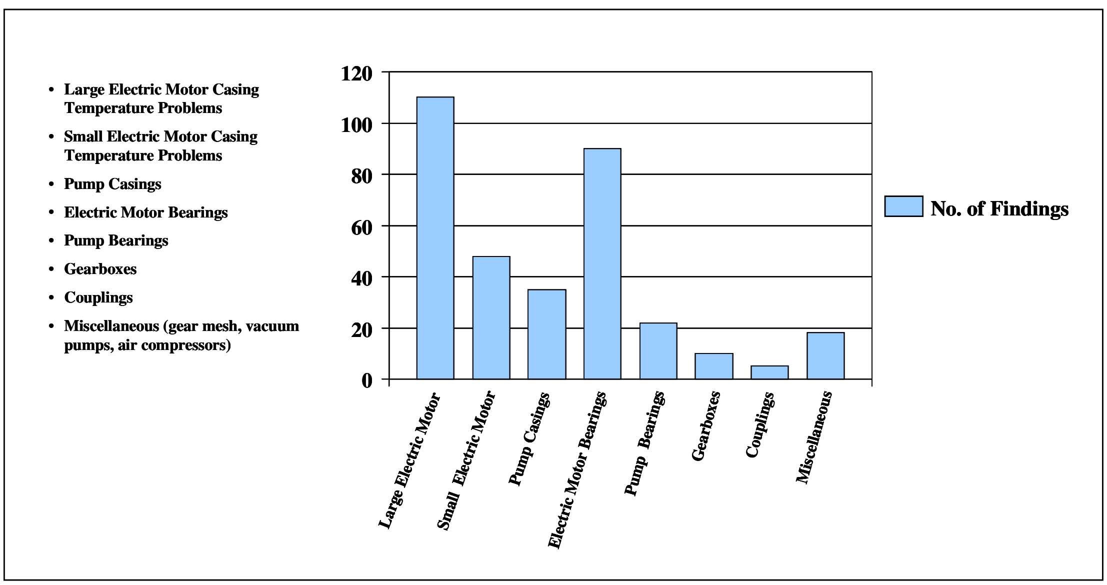


Figure 10: Rotating Equipment – Number of Findings

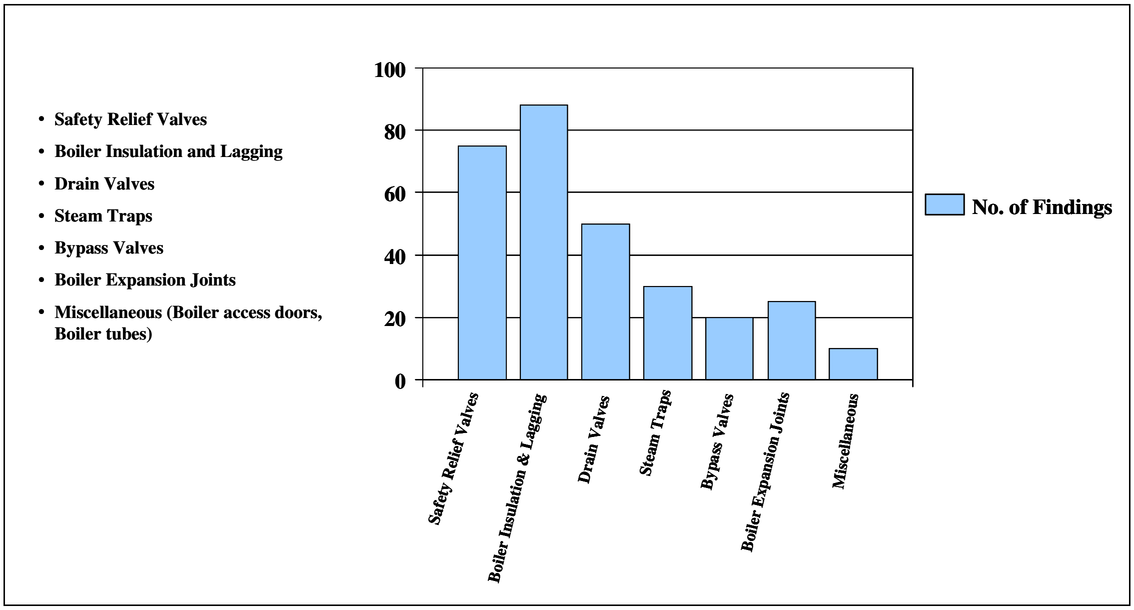


Figure 11: Performance Equipment – Number of Findings

It is evident then that IRT is very useful in applications other than electrical components, with approximately 40% of the above findings being on rotating and performance components. Much of what is being surveyed today is dependent on who is performing the survey, what are the critical or costly problems present at your specific plant, and the type and capabilities of IR camera being used. For instants, if a person with a mechanical background is the IR thermographer, than that experience would lead towards mechanical components, if the thermographer is an Operator, then system data may be the biggest concern. In addition, many enhancements have been made to the IR equipment over the past 10 years. These enhancements have provided the user with better resolution, smaller cameras and additional accessories, all of which provide the user with improved capabilities of investigating areas not available before. Finally, through research, many new situations are being discovered by organizations such as EPRI in areas that are costing the utilities a decrease in performance, forced outages, and/or high maintenance costs.

Additional areas not previously identified are being investigated using IRT. Some of these applications have been validated as successful or unsuccessful, and some are still in the early stages. Some of these areas are: electrical – relays, exciters, bus duct, isophase bus, batteries, and dry transformers; performance – internal boiler, boiler air-in leakage, condenser tube leakage, underground steam leaks, and condenser air-in leakage; rotating equipment – cooling systems; and, switchyard – bushings, coupling capacitors, current transformers, disconnect switches, distribution lines, insulators, lightning arrestors, load tap changers, power transformers, and transformer cooling systems.

Training/Certification

Thermography Training has improved dramatically in the past 20 years. Thanks to the combined efforts of the equipment manufacturers, industrial users, thermographers themselves, and the American Society of Non-destructive Testing (ASNT), training has developed from basic instruction on the use of the equipment to full-fledged levels of competence and their corresponding certifications.

Around 1980, a few highly recognized leaders in the infrared industry along with concerned businesses decided to work toward the standardization of the qualifications of those performing IR inspections and services. This group led the effort towards a national Standard. They approached the ASNT about the possibility of the development of an infrared Standard for training and certification requirements, since the ASNT Standards are internationally acknowledged as qualification Standards for Nondestructive Testing (NDT).

The ASNT Thermal Infrared (TIR) Committee was subsequently formed in the fall of 1989 to develop the Thermal/Infrared Testing Method for inclusion into SNT-TC-1A. This committee consisted of recognized leaders in the infrared community including consultants, trainers, industry and equipment manufacturers which provided the TIR committee with a vast experience level. Through an extreme amount of well-organized work, a new TIR method was ready to be published in the 1992 SNT-TC-1A as the 10^{th} NDT technique.

Since then continuous efforts have been made to refine and enhance the SNT-TC-1A. In 1996, vibration techniques were approved and along with the thermal infrared methods resulted in the development of a Predictive Maintenance (PDM) track. This PDM track was incorporated in the 2001 version of SNT-TC-1A. This enables the infrared professional to qualify for certification in either NDT or PdM. The PdM track is centered on the conventional predictive monitoring of industrial equipment for early stages of degradation that could develop into a probable failure of the equipment. The PdM examination typically deals with equipment that is operating or is in service and inspects the operating characteristics for indications of degraded conditions. The NDT track is targeted at the examination of materials to identify areas of dis-bond, voids, thinning of material and many other problems within a component. The NDT examination is frequently performed as a quality check of new components as they are being produced or as a periodic examination of the component for material problems after it has been placed in service.

The TIR method was recognized quickly as the Standard for developing qualification requirements for certifying individuals in the infrared field. Since SNT-TC-1A lists the suggested training that an individual should have prior to being qualified for certification, it also became the recognized requirements for those conducting training and certification programs. Nearly all of the infrared training institutions adopted the suggested curriculum as outlined in SNT-TC-1A. This provided the expanding technology with the consistency in both training and certification resulting in a means to evaluate the qualifications of IR operators.

Three levels of ASNT certification are available, Levels I, II, and III with Level III being the highest that can be achieved. The suggested roles and responsibilities for each Level are detailed in ASNT SNT-TC-1A. The following bulleted items are the major points of such a program:

- All candidates seeking ASNT TIR certifications at this time are employer certified.
- The employer develops a written program utilizing Recommended Practice Number SNT-TC-1A as a guide.
- The candidate seeking certification meets the training and experience requirements of the employer's written program.
- The candidate takes a visual acuity and color contrast differentiation test.
- The employer administers the testing that meets the requirements of the written practice. The testing is typically both written and practical application and is given and verified by a Level III.
- Upon successful completion of all of the requirements of the employer's written practice, the certification is granted.
- Re-certification requirements are outlined in the employer's written program.

Currently, anyone desiring to obtain proficiency in the thermal infrared technology has a large number of training options to choose from; and, seeking a level of certification in accordance with the ASNT is up to the individual and the employer. However, ASNT certification is not a requirement in all cases.

Report Generation

Generating a comprehensive IRT report is extremely important. Most IRT software products provide the capabilities to generate an 'exception' page for each finding. An exception page generally provides an area on which to paste a visual image and thermal image (thermogram), alongside a text section that includes a description of the finding, recommended action, and some other details, i.e., temperature rise, load, location, etc. This information is critical to identifying the problems; however, it does not provide the plant with a great deal of other information that was gathered during the survey, such as the condition of the components that are operating properly. In addition, if the IRT Report only identifies the anomalies found then it is always the bearer of bad news. Unfortunately this was how the majority of reports were generated for years, and many are still being generated this way. Predictive Maintenance (PDM) programs, however, have changed how data is converted into action, and also how the information is provided to the customer.

PDM is a process that uses all of the tools in the tool bag, as well as other pertinent information (operations, maintenance, performance, etc.) to make the best decision on the condition of a component and what action should be taken. For example, if a problem was found on a piece of rotating equipment using IRT, then the IR thermographer would collaborate with the vibration and oil specialists to determine if they found any irregularities with the same component. In addition, depending on the type of problem, the IR thermographer may review the operator's log or past maintenance histories. The bottom line is to utilize all of the data available to make the best possible decision.

PDM is also a process that is intended to provide the condition of all plant components; weather the **'health'** of a component is good or bad. Knowing what is operating correctly is as important as knowing what is not operating at its optimum condition. For instance, it is important for an Operator to know that if a spare motor is needed, it is operating properly and it is available. It is also important to know that when the last time an IRT survey was performed that a 1C BFP Motor was not online; and, therefore, was not surveyed. As a result the recent failure may have shown signs of a developing problem during the last survey, instead of diagnosing it as a catastrophic failure. The purpose of keeping track of all components being surveyed is to better understand the component's operating conditions, so that improvements can be made regarding how the data should be taken to ensure that the data being collected defines its condition. If 500 plant components are being observed and only 10 show signs of deterioration, why not provide an IRT report that lists 490 healthy components and 10 exceptions? Your maintenance department would welcome the praise for doing a great job.

Conclusion

It has become evident that the equipment, techniques and applications of IR thermography have developed significantly to where thermography now enjoys wide-spread use. With the proper equipment and training, it has been demonstrated time and again that it is a beneficial tool for the early detection of developing problems which can result in substantial cost savings to the user.

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ULTRASONIC TEST TECHNIQUE ON INSULATION HOSE OF GENERATOR

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Abstract

An ultrasonic test (UT) was effective and required for the inspection of insulation hoses in a turbine generator, because UT can detect a harmful crack in the hoses and this leads to high reliability of the generator.

However, it was very difficult to apply UT to examine the insulation hoses by using conventional ultrasonic probes for testing steel, because of the difference in acoustic property of steel and the hoses, which are made of Polytetrafluoroethylene (PTFE). PTFE has large ultrasonic attenuation and slow wave velocity. So, the conventional probe is hard to transmit an ultrasonic wave directly to the location of a crack which exists just under the edge of metal fittings of hose ends.

To detect such cracks in the insulation hose, new effective UT probes have been developed. By using those new probes, it is possible to transmit an ultrasonic wave directly to the 5 mm inner area from the edge of a metal fitting of hose ends. In addition, new probes apply UT not only to straight hoses but also to curved hoses in both axial and circumferential directions.

The new developed UT probes were applied on the insulation hose and evaluated. As a result, the new probe characteristics shows high sensitivity to the UT of the insulation hoses.

1. Introduction

The soundness of insulation hoses in water-cooled turbine generators was checked by high-pressure tests in a manufacturing process and total leakage tests for all stator coils and hoses at maintenance inspections. However, these tests cannot detect small cracks in the hoses. So, in order to keep the reliability of generator higher, an ultrasonic test (UT) of the insulation hoses was required.

As a result of this study, UT probes for insulation hoses were developed and ultrasonic test technique on the insulation hose was established.

2. Insulation hoses applied to turbine generators

Normally, large capacity turbine generators have water cooling system for stator coils to improve the efficiency. The insulation hoses are applied to connect stator coils with header rings of cooling water. (Ref. Figure 1)

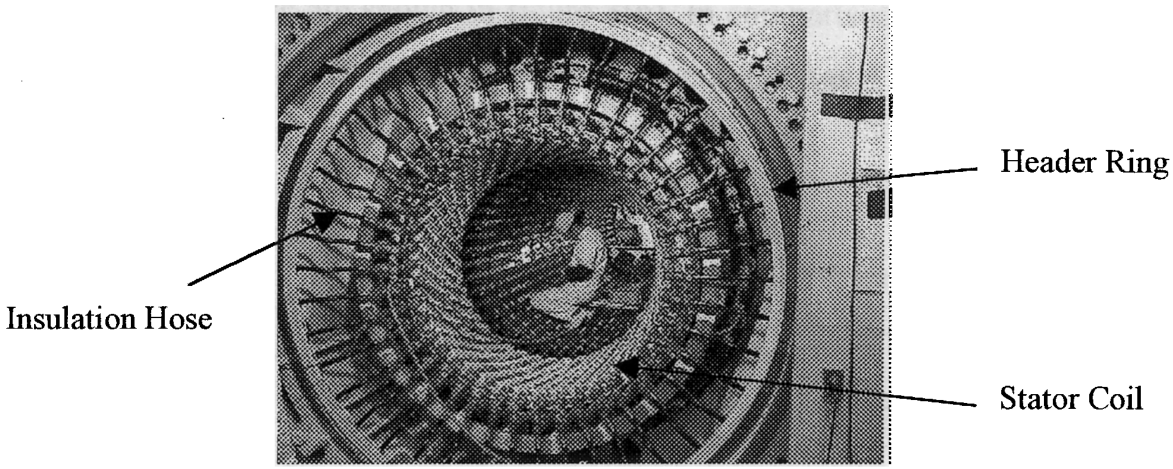
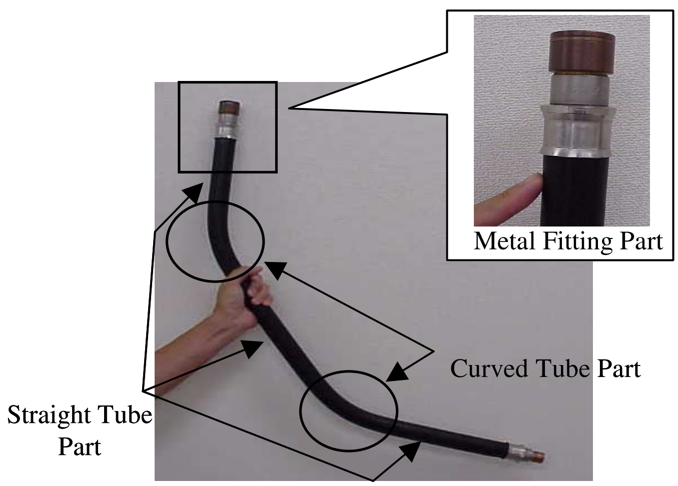
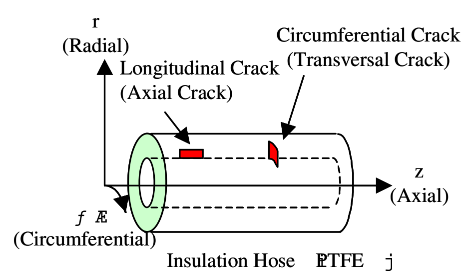


Fig. 1 Insulation Hoses Assembled in a Turbine Generator

The typical shape of the insulation hose is shown in figure 2. The insulation hose is consisted by three parts, a metal fitting part, a straight tube part, and a curved tube part. The conventional straight beam UT is not effective to inspect the crack which exists under the edge of the metal fittings of the hose ends.



(a) Insulation Hose



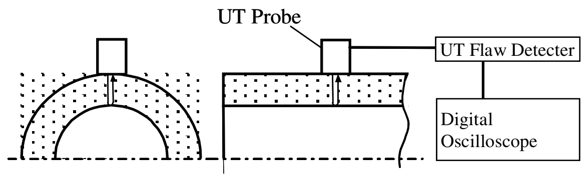
(b) Direction of Defects

Fig. 2 Insulation Hose and Direction of Defects

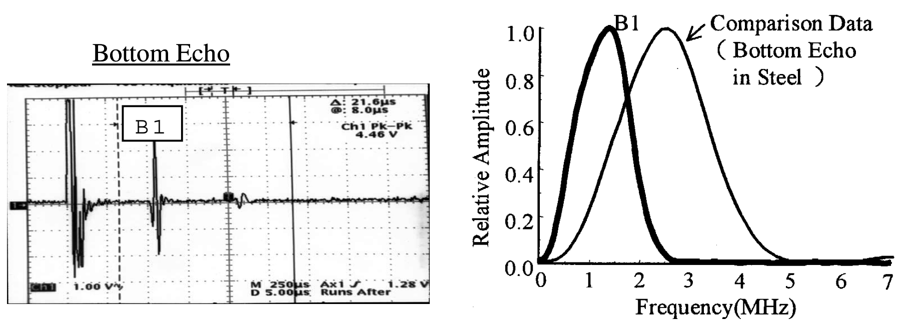
3. Ultrasonic property of insulation hose

3.1 Attenuation property due to frequency

As a preliminary study to apply UT to PTFE, we examined basic ultrasonic property in the insulation hose. At first, we examined frequency characteristics of ultrasonic wave. As shown in figure 3(a), we performed UT with the straight beam probe on the surface through a couplant, glycerin, and received the reflection wave from the inner surface of the insulation hose (echo B1: 1st bottom echo). We used UT probe for 2.25MHz. The wave form and frequency spectrum of received reflection wave are shown in figure 3(b). In comparison with steel, PTFE has large attenuation coefficient in the high frequency component and has a peak spectrum at the lower frequency.



(a) Outline of Frequency Characteristic Test



(b) Test Results for 2.25MHz Probe

Fig. 3 Attenuation Property due to Frequency

3.2 Comparison between insulation hose (PTFE) and steel on ultrasonic property

As UT is normally applied to the inspection of steel, we compare the steel with the insulation hose on the ultrasonic characteristics. (Ref. Table 1)

Table 1 Ultrasonic Property of Steel and Insulation Hose

		Steel	Insulation Hose(PTFE) Test Result
Specific Gravity		7.7	2.2 *
Sound Speed	Longitudinal Wave	5900 m/s	1150～1350 m/s
	Shear Wave	3230 m/s	390 m/s
Attenuation Coefficient		～0.1 dB/cm	17～22 dB/cm

* Attributed to Krautkramer by 「UT skill-Theory and Practice-」

Insulation hoses have large ultrasonic attenuation and slow wave velocity, compared with steel. The influences of these characteristics are described as follows. (Ref. Figure 4)

(a) The influence of large ultrasonic attenuation

The attenuation coefficient of longitudinal wave in PTFE is large. For the large attenuation of ultrasonic wave, ultrasonic intensity becomes smaller in transmitting wave, so that the reflection from the defect becomes small. Therefore, SN (signal/noise) ratio becomes small even if the ultrasonic transmission distance in the hose is the same as that of steel.

(b) The influence of slow wave velocity

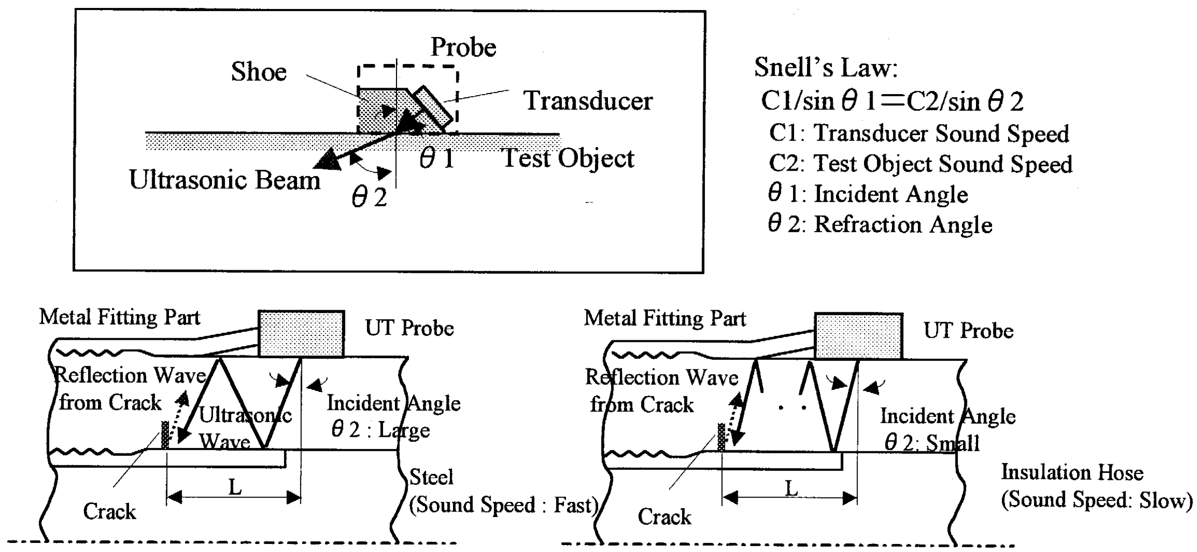
Generally, the relation between incident wave and refraction wave is known as Snell's Law shown in following equation (1).

$$C1/\sin\theta 1 = C2/\sin\theta 2 \qquad (1)$$

Here ; C1 : ultrasonic velocity into the shoe, C2 : ultrasonic velocity into the test piece,

θ1 :incident angle of ultrasonic beam into test piece, θ2 :refraction angle of ultrasonic beam inside test piece.

In case of low C2, θ2 would be small and the transmission distance would become long, which makes large attenuation of reflection echo.



(a) If Hose Material would be Steel (Assumption)

(b) Hose Material is PTFE

Fig. 4 The Influence of Ultrasonic Characteristics by Sound Speed Difference

4. Development of UT probes for inspection of insulation hose

4.1 Mode conversion of longitudinal wave

In case of inspecting steel by longitudinal wave, the sensitivity of UT is affected by the mode conversion from longitudinal wave to shear wave in the boundary surface. Therefore, the mode conversion of longitudinal wave in insulation hose was checked. We calculated the mode conversion ratio by means of theoretical values that longitudinal wave velocity is 1250m/s and shear wave velocity is 390m/s. The calculated result on insulation hose is shown in figure 5. This result shows that the mode conversion ratio is only 20% even if the incident angle is 60°in which the conversion to shear wave is the largest. Because the influence of mode conversion is small, the longitudinal ultrasonic wave can be applied for insulation hose.

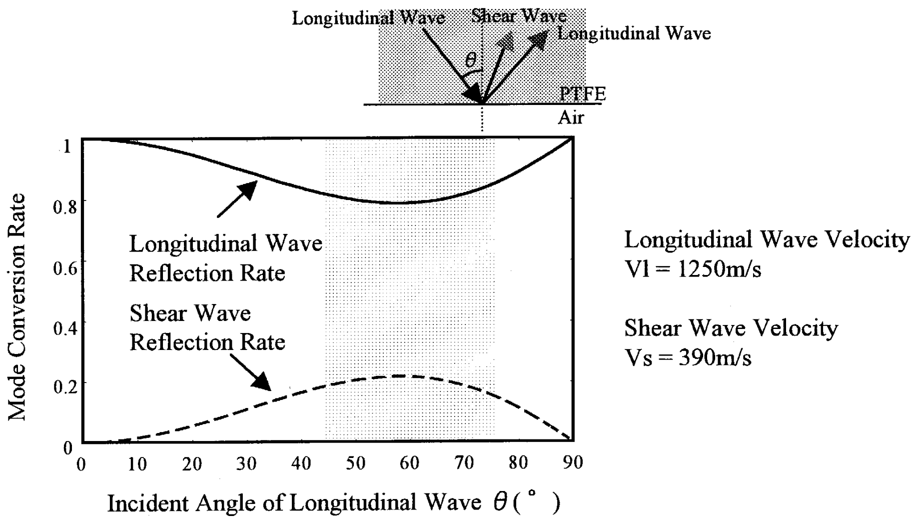


Fig. 5 Ultrasonic Wave Mode Conversion in the Boundary Surface between Insulation Hose (PTFE) and Air

5. Performance Test of UT probes

5.1 Performance Test of UT

We considered several kinds of probes for the different constructions of insulation hose and the direction of the crack. The performance test for developed probes were carried out by means of artificial defect created in insulation hose (the artificial defects were created in the edge of insulation hose; ref. figure 6). The test condition is as follows.

(a) Instruments and test piece

UT angle beam probe: the developed probes for the circumferential cracks, the longitudinal cracks in straight and curved tube, and the circumferential cracks in metal fitting part

Test piece: the artificial defect (defect height: (one tenth), a quarter, two fourths, three fourths, four fourths (hose edge) of hose thickness) were created in insulation hose.

(b) Test procedure

- The maximum echo of the full depth (four fourth) defect was established from the full edge corner of test piece which was flat cross section of insulation hose. The echo of the full depth defect was set CRT (Cathode Ray Tube) 100% on the display by tuning sensitivity. This sensitivity is called standard (basic) sensitivity.
- For metal fitting part, in order to examine the 5 mm inner area from the edge of metal fit hose end, UT probe is fixed in the location of which the distance between the edge of test piece and probe is 5mm, and then we set up CRT100% sensitivity.
- After setting CRT100% sensitivity by full edge, the detection values for one tenth, a quarter, two fourths, three fourths, four fourths of hose thickness were recorded as calibration data.

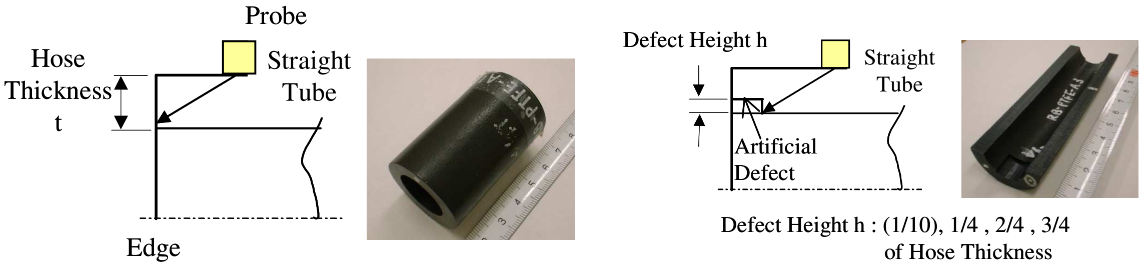


Fig. 6 Test Pieces for UT Calibration

5.2 Performance Test results for artificial defect

As an example of these test results, the UT result of circumferential cracks in the straight tube is shown in figure 7. These data show that the echo level is about CRT70% for the defect with a quarter of hose thickness. In this case, noise echo level was almost CRT10%. Including other probes, echo level for the defect with a quarter of hose thickness is shown in table 2. The summary of calibration results is below.

(a) When the thickness of artificial defects are more than a quarter of hose thickness, the echo levels for longitudinal and circumferential crack in insulation hose are more than CRT40%.

(b) The detecting level was fixed at CRT20% which was almost +6dB higher than the noise level.

(c) The acceptance level was fixed at a quarter (1/4) of hose thickness considering the adequate level difference from the detecting level.

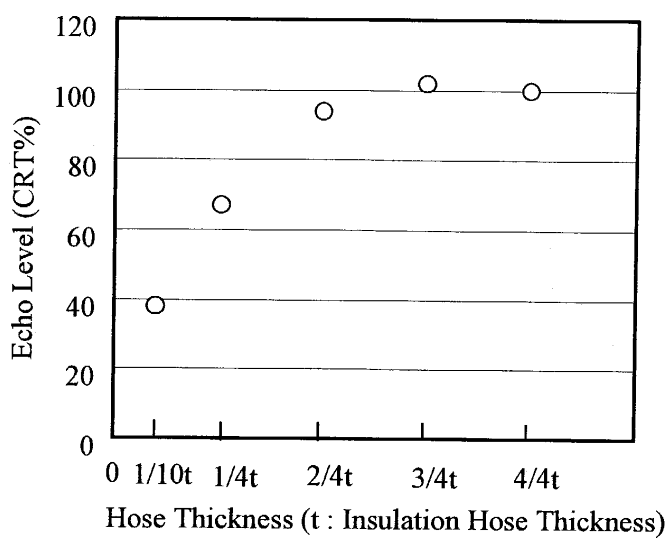
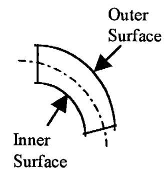


Fig. 7 Calibration Test Results for Artificial Defect (Circumferential Crack for Straight Tube)

Table 2 Detecting Echo Level for Artificial Defect
(Defect: A Quarter of Hose Thickness)

Probe	Test Piece		Transversal Crack	Longitudinal Crack
For Metal Fitting Part	Metal Fitting Part		A	
For Straight Tube	Straight Tube		A	A
For Curved Tube	Small Curved Tube	Inner Surface	B	A
		Outer Surface	B	A
	Large Curved Tube	Inner Surface	B	A
		Outer Surface	A	A



A : 50%～
B : 40～49%

6. Inspection of insulation hose

We applied the developed probes to UT inspection of insulation hose.

(a) Test procedure

- The maximum echo of the full depth (four fourth) defect was established from the full edge corner of test piece which was flat cross section of insulation hose. The echo of the full depth defect was set CRT100% on the display by tuning sensitivity. This sensitivity is called standard (basic) sensitivity.
- We carried out UT after drying by heating and vacuuming in order to evacuate water from insulation hose because water has a bad effect on crack detection.
- In addition, we inspected with +6dB higher sensitivity than standard sensitivity in order to prevent from missing defects.

(b) Application of Distance Amplitude Characteristics

Because the attenuation of ultrasonic wave is large in insulation hose, the depth variation of reflection source (defect) from outer surface makes the difference of transmission distance and the considerable difference of detected echo level.

Regarding the inner defects in the hose, we evaluated the defects by ultrasonic Distance Amplitude Characteristic (DAC) curve which is basically described in JIS (Japanese Industrial Standards) Z 3060 "Method for ultrasonic examination for welds of ferritic steel" and JEAG (Japan Electric Association Guide) 4207 "Ultrasonic examination for in-service inspection of light water cooled nuclear power plant components".

7. Conclusion

We developed a new UT technique for insulation hoses and the following items have been established.

(a) UT probes for insulation hoses were developed and calibrated. By means of these probes, the defect which is more than a quarter of hose thickness can be detected clearly.

(b) It is possible to inspect defects which are in the 5 mm inner area from the edge of metal fittings of hose ends.

(c) Considering the large attenuation of ultrasonic wave in insulation hose, defects are evaluated by applying the DAC curve.

CASE STUDIES IN MAINTAINING PIPING RELIABILITY BY ECONOMICAL PREDICTIVE METHODS FOR INSPECTION PLANNING

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ABSTRACT

Deregulation and regional electricity demands have significantly altered the duty of many power plants. Merchant plants with second generation combined cycle units have forced some older combined cycle units with Heat Recovery Steam Generators into cycling operation after relatively long periods operating base loaded. Rising natural gas prices have made retired coal-fired units competitive as seasonal peaking units in some regions. Nuclear units typically own a majority of the baseload capacity in many areas; all other units are competing for the marginal base load, peaking loads and depending on their operating strategy, AGC operation.

This paper provides results from recent piping inspection planning projects where predictive maintenance methods were applied to limit the scope of piping inspection to high risk locations. The number of locations subsequently inspected were determined typically using economic criteria specified by the Owner. Risk-ranking predictive methods have been developed that combine information from field walkdowns, piping geometry and materials information via engineering calculations of stress and corrosion rates where uncertainties are explicitly considered.

These case studies review inspection plans in high energy piping for high-speed erosion, erosion-corrosion, creep, Type IV weld cracking at newer merchant plant combined cycle units, first generation combined cycle and cogeneration (PURPA) units, circulating fluidized bed units, new low-Nox coal-fired units and traditional radiant coal-fired units. Inspection results have

confirmed that more severe damage occurs in locations with high risk rankings. These results demonstrate that piping integrity can be managed within the economic constraints imposed on the Owner by the deregulated power market.

OVERVIEW

This paper provides an overview of an inspection planning approach that was developed within the ever tightening cost constraints of the deregulating marketplace. Client requirements to identify quantitatively high-risk locations led to the development of simple spreadsheet tools for FAC Wear damage and ranking of highly stressed locations. The approach is being applied at traditional utility power plants, circulating fluidized bed plants, cogeneration facilities in utility and pulp and paper service and gas-fired combined cycle plants. Five Case Studies present results from recent field experiences.

Piping reliability is essential to ensure plant safety and to be successful in an increasingly competitive market place. High energy piping is of most concern including feedwater, drains from high pressure heaters, desuperheat, main steam and reheat systems. Failures of high energy piping systems often result in injury and or death of plant personnel, consequential equipment damage and often require lengthy and costly repairs. Piping failures continue to occur in relatively new as well as older plants and in some cases where extensive inspection programs are already in place.

Figure 1 summarizes the general steps in the process of piping inspection prioritization.

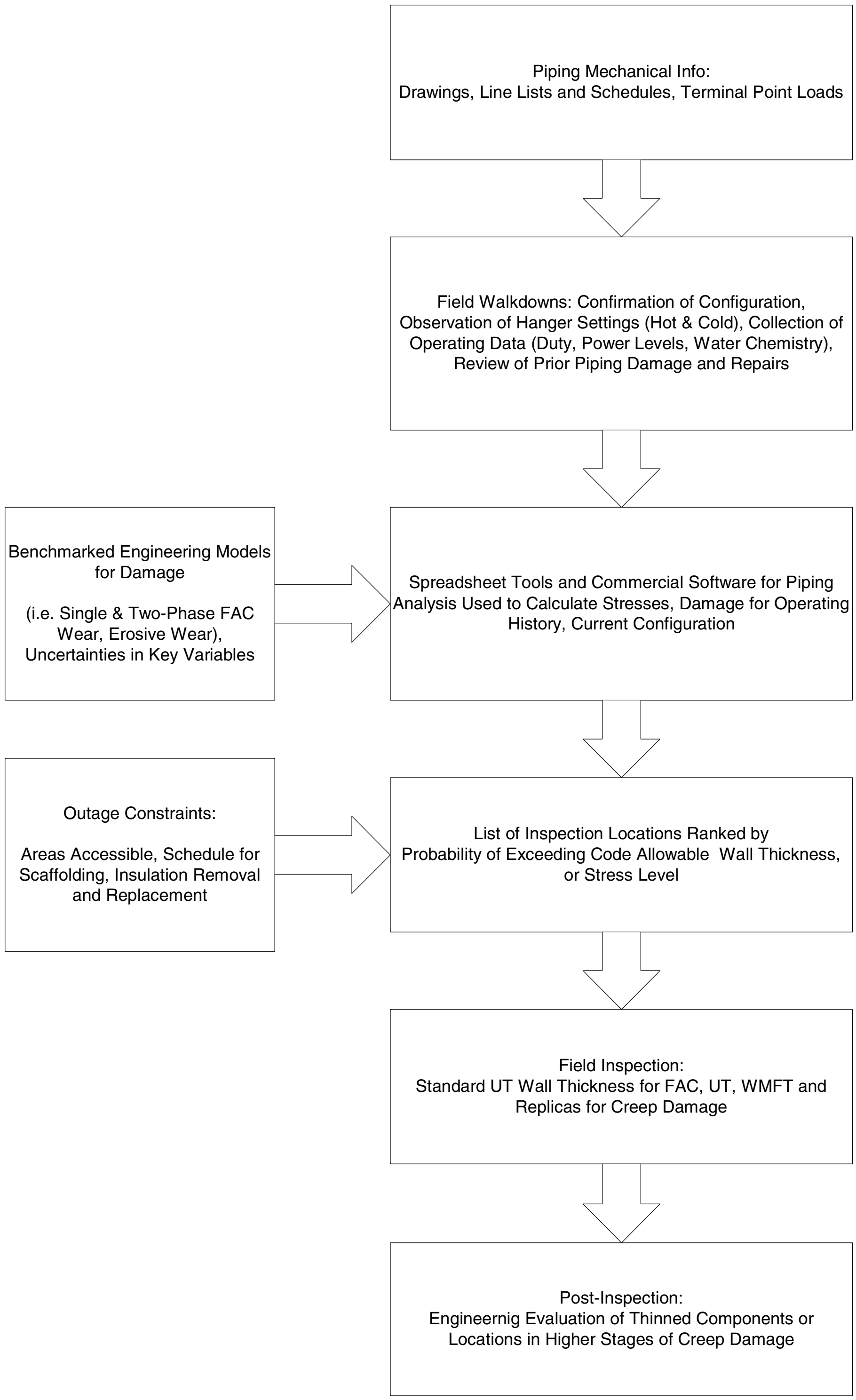

Figure 1. Risk-Prioritization of High Energy Piping Inspection

Plant A

Location/Date Commercial: Northeastern US/1960

Plant Type/Fuel: Tangentially Fired Radiant Boiler/ Pulverized Coal

Rating/Duty: 145 MW/Daily Cycling

History of Piping Damage: Extraction Line Water Hammer ca. 1980

An incremental approach is applied at this Plant to confirm the integrity of high energy piping. For the past 3 years, one line has been selected for evaluation and inspection at each annual boiler maintenance outage. Table A-1 summarizes the extent and duration of these outage activities.

The first evaluation was of the 14th stage extraction line which was subject to severe water hammer event. Figure 2 indicates the significant deformation that was caused by this high energy impulse load. Following review of the field condition including the adequacy of pipe hanger supports, it was decided that NDE inspection was not required. Weight , pressure and thermal expansion stresses were calculated to be within the acceptable limits of the ASME B31.1 Power Piping Code (Reference 1) as required by Paragraph 104.8 in the present as-installed condition considering the operating history of the system. The support system (spring hanger settings) were providing an excess upward load such that the system piping was displaced upward and equipment nozzle loads were excessive. It was recommended that spring hanger loads be adjusted to approach the optimum settings calculated by a piping flexibility analysis. Pipe hangers were then adjusted to restore proper support to the line at temperature.

The second evaluation was a complete FAC evaluation for all susceptible components in the condensate (low pressure) and high pressure feedwater system from the discharge from the condensate pumps to the economizer inlet. Table A-2 provides the recommended inspection list that resulted from applying a risk-based FAC inspection prioritization. The approach is a predictive one with insights gained from the Pleasant Prairie pipe failure (Reference 2) and other industry experience (References 3-6).

Table A-3 shows the reasonable agreement between the maximum wear determined by traditional UT and the maximum predicted from the inspection prioritization analysis. Two tees were determined to have moderate thinning and required further UT inspection and engineering evaluation. Both were determined to have sufficient remaining wall thickness to comply with the branch reinforcement requirements of the ASME B31.1 Code.

A third inspection plan was developed for the Main Steam piping. At Plant A, the Main Steam piping is ASTM Grade A-335-P11 carbon steel (1 ¼% Cr, ½% Mo) that has been inservice for more than 250,000 hours at 1000F and 1950 psig. The steam flow rate is about 1.1 x 10^6 lb_m/hr. This Main Steam piping is 16" in the main spoolpieces with 12" branches to the turbine stop valves and 8" turbine inlet piping. Field walkdowns in the hot and cold condition were performed to record all pipe hanger settings. This information was used in conjunction with terminal loads to perform a complete piping flexibility analysis.

While creep rupture failure of this material was not a concern, Type IV creep cracks at highly stressed weld locations are (Reference 7). Stresses were compared with Code allowable stresses and used with creep life assessment calculations where uncertainties were treated explicitly to obtain an inspection list ranked by risk of (Type IV) creep damage. A weighted least squares correlation was developed to obtain an improved correlation of Larson-Miller parameter with stress. Figure 3 indicates the excellent agreement between the data for P11/T11 and the 95% lower limit vs. stress. 7/12 hangers were readjusted based on the results of the flexibility analysis. Proper support is required to prevent the possibility of sagging (Figure 4) and the attendant high stresses that result at terminal points. Table A-3 presents the Final Inspection List. Figures 5 and 6 indicate two of the inspection locations.

Inspection results did not detect creep cracks in weldment and replica analyses confirmed that the Main Steam piping does not have creep voids forming after 260,000 hours of service.

Table A-1. Inspection of High Energy Piping

Inspection	*Locations*	*Schedule[1], days*
Extraction Line	VT Only	1.0
Condensate & Feedwater	8	3.0
Main Steam	12	3.5

Table A-2. Plant A FAC Inspection

Location	*Recommended Inspection*	*Measured Wear (UT), mils*	*Predicted Upper Limit on Wear, mils*
BFP Discharge to 11th Stage Heater Inlet	UT Nozzle and 2D of 8" SP Downstream on BFP 1-2 Discharge	100	177
	Visual Inspect Check Valve and UT 2D of 6" SP Downstream of Check Valve on BFP 1-2 Discharge	80	133
	UT 100" SP Downstream of Gate Valve on BFP 1-2 Discharge (optional - depending on Check Valve Inspection)	Not Required	
	UT 10" x 10" x 10" Tee and 2D of Branches (BFP Discharge Merge)	106	195
11th Stage Outlet to 8th Stage Inlet	UT 180 deg Bend and 2D Downstream	114	160
8th Stage Outlet to Economizer Inlet	UT 10" x 10" x 10" Tee and 2D Downstream (merger with heater bypass downstream of 145 A-1)	115	102
	UT 2D of 10" SP Downstream of Valve 145 A-2	180	76
	UT 2D of 10" SP Downstream of FWS-AOV LVL-48 and Downstream Valve (no id)	85	102.5
	UT 10" x 10" x 10" Tee and 2D Downstream (merger with heater bypass downstream of FWS-AOV LVL-48)	80	102.3
	UT 2D of 10" SP Downstream of Angled Check and Gate Valve (Just Before Economizer Inlet	Deferred to Next Outage	

[1] Includes estimate of insulation removal, NDE inspection, insulation replacement

Table A-3. Plant A - Main Steam Piping Inspection Locations

Inspection Location ID	*Description*	*Inspection Techniques*
1	Lower Turbine Inlet Nozzle Branch S	UT weld HAZ, MT, Replica
2	Lower Turbine Inlet Nozzle Branch N	UT weld HAZ, MT, Replica
5	Upper Turbine Inlet Nozzle Branch S	UT weld HAZ, MT, Replica
8	Upper Turbine Inlet Nozzle Branch N	UT weld HAZ, MT, Replica
12 and 14	16” Piping at Boiler Superheater Outlet Header	UT weld HAZ, MT, Replica
3 or 4 or 6 or 10	Turbine Inlet 8” Upper Elbows (Branch N or Branch S)	UT weld HAZ
7 or 13 or 17 or 18	Turbine Inlet 8” Lower Elbows (Branch N or Branch S)	UT weld HAZ
11 and 22	16” MOV Gate Valve (upstream and downstream)	UT weld HAZ, MT, Replica
15 or 16 or 19 or 20	Turbine Throttle Valve Downstream (8”) Side	UT weld HAZ
9 and 21	16”x12”x12” TEE (16” upstream and both 12” branch welds)	UT weld HAZ, MT, Replica
23	100° 6’8” LR Elbow at 180’ 0”	UT weld HAZ, MT, Replica

Figure 2. Plant A – 14th Stage Extraction Line – Water Hammer Damage

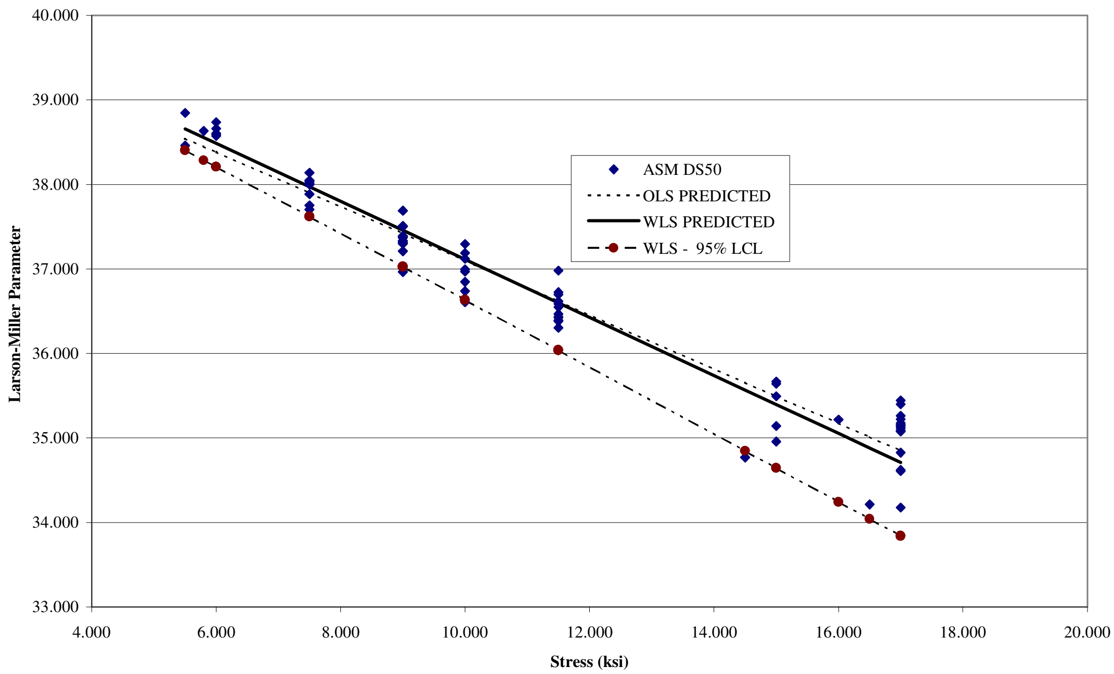

Figure 3. Larson-Miller Correlation vs. Stress (ASM DS50 Data for Pipe, Tube Only)

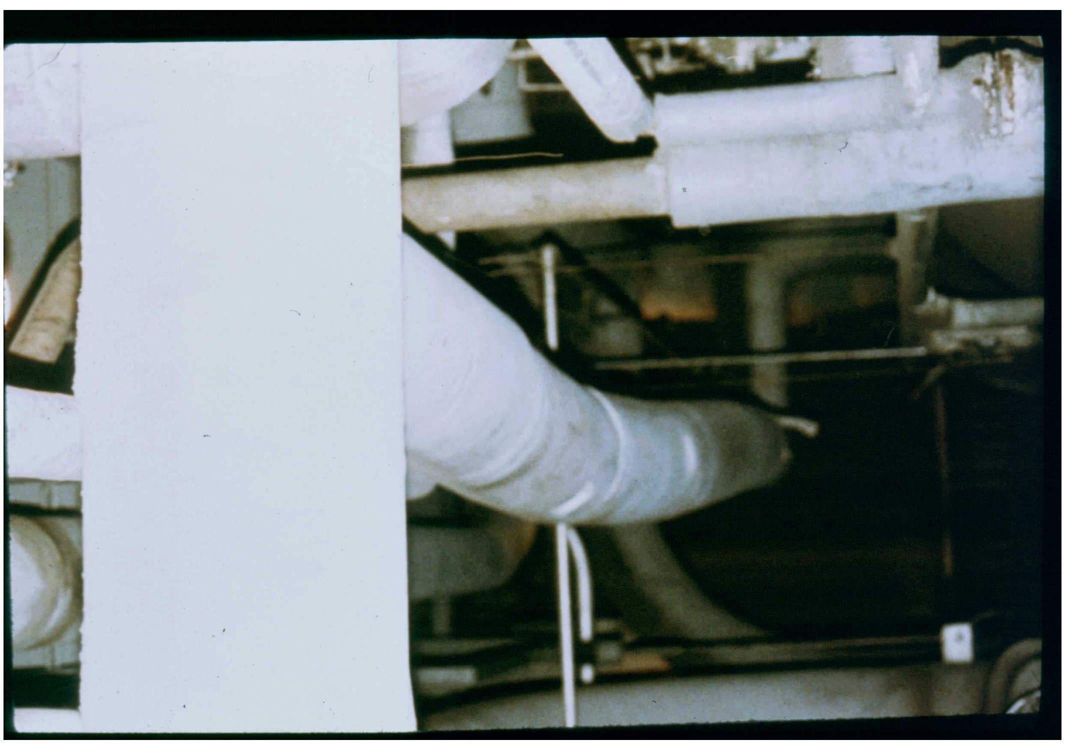

Figure 4. Sagged Main Steam Piping

Figure 5. Plant A Main Steam Outlet Terminal Header Inspection Location

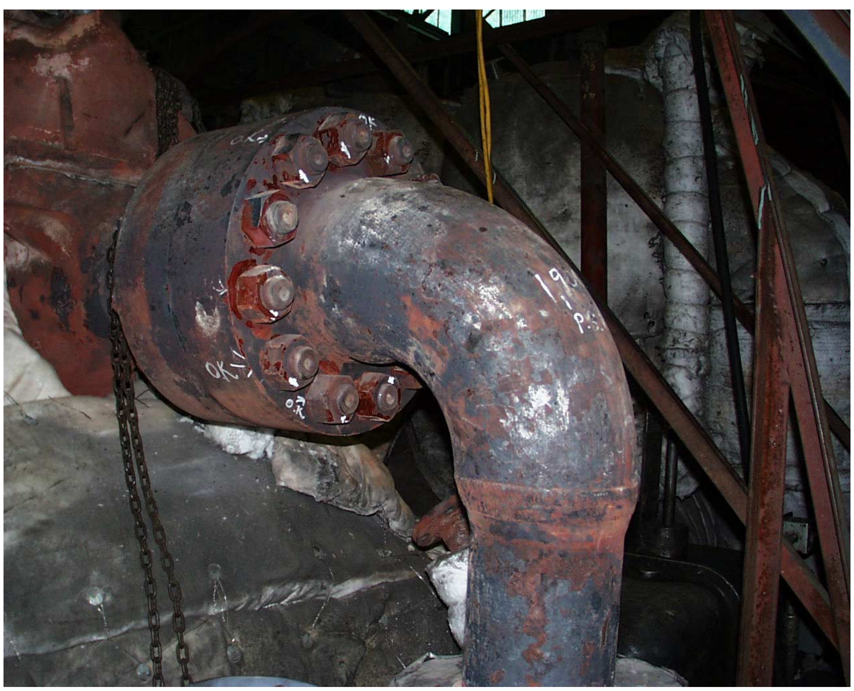

Figure 6. Plant A Turbine Inlet Nozzle Prepped for Inspection

Plant B

Location/Date Commercial: Midwest US/1966

Plant Type/Fuel: Tangentially Fired Radiant Boiler/ Pulverized Powder River Basin Coal

Rating/Duty: 205 MW/Baseload

History of Piping Damage: None

The evaluation at Plant B was a complete FAC evaluation for all susceptible components in the condensate (low pressure) and high pressure feedwater system from the discharge from the condensate pumps to the economizer inlet. Table B-1 indicates the number of locations and schedule for this effort. Table B-2 provides the recommended inspection list and a comparison of the measured wear from traditional UT with the predicted wear.
Figure 7 is a typical economizer inlet area, prepped for UT inspection.

Table B-1. Inspection of Feedwater Piping

Inspection	Locations	Schedule[2], days
Condensate & Feedwater	10	4

Table B-2. Plant B FAC Inspection

System	*Inspection Location*	*Measured Wear (UT), mils*	*Predicted Upper Limit on Wear, mils*
BFP Discharge	UT 5" x 6" Expanding Ell	169	197.7
	UT 6" x 5" Reducer	141	102.6
	UT 6" LR (5D) Elbow	221	194.6
	UT 8" x 8" x 6" Tee	147	201.4
HTR #4 Inlet & Bypass	UT 8" x 8" x 8" Dead Main Tee	358	201.4
	UT 8" 90 LR Elbow	224	197.7
	UT 8" LR 180 Elbow	106	76.3
	UT 8" 45 Elbow	106	145.0
Economizer Inlet	UT 8" x 6" Reducer at Inlet	80	111.2

[2] Includes estimate of insulation removal, NDE inspection, insulation replacement

Figure 7. Plant B Feedwater Piping – Economizer Inlet – Prepped for UT Inspection

Plant C

Location/Date Commercial: Mid-Atlantic US/1994

Plant Type/Fuel: Circulating Fluidized Bed Cogeneration/ Pulverized Coal

Rating/Duty: 225 MW/Baseload, Baseload & 50,000 pph Steam Sendout

History of Piping Damage: Feedwater FAC, Desuperheater Spray Steam Pitting

An incremental inspection approach is also applied at Plant C to confirm the integrity of high energy piping. This is a relatively new coal plant with about 50,000 fired hours. One line (high pressure feedwater) was selected for evaluation at the spring 2001 outage; additional inspections will be performed at future annual boiler maintenance outages. A field walkdown of the Main Steam and Hot Reheat piping in the hot and cold condition was also done to prepare for the future inspection of high stress locations in these lines such as the Wye indicated in Figure 8. Table C-1 summarizes the extent and duration of these outage activities.

UT inspection at Plant C confirmed that, with one exception, all locations inspected still have margin above the nominal wall thickness in the Plant C Piping Line List Specification.

However, this plant has experienced several piping failures due to FAC (see repairs indicated in Figures 9-10). The higher upper limits on predicted wear rates correspond to plant conditions that have a relatively high risk for continued FAC damage. The relative amounts of wear at Plant C after 50,000 hours are of the same magnitude or greater than the wear at other Plants with more than 250,000 fired hours. Reinspection of high-risk components within 3 years was recommended.

Table C-1. Inspection of Feedwater, Hot Reheat and Main Steam Piping

Inspection	*Locations*	*Schedule[3], days*
Feedwater	12	4.0
Hot Reheat	8	Future outage
Main Steam	11	Future outage

Table C-2. Plant C FAC Inspection

System	*Inspection Location*	*Measured Wear (UT), mils*	*Predicted Upper Limit on Wear, mils*
Economizer Inlet	90 Elbow Upstream of Economizer Inlet	336	230
FW Reg Station	Straight Pipe Downstream of FW Reg Station	93	TW
	90 Elbow Downstream of FW Reg Station	316	TW
	Straight Pipe Downstream of MFW Reg Valve	91	TW
	Straight Pipe Downstream of FW Reg Startup Valve	171	TW
BFP Discharge	BFP A Discharge Reducer	187	TW[4]
	BFP A Discharge 45 Elbow	190	TW
	BFP A Discharge Straight Pipe	109	TW
	BFP B Discharge Reducer	188	TW[5]
	BFP B Discharge 45 Elbow	234	TW
	BFP B Discharge Straight Pipe	64	TW

[3] Includes estimate of insulation removal, NDE inspection, insulation replacement
[4] TW: through-wall, these components have failed due to FAC at Plant C
[5] TW: through-wall, these components have failed due to FAC at Plant C

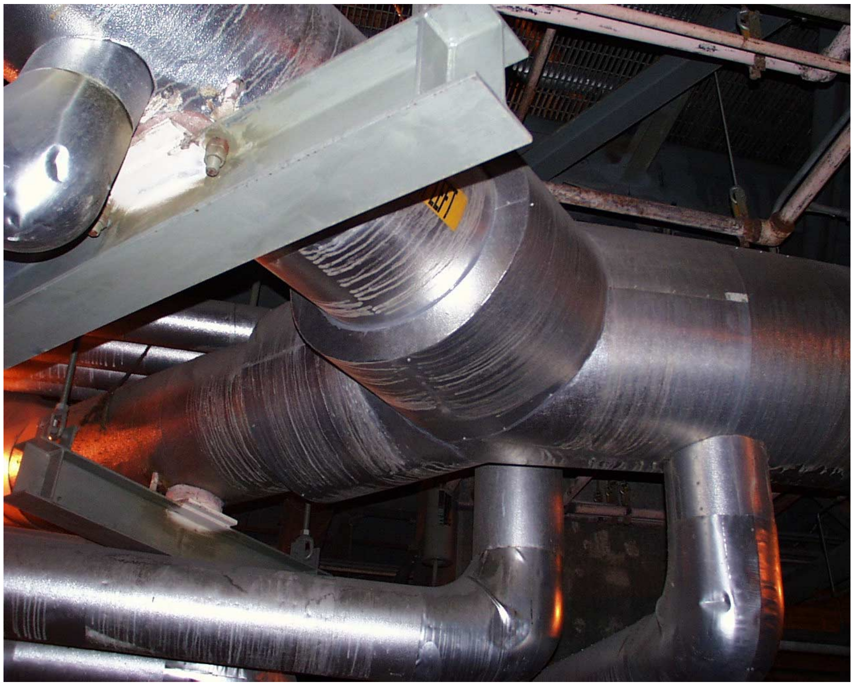

Figure 8. Plant C - Main Steam Piping Wye – Typical High Stress Location

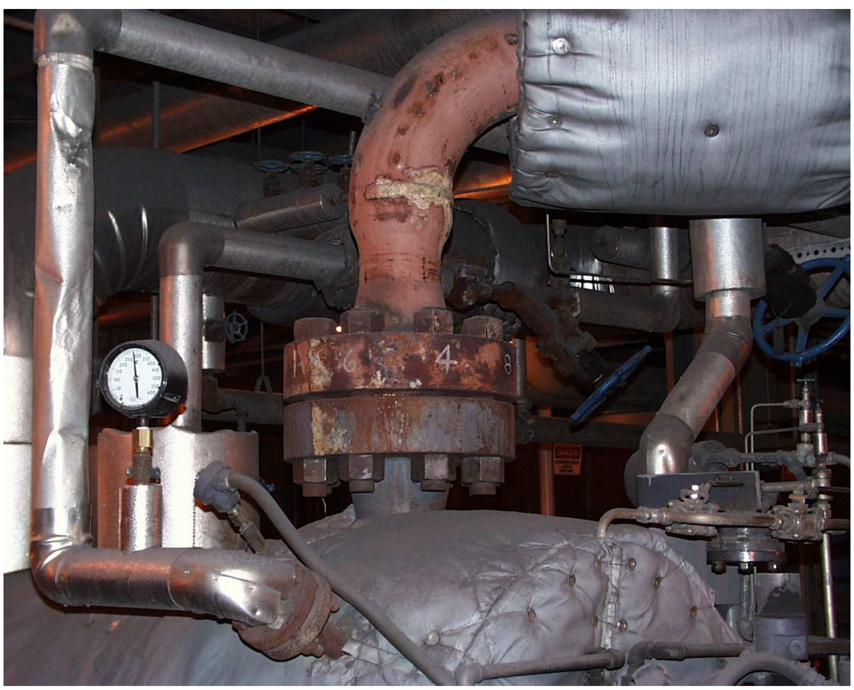

Figure 9. Plant C Feedwater Piping –Repaired BFP Discharge Damaged by FAC

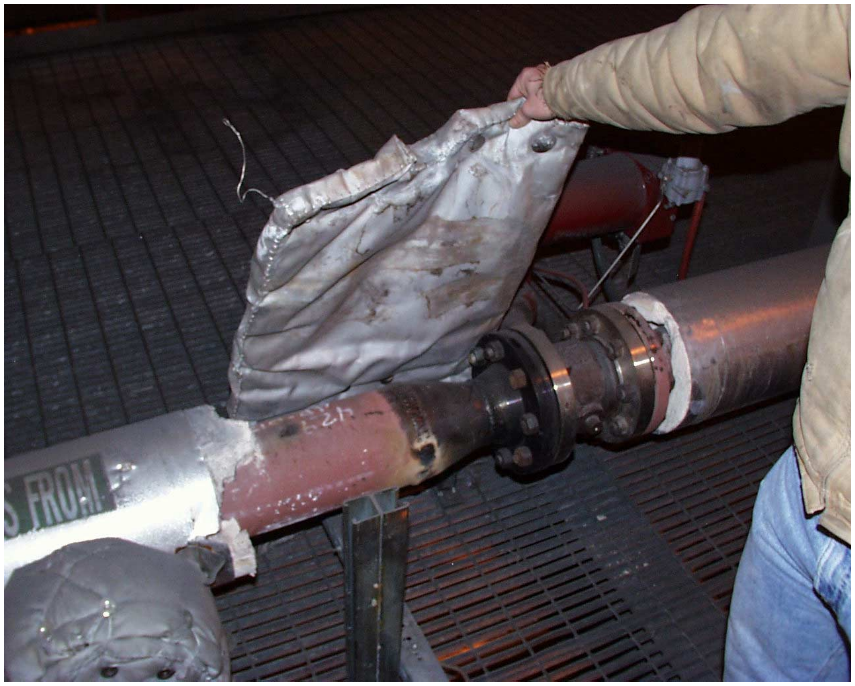

Figure 10. Plant C - Heater Drain Line –Repair of Expander Damaged by FAC

Figure 11. Plant C - Heater Drain Line –FAC Failure of Expander

Plant D

Location/Date Commercial: Southwestern US/2001

Plant Type/Fuel: GT-CC/ Natural Gas

Rating/Duty: 1000 MW/Merchant Plant

History of Piping Damage: None

Pre-commercial baseline measurements of feedwater piping downstream of the boiler feedwater pump regulation valve was made at high risk locations. Table D-2 summarizes the inspection results that confirmed (slight) margin above nominal wall thickness. These results establish a benchmark for future evaluations of wall thinning.

Table D-1. Inspection of Feedwater Piping

Inspection	Locations	Schedule[6], days
Condensate & Feedwater	3	1.0

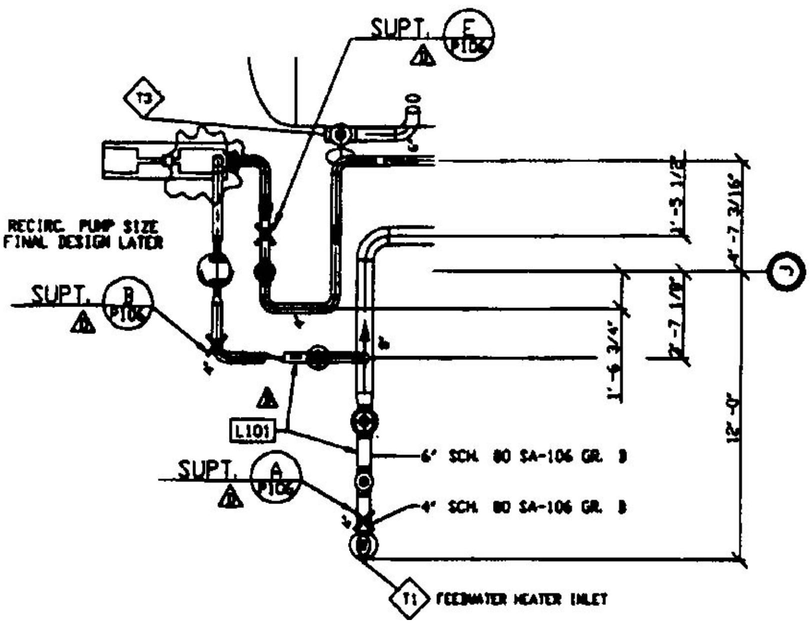

Figure 12. Plant D – Feedwater Piping – BFP Discharge

[6] Includes estimate of insulation removal, NDE inspection, insulation replacement

Table D-2. Plant D Feedwater Piping Baseline

System	*Inspection Location*	*Nominal Wall, mils*	*Measured Wall, mils*
FW Reg Station	Location "A"	500	530
	Location "B"	500	500
	Location "C"	500	520

Plant E

Location/Date Commercial: South Central US/1967

Plant Type/Fuel: Tangentially Fired Radiant Boiler/ Natural Gas

Rating/Duty: 304 MW/Baseload (Summer Only)

History of Piping Damage: None

Plant E currently operates primarily in the summer months, although it was operated baseload for many years. An evaluation of FAC damage to high pressure feedwater piping was performed in 2001. Table E-1 summarizes the extent and duration of these activities. Table E-2 lists the recommended inspection locations and provides a comparison of the measure wear with the predicted wear from the risk evaluation. Standard UT wall thickness measurements confirm that wear has resulted in wall thinning of some piping. Again, these results show good agreement between measured and predicted wear. At this plant, chrome content was verified in range (and in particular, above zero) by material alloy assay. While low chrome content is typical of carbon steels, FAC pipe failures such as the Pleasant Prairie pipe failure have been associated with the extreme of zero chrome content. Reinspection of high-risk components within 5 years was recommended for Plant E.

Table E-1. Inspection of Plant E Feedwater Piping

Inspection	Locations	Schedule[7], days
Condensate & Feedwater	10	3.0

[7] Includes estimate of insulation removal, NDE inspection, insulation replacement

Table E-2. Plant E FAC Inspection

System	*Inspection Location*	*Measured Wear (UT), mils*	*Predicted Upper Limit on Wear, mils*
DA Level Control Station	Tee (Dead Branch)	28	67.3
	Reducer (6" end)	28	143.1
	6" Elbow after Valves	12	143.1
	Expander	24	143.1
	10" Elbow	26	91.2
BFP 2A	Pump Nozzle	124	128.3
	6" Elbow	22	128.3
	Straight Pipe	106	128.3
Downstream of FW Regulation Station	6" Elbow	70	65.8
	6" Elbow	80	128.3

Conclusions

Five case studies were presented in this paper where several strategies were applied to evaluate high risk locations in high energy piping. These case studies indicate that high risk locations for FAC wear can be reliably identified with relatively simple tools. Inspection results tend to confirm the range of wear predicted, although newer plants sometimes experience more damage than older plant based on fired hours. Smaller actual wall thickness and higher flow rates (velocities) may account for some of the added damage to newer units. Also, older units were operated a larger portion of their life baseloaded; newer units are often cycled daily and in some instances seasonally as well.

Examples were also presented of high temperature piping inspection plans and results for highly stressed locations in Main Steam and Hot Reheat piping. Damage to high temperature lines due to creep or Type IV weld cracking is less common than FAC damage. There are therefore fewer opportunities to compare damage identified in the field with predictions used to establish Inspection Plans.

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Development of Expert System with Bayesian Networks for Application in Nuclear Power Plants

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ABSTRACT

A nuclear power plant (npp) is a complex special system that requires detailed health monitoring for improving performance assessment and reliability. This fact brings the application of *on-line diagnosis* and *prognosis* on the modules, systems and components existing in the npp's. In order to apply on-line health monitoring effectively and efficiently, it is necessary to use techniques that can quantify certain issues. The primary issue is quantifying both *the expected performance and the uncertainties* of the system reliability, which is reasoning under uncertainty . In doing this, it is beneficial to know the probability values associated with each possible system state; its availability, reliability and its dependence upon a possible action. The system states and the actions are associated with cost or benefit to the operating system, which is handled by the *utility* concept. Actions represent the content of the *decision making* in the relevant system. An action causes a change of state probability density function (pdf) from a

prior to a *posterior* distribution. *Bayesian Networks (BN),* which are able to handle these challenges in complex environments, are appropriate for application in on-line health monitoring, fault diagnosis and predictive maintenance in the nuclear power plants.

The objective of our work is using the *knowledge engineering* techniques to introduce the *smart expert systems* to nuclear power plant operations. The scope of our project is predicting the behavior of the system under operation and providing advisory information about the possible actions and the net beneficial consequence of these actions. Predictive modeling of the failure progression and diagnosis, as well as the advice concerning maintenance actions for the monitored system is being established by the help of experts' judgements. The knowledge elicited from the experts is necessary in defining the behavior of the system under all possible conditions within the operational domain. This primarily involves three major parts. First part is constructing the functional hierarchy in the monitored system. The second part is providing the state subjective probability distributions. The final part is estimating the relative utility values associated with the states and the actions. The software tool that has been employed in this study as the expert system shell is the HUGIN Prof ™, which uses the Bayesian and decision theories in its inference engine in accomplishing the assessments. The modeling of the systems are made by using the *causal directed acyclic graphs (DAG)* in this tool. This developing product is initially being applied to a high energy, horizontal, centrifugal pump lubrication system mock-up for validation. Our project is funded by USDOE-NERI program.

I. INTRODUCTION

The purpose of this report is to present the concept and development of a prototype expert system to serve as a decision support system for the reliability improvement and maintenance planning in future and currents nuclear power plants. This study is a part of the USDOE-NERI program, "Smart equipment and systems design to improve reliability and safety in future nuclear power plant operations". A nuclear power plant must be maintained to satisfy the Technical Specifications and other rules and regulations during all operating phases, including normal and unscheduled operations. Adherence to these requirements leads to handling a large information database involving numerous plant components. Prediction of the possible fault occurrences, diagnosis of failures to identify which component(s) to maintain is usually time-consuming and it is vulnerable to human errors and omission due to the large scale of information to be handled. Another problem is to determine whether taking a plant component out of service to repair or to apply on-line maintenance to the component is the most beneficial decision. To this effect, a reliable expert system is necessary for sound decision support, on-line diagnosis and predictive maintenance in the nuclear plants. For this, the knowledge of the experts in the relevant area, needs to be assimilated for implementation within the technical information database, that is to say, within the knowledge base of the expert system.

The proposed and developed expert system, within the scope of this paper, focuses on the bearings of the charging pumps in the pressurized water nuclear power plants. The initial task of the USDOE-NERI Smart program has been to:

- Develop a methodology for evaluating plant structures, systems and components (SSCs) to identify those that would benefit most from application of Smart program concepts.
- Select a demonstration component.
- Determine an optimum health monitoring plan for the selected component, including identification of its failure modes.

The main selection criteria included:

- High failure rate.
- Sufficiently long repair time to cause significant lost generation.
- Well-known failure modes.
- Availability of accessible locations allowing sensor installation and data acquisition.

A study of failure rates and modes has been done to analyze data of SSC contributions to forced outages, using the NRC MORP2 database for monthly reports between 1990 and 1999 for 14 PWR and 13 BWR units. The most significant result was the identification of rotating machinery, including pumps, as the primary contributors to forced outages in LWRs. Along with their application in both charging and feedwater systems, this result led to the selection of a high energy, horizontal, centrifugal pump as the demonstration component for the project. From the same study, it has been found that the bearings are the components in the relevant pumps, which serve as one of the most frequent cause of pump failure. Hence, the expert system, which is involved in this part of our project is called the “Smart-Bearings”.

Therefore, the examples in this paper are concentrated around the bearing failure diagnosis and attack the maintenance issues of the bearings with the expert system approach. The computer programs constructed in the modeling of expertise is called *expert systems.* The goal of an expert system is to develop a software tool that achieves a high level of performance on problems that are difficult enough to require significant human expertise and understanding for their solution. The knowledge representation and reasoning paradigm that are adopted for our project are based on Bayesian Theory and Bayesian Networks. The software tool, which is used in preparing the expert system has been Hugin Prof-5.6, which is attained by PhD license from Hugin Expert.

II. KNOWLEDGE BASE

The knowledge base of the expert system is structured with three major modules: (1) the functional hierarchy in operation of the component, along with causal relations, (2) possible set of action decisions, (3) the conditional probability values within the state, and the utility functions for the actions and state changes. These modules, altogether, define the behavior of the component under all defined sequences of operation. The modules (1) and (2) comprise the qualitative information in the knowledge base. The module (3) represent the quantitative information in the technical information database.

1. Functional Hierarchy and Causal Relations

The *functional hierarchy* in the bearings system is composed of the following:

- Top event (failure mode) of bearing-seizure
- Faults that would cause the top event in order of functional relation
- At successive states of the hierarchy, faults that would cause the previous layer of faults in the hierarchy
- Features, which are measured to get information on the status of the relevant component.

The functional hierarchy is an efficient and organizational way of expressing the pre-structure of the system on which the expert system will be applied. Table 1 shows the functional hierarchy that is adopted for this experts system. It also reflects the range of problems that the expert system is expected to solve.

Table 1: Faults and features related to the Bearing Seizure (Failure Mode)

BEARING-SEIZURE	Bearing Seizure (Failure Mode)
BE-CLR	Improper Clearances (Fault)
CLR-TGT	Clearances Too Tight (Fault)
BRG-LUB-TMP	Bearing Oil Temperature (Feature)
BABBIT-TMP	Babbit Temperature (Feature)
CLR-LSE	Clearances Too Loose (Fault)
RATIO-HARM	Ratio of Harmonic Vibrations (Feature)
NUM-HARM	Number of Harmonics (Feature)
CLR-ASY	Axial Asymmetry (Fault)
BRG-LUB-TMP	Bearing Oil Temperature (Feature)
1X-PHASE	1X Phase
2X-SHAFT-VIB	2X Shaft Vibration
BE-LOAD	Improper Loading (Fault)
LOAD-STO	Static Overload (Fault)
BRG-LUB-TMP	Bearing Oil Temperature (Feature)
BABBIT-TMP	Babbit Temperature (Feature)
RATIO-ORBIT-AXES	Ratio of Orbit Axes (Feature)
SHAFT-ECCY	Shaft Eccentricity (Feature)
LOAD-STU	Static Underload (Fault)
RATIO-ORBIT-AXES	Ratio of Orbit Axes (Feature)
ENERGY-BAL	Energy Balance (Feature)
SHAFT-ECCY	Shaft Eccentricity (Feature)
SUB-SYNC-VIB	Subsynch. Vibration (Feature)
LOAD-DYO	Dynamic Overload (Fault)
BABBIT-TMP	Babbit Temperature (Feature)
2X-VANE-PASS	2X Vane Pass (Feature)
SHAFT-VIB	Shaft Vibration (Feature)
VISCOSITY	Oil Viscosity (Feature)
BE-LU	Improper Lubrication (Fault)
LU-PRE	Bad Oil Pressure (Fault)
LU-TMP	Bad Oil Temperature (Fault)
BRG-LUB-TMP	Bearing Oil Temperature (Feature)
LU-QUAL	Inadequate Oil Quality (Fault)
QUAL-CHM	Chemical Contamination of Oil (Fault)
CONCENTRATION LEVEL	Infrared Spectroscopy (Feature)
VISCOSITY	Viscosity (Feature)
QUAL-DRT	Dirt/Debris in Oil
PART-COUNT	Particle Count (Feature)
BABBIT-MASS	Babbit Mass (Feature)
QUAL-DEG	Oil Degradation
VISCOSITY	Viscosity (Feature)

Color Code in the Table 2: Failure Mode, Fault, Sensor Feature

The *causal relations* are derived from the functional hierarchy in this physical system. However, the hierarchy itself is not enough to specify all the causal links among the variables of the bearing system failure. For instance, the cases of improper clearances and improper load are possible cause to yield bearing seizure independently. However, it is also possible to have improper clearances due to improper load, hence this is an extra relation, which cannot be displayed with a simple fault tree or functional hierarchy. Such links, which are suggested by the domain experts, are implemented to the structure of the model.

Each of the variables at this stage of causal-relations-structure, which are the failure mode, faults and features, are associated with discrete states. The states that characterize the faults and failure mode are most of the time *normal, intermediate* and *severe.* There are a few exceptions to this format, where defining a different set of states has been more appropriate.

The states that characterize the features are most of the time denoted as *low, normal* and *high*, which also corresponds to the measurements of these features. There are some exceptions to this format, as in the case of the faults. This is due to the fact that, there are situations where the readings from the features are not considered as "normal" when the magnitude of the measurement is normal. A "low" reading is rather preferred as the healthy measurement at such situations. Then, the states are redescribed as *low, medium,* and *high,* and the consideration is made accordingly.

2. Action Decisions

The module, or the portion of the expert system, which covers the possible maintenance actions, consists of decision-making options. The expert system is aimed to have the ability to draw conclusions and to advise for an appropriate maintenance action based on two concerns. The first concern is the state of the fault/failure mode, which is not known perfectly. The second one is the existence of uncertain predictions of future changes that might follow a particular action. In the way to comply with this aim, action variables are incorporated into the expert system structure. The action variables embed the *trip, maintenance* and *no-action* options. *Trip* corresponds to taking the unit out of service, and maintenance is done when the component is off-line. *Maintenance* corresponds to the situation where service is given to the component when the unit is still on-line operating. *No-action* corresponds to the situation where no service is given to the component either on-line or off-line. The consequences of these options are considered in short time intervals following the actions.

In decision making on the probable actions, the model considers taking the most beneficial option based on the net utility joined with each relevant variable (fault or failure mode) in the structure. The details of the utility concept are presented in Section III .

At this stage in building the knowledge base of the expert system, the overall structure is as in Figure 2a-e. This is an influence diagram of the smart-bearings. The influence diagram shown in Figure 2a-e includes the directed acyclic graph of the causal relations, the decision nodes for the actions and the relevant utility representation. The meanings and the functions of these terms will be presented in Section III. At this point, it is sufficient and informative to lay out the basic structure in the knowledge base of the expert system.

III. HOW THE EXPERT SYSTEM TOOL WORKS

There are two main components of the expert system. These are the knowledge representation, and the reasoning paradigm.

The knowledge representation is made of two sources:

- *qualitative part:* the graph representation,
- *quantitative part:* the associated probability model,

where each part is constructed by knowledge elicitation from the domain experts for this project. The graph representation covers the *directed acyclic graphs* and *the influence diagrams.* The associated probability model, for reasoning under uncertainty, for the quantitative analysis in the solution is *Bayesian* and *decision theories.*

1. Graph Representation

The qualitative representation of the causal relations is handled with the use of the *directed acyclic graphs (DAGs).* The graph determines the structure and the semantics of the reasoning. The variables (the failure modes, the faults and the features in the structure) together with the directed edges (the casual directions) form the DAGs. Each variable in the DAG has a finite set of mutually exclusive states. These were explained in Section II, as for instance, *low, normal, high* for the feature variable states, *normal, intermediate, severe* for the fault or failure mode states, etc.

The DAGs are complemented with the decision and utility concepts, and the relevant nodes, in this study. Therefore, in fact, the DAG is extended over the chance nodes (for the variables: the failure modes, the faults and the features), decision nodes (for the actions: trip, maintenance, no-action) and the utility nodes (for the cost/benefit). The extended version of the graphical representation, which cover the decision trees along with the causal relations between the variables, is the final *influence diagram.* The requirement on the influence diagrams is that there is a directed path comprising all decision nodes. This is to indicate the order of decisions taking place in the structure. However, until this part of our study, the order of decision has not been an important point. Therefore, the connections are made to comply with the theoretical and computational requirement.

2. Probability Model

The reasoning under uncertainty is handled by using the Bayesian Theory and the decision theory, as the probability models. Hence, in the diagrams, to each variable *A* (fault C_, failure mode F_, feature S_) with other parent variables, ($B_1, B_2, \ldots, B_n$), there is attached the potential table, or the conditional probability table $P(A| B_1, B_2, \ldots, B_n)$. This brings the definition of the graphs to *Bayesian Networks.*

The probabilities over the unobserved variables, given the setting of the observed variables (i.e. evidence) should be computed. This is *diagnostic* reasoning task, where effects are made known and the causes are inferred. The computations involved in this inference are spent on making the relevant pieces of gathered information explicit. That is to start with the measured features, and to infer to the possible fault or failure modes, which would be the causes to the changes in the feature readings. This is the propagation in the opposite direction of the causal arrows, and the computations are held with the Bayesian theory.

The basics behind the Bayesian theory is summarized as follows:

Conditional Probability: The basic concept in the Bayesian treatment of certainties in causal networks is *conditional probability.* A conditional probability statement is of the following kind:

"Given the event b, the probability of the event a is x"; $P(a|b)=x$

Fundamental rule: $P(a|b)P(b) = P(a,b)$;

where *P(a,b)* is the joint of the event *a* and *b.*

Bayes rule: $P(b \mid a) = \frac{P(a \mid b)P(b)}{P(a)}$,

where the probabilities can be based on frequencies or may also be subjective estimates of the certainty of an event.

In the current calculations, the tool adopts the chain rule for Bayesian Networks, which is stated as:

The chain rule for Bayesian networks: Let BN be a Bayesian network over the set of variables $U = \{A_1, \ldots, A_n\}$. Then the joint probability distribution P(U) is the product of all conditional probabilities specifies in BN

$$P(U) = \prod_i P(A_i \mid pa(A_i)),$$

where $pa(A_i)$ is the parents of A_i. Let $\underline{e}_1, \ldots, \underline{e}_n$ be findings - evidence -, then

$$P(U, e) = \prod_i P(A_i \mid pa(A_i)) \prod_j \underline{e}_j,$$

and,

$$P(A \mid e) = \frac{\sum_{U \setminus \{A\}} P(U, e)}{P(e)}.$$

The task of determining the actions to take on the faults are computed on the criterion to have the highest expected utility. The usefulness of a decision or the usefulness of the state of a variable can be measured on the utility scale. Since there are several kinds of utilities in this problem (as the utility of an action, which is the relevant cost, and the utility of a state, which is the beneficial availability of the component), these scales are assigned a common unit. This assumption may seem dubious but has a sound reasoning. Then, this optimization is managed as in the decision tree solutions, with the concept of expected utility. For each set of actions, D, (which are left the same for this part of the project: trip, maintenance, no-action), the expected utility, EU, is calculated over the domains $X_1, X_2, \ldots, X_n$ (the states of the faults or the failure modes in this study), with the utility functions (or values) $U_1, U_2, \ldots, U_n$, given the evidence, *e*, (which is collected from the measured features).

$$EU(D \mid e) = \sum_{X_1} U_1(X_1) P(X_1 \mid D, e) + \ldots + \sum_{X_n} U_n(X_n) P(X_n \mid D, e)$$

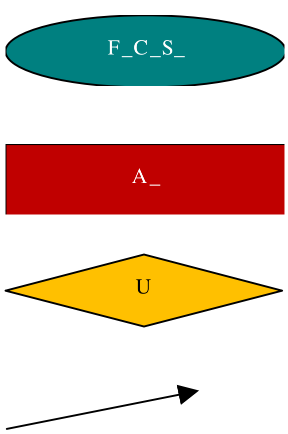
and a decision action, *d*, from the set D, maximizing EU(D|e) is chosen as an optimal action.

In the structure of this problem, there are three utility function sets related to each fault. First is the utility of the action, second is the utility of the states of a fault before an action is taken, and the last is the utility of the states of a fault after an action is taken.

During the course of this study, the utility values have not been elicited from the experts, yet. Therefore this task is not completed. However, it will be done in the future work.

Table 2: Nomenclature in Expert System Structure

F_xxx	Discrete chance node representing a *failure mode xxx* from Table 1
C_xxx	Discrete chance node representing the *fault xxx* from Table 1
y_xxx*	Discrete chance node representing the *fault or failure mode, y, of xxx* from Table 1, after an action is taken
A_xxx	Decision node representing the decision on actions to *fault or failure mode of xxx*
U_xxx	Utility node representing the value of the *state of the fault or failure mode of xxx*
U_A_xxx	Utility node representing the cost of *an action on the fault or failure mode of xxx*
MED_xxx_#	Discrete chance node representing the *mediating variable for the failure mode, fault or feature xxx, appearing* $\#^{th}$ *time*



Discrete chance node for failure mode, fault or feature, associated with a conditional probability table in the input

Decision node, associated with a set of actions

Utility node for cost/benefit/expected utility analysis, associated with a set of values.

Causal relation link between the cause and the consequence

Figure 1: Variables that are used in the Expert System

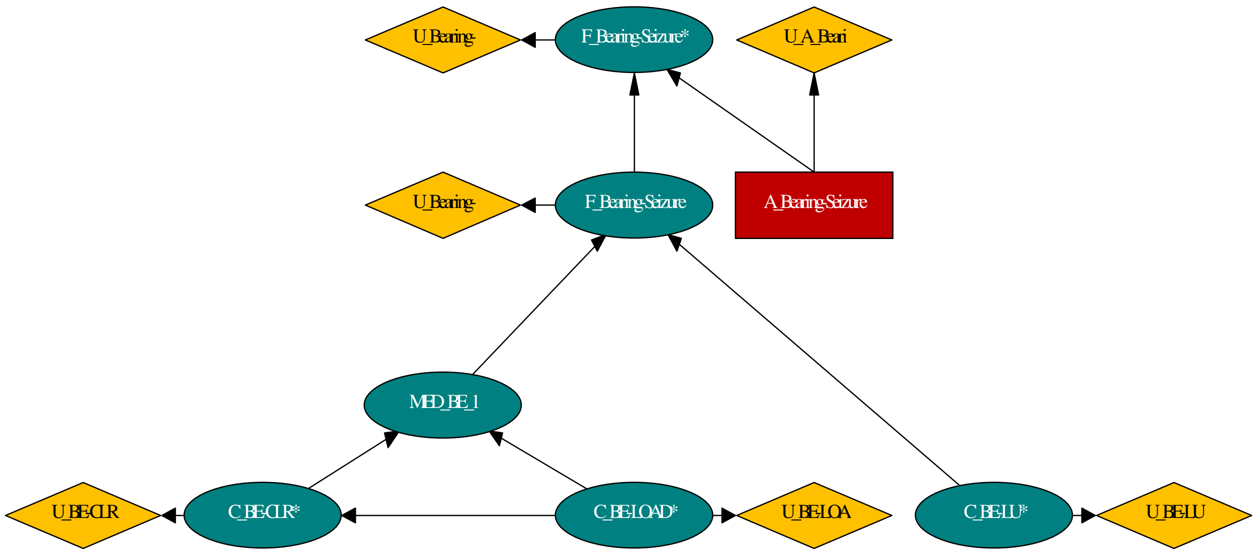


Figure 2-a: Top Part of the Complete Structure – Influence Diagram – of the Smart Bearings

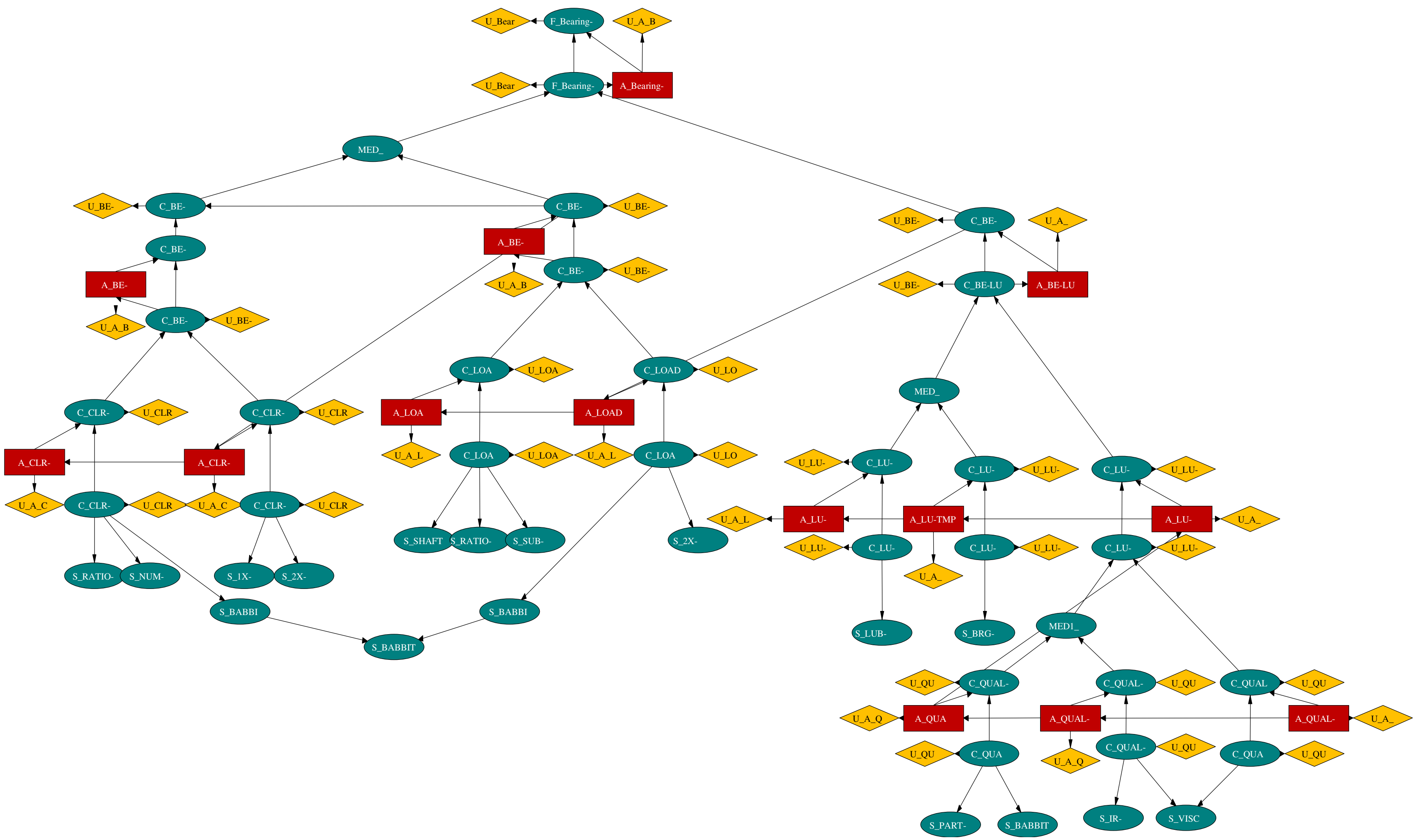


Figure 2-b: Complete Structure – Influence Diagram - of the Smart-Bearings

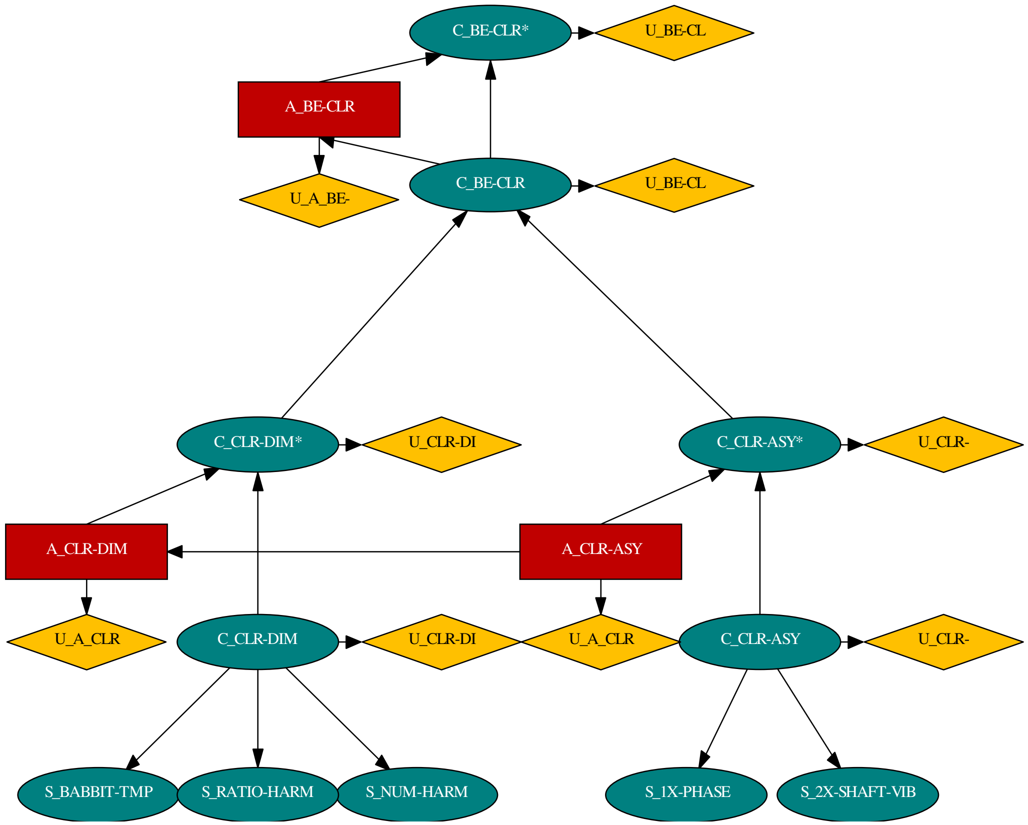


Figure 2-c: The Branch Related to Improper Clearances in the Complete Structure – Influence Diagram – of the Smart Bearings

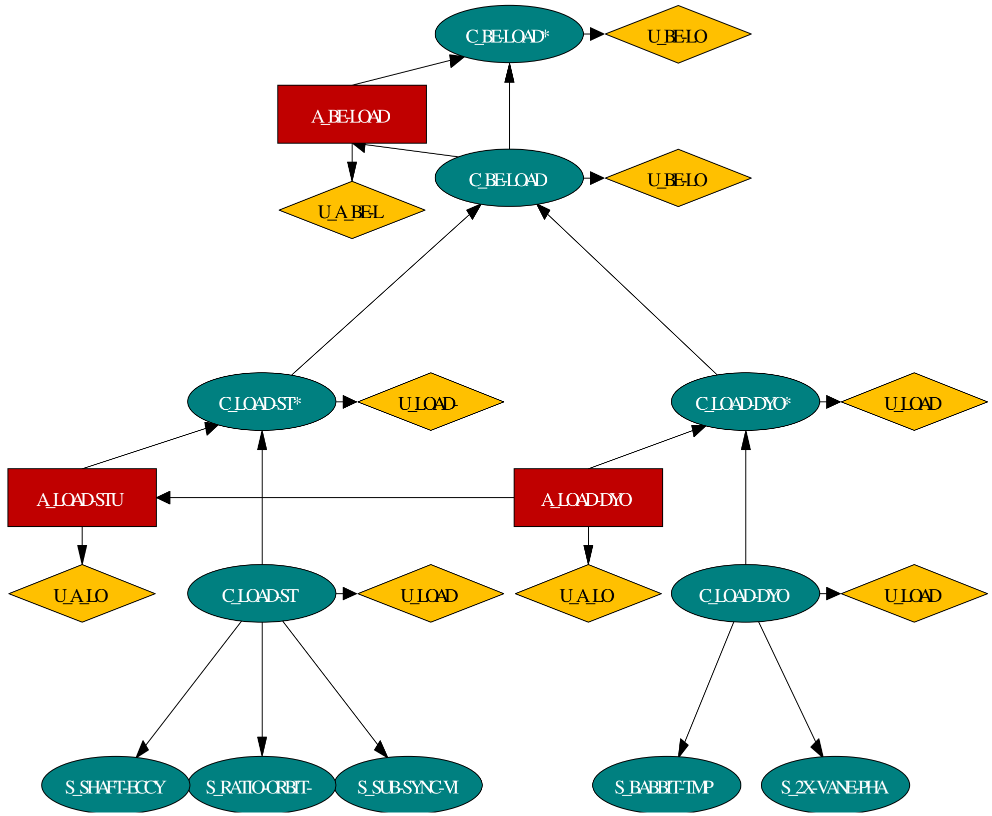


Figure 2-d: The Branch Related to Improper Load in the Complete Structure – Influence Diagram – of the Smart Bearings

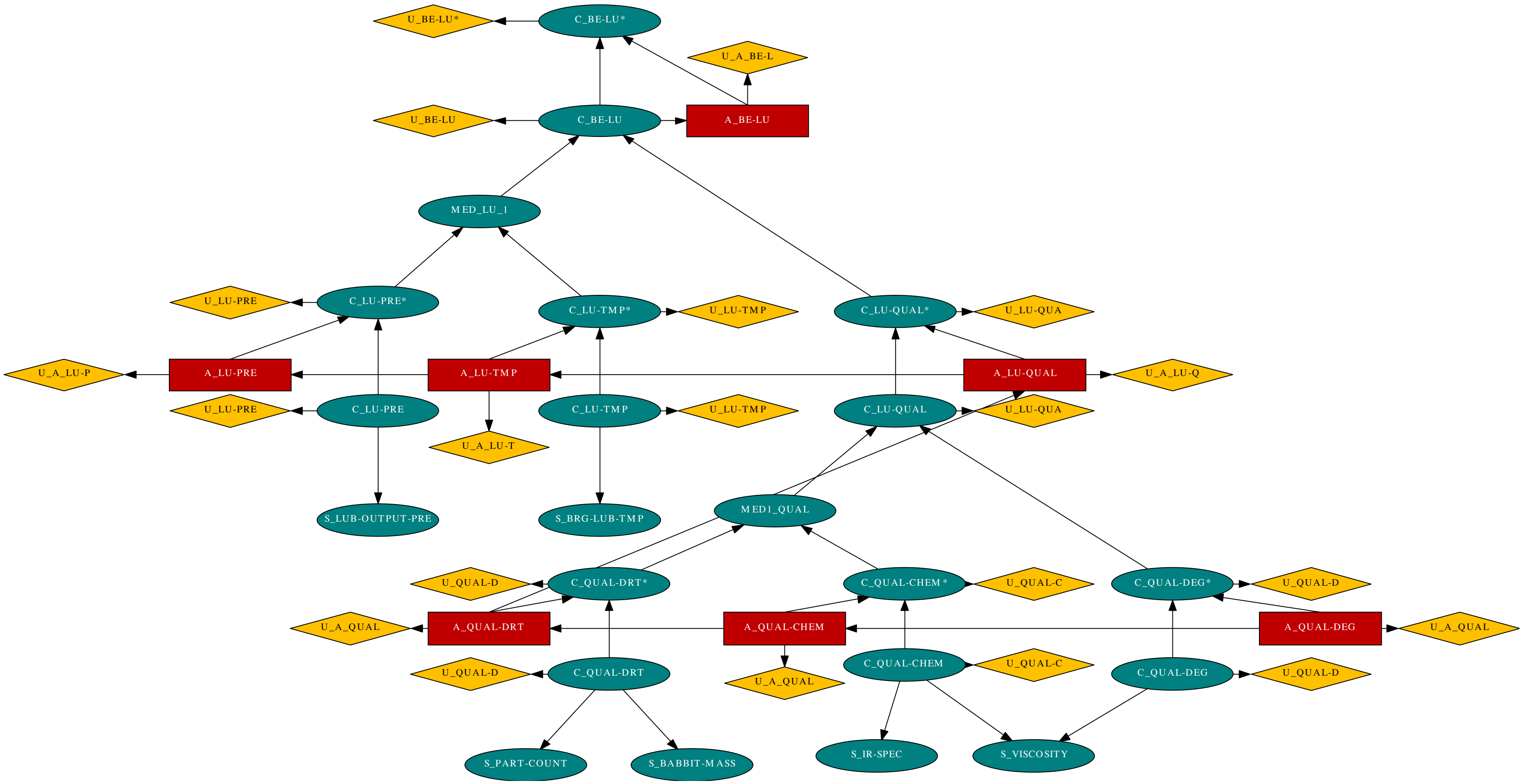


Figure 2-e: The Branch Related to Improper Lubricant Properties in the Complete Structure – Influence Diagram – of the Smart Bearings

3. The Conditional Probability and Utility Values

The quantitative information embedded in the knowledge base is composed of the conditional probability input values and the utility function values.

The basic concept in the treatment of uncertainties in the above causal networks is conditional probabilities. This is the probability of an event in the model (the event at the end of the arrow = child), given the evidential event (the event at the beginning of the arrow = parent). However, there is lack of sufficient data to derive the conditional probabilities in terms of frequencies. Therefore, these probabilities are elicited from the experts in terms of subjective estimates of the certainty of events modeled in the structure of the expert system.

The second part of the quantitative information in the data base is the utility values associated with the state changes, and with the actions. The need for this is due to the treatment of the decision problem embedded in this structure, with the utility theory. The decisions are evaluated on the basis of the usefulness of their consequences. The usefulness is measured on the numerical scale called *utility scale* in the scope of this project. However, the utility values have not yet been elicited from the experts. This is a near future work to be completed for activating the decision making ability of this developing tool.

IV. THE TASK OF SMART BEARINGS -ILLUSTRATION

The experts system designed for the bearings in the charging pumps is able to comply two tasks. The first one is to diagnose possible faults associated with the operation of the bearings given the measurements on the features, which are the eventual symptoms. The second is to predict how the measurements could change at certain faulty operation. Another feature of the system, which has been one of the purposes but which couldn't be finished is its ability to make decision about taking maintenance actions. This is not possible, yet, because the part in the knowledge base which helps to make the decisions is not completed. This is one of the future work on this system. For instance; for "high" readings on the measurements of the features "ratio of harmonics" and "number of harmonics", the system indicates that the possible failure is in the clearances of the bearings. However, clearances could fail due to dimensional fault or asymmetry. The system especially diagnoses that the failure is in the dimensional failure of the clearances rather than the asymmetry failure. This is a very reasonable finding, validated by the domain experts.

Example:

The set of measurement readings are on 1X-Phase and 2X-Shaft-Vibr. The reading for 1X-Phase shows “high” and reading for 2X-Shaft-Vibr shows “medium”. These are to be entered by the user, by clicking on the high and low states of these variables in the run mode of the program. In the run mode, all the state probabilities of all the variables are available to the user to be accessed through the graphical user interface. The evidence entry is now by the user, however, in actual operation it should be with no user interface, where data should be fed to the entries directly. The readings of the measurements, which are entered to the program, are the new evidence of the expert system. The next step is to propagate the new evidence through the structure. This initiates the mathematics of the tool (as explained in Section III). The new probability distributions for all the states of all the variables are displayed to the user. The new evidence shows its effect by changing the probability distribution on the states of the relevant faults only. In this case, the system indicates that:

Table 3: Example problem

States	Asymmetry		Clearances	
	Initial Probability Distribution	Final Probability Distribution	Initial Probability Distribution	Final Probability Distribution
Normal	0.7	0.488	0.361	0.331
Intermediate	0.2	0.233	0.309	0.304
Severe	0.1	0.279	0.33	0.365

No other state probability changes are observed in the resulting list, therefore the indication is that the likely failure is from the clearances of the bearings, and specifically due to asymmetry.

Range of problems: At this stage, the expert system can handle the range of problems, which are listed in Table 1. These are all the faulty operation states that the bearings can face. The system can accomplish the diagnosis task with discretely given measurements in discrete states. When a new module based on rule base is added to the lower level of the system, the readings can be categorized rather continuously, and the system can handle more uncertainty by different ranges of feature measurements.

In addition, when there are multiple symptoms of different fault states, it is rather easy for the system to determine the faults, because almost all the features that are relevant to each fault are separate. In the course of this study, this has been accomplished by providing as much different features as possible for each fault.

The currently lacking part of the system is the inability to give sound advice on the maintenance actions. This will become possible after eliciting the relevant utility values from the domain experts.

V. CONCLUSIONS

The designed expert system is able to well handle various diagnosis aims given the collected evidence by entries in the run-mode. This is propagation in the opposite direction of the causal relation arrows. The evidence collected refers to the state of the features. It is also able to well predict what the behavior of the features, or of another fault, which are connected to the current fault variable, will be. This is propagation in the direction of the causal relation arrows in the graphs.

The knowledge presentation, which covers both the qualitative and quantitative information in the form of graphical representation, has been found very useful and convenient. The software tool to utilize these features was also very well serving.

The knowledge and reasoning related to the functional hierarchy and to the causal relations was rather easily elicited from the domain experts, and translated to the graphical representation and solution. There have been iterations and changes in the overall structure during the development, but this is an expected consequence due to the nature of the task.

The quantitative information, which is the conditional probability tables associated with each variable in the structure, was very hard to elicit and complete. This is due mainly to two reasons. The first is the complex structure of the physical system. The second is the depth in which the expert has to think while providing his subjective assessment of the probability values. Eventually, once this level was overcome, the result was quite strong and efficient in complying with the task..

The system, at the moment, cannot give accurate advice on the actions because the utility values have not been provided by the domain experts, yet. However, this does not mean that the system cannot do it. It is designed and structured to be capable of handling this task, too. This aim will be accomplished in the following studies.

The conditional probability tables associated with each variable in the structure, was very hard to capture, due to the reasons that were mentioned in the previous section. This is a built in problem in Bayesian techniques, due to exponentially growing amount of information, which becomes necessary as one increases the number of parent nodes. This is a burden on the experts while trying to yield their knowledge. This problem has been overcome by adding mediating variables to the Bayesian networks. These mediating variables do not represent any physical variables related to the bearings system itself. But they combine two parent nodes at a time, to carry the information form them. Then, the mediating variable itself is combined with the other nodes to the common child node. This changes the resulting probability distributions slightly, but doesn't change the set of possible diagnosis options much, because the mediating variables have the similar set of states as faults, and the tables relevant to them are completed appropriately, too.

There have been several issues that have been noticed during the course of this study. The main points are:

- It is difficult to get hold of the domain real experts. Though, when they are available, they are very helpful and efficient with the correct approaching manner. There is need to the experts yet to complete the quantitative knowledge base, to have the system work more thoroughly.
- It is almost impossible to get the knowledge correct at once. Iterations have been necessary to the structure of the model and to the quantitative knowledge base during the development of the expert system.

Both points are the main issues which are being dealt with in expert system design in the field of artificial intelligence applications in the industry.

This approach to handling on-line diagnosis and predictive maintenance with expert system design will allow plant designers to simplify designs without comprising reliability and safety. It is taken as another step to move towards a risk-based regulatory concept and application. In addition, this methodology provides a blueprint for creating the capability to predict the mean time to failure of the SSCs, therefore becomes an aid to decrease the operations and maintenance costs, while enhancing the reliability.

FUZZY DIAGNOSIS SYSTEM TO GENERATORS

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Abstract

Part of hidden insulation troubles in a power plant are simply caused by over-maintenance, for maintenance is considered as some sort of interference with the stability system. Condition monitoring, diagnostics and predictive maintenance are crucial problems for discussion. The insulation condition monitoring and diagnostics to generators with the technology of radio frequency and fuzzy diagnosis is a contribution to condition-based maintenance, which has been confirmed in practice. The generator is an apparatus with complicated system. There are no definite mapping relationships amongst symptoms, causes, effects and faults. A fuzzy set offers an adequate description of objects and things in their neutral and transferring state. The application of the concept and method of a fuzzy set to insulation fault diagnosis of a generator is characterized by multi-factor diagnosis and simulation of human thought. It can use the amount of fault symptoms already available to determine the condition of the insulation system of a generator and reveal the trend of future development in order to eradicate the faults thoroughly. The majority of generator failures are caused by short circuits resulting from the damaged insulation. The expert system proposed in this paper centers on the SJY-1 RF Monitor for condition monitoring, and adopts a two-level diagnostic function (Level 1 is on-line radio frequency automatic monitoring and diagnosis, and Level 2 is off-line and questionnaire-type interactive diagnosis). Therefore, it can cover a large scope of insulation faults in a generator.

Key words: generator; insulation; fault detection; condition based maintenance; fuzzy diagnosis; expert systems

0 Introduction

A generator failure usually occurs suddenly. When a generator fault happens, it will be a disastrous event. Hence, fault diagnosis for the power system is always an attractive research field today.

Every turbine generator has a relay protection system, and all the relay protection devices will be adjusted to certain required values. When the operation parameter and the condition parameter reach or exceed the preset values, the relay protection system will give an alarm or cut off the power, which is a traditional way but not a positive way for generator protection. Switching off the system as a result of the protection will often cause serious damage to electrical equipment and make big economic loss. So the generator failure must be detected beforehand and this is what is called fault diagnosis, which aims at taking preventive measures to stop any failure from happening.

On the other hand, the majority of generator failures are caused by short circuits resulting from the damaged insulation. The SJY-1 Radio Frequency Monitor developed by SSPU can perform on-line monitoring of the insulation condition of a turbine generator, and therefore it can serve the purpose of giving fault warnings beforehand. There are about 70 such instruments running in China these years and we have already accumulated quite a lot of running experience. On the basis of this, there are subjective and objective conditions for setting up and developing a generator diagnostic and expert system, and it is possible to make further improvements on ways of maintenance for faults and failures, changing from the existing Breakdown Maintenance and Preventive Maintenance to Condition Maintenance. Thus, the overhaul cycle can expect to be prolonged from 4 years to 7 or 8 years, and the service period of a generator can be extended, hence promoting the scientific management of the power equipment.

1 The Fuzziness of Information Environment of Generator Breakdowns

The structure of a turbine generator can be divided into several major subsystems, including stator, rotator, hydrogen, oil, water and so on and the concerted working of these subsystems ensures the normal operation of the generator. The aging of insulation is mainly caused by such factors as electricity, heat, mechanism and environment, and it is quite difficult to make an accurate estimation of the insulation condition. This is because among most of the operational parameters of the system, there are neither strictly logic nor definite quantitative relations, so the relationship between the phenomenon, principle and mechanism of a generator failure is quite an uncertain nature. On the one hand, one failure may be expressed in the form of several kinds of fault symptoms; on the other hand, several causes of a failure may display only one fault symptom at the same time, i.e. there is no one to one correspondence between failures and fault symptoms. The relationship between failures and fault symptoms is fuzzy and complicated, so it is quite difficult to perform fault diagnosis by establishing a precise mathematical model.

The uncertainty of something can be expressed as randomness and fuzziness. Randomness is caused by the uncertainty of causality of things, which is dealt with by probability and statistics; fuzziness means that the boundary of something is unclear, ie. there is neither definite meaning in terms of quality nor clear boundary in terms of quantity. The fuzzy conception of indefinite boundaries is an objective attribution of the matter. It is the result of the transition that exists between differences of things, and not caused by the failure of a man's subjective understanding to match the objective reality. Randomness and fuzziness are both independent of and related to each other. The uncertainty of the running condition and failure phenomena of a generator is expressed in the form of either randomness or fuzziness, and even after the breakdown happens, the result may be fuzzy.

On the other hand, the complexity means fuzziness. The more complex is a system, the less of precise capability in significance. Therefore, it is more intensive with its fuzziness. As a turbine generator is a complicated system with many factors, it is unable to consider all factors with it. Only major factors can be studied, in other words, it is studied in the compressed lower factor space. This makes conceptions fuzzy. Generally speaking, a difficulty problem may be simplified if deal it with different ways, or with a suitable description. Our expert system, in which conceptions and methods of a fuzzy set are used, is relatively simple and suitable for the turbine generator.

2 The Scheme of a Fuzzy Diagnosis Expert System for Insulation Faults in a Generator

(1) Range of Application

300MW and 600MW turbine generators.

(2) Diagnosable Fault Types

Generator faults of electricity and insulation.

(3) Features of the Expert System

1) Two-Level Diagnostic Functions

Level I – online monitoring and fault diagnosis of the insulation condition of a generator, using the data of a RF monitor.

Level II – questionnaire-type interactive diagnosis, which includes

i. Searching archives for the history of a generator.

ii. Analyzing data, such as temperature, pressure, vibration and etc.that are obtained by means of other detection instruments. These dynamic signals in the generation process carry rich information about the condition of a running generator.

iii. Searching for relay protection information of possible fault places.

2) Resort to the Expert.

It is possible to correct or change an answer to a problem in the interactive diagnosis.

3) Reasoning

i. Beginning with measured data, regulation is got from knowledge library by forward inferring which is based on reliable factors and is a determined process. When more information is needed, backward inferring is used. According to the possibility of fault cause, diagnosing sequence is listed which will be fuzzily sorted.

ii. For an undetermined fault, it is difficult to locate a fault place. To diagnose multi-factor fault, fuzzy clustering is used which use many distinctive expert experiences and multi-factor technical diagnoses information. By fuzzy logical reasoning, it is possible to reveal a fault in a small range.

4) Structure of the System

The expert system contains several parts, such as fuzzy knowledge library, fuzzy database, fuzzy reasoning machine, knowledge acquiring program, interpreter and user interface etc. Its structure is shown in fig. 1.

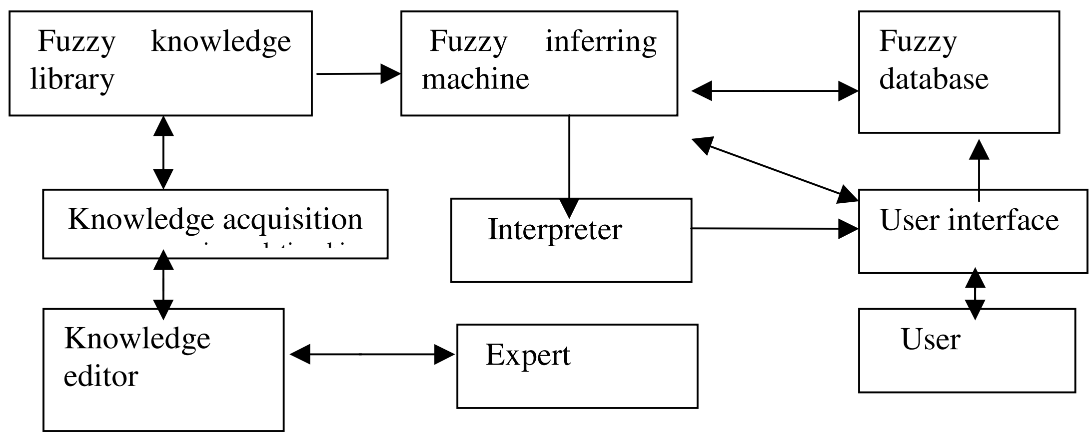

Fig.1 Structure of the system

3 Mathematical Description of the Diagnostic Model

1. Fuzzy Relationship Matrix

A fuzzy relationship matrix is used to describe the fuzzy relation between fault cause and symptom of turbine generator.

A set of fault causes of generator is

$\boldsymbol{Y}=\{y|_{i=1,2,3....,n}\}$..................(1)

A set of symptoms of generator is

$\boldsymbol{Z}=\{z|_{j=1,2,3....,m}\}$..................(2)

Because y_{Ii} corresponds to several z_j, and also z_j corresponds to several y_I, there is no one to one mapping relations between ***Y*** and ***Z*****.** Relationship between them is a fuzzy relation matrix. Fuzzy relation matrix defined on ***Y*** and ***Z*** is

$$\boldsymbol{R}=\begin{vmatrix} r_{11} & r_{12} & r_{1j} & r_{1n} \\ r_{21} & r_{22} & r_{2j} & r_{2n} \\ r_{i1} & r_{i2} & r_{ij} & r_{in} \\ r_{m1} & r_{m2} & r_{mj} & r_{mn} \end{vmatrix} \text{...............(3)}$$

Element r_{ij} is the membership function between y_i and z_j and its range is [0,1]. The value of r_{ij} shows degree of possibility, which cause y_i to be existed when z_j appears. If $r_{ij}=d$ and $r_{(i+h)}=m$, and also $d, m \in [0,1]$, then reason of z_j appearing is caused by y_i or y_{I+h} or both of them.

2. Fuzzy Diagnosis Rules

The key problem of the result correctness of the system is the value of correct membership r_{ij} in matrix $\boldsymbol{R}$. According to particular condition, following way can be used to get the value:

1) By fuzzy statistic test (statistic analysis by accumulative fault data).

2) By two elements contrast sorting.

3) By the result of logic reasoning.

4) By diagnostic analysis of fault.

5) By expert experience and running standard.

6) Progressively formed by "learning".

7) Calculation of membership function

Our system is designed to use methods 1, 5 and 7, and use them in combination.

Example: Table 1 shows relationship between RF symptom and insulation status in which data were detected by SJY-1 RF monitor. The degree of subjection can be fuzzily processed by relationship between RF symptom and insulating status.

Table 1 Relationship between RF Symptom and Insulation Condition

Insulating status	**Fault characteristic** (μV)	**Running management of a generator**
Safe	≤300	Long time running is accepted.
transferring state	300~1000	Keep on running.
Attention	1000~3000	Pay attention to or schedule to maintain.
Alarm	3000~7000	Stop to maintain at suitable time.
Danger	7000~10000	Stop at once.

The membership function is described as follows

$f(x)=0 \quad x \in (0,300)$

$f(x)=4.286\times10^{-4}x-0.1285 \quad x \in (300,1000)$

$f(x)=1\times10^{-4}x+0.2 \quad x \in (1000,3000)$

$f(x)=1.25\times10^{-4}x+0.125 \quad x \in (3000,7000)$

$f(x)=1 \quad x \in (7000,10000)$

Because of the complexity, multi-factors, randomness of symptom information and fuzziness of a fault cause are considered, the information is undetermined. At the same time, a system has characteristics of both fuzzy and dynamics. So, diagnose instrument provide diagnosing conclusion according to the rule of maximum subjecting. That means that a highest degree of relativity is considered as cause of a fault in diagnosing. At the same time, fuzzy optimizing and fuzzy strategy can be made by fuzzy decision which fuzzy sorting and similar preference comparing is included for possible faults.

4 Fault Optimization and System Clustering Analysis

Fault optimization is a critical operation. Within several assumed faults, one must be chosen. In the procedure, both experience and theoretical knowledge are included. The guiding idea of similar preference comparing is reverse inferring. A fault, which has similar symptom, is selected by comparing several faults that are provided by experience and optimized through symptom comparing. It may not be precise enough but it's reliable.

Clustering analysis is one kind of multi-factor analysis method of "like attracts like" in statistics. Relativity of samples, such as symptom indexes in fault forecasting of a generator, is determined mathematically to realize sorting. In clustering, distance between samples is calculated and then the nearest points are combined to one class. After that, distance between classes is calculated and the nearest classes are combined to a new class. These steps are repeated until one class is reached. Finally, a cluster tree is resulted, as is shown in fig 2.

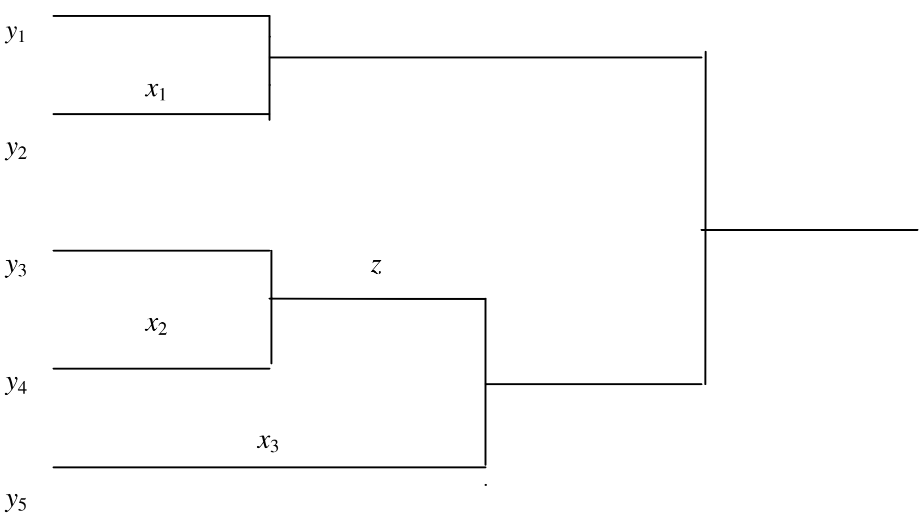

Fig. 2 The clustering tree of system

Fuzzy clustering analysis is used to make pattern recognition. Because generator is a complex system, dynamic clustering analysis is applied to minimize computing work. Initially, sample is roughly separated, and then optimizing rule is used to correct repeatedly until reasonable clusters are reached. Fig. 3 shows the steps that are needed for the dynamic clustering analysis.

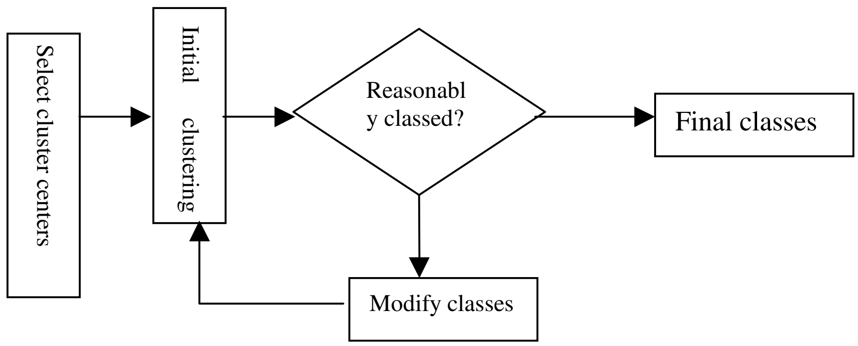

Fig. 3 Dynamic clustering analysis

5 Conclusion

1. For complex large generators, troubleshooting is difficult to be detected by human senses and experience, and checking by disassemble at any time is also not permitted. Due to several correlated systems are existed in a generator, their fault origin and symptom is behaved multi-factor and undetermined. It's possible to forecast a fault through early symptoms by using our expert system that is built on fuzzy set, and fault diagnosing and trend analyzing is easily performed to make some reasonable maintenance plans.

2. Generator failure is caused mainly by short circuits that result from insulation breakdown. Because SJY-1 RF Monitor can monitor insulation condition of a generator automatically, with the Monitor as the main device for condition monitoring and diagnosis and the expert system adopting the two-level diagnostic functions (Level 1 being online automatic diagnosis and Level 2 offline, questionnaire-type interactive diagnosis), it is possible to cover a wide range of insulation faults of a generator.

3. For the diagnosis of complicated and multi-factor faults, it is necessary to break them down into many pieces of unique expert experience and diversified technical diagnostic information to conduct fuzzy sorting, and make the fault range for diagnosis as smaller as possible through fuzzy logical inference.

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EPRI SOLUTIONS

Gaining Strategic Leverage Through Planning & Scheduling

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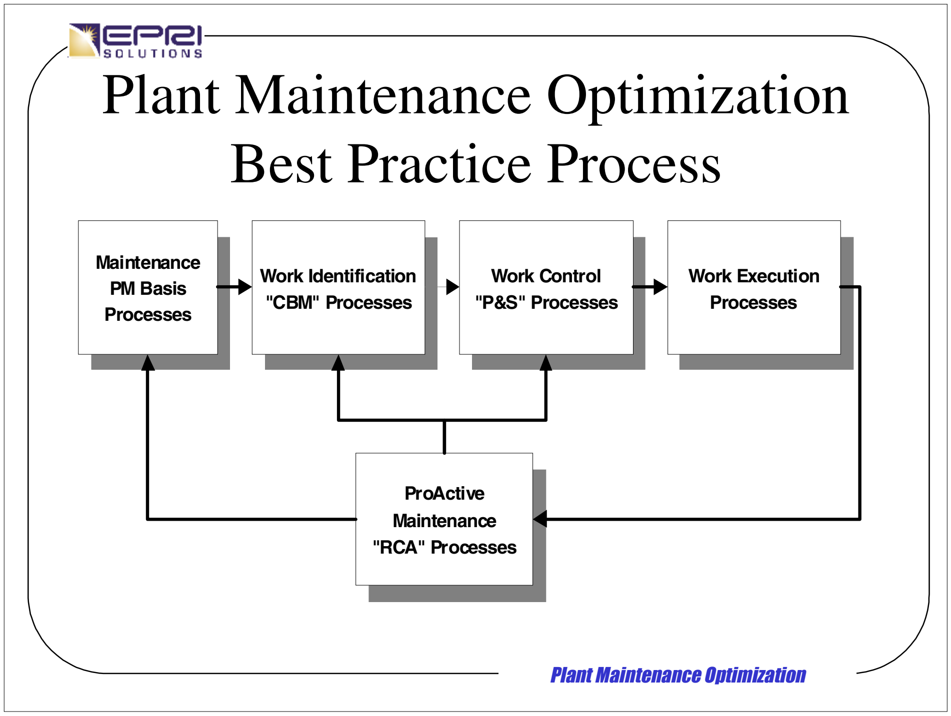
Plant Maintenance Optimization

The profitability of a power plant is often attributed directly to the successful management and execution of its maintenance program. Plant maintenance can be a costly exercise, not only in terms of labor utilization but also more importantly with respect to its impact on the ability to keep the plant running; unplanned downtime resulting from poorly maintained equipment impacts directly on the bottom line.

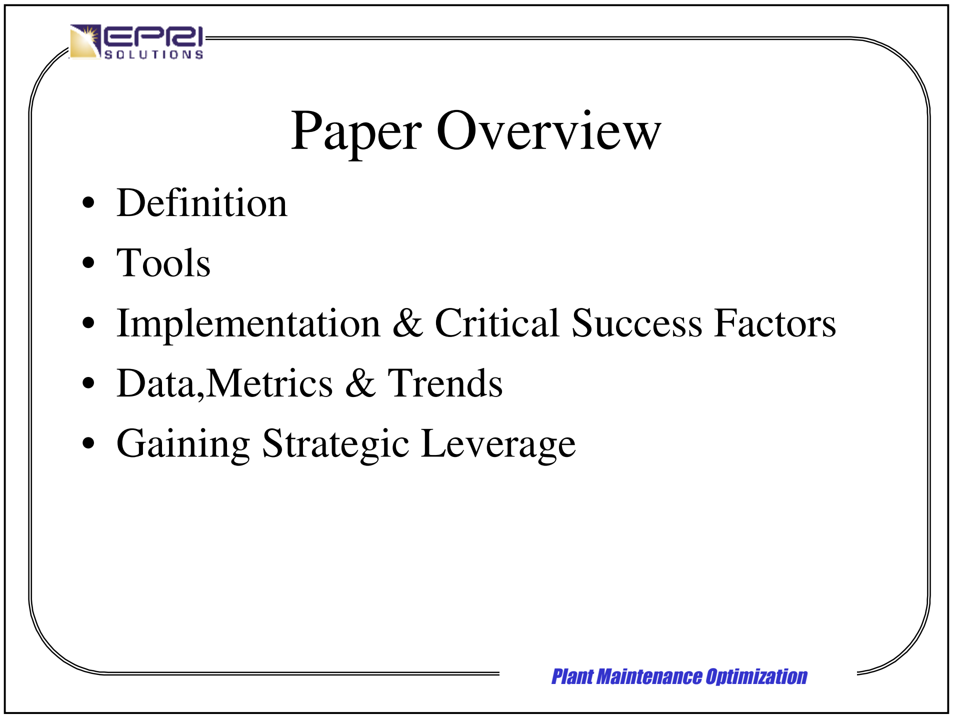
In 2000, EPRI Solutions, a subsidiary of the Electric Power Research Institute (EPRI), began performing Plant Maintenance Optimization (PMO) improvement programs refined by years of EPRI PMO R&D efforts. These programs have been performed at many utility sites and are aimed at assisting plants to achieve strategic competitive advantage through the optimization of their plant maintenance practices.



The EPRI Solutions PMO program encompasses:

- The development and coaching implementation of a relevant and well-managed preventive maintenance (PM) program.
- The development and coaching implementation of a comprehensive predictive maintenance program (PDM)
- The development and coaching implementation of a disciplined planning and scheduling process
- The development and coaching implementation of ProActive Maintenance with the associated root cause analysis processes.
- The conceptual adoption of accountability systems providing direction and discipline to the maintenance processes

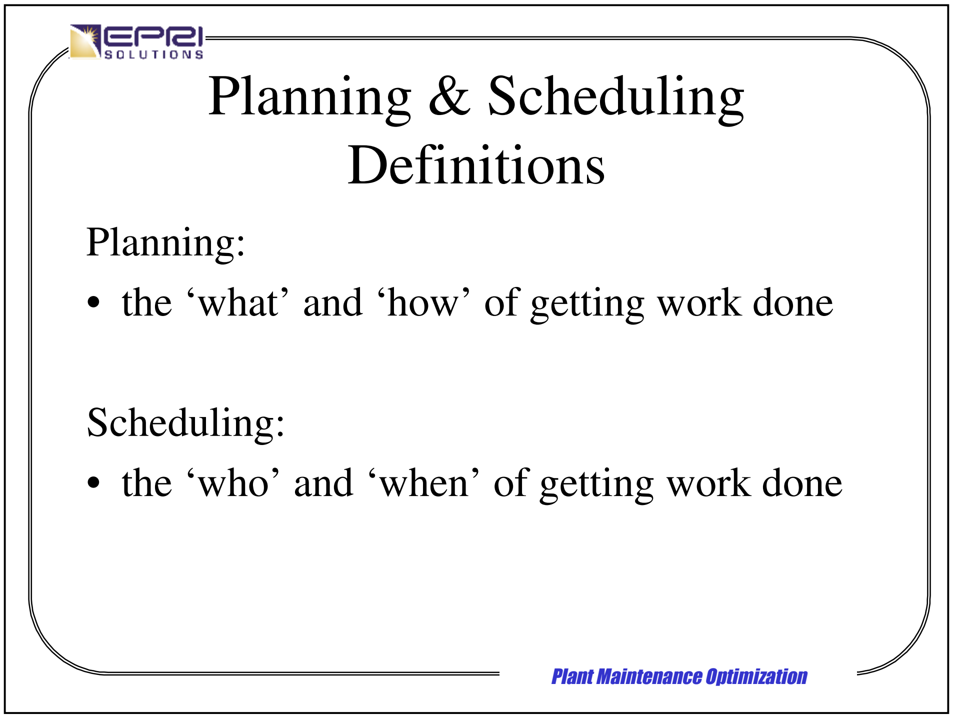
A critical key to the achievement of "world class" PMO is the effective and efficient planning and scheduling of maintenance work. Best practice Planning & Scheduling can result in improved resource utilization of 30% to 40%. This is a significant factor in this era of reducing costs and managing organizations with limited resources.



This paper will present the necessary tools and concepts to optimize Planning and Scheduling (P&S) programs. This includes a model of how P&S should be laid out and presented and how each participant's roles and responsibilities affect the outcome. Discussion on how new behaviors are inculcated into the organization is presented.

Using examples and vignettes from actual ' on the job' experiences this paper will

- Define Planning & Scheduling
- Describe the tools used in Best Practice Planning & Scheduling
- Discuss how Best Practice Planning & Scheduling is achieved
- Talk about data, metrics and trends, that is, how you sustain Best Practice
- and finally, clearly illustrate the relationship between Best Practice Planning & Scheduling and strategic leverage



So how do you define planning & scheduling?
Planning is the 'what' and 'how' of getting work done. The primary concept behind planning is to remove as many obstacles to smooth job accomplishment as possible, prior to starting the job. The pay off to this approach is significant in terms of reduced maintenance expenses and increased uptime for the production equipment. The bottom line impact of planning and scheduling is less overtime pay, a reduction in contractor use and allowing attrition to occur without having to replace crafts people.

If planning is the 'what' and 'how' then scheduling is the 'who' and 'when' of getting work done. In this step of the work management process the objective is to choose the work to be done, finalize the coordination of resources, and most importantly, commit to getting the work done by a specific date.

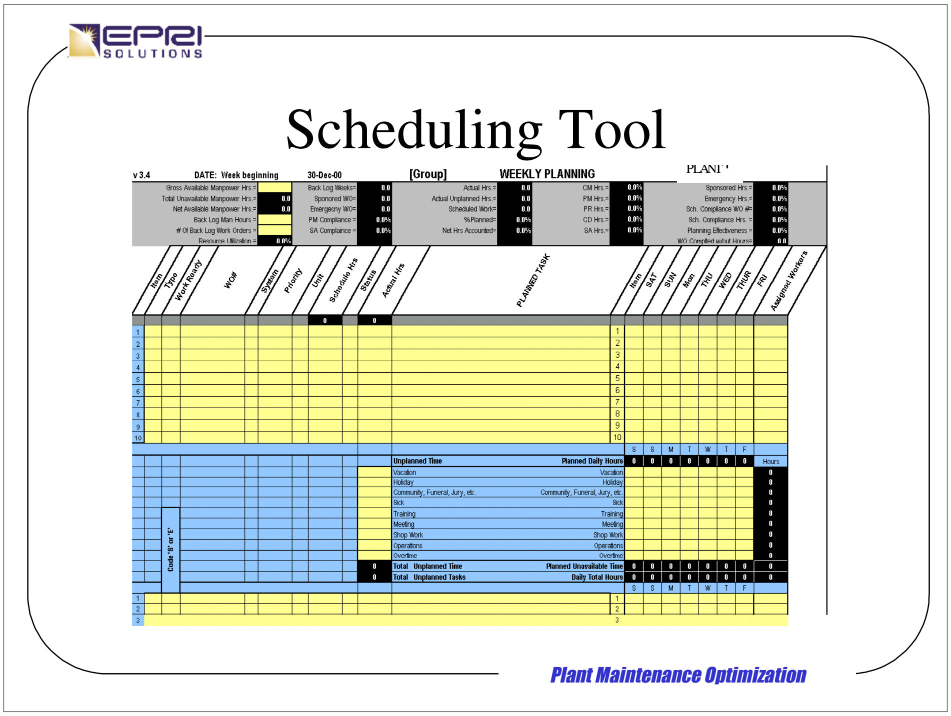
TOOLS

The platform from which Best Practice Planning & Scheduling can be achieved is created through the adoption of the following tools:
•The Scheduling Tool (otherwise known as the 4 week rolling schedule)
•Work Packages
•Outage Plans
•and a Meeting Structure

Scheduling
The scheduling tool is a comprehensive, computerized, easy to read form that allows all concerned parties to view what work is in progress, what work is upcoming and what work has been completed over a rolling four week period. Included on the form are all metrics required to comprehensively track work progress.

The method involved in generating the scheduling tool is as follows:

Schedule jobs into weekly buckets starting with week one and progressing out to week four. The further out in the future you go with scheduling, the smaller the resource loading. See details below for an overview of tasks for each week. Percentages refer to resource loading.



Review (T-1)	All job status completed and hours accounted for, sponsored and emergency work
In progress (T0)	Identify all jobs that will and will not be complete, sponsored and emergency work
Next week (T1)	Have foremen commit to schedule. Make sure all planned work is still a go. (80%)
2nd week out (T2)	Identify work that needed planning and determine if it should stay on schedule or be moved further out. (70%)
3rd week out (T3)	Quick overview (50%)
4th week out (T4)	Identify any work that needs planning and commence the planning process. (30-50%)

Jobs are placed on the schedule by value ranking the backlog. The backlog includes all jobs, regardless of status, that have been identified, but are not yet complete. Backlog is all uncompleted maintenance work. Managing the backlog means using the backlog daily as a tool to make decisions, decisions about what to plan, what to schedule, how many craftspeople are needed, when to take equipment out of service, when to use contractors, when to schedule vacations etceteras. With greater efficiency around completing work comes the ability to reduce backlog and take on new projects. Planners schedule by work order rank and resource availability. Sponsored work is any job that augments a planned task and is not an emergency.

Committing to the work on a schedule implies that everyone involved in that commitment will do everything within his or her control to complete the work as scheduled. This is the fundamental concept behind scheduling. With the completion of the scheduling step in the work management process, the organization will have achieved setting up for the right work, at the right time and with the right resources.

Optimal use of this tool allows plans to be formulated in advance, thus saving time, and reducing miscommunications around work. Sponsored work and emergency work can be easily identified and subsequently tracked. Variances can be addressed, for instance, in the case of sponsored work, ‘why is the work not being planned in advance’. As tasks are determined in advance, resource utilization will be more effective. Additionally, components and systems that are failing can be identified, tracked and addressed, thus increasing the reliability and availability of the plant.

Work Packages

Work packages are comprehensive sets of information required to complete specific jobs. They are compiled by planners using a variety of methods including but not limited to; walking down the job, interviewing systems experts, checking inventory and gathering pertinent history.
A work package should be assembled in a manner that is consistent from one job to another. Craftspeople can rely on getting similar information presented in the same format from job to job. This breeds familiarity and improves efficiency. The work package should contain job steps, material list, labor estimates, cost estimates, drawings and other equipment documents. With well-developed work packages Craftspeople can eliminate wasted time in trying to track down information and materials. They are particularly useful in the instances of new and unfamiliar job tasks.
Complete work packages need to be available for all jobs requiring them in a concise and easy to follow lay out. All the jobs requiring work packages that were identified in week 4 should be completed and ready to go by week 2 or the work needs to be postponed.

Outage Plans

Outage plans describe in detail all the work to be completed in an outage whether forced or planned. All plans are placed in order of time sequence, importance and duration.
The development of an outage plan must commence well in advance of the outage. The planners will systematically work through each step of the outage to develop an overall logical plan along with detailed work packages. In the case of a forced outage, planners need to maintain a list of work packages that are complete and listed in sequence by time, manpower and cost.
With a well-determined outage plan an organization can greatly reduce time wasted as a result of afterthoughts and downtime associated with disorganization. Durations can be trimmed resulting in reduced overtime and costs and, most importantly, returning the unit to generation sooner.

Meeting Structure

A well thought out meeting structure is an essential tool in achieving best practice planning and scheduling.

Planning and scheduling meetings are designed to gather, integrate and dispense information. A weekly meeting addressing scheduling is used to enlighten management as to the current status of work tasks and the workforce and inform them of future intentions. All people affected by planning and scheduling are required to attend this. Smaller meetings, with select attendees, are conducted throughout the week to gather and discuss the current and future status of maintenance activities.

These meetings bring to the foreground unforeseen obstacles that need to be addressed in a timely manner in order to achieve a smooth completion of tasks. Issues addressed include coordination, timing, resource sharing and materials etc. These meetings also provide a forum for a collective group of pertinent people to solve roadblocks, thus saving time and potential miscommunications.

Implementation & Critical Success Factors

- Senior Management Support
- Coaching/Training
- Roles & Responsibilities
- Communication
- Time & Patience

Plant Maintenance Optimization

The adoption of tools alone will not lead to best practice planning and scheduling. Many plants use these tools but are not achieving the optimal results required to strategically leverage them against the competition.

Senior Management Support

Buy in by senior management is the first step to achieving success. Support at this level is essential in setting expectations and directions for planning and scheduling activities. Reinforcement of concepts, upholding of ideas and leading by example are critical in creating a positive environment in which to introduce and effect change. Management sets the tone, keeps people focused and maintains the appropriate sense of urgency.

Coaching & Training

In-depth hands on coaching and training will help to expedite the entire process. A well-trained coach dedicated solely to the planning and scheduling implementation has the knowledge to answer questions in real time, demonstrate appropriate behaviors and guide/direct the process to maximize sustainable change in the shortest period of time possible. The initial coaching involves intense interaction with all players and gradually tapers down to distance monitoring.

Role and Responsibilities

Roles/responsibilities and expectations should be well defined, understood and clearly communicated. This will:

•ensure that the appropriate amount of importance is attributed to the new roles
•identify who has ownership over what tasks minimizing potential confusion and time wasting
•help reduce duplication or non occurrence of a task (that is, diminish the 'pass the buck' syndrome)
•set up points of contact
•and expedite the success of the new roles.

Some examples of roles and responsibilities are as follows:

•Planners develop detailed work packages and own and maintain the work week schedule.
▪System Owners develop equipment **action plans***

***Action plans** are based on; History, PM, PDM, Operator Rounds, and process data trends

▪Foremen are responsible for providing resource allocation and job scope input to the coordinators for job planning. They also take the output from the Friday Work Control Meeting and Daily Operations Meeting to complete workweek daily job sequencing to assure that optimum scheduling is accomplished.

Communication

A strong sense of team work and solid communication must exist between all players: Operations own the units, planners own the schedules and plans, team leaders own the resources and system owners own the systems. To achieve best practice no individual group can function in isolation. Additionally, good communication will often result in potential problems being exposed well ahead of time.

The key elements in achieving effective and efficient communication in this setting are:

•the use of agendas to ensure uniformity
•tight chairmanship to keep meetings on track and reinforce time constraints
•training people to provide the appropriate type of answer given the setting, thus reducing potential time wasting. For example, when to respond with yes/no, when to provide detail, when to problem solve etc.
•encouragement of honest and open communication amongst all players
•the adoption of both formal and informal communication avenues
•demonstration of efficient and effective communication by senior management

Time and Patience

Time and patience are critical to achieving best practice. Both are necessary in order to implement new ideas and let them take hold. Managers involved will benefit from understanding exactly where the process is up to at any given time. This will allow them to rationally address timing issues such as when to introduce a new process and when to wait for a while. Do not to expect too much at first and provide lots of positive reinforcement!

Finally, the real key is recognizing that the tools are only a vehicle on the road to achieving cultural change and a whole new way of thinking.

Sustaining Best Practice

- Data
- Metrics
- Trending

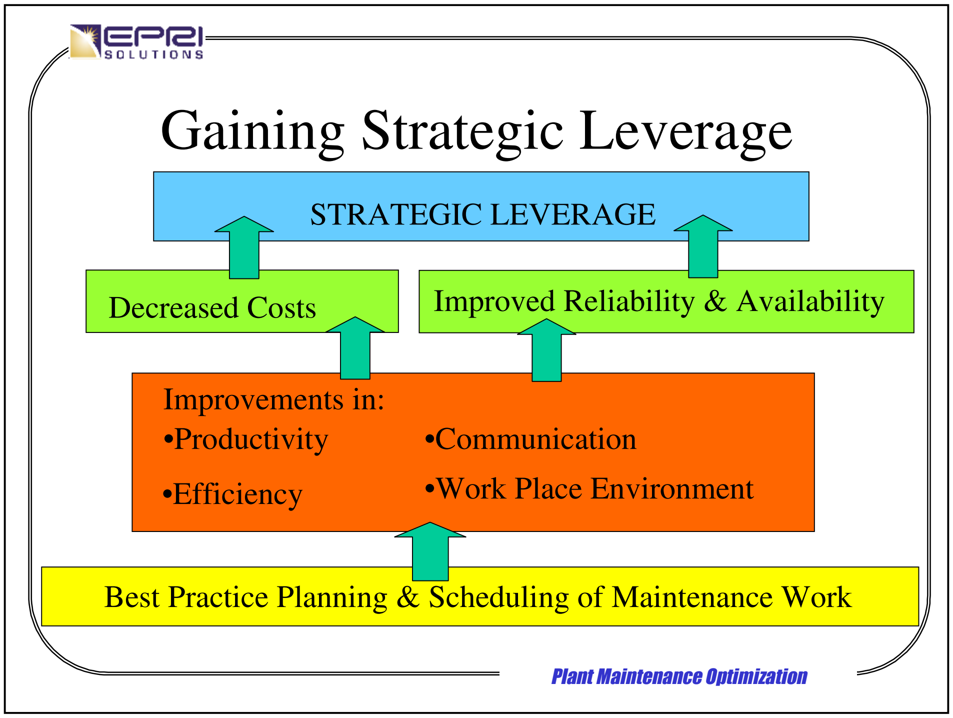
Given that you have been successful in implementing best practice planning and scheduling how do you sustain it? This is achieved by being proactive both in monitoring/tracking your progress via well chosen metrics and acting upon your findings where relevant.

Metrics are generated through the collection and collation of data. Data needs to be presented in a concise easy to read format that provides the ability to track: type of work order, if the work is planned or not, system (area), value ranking (via the equipment owner), estimated hours, status, actual hours, short description and days to be worked etc.

Plant effectiveness will be enhanced with the provision and monitoring of key metrics. Metrics require careful design and calculation in order to provide useful and meaningful information. This information can be used to track how well the maintenance program is maintaining the plant, whether or not the resources are being used efficiently and if the schedules are an accurate representation of current and potential work. Plant efficiency and productivity will increase with proper monitoring and corrective action as needed.

Initially, there is only enough data collected to establish a baseline. Data collected in these early stages is prone to being incorrect due to errors made in the course of becoming familiar with the new tools and processes. A learning curve often exists as to what information is important and the amount of information required. Thus, in the beginning of the process, trends are a more accurate way to determine if the maintenance program is heading in the right direction. Information to be trended can include preventative maintenance compliance, schedule compliance and planning effectiveness.

Assessment
A quick word on assessment. Essentially, the key to conducting a good assessment is a solid understanding of what is required to achieve best practice planning and scheduling. This includes understanding the nature and purpose of the tools as I have described along with the critical success factors outlined.



Thus, a plant can gain strategic leverage through the adoption of best practice maintenance planning and scheduling. When this is achieved the organization can expect to see dramatic improvements in and around productivity, efficiency, communication and the work place environment. These factors lead to decreased costs and improved reliability and availability- all predominant keys that can be used to attain strategic leverage over the competition.

Additionally, the effective use of planning and scheduling tools allow the plant to track where and how the money is being spent and, hence, a better understanding of cost.

The new behaviors and processes adopted in the implementation of best practice maintenance planning and scheduling will spill over into other areas of the plant. Operations and preventative maintenance will also reap the benefits further increasing the competitiveness of the plant.

Finally, the tools and processes described here are not restricted to an energy plant setting and may be equally beneficial in a manufacturing or other heavy industry setting.

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2000 'Best Practice Guideline for Maintenance Planning and Scheduling' Electric Power Research Institute

INSPECTION DATA INTERACTIVE PROCESSING SYSTEM

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Abstract

The Inspection Data Interactive Processing System (SITDI) solves, in an integrated manner, the tasks of management, treatment, and control of documentation generated during erection and life of a power plant. This software is a highly innovative tool, which consists, basically, of a graphic information system that gathers each component's data, and links it with its graphic display.

The Inspection Data Interactive Processing System is a database, which contains all the power plant data. The type of information that can be stored ranges from references to design code, technical drawings and erection data, to inspection results or comments on the last repair carried out. A Geographic Information System provides the connection between the database and the representative drawing. This easy-to-use tool allows the users to manage all information gathered during past inspections and plan future ones.

Technical drawings of each of the components are drawn using CAD software. The discretization of each of the components is done together with plant's personnel. This will let the utility keep the original codification that has been in use up until the software is installed. Using a software tool and an internal code, each discretized component will have a corresponding set of characteristics in the database.

SITDI makes it possible to combine the information supplied by Non Destructive Examination (NDE) and failure analysis with remaining life calculations. Some of the features of the system include: integral management information, retrieval of inspections' historical data, boiler tubes remaining life calculations, data spatial analysis, predictive maintenance, display format customized for each plant, and cost control tools. These capabilities, along with task scheduling tools, make SITDI and invaluable support for planning and developing and efficient predictive maintenance. Therefore, it contributes to reduce the number of forced outages, as well as reducing inspection and maintenance costs.

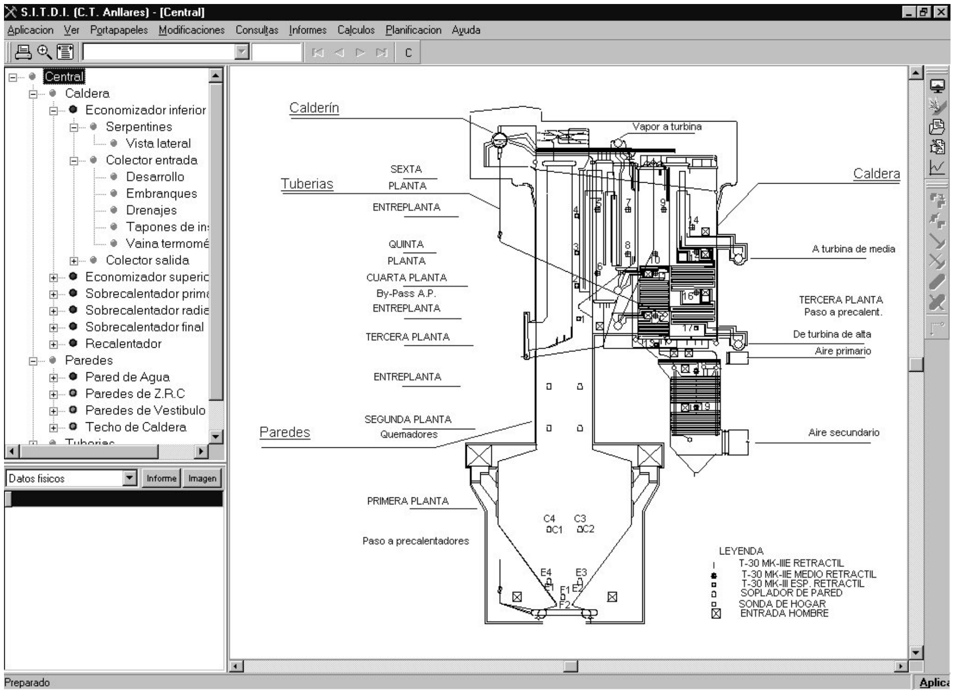
Introduction

It has been found, through experience, that a large amount of data and documentation is generated through erection and life of a power plant. This documentation and data needs to be used during operation to provide a better service. Therefore, plant's personnel found the need for a tool that would keep this information organized and easy to access.

In order to solve this problem, data bases were developed so as to keep all equipment and historical inspection data stored. But still, this "easy to use" tool was far from real. A step ahead is the development of a link between these databases and a graphical representation of the component/equipment. This step would provide an easier understanding of the information that has been gathered through the years, for it would give a "physical" view of the component and the data that is associated to it.

The close relationship between the information and the graphic representation of the component helps maintenance for the following reasons:

1. The user understands data easier.
2. All information gathered for equipment or component is easily accessed through its graphic representation increasing the speed in recovering specific data.
3. The addition of this graphic characteristic provides an interesting tool for drawing conclusions.
4. It also helps to find otherwise "hidden" relationships between stored data, that is results of different NDE techniques.



View of a boiler and its components

Inspection Data Interactive Processing System

This system has been developed, entirely, by norcontrol soluziona. It is a powerful tool that provides the ability to visualize, explore, enquire, and most importantly, analyze data graphically.

The Inspection Data Interactive Processing System is an application for processing inspection data supported by a database and a geographic information system. The type of information stored in the database ranges form design standards, drawings, and erection data to historical inspection data or results from the last carried out repair.

1. Power Plant – System's Relationship

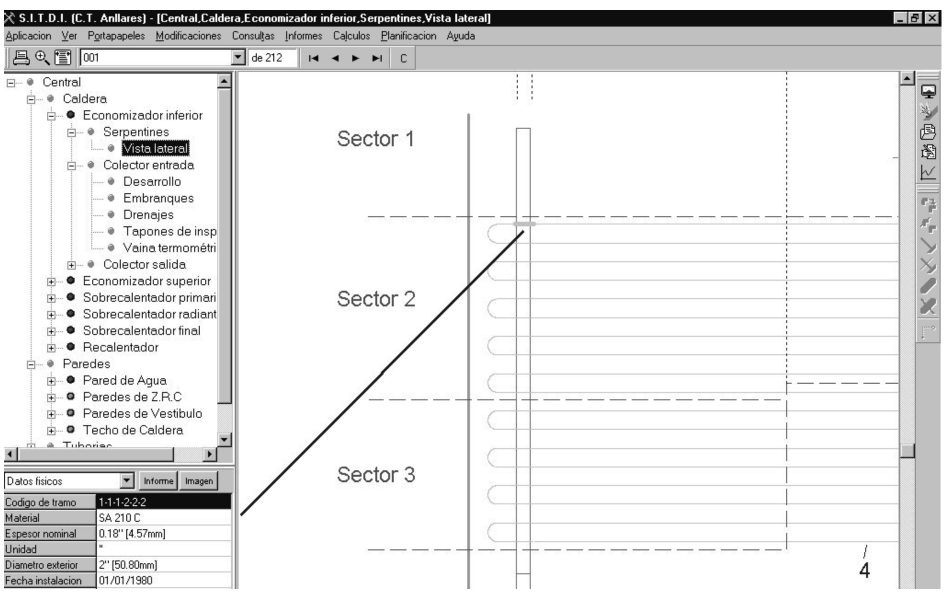
The plant's boiler and its accessories are going to be graphically represented in the system. Therefore, these are the steps to be followed in order to be able to relate the graphic information with the data:

1.1. Technical drawings

In order to be able to represent the equipment/component graphically, technical drawings of each of the components that are going to be included (boiler, pipes, accessories, etc.) are drawn. For this purpose CAD software is used.

1.2. Components' discretization

From the technical drawings that result from the step that has been covered above, and using a software tool, also developed by Norcontrol Soluziona, each of the smallest significant part of the boiler, or pipe, etc. is discretized. That is, each part will have a "name" that is given using an internal code. This will mean that each smallest significant part will have a unique name in order to be able to identify it when using the system. This also facilities the future relationship between the drawing and the data stored in the database.



Part of the boiler and example of data stored

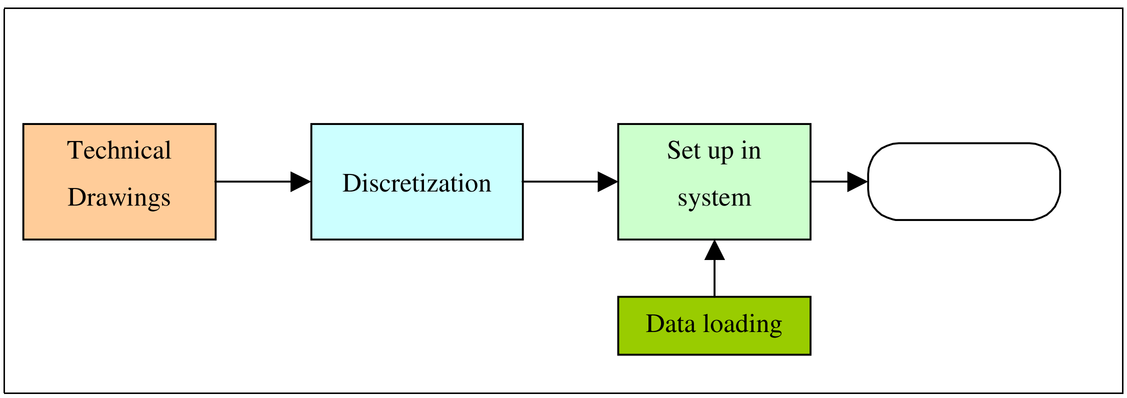
The discretization of each of the components to be included in the system is done together with plant's personnel. This will allow the utility the opportunity to keep the original codification that has been in use up until the software is installed.

1.3. Set up in the system

Once the technical drawings have been done and the discretization is completed the component is ready to be included in the system. In order to do this, each of the parts with its alphanumeric name is included in the database, so as to be able to relate to this name its design standards, inspection data, or other information that could be needed by the utility.

1.4. Data loading

Lastly, the data relating to the component needs to be loaded into the database. This can be done from the system itself.



SITDI conects with diferents datalogger systems to receive inspection data.

2. Inspection Data Interactive Processing System Features

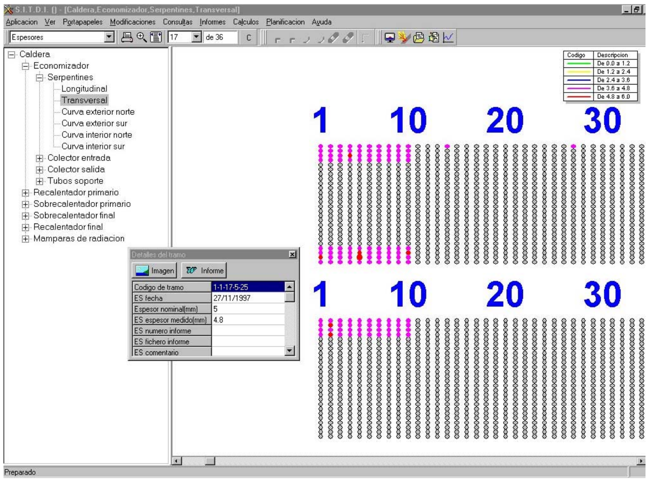
The following are the features that can be found when using this tool.

2.1. Available information in the system

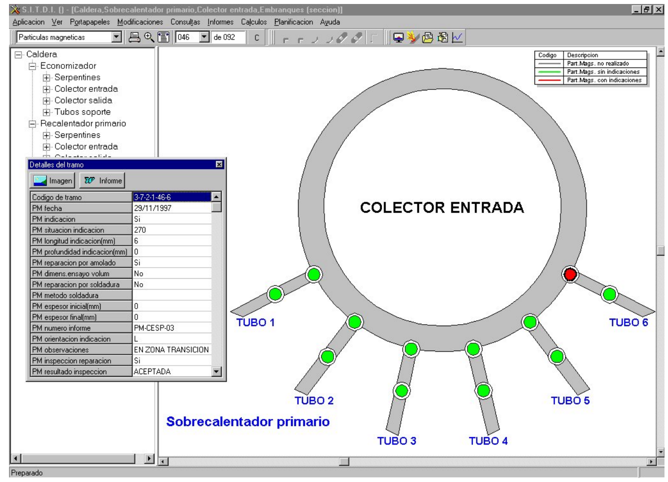
- **Non-destructive examination data**

  Non-destructive examination data can be stored in each component (visual inspection, magnetic particle, ultrasonic testing, liquid penetrant, hardness examination...)

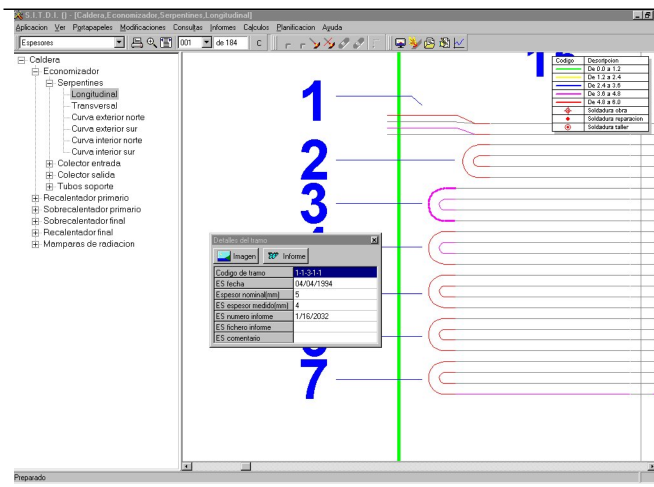
This inspection data can be visually enquired from the drawing or retrieved through a printed-out report after searching through the database with a defined criterion (components, dates, results...)



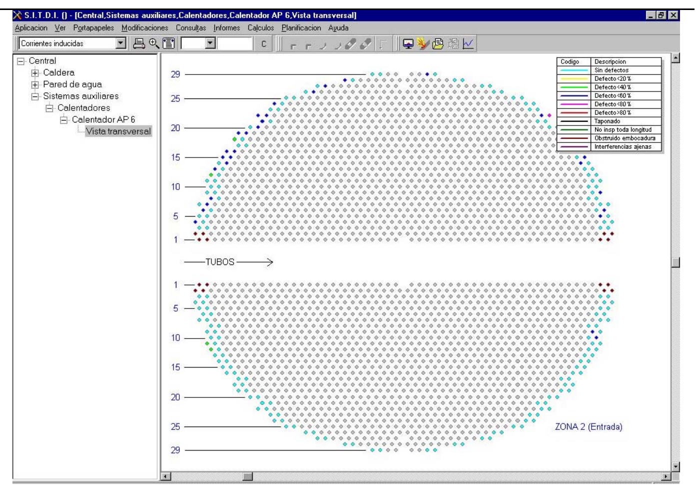
UT data inspection



Magnetic Particle data inspection



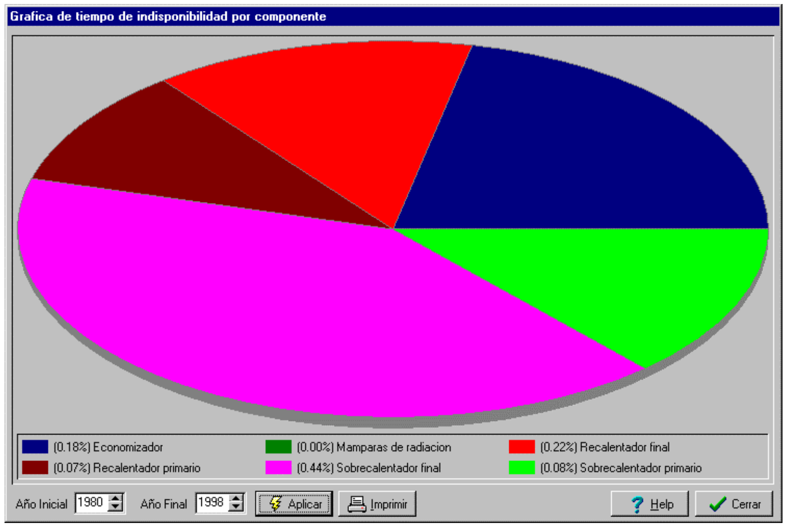
UT data inspection (Side View)



Eddy current Inspection

- **Graphics**

  Part of the information contained in the database can be reviewed through graphics, such as component failures, component's unavailability, minimum thickness of a coil in a specific zone, etc.

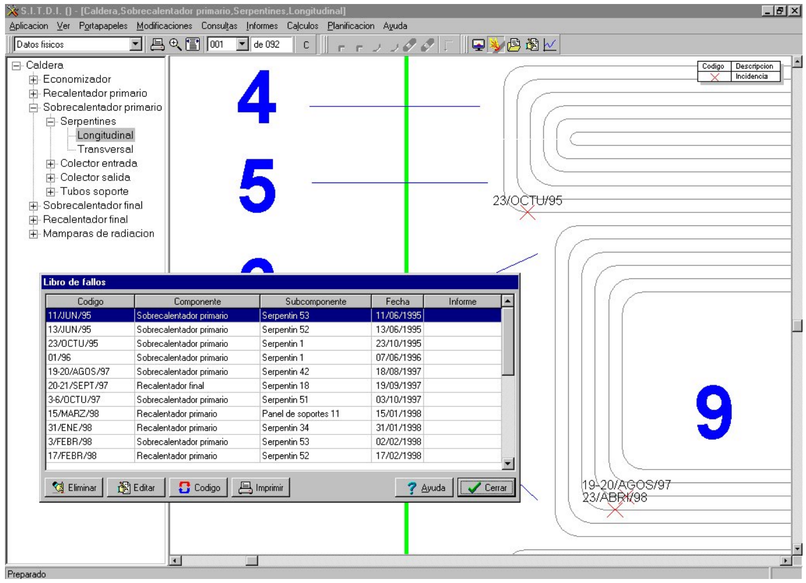


Component's unavailability

- **Failures**

  This tool allows the utility to keep track of failures that have occurred in the power plant. Data relative to the failure can be stored, such as: component where it happened, failure mechanism, date and time, time of unavailability, description of the failure, etc., as well as works carried out due to the failure.

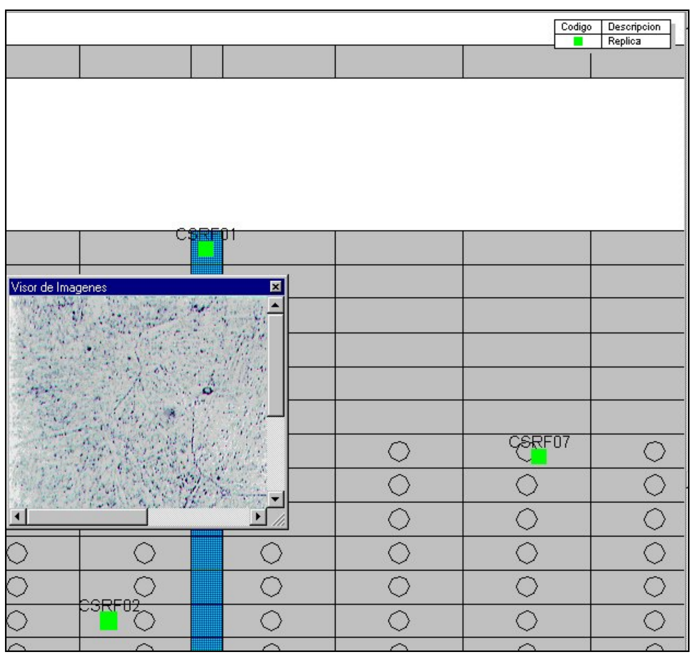
  All failures can be viewed though a "book of failures" where all of them are listed. If a particular failure is selected, a window will show all the information related to it.



View of failures

- **Replicas**

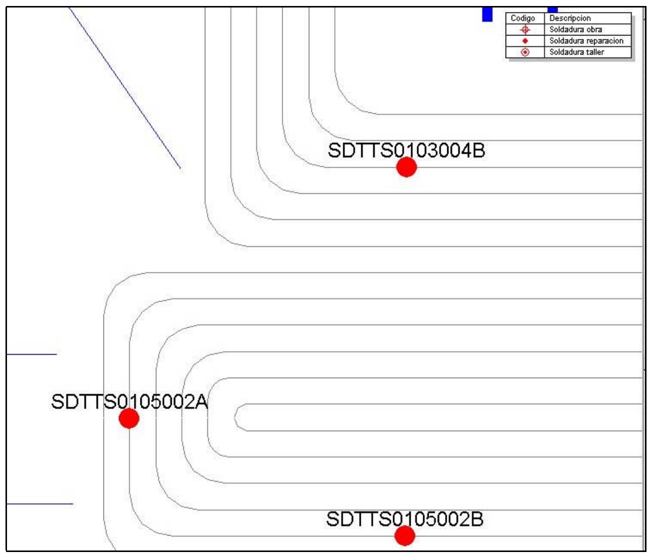
  Replicas' data (microstructural features in base metal, affected zone, weld, hardness measurements, ...) and images of those can be stored in the system



Replica in a header

- **Welds**

The System allows the utility to store data of welds that have done in the power plant. Data relative to the weld can be stored, such as: position, date, welder, procedure, type of inspection, result...

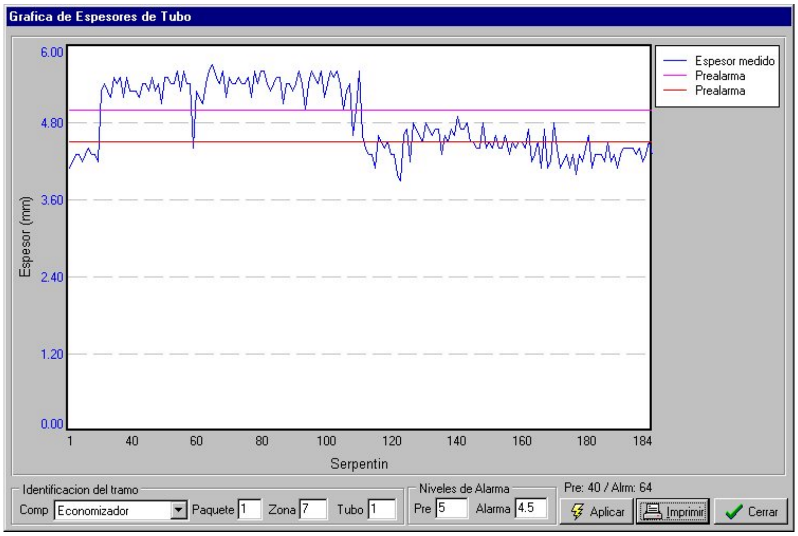


Welds in a Reheater

2.2. Calculations for maintenance

- **Thickness analysis**

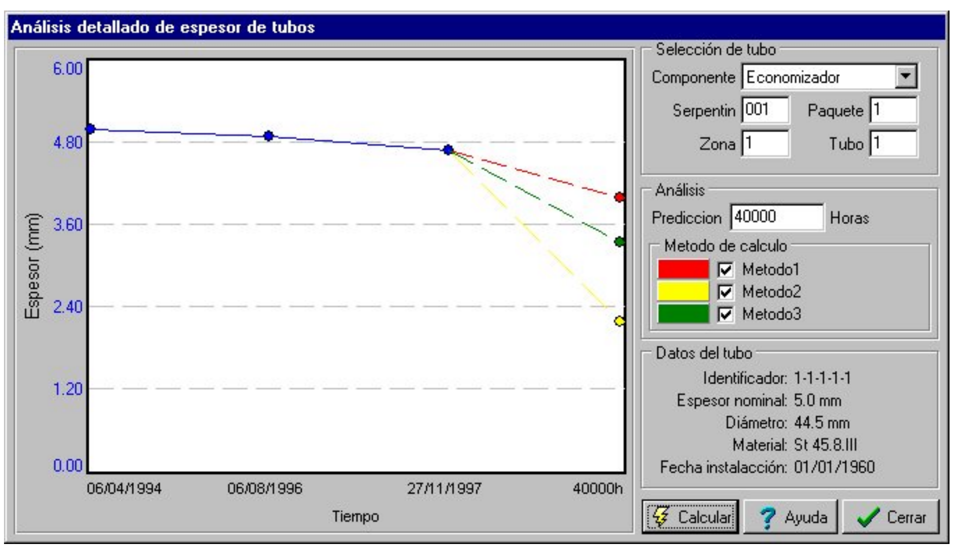
  This tool allows the user to see the comparison between the nominal thickness of a tube and its actual thickness that has been measured and loaded into the database.



Thickness analysis in a economizer

- **Boiler tube's thickness prediction**

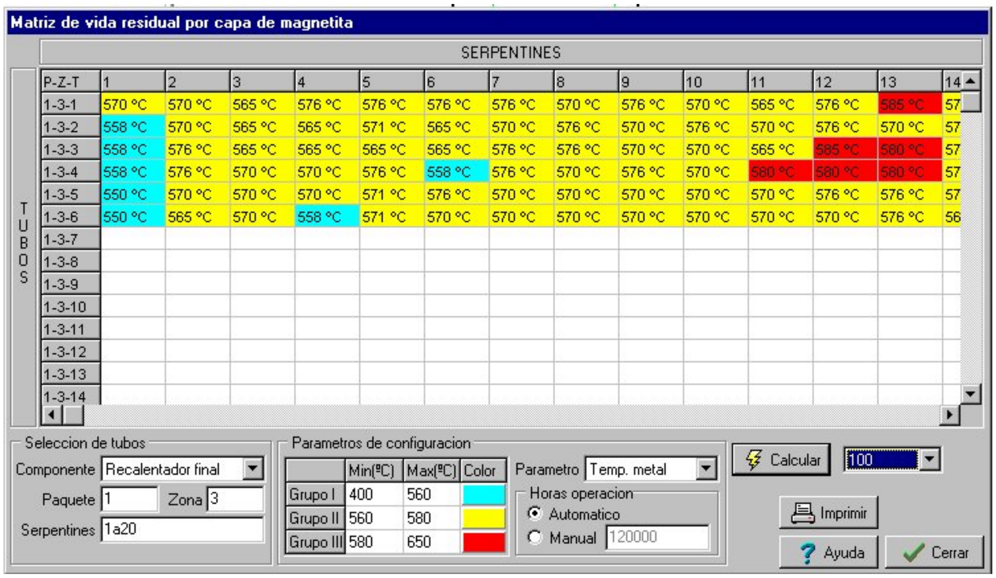
  Using three different mathematical analyses, the future thickness of a particular tube after a period of operating hours can be calculated. This tool will help on predicting the thickness of a component after a number of operating hours.



Economizer tube thickness prediction

- **Remaining life of a tube**

  This calculation is similar to that of thickness analysis. It will estimate the remaining life (number of operating hours) of a particular tube or set of tubes. It can also show and calculate the mean operating temperature of the metal.



Remaining Life of a reheater (Temperature matrix)

<u>2.3. Planning</u>

- **Tasks' scheduling**

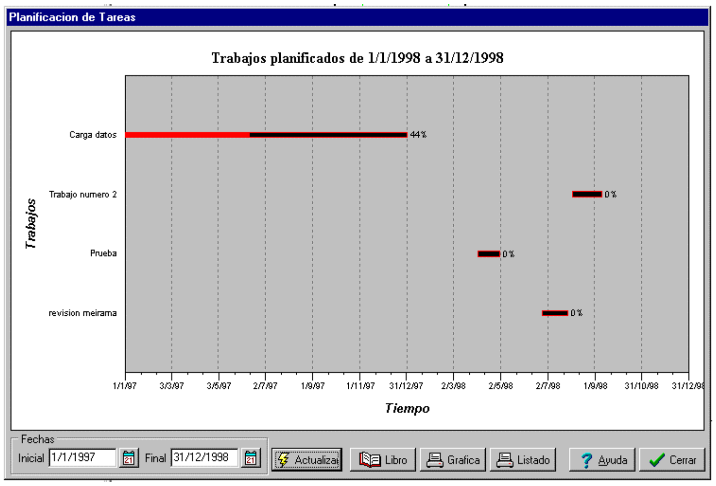
  Activities related to inspection of the boiler, pipes, or accessories, can be planned with this tool along a period of time.

- **Agenda**

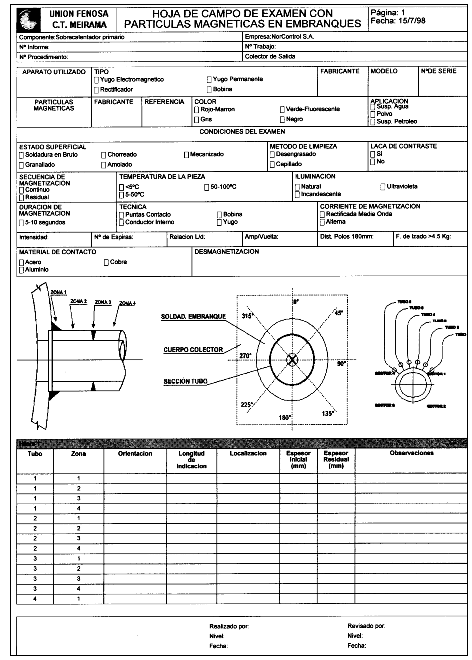
  It allows the user to organize personals or work tasks.

- **Inspections summary**

  For each inspection, it will give a summary of the NDE techniques used, their scope and their results.



Tasks' scheduling



Inspection Reports

3. Conclusions

SITDI makes it possible to combine the information supplied by Non Destructive Examination (NDE) and failure analysis with remaining life calculations. Some of the features of the system include: integral management information, retrieval of inspections' historical data, boiler tubes remaining life calculations, data spatial analysis, predictive maintenance, display format customized for each plant, and cost control tools. These capabilities, along with task scheduling tools, make SITDI and invaluable support for planning and developing and efficient predictive maintenance. Therefore, it contributes to reduce the number of forced outages, as well as reducing inspection and maintenance costs.

SITDI is instaled in the plants of UNION FENOSA GENERACION listed below:

- Anllares Fossil Power Plant
- Narcea Fossil Power Plant
- Meirama Fossil Power Plant
- La Robla Fossil Power Plant
- Sabon Fossil Power Plant

- Velle Hydro Power Plant
- Bolarque Hydro Power Plant
- Sogama Biomass Plant

4. Acknowledgments

The authors gratefully acknowledge the cooperation of UNION FENOSA and personnel of power plants for their continued technical support.

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Overhauling the Plant Maintenance Process

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Hoosier Energy R.E.C., Inc.

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Overview
Hoosier Energy is a rural electric generation and transmission cooperative utility with headquarters at Bloomington, Indiana. Hoosier Energy owns and operates two power stations – the Frank Ratts Generating Station commissioned in 1970 and the Merom Generating Station commissioned in 1981.

This paper will describe changes that Hoosier Energy implemented at the Merom Generating Station during the time period 1997 to 2000. These changes were implemented to improve the performance of the station. The changes involved work culture as well as work practices.

Merom Generating Station is a two unit, 1000 mw power station that burns Indiana coal. The station has Riley boilers, Westinghouse turbine-generators, Riley ball tube mills, Buell precipitators, Mitsubishi co-current FGD and a solid waste landfill. The station is designed without redundant equipment for full load capability.

Author
This paper is written by Dennis Watson. He has 23 years of electric utility generating station experience. Dennis has a Bachelor of Science degree in Mechanical Engineering from Rose-Hulman Institute of Technology in Terre Haute, Indiana. He is a registered professional engineer in the State of Indiana.

Dennis has been the Maintenance Manager at Merom Generating Station since January of 1997. He has been employed by Hoosier Energy since 1980. Dennis has held several positions during his employment with Hoosier Energy including Efficiency Engineer, Sr. Results Engineer and Technical Services Superintendent.

History
The first 15 years of operation of the Merom Generating Station could be characterized as typical for the time period and utility business during that time. The plant had 11 different maintenance areas and supervisors. Maintenance was performed based upon a daily phone call to Operations.

It was rare to run units at full load except for testing. Ball tube mills were routinely removed from service on nights and weekends. If an equipment or unit outage was needed, it was generally no problem to arrange it.

Scheduled unit outages were every 6 months in the early 1980's. The interval was extended to every year in the late 1980's. The interval was extended to every 2 years in the early 1990's. The interval was extended to every 2 ½ years by 1995. Major turbine overhauls were on 5 year intervals.

Station staffing peaked at 285 people during the late 1980's. Total maintenance department staffing peaked at 105 people. IBEW local union 1393 represents craft workers at the station.

Why Change?

The deregulation of the electric utility industry was becoming a part of the landscape during the mid 1990's. During 1996, Hoosier Energy formulated a strategic plan. This plan included aggressive targets for station availability, heat rate and cost to produce electricity. The station was given the job of finding ways to achieve these targets.

The Plant Manager and Maintenance Manager attended the EPRI 1997 International Maintenance Conference held at Baltimore, Maryland during August 1997. While they were there, they were exposed to the Plant Maintenance Optimization (PMO) project that was available through EPRI and its contractor, the Reliability Management Group (RMG).

The Plant Manager and Maintenance Manager were impressed with the focus of the PMO project: culture as well as work practices. They concluded that this project was worth pursuing.

Upon their return, they met with the Vice-President of Operations who provided his support and corporate stewardship for this $1,000,000 project. The project began during October 1997.

Assessment

An eight person team from RMG performed a six week assessment during October and November 1997. Nearly every employee was interviewed, individually or in groups. From these interviews, an assessment of the station culture and work practices was derived.

The basis of the assessment was a value-based maintenance grid, developed by EPRI and RMG. Grid categories ranged from work orders, labor and materials estimating, equipment custody and cleanup to failure analysis, communication channels, teamwork and structured problem solving. The assessment grid is contained in Appendix A.

As a result of the assessment, it was determined that there would be value in implementing the PMO project. Two or three RMG personnel were on site full time beginning in February of 1998.

Foundation Team

The first order of business was to establish a foundation team. The foundation team consisted of 28 personnel: 14 company personnel selected by the Plant Manager and 14 union personnel selected by the Assistant Business Agent.

The foundation team was charged with the task of developing vision, mission and value statements for the station. This was a long and difficult task. The value of the foundation team developing vision, mission and value statements was that we learned how to talk and listen to one another. RMG facilitated this process. Without their facilitation, we may have failed. The vision, mission and value statements are listed in Appendix B.

One of the most important things we learned during this process was what is meant by consensus. Our definition of consensus is "can you live with it?." Consensus decisions are an important part of a participative management process and were essential in the formulation of new work practices.

Once the vision, mission and value statements were developed they were displayed all around the plant site. We established a process for dealing with issues that were "out of sync" (OOS) with our vision, mission and values. This process consisted of assigning action teams to provide a recommended solution to the foundation team for approval.

OOS was defined as "Any condition, situation or event (existing or potential) that does not support our vision or mission and/or is in conflict with our values." Over 300 OOS were obtained during the first several months of the project. We have steadfastly worked on this list such that we have less than 20 OOS conditions today.

Contractual issues are not undertaken by the foundation team. Any OOS relative to contractual issues are resolved via the grievance procedure.

A Joint Union Management Committee (JUMC) was formed. JUMC consisted of corporate and plant leaders as well as union leaders from the union hall and plant site. JUMC developed an employee bill of rights.

JUMC also worked to improve relations between the company and union. JUMC did not take the place of traditional contract negotiations. JUMC caused training for company and union personnel regarding interest based bargaining. This training, provided by the Federal Mediation Service, was very beneficial at helping our culture to improve.

Work Practice Development

The development of work practices began during June 1998. Work practices were to be developed from the ground up; there were no written maintenance work practices in place. The work practices were developed around the following concepts:

1. Planning and scheduling for maintenance efficiency
2. Predictive maintenance and failure analysis for prevention of failures
3. Work identification and scheduling by operations for effective use of resources
4. Work must be documented to avoid reinventing the wheel
5. Customer and supplier relationships are established
6. Changes are periodically required to work practices

A work practices steering committee (WPSC) was formed to determine what work practices were needed and to develop and implement these work practices. The WPSC consisted of the Plant Manager and his direct reports as well as a member of the CMMS core team.

The initial writing of these work practices was a long and difficult job. We spent six months, working five hours daily, four days per week, in meetings developing these procedures. We did a lot of work outside of these meetings. Without the facilitation by RMG, we would not have completed this job. As well, the skills and knowledge that we gained from the foundation team process were essential to our success.

An important technique that we used to develop work practices was flow charting. We found that it was much more efficient to get the work practice down on paper in a basic flow chart format prior to writing the work practice. The flow chart that was developed for the work assignment, execution and completion procedure is listed as Appendix C.

Action teams developed several of these work practices. Action team participation resulted in a high degree of buy-in when implementation began. Action team members included supervisors and craft workers. The general concept was to try and include personnel who would be affected by the work practices in the development of the work practices. Action team participants become the champions of the implementation effort.

Work Practices Manual

Our Work Practices Manual contains the following procedures:

1. Work identification and approval
2. Work planning
3. Long range scheduling
4. Daily work scheduling
5. Assignment, execution and completion of work
6. Work order closure
7. Operator check sheets and routes
8. Work practice measurements
9. Backlog review and purge
10. Failure analysis
11. Design change request
12. Predictive maintenance
13. Streamlined reliability centered maintenance
14. Master parts list
15. Preventive maintenance
16. Clearance permit system
17. Change procedure

Work Practice Implementation

Implementation of the work practices consisted of training all personnel on the new work practice and then auditing the results of the implementation. Implementation was a perseverance test. Were it not for the champions, implementation may have failed.

A new CMMS was implemented starting in May of 1997. In retrospect, implementing a new CMMS at the same time as the changing of work practices was not desirable. Doing both activities concurrently resulted in a lot of confusion and rework.

The Basics of Our Work Practices

Work identification and approval is the first step in the work practice procedures. The operating groups primarily perform this procedure, however, all personnel have been trained in this regard.

We have 3 priority codes for work that requires a derate or unit outage. We have 3 priority codes for work that does not require a derate or unit outage:

Emergency – do it now
Urgent – do it on the first available schedule
Planned – do it as part of the LRS process

Work planning is the next step. This step consists of conversion of work requests to work orders. This step also is the planning step for the work. There are 3 basic steps to work planning: pre-planning by a planner, field scoping by a craft worker and work package assembly by the planner.

The long-range schedule (LRS) is at the center of our maintenance work practice process. It is a 3 week schedule, loaded at 90% of available resources for week 1, 60% of available resources for week 2 and 30% of available resources for week 3. Every Friday, there is a LRS meeting to review and modify the 3 week schedule. Work packages identified during the LRS process are provided to supervisors on a weekly basis.

From the LRS, a daily work schedule (DWS) is compiled. The DWS is prepared by 10am today for tomorrow's work. A DWS meeting is held daily at 1pm to coordinate work activities.

Work assignment, execution and completion (AEC) is the work practice that is used by the supervisors when assigning and overseeing work. There are provisions for tailgate meetings as well as documentation requirements for craft workers regarding the completed work order.

Work order closure is the conversion of work orders from the completed to closed state. Closure is performed by planners. Closure is an audit of the information provided on the work order.

Other Work Practices

Backlog review and purge is performed quarterly in order to ensure the accuracy of the work order database.

Failure analysis and design changes are utilized to prevent failure recurrence or to improve the reliability or efficiency of equipment.

Preventive and predictive maintenance procedures are essential parts of the station maintenance strategy. A predictive maintenance team meets monthly to integrate diagnostic services provided by different personnel. The equipment and technology matrix used by the PdM team is listed in Appendix D.

One goal of the predictive maintenance team is to cause work on critical equipment to be placed on the LRS. EPRI was instrumental in the development and auditing of this work practice.

The clearance permit system (CPS) was re-written as a work practice in order to implement CPS improvements and to better communicate CPS expectations to our work force.

The master parts list (MPL) procedure exists in order to specify the methodology for assigning parts to equipment and systems. The availability of parts has been an issue for us as we try to improve reliability while trimming inventory.

More Work Practices

The work practices measurements have undergone several iterations and are our most dynamic work practices. We have refined the maintenance key performance indicators (KPI's) several times. Appendix E contains the maintenance KPI's.

There are station KPI's as well. We also use KPI's for outages. These KPI's are reviewed on a weekly or monthly basis; many are important parts of our performance management program goals. KPI's are used to identify mwh loss, backlog of work, effectiveness of LRS process, WO's awaiting parts and other important parameters.
Operators have check sheets and routes specified for equipment rounds. These procedures also provide for the review of trended data.

A change procedure (CP) is in place to facilitate methods for causing written work practices to change. Any person may submit an OOS for a work practice. This OOS gets reviewed and acted upon by the work practices steering committee (WPSC). The WPSC continues to meet on an average of twice monthly for the purpose of monitoring and improving station work practices.

Streamlined reliability centered maintenance (SRCM) has been implemented on 2 of the 13 station systems identified in the assessment. The purpose of SRCM is to optimize preventive maintenance activities for a system.

Outages

Scheduled outage planning and execution are being performed in a different manner than 5 years ago. An outage team is utilized for planning and executing the outage. The team consists of approximately 25 members from supervision, craft workers, engineers and managers. The maintenance manager is the team leader. The outage organizational chart is listed in Appendix F.

We have developed an outage hot list concept for unscheduled outages. This is a list of work to be performed at our next unit outage opportunity. We typically plan for about 300 hours of work to be performed during a 36 hour unscheduled outage. This list is reviewed at every LRS meeting. The operating groups control the list contents. The hot list is available for public viewing on our local area network.

The team concept for outages is applied with corporate personnel as well. The Operations Vice-President, his staff and station management personnel meet monthly to coordinate outages between the power stations and dispatch. This group is responsible for the decrease in scheduled outage frequency, as well as establishing a summer prep outage for each unit during the spring of each year.

Station & Maintenance Organization

The station is organized into 4 departments: operations, maintenance, engineering & performance and administrative. Personnel are assigned to projects across departmental lines. This is particularly prevalent for scheduled outage activities.

Prior to PMO, the station was organized into 6 departments: operations, FGD, technical services, maintenance, office services and general services. Personnel worked within their department.

The maintenance department has 92 personnel: 77 craft workers in 5 work groups, as well as 15 supervisory and clerical personnel. There are 47 mechanics, 17 electricians and 13 controls and instrument technicians. Supervisory and clerical personnel consist of 5 front line supervisors, 5 planners, 2 relief supervisors, 2 schedulers and the maintenance manager.

Prior to the PMO project, there were 99 personnel in the maintenance department: 83 craft workers in 11 work groups, as well as 16 supervisory and clerical personnel. There were 54 mechanics, 16 electricians and 13 controls and instrument technicians. Supervisory and clerical personnel consisted of 11 front line supervisors, 1 planner, 2 schedulers and 2 managers.

Planning and scheduling is centralized in order to establish and maintain a culture for planning and scheduling work and to facilitate coordination and sharing of resources. Relief supervisors are used for attendance relief, as well as to allow front line supervisors to perform special projects and outage planning.

Conversion to a planned and scheduled maintenance concept meant that supervisory personnel were reassigned based upon their strengths as a planner or as a leader. Job specification revision occurred several years after the reassignment of personnel to new job duties. In retrospect, this would have been better done at the beginning of the PMO project.

Attrition was used to reduce the number of maintenance craft workers employed. An early retirement program and attrition were used to reduce the total number of supervisory and clerical personnel employed.

Some Lessons Learned

1. *Best practice duplication.* Duplicating the work practices of others without consideration for work culture differences usually results in an unsuccessful work practice implementation. Put another way: if you are always imitating others, the best you can be is second best.
2. *I'll do it myself.* If we did not have a consultant on site, the changes we made would not have been written or would not have "stuck." Simply put, we would have reverted back to our old behaviors. RMG would not let us do that. They helped us persevere with development and implementation of new work practices.
3. *One time change.* We have found that change is necessary and happens frequently to certain work practices while others change less frequently if at all. We found that starting off with a basic work practice and then working to change and improve it within our

culture, was the best way to achieve excellence. We subscribe to the adage "crawl, walk, run, fly, beam me up."

4. *Productivity = efficiency x effectiveness.* Operations determines the effectiveness of maintenance work by determining what maintenance needs to work on. Maintenance determines the efficiency of maintenance work through proper planning, scheduling, execution and completion of work.
5. *Input = buy in = champions = successful implementation.* If you have the opportunity to provide input to the decision making process and this input is utilized, you "buy in" to the decision that has been made. This "buy-in" causes people to be champions for the decision. Champions are needed on the factory floor in order to successfully implement work practice improvements in a reasonable time period. Buy in from union leadership was an essential part of improving our work culture.
6. *Importance of culture*. Work practices are what we do to get work accomplished. Culture is how we go about getting work accomplished. Culture is how we interact with one another. Culture and work practices are interdependent upon one another. It was necessary for us to improve our culture prior to improving our work practices. If we had only focused on work practices, we may have failed in their implementation.
7. *Can you live with it?* This is the question we asked when trying to arrive at a consensus decision. It was our best definition of consensus. You have consensus when every member of the group honestly answers yes to this question.
8. *Job specifications*. If you are going to change the job duties of personnel, change their job descriptions prior to implementation. Involve these personnel in the changing of the job descriptions. Play to your strengths when changing the duties of personnel. Emphasize the positive reasons for changing duties.
9. *Meetings.* Meetings are effective methods of exchanging information and making decisions so long as some basic methods are consistently applied:
   - Set an agenda prior to the meeting
   - Send the agenda prior to the meeting
   - Stick to the agenda during the meeting
   - Establish time limits for the meeting and stick to them
   - Maintain an action item register during the meeting
   - Review the action item register prior to meeting conclusion
   - Provide meeting notes to all participants and interested non-participants in a timely manner upon meeting conclusion

Project Results

Following are some performance statistics for the Merom Generating Station:

Comparison years:	1996 to 2000
Equivalent availability:	80.1 to 85.5%
Net heat rate:	10529 to 10488 btu/kwh
O/M cost:	$4.45 to $3.96 per mwh
Inventory:	$11,050,000 to $10,150,000
Personnel:	255 to 221

Contact Information

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Appendix A – Assessment Grid

Work Culture	Leadership & Goals	Accountability	Active Communication Channels	Structured Problem Solving	Delegated Decision Making	Innovations & Continuous Improvement	Technical & Managerial Training	Self-Managed Teams & Teamwork	Total Customer Satisfaction	
Cost Effective Technology	Formal Failure Analysis	Craft Skills Training & Qualification	Unit Capacity Management	Unit Availability Management	Heat Rate Control	Fuel Use Optimization	Networked Information Systems	Asset Management		
Computerized Mgmt System	Work Order System & Life-Cycle	Table-Driven Structure	Work Mgmt & Backlog Indicators	Equip Costs & Performance Indicators	Equipment Failure Analysis	CMS Access & Work Mgmt. Training	Materials & Purchasing Integration	Unit Load Schedule Integration	Accounting & Payroll Integration	
Prev & Pred Maintenance	Formal PM Program	Joint Resource Commitment	Annual PM Review	PM Effectiveness Indicators	Formal PdM Program	PdM Effectiveness Indicators	Streamlined RCM			
Work Mgmt Tools	Backlog Indicators & Trends	Job Priority Use & Review	Work Mgmt Effectiveness Indicators	Labor ST & Overtime Reports	Resource Leveling	Equipment History & Costs	Top Ten Problem List	Availability & Reliability Indicators	Financial & General Indicators	Action Item Lists
Work Scheduling	Jointly Prioritized Planned Work	Formal Scheduling Meetings	Contractor & Plant Coordination	Daily Crew Schedule	Schedule Compliance Review	Periodic Purging of Backlog	Long-Range Schedules	Outage Progress Updates	End-Of-Outage Testing & Start-Up	Post-Outage Analysis & Measurement
Materials	Accurate & Organized Inventory	Stock, Tools Issues & Returns	Non-Stock Issues & Returns	Receiving & Shipping	Quality Assurance & Control	Materials Staging & Delivery	Vendor Stocking	Vendor Certification & Performance	Materials Effectiveness Indicators	
Work Planning	Prioritized & Accessible Plng Backlog	Labor Hours Planning for Crafts	Materials & Parts Planning	Field Job Scoping	Standard Job Plans	Planning Effectiveness Indicators	Craft Participation in Planning	Outage Planning		
Ops/Maint Teamwork	Early Work Identification	Equipment Custody & Preparation	Clean-up & House-Keeping	Operations Checksheets & Routes	Clearances & Process Safety Management	Internal Cust Satis Process	Operations SOPs	Operator Certification & Training		
Work Order	Unique Work Order # & Record	Equipment Identification & Label	Complete & Accurate Symptom	Clear Priority System	Defined Approval Process	Labor & Materials Estimating	Acceptance of Completed Work	Labor & Materials Actuals	Complete Work Histories	Organized Filing System

MEROM GENERATING STATION

☛ VISION STATEMENT

At Merom Generating Station, we share in a vision to create an enjoyable environment of mutual trust and respect with open and honest communications leading to an effective and efficient work place.

☛ MISSION STATEMENT

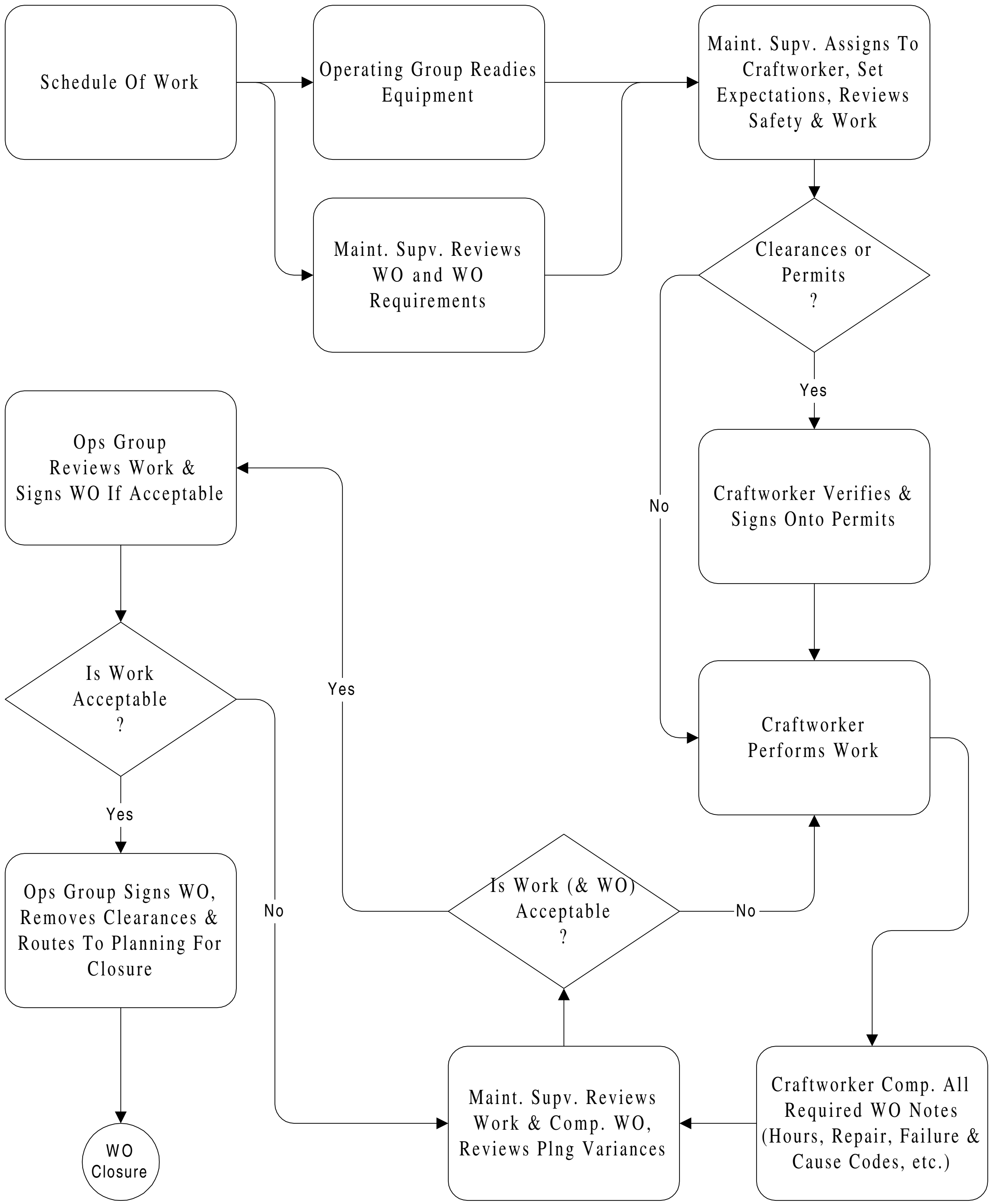
Our Mission is to produce reliable, low cost electricity for all consumers, in a safe and environmentally sound manner.

☛ VALUE STATEMENTS

We, the employees, are dedicated to the following values:

- **We will create and maintain a safe, secure, enjoyable workplace, through a well trained work force, where employees go home in as good a condition or better, than when they arrived.**
- **Employees share in the knowledge that their personal security is achieved by cooperating in the operation of a successful power plant.**
- **Merom Generating Station will be an environment where trust and honesty are the foundation for mutual respect, openness and fairness.**
- **We support an environment that shares information openly and honestly, without retribution, while seeking mutual understanding.**
- **We will demonstrate teamwork through a dedicated, reliable and efficient work force that shares the load.**
- **We will enhance employee knowledge and professionalism through training and timely feedback.**
- **We value job satisfaction, through fair compensation, mutual respect, teamwork and where each job produces meaningful results.**
- **We see all employees as our most important assets, where their ideas are valued and encouraged.**

Appendix C – Assignment, Execution and Completion Flow Chart



Appendix D – Equipment and Technology Matrix for PdM

Each EQID has two rows of information as shown. Upper row is the equipment status per the technology owner.

Second row contains frequency, month and year of last test or inspection (if applicable)

A
Q3-99

Tech owner's opinion of equipment status. A=acceptable, M=marginal, U=unacceptable, OOS= Checked

Frequency (A=annual; S=Semi-Annual Q=quarterly;M=monthly;D=daily); Month and year of last test or inspection (ex. 3-99=March, 1999) if applicable. A "0" indic

eqp_code	Equipment	Overall Equipment Status	Maint. History & Observations	Functional Tests / Performance Tests	Vibration	Infrared Thermography	Oil Analysis/Water Chemistry	Process Data	Leak Detection	Operator Observations	Electrical & Current Testing	Comments	PDM Recommendation
	UNIT 1 WATER CHEM	A					M 0	0				Phosphate usage +-5 lbs/day-ammonia usage higher than Unit 2	Conduct phosphate hideout test
	UNIT 1 EHC FLUID SYSTEM (skid, tank, EH pumps...etc)	A	A		A M1-01		A M1-01	A		A			
1-AR-P-1A	A COND AIR RMVL VAC PMP	A	A		A M1-01	NC 0		A	NC 0	0	A S12-00	seal leaking, pump scheduled for changeout during spring outage	
1-AR-P-1B	B COND AIR RMVL VAC PMP	A	A		OOS M9-00	NC 0		A	NC 0	A	A S12-00		
1-CA	COMPRESSED AIR SYSTEM	A	A			NC 0		A	NC 0	A			
1-CA-C-1A	A MAIN AIR COMPRESSOR	A	A	NC	A M1-01	NC 0	A Q9-00	A	NC 0	A	A S12-00		
1-CA-C-1B	B MAIN AIR COMPRESSOR	A	A	NC	OOS M12-00	NC 0	A 0	A	NC 0	A	A S12-00		
1-CW	CIRC WATER SYSTEM (LO, screens, wash pumps..etc)	A	M		A M1-01		A Q9-00	A	NC 0	M		West Nozzle 1A screen plugging	
1-CW-P-1A	A CIRC PMP	A	A	NC	A M1-01	NC 0	A Q9-00	A	NC 0	A	A S12-00		
1-CW-P-1B	B CIRC PMP	A	A	NC	A M1-01	NC 0	A Q9-00	A	NC 0	A	A S12-00		
1-CO-1	MAIN CONDNSR	A	A	NC		NC 0		M	NC 0	M		High inlet pressures needs mechanically cleaned, Amertap still an issue., Inlet valves won't isolate	
1-CO	CONDENSATE SYSTEM (transfer pumps, valves..etc)	A	A		A M1-01			M	NC 0	A		Marginal pressure at high loads.	
1-CO-P-1A	A CONDENSATE PMP	A	A	NC	A M1-01	NC 0	N/C 0	A	NC 0	A	A S12-00		
1-CO-P-1B	B CONDENSATE PMP	A	A	NC	A M1-01	NC 0	N/C 0	A	NC 0	A	A S12-00		
1-EC	COOLING WATER SYSTEM (misc pumps, tower...etc)	A	A		A M1-01	NC 0		A		A			
1-EC-F-1A	A COOLING TWR FAN	A	A	NC	NC M12-00	NC 0	A Q9-00	A		A	A S12-00		
1-EC-F-1B	B COOLING TWR FAN	A	A	NC	NC M12-00	NC 0	A Q9-00	A		A	A S12-00		
			A	NC	A	NC		A		A	A		

Appendix E – Maintenance KPI's

Hoosier Energy
Merom Generating Station

Week Beginning 2/19

MGS KPI's

Work Group	Target	MM1	MM2	MM3	IE1	IE2	Maint. Sub Total	FGD	MH	OPS	CO	OPS. Sub Total	Prod Eng	Total
Total Work Orders Completed		13	30	20	51	37	151	15	4	22		41		192
WO's Scheduled			50	38	39	39	166	27	19	24		70		236
WO's Completed			35	32	37	35	139	17	4	16		37		176
% Completion	75%	0%	70%	84%	95%	90%	84%	63%	21%	67%	0%	53%	0%	75%
EWO's Scheduled		4	5	9	7	10	35					0		35
EWO's Completed		2	3	5	5	10	25					0		25
% Completion		50%	60%	56%	71%	100%	71%	0%	0%	0%	0%	0%	0%	71%
UWO's Scheduled		15	6	17	8	4	50					0		50
UWO's Completed		11	3	4	4	3	25					0		25
% Completion		73%	50%	24%	50%	75%	50%	0%	0%	0%	0%	0%	0%	50%
Total No. Work Orders		1048	764	706	1019	628	4165	205	139	295	217	856	50	5877
Previous Wks Total NO. W.O.s		1192	809	760	1196	783	4740	203	123	302	190	818	50	6376
Work Orders (OEP, OEU, OU)		309	156	53	97	55	670	2		3	132	137	13	944

Planning	MM1	MM2	MM3	IE1	IE2	MM YTD	FGD	MH	OPS	OPS YTD
Rework Work Orders	0	0	1	2	0	3				0
Rejected Work Packages	0	0	0	0	0	4				0
Field Scoping Sent	9	3	2	0	0					
Field Scoping Completed	0	3	2	0	0					
% Completion	0%	100%	100%	0%	0%					
Current Field Scope Backlog	71	5	5	5	12					
Previous Wks Field Scope Backlog	62	10	7	5	12					
Previous/Previous Week Backlog	68	10	7	5	12					

Parts & Requistions		YTD
WO's scheduled w/parts	189	
Total parts issued	386	
Untimley Part Returns	0	
WO's w/part delays-current wk	2	
Backlog of WO's w/part delays	35	

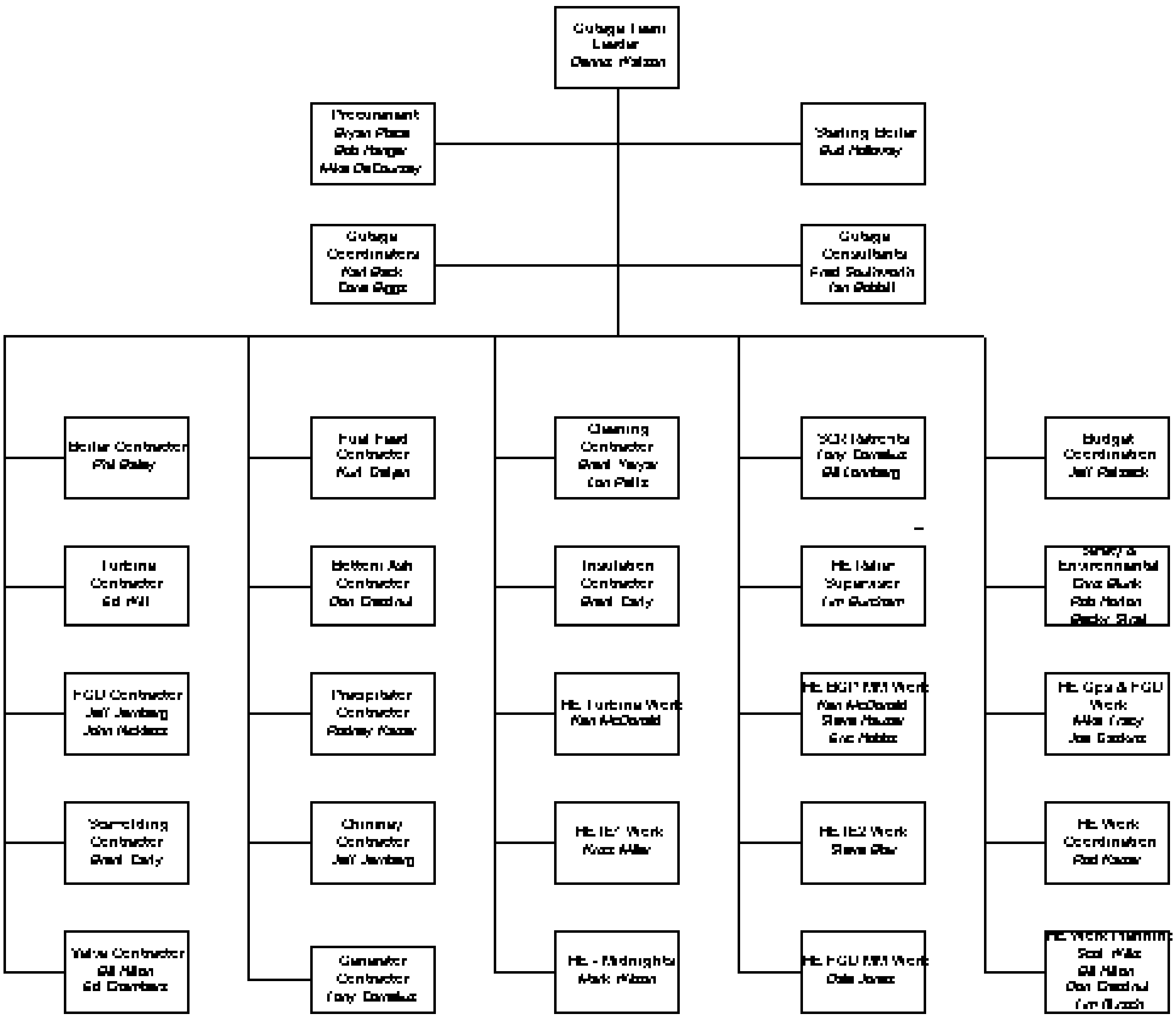
MPLS	MM	IE
Part No's Entered into Ramco	49	56

Total Open Purchase Req's	252
Previous Wks Total Open Requisition's	281

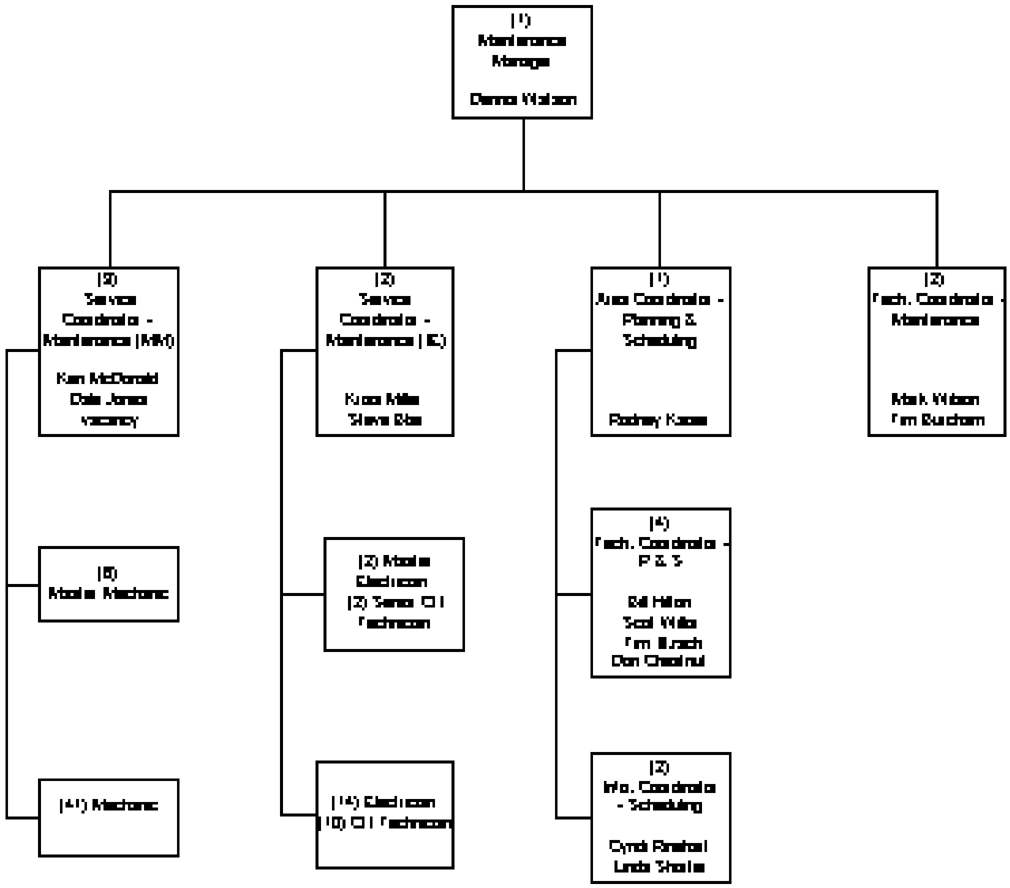
RAMCO Generated KPI's

Work Group	Maint.	MM1	MM2	MM3	IE1	IE2	YTD
% Resource Hours Sch.	86.0%	80.0%	79.0%	83.0%	107.0%	81.0%	77.7%
% Urgent Hours	14.9%	12.9%	11.8%	27.4%	9.1%	18.7%	16.1%
% Planned Hours	13.5%	10.2%	30.0%	20.8%	18.2%	23.0%	21.8%
% PM and PdM Hours	42.9%	51.9%	55.2%	11.6%	46.1%	35.6%	22.7%
% Blanket Hours	21.5%	22.7%	25.7%	25.7%	24.1%	6.4%	27.3%
% Emergency Hours	7.2%	2.2%	7.0%	14.4%	2.4%	16.3%	15.2%

Appendix F – Outage Organization Chart



Appendix G – Maintenance Organizational Chart



EXELON NUCLEAR
PROACTIVE MAINTENANCE PROGRAM
AND BEST PRACTICES
June 2001

BACKGROUND:

Proactive Maintenance is one part of the total Plant Maintenance Optimization process and is the component that provides continuous improvement to mitigate repeat failures and unnecessary tasks. Proactive Maintenance is an on-going process and not a one-time study. As such, this process provides continuous improvement in “what” work is performed, “when” this work is performed and “how” this work is performed. Major failures that result in a loss of availability or costly repairs are easily identified and usually are investigated to determine a “root cause” of the failure. The results of this study provide actions that when implemented prevent a reoccurrence of the failure. Safety, environmental and regulatory events are generally easily identified and studied to prevent a repeat occurrence. Less dramatic events occur during the operation and maintenance of power plants. These events are often not identified and therefore not corrected resulting in an impact to maintenance budgets, manpower and resource utilization efficiency. A comprehensive Proactive Maintenance Program will identify all opportunities to improve reliability, safety, environmental and regulatory compliance while reducing operating and maintenance costs.

Exelon Nuclear with support from EPRI has initiated a project to develop and publish a guideline to establish a Proactive Maintenance Program. This guideline will be based on the “best practices” in use throughout the utility industry and non-utility industries. The process used to develop this guideline is to assess existing programs and select the best practices. A team has been established to perform these assessments and develop the guideline. The guideline will be completed and published by the 4th quarter of 2001.

INPO Equipment Reliability document AP-913 was used as the basis in developing a simple yet effective criteria for providing valuable maintenance feedback to determine the “as-found” condition of plant equipment.

The following information is from a recent assessment performed by EPRI for the Proactive Maintenance program at Exelon. The assessment demonstrates best practices and areas for improvement for the program.

EPRI / EXELON NUCLEAR
PROACTIVE MAINTENANCE PROGRAM
Assessment

EXELON NUCLEAR PROACTIVE MAINTENANCE PROGRAM ASSESSMENT

EXECUTIVE SUMMARY

The Proactive Maintenance Program in place at Exelons four regional Mid Atlantic Nuclear plants (Limerick, Oyster Creek, Peach Bottom and Three Mile Island) and is a comprehensive model designed to identify plant components that may be wearing out earlier or later than expected, failing unexpectedly or experiencing repeat failures. The program captures component failures (corrective maintenance) and PM tasks that are not optimized for scope or frequency. When considered with other programs previously established at the plants to address major failures, safety, environmental and regulatory events the total "continuous improvement" efforts are very comprehensive. The program is the best observed by EPRI as part of the project to develop a Proactive Maintenance Guideline.

Maintenance Optimization depends on certain key elements. A Proactive Maintenance Program depends on many of the same key elements. The key elements that were reviewed during this assessment included:

- Work Identification
- Work Order Closeout
- Work Management Systems
- Organization
- Accountability
- Organization
- Leadership
- Metrics
- Communication
- Goals
- Benchmarking
- Training
- Roles & Responsibilities

Each of these elements are clearly identified in the Proactive Maintenance Program and are generally well documented in the MAG-CG-510 procedure, Desktop Guide or Training materials.
The program is comprehensive in design and implementation yet is expected to require only ½ Full Time Equivalent of a resource (once the program is mature). Assuming this target is achieved the payback of the program will be significant. In addition to the overall good design of the program, specific elements should be noted. These include the use of "condition codes" for identifying and filtering tasks, worker input and worker feedback, required action date for change requests, clearly defined roles and responsibilities and an excellent "training program".

This report contains overall and specific findings with nine (9) recommendations. Generally the recommendations address only minor documentation issues, information management tools and continuation of the communication, employee involvement and training elements.

INTRODUCTION:

The Mid-Atlantic Regional Operating Group (ROG) has established a Proactive Maintenance Program to identify and address improvement opportunities in routine maintenance performed at their plants. Limerick, Peach Bottom, Three Mile Island and Oyster Creek plants are in various stages of implementing this Proactive Maintenance Program. A PAM program assessment was performed by EPRI to determine the effectiveness of the program and to identify and report "best practices" of the program. The assessment was performed primarily at the Limerick Generating Station and the regional headquarters at Kennett Square. The assessment reviewed the key elements of the Proactive Maintenance program that focuses on routine maintenance. No assessment of the programs to address major events was performed although information was gathered on these programs.

The assessment took place during March 2001. Preliminary findings were submitted to the Exelon project team during the assessment and many of the recommendations were immediately implemented. The preliminary findings document is included as an attachment to this report. The Exelon program was presented to the EPRI team in April 2001. This report summarizes the findings and recommendations based on the Proactive Maintenance Program assessment.

PAM PROGRAM

The Proactive Maintenance program includes four elements (ref: MAG-CG-510). These elements are:

- Soliciting feedback on the "As-found" condition of components by the performing organizations with their recommendations for changes to the maintenance performed on that component.

- Review of selected "As-found", "Work performed", and "Suspected Cause of Failure" remarks from completed work including Corrective Maintenance, Preventive Maintenance and Surveillance Tests.

- Participation in evaluation and corrective actions for repetitive component failures to determine if design or operational changes would permanently eliminate or minimize failures.

- Classification of corrective and preventive tasks into subtasks which define where maintenance resources are being used.

The "As-found" description is essential in determining if a component is "wearing" as expected or it is "wearing" more or less than expected. The Condition Codes (see MAG-CG-510-4) in addition to the "As-found" remarks, "Work Performed" and "Suspected Causes of Failure" remarks provide a methodology of selecting components whose maintenance tasks should be reviewed. The technician who is responsible for completing these sections of the Work Order is the best-qualified individual to provide this information. The process of having the maintenance technician match the "as-found" condition with the appropriate condition code (below) into the CMMS provides a simple approach for trending and fine tuning of the existing PM / PdM program.

The site PAM site Coordinator is the initial reviewer of the completed work comments. The Condition Codes provide a method of filtering work orders for review. Each work order is coded by the maintenance technician performing the tasks using one of the following codes:

- CONDITION CODE 1 – C1: Unanticipated Failure
- CONDITION CODE 2 – C2: Failure, Not normal wear
- CONDITION CODE 3 – C3: Failure, Normal wear
- CONDITION CODE 4 – C4: Out of Tolerance
- CONDITION CODE 5 – C5: Reliability Degraded
- CONDITION CODE 6 – C6: Within Tolerance

- CONDITION CODE 7 – C7: Satisfactory
- CONDITION CODE 8 – C8: Superior/Like New

A pocket card was developed and training of the Maintenance Technician in their roles and responsibilities for properly identifying and utilization of the Condition Codes. These codes have been derived from the INPO AP-913, "Equipment Reliability" document.

The review process includes generation of the "CREM" (Closing Remarks) report based on the condition code filters, reading all work order comments, soliciting additional input from the maintenance technician for clarification and providing feedback to the maintenance technician. Based on the initial review, the PAM site Coordinator will determine if a "root cause" investigation is needed and process accordingly, request a change to the PM basis or initiate a review by the PM Coordinator. The PAM site Coordinator provides a "need by" date for all PM basis change requests.

The PAM site Coordinator is also responsible for tracking the status and disposition of requested changes and providing feedback to the initiating maintenance technician, Mid-Atlantic ROG Coordinator and plant management. The PAM site Coordinator provides site PAM Performance Indicators.

The PAM site Coordinator is responsible for categorizing all completed work into the following definitions (see MAG-CG-510-3):

Corrective Maintenance: Expected (CM-E)
Corrective Maintenance: Unexpected (CM-U)
Preventive Maintenance: Restore/Replace (PMRR)
Preventive Maintenance: Condition Monitoring (PMCMT)
Condition Directed Maintenance: (CDM)
Proactive Maintenance: (PAM)
Miscellaneous: (MISC)

The categorizing of work provides a capability to analyze where maintenance resources and dollars are being expended.

The role of the Proactive Maintenance Program Specialist (Mid-Atlantic ROG Support) is to provide overall coordination between the site programs. This individual is also responsible for the overall program goals and objectives, program performance indicators and to determine the return on investment of the proactive program.

<u>OVERALL FINDINGS:</u>

The PAM Program that was included in this assessment primarily focuses on the identification of improvement opportunities in routine maintenance and minor corrective maintenance. The ability to identify these opportunities is dependent on the feedback from the maintenance technicians. The quality of the remarks is key to the success of the program. The use of Condition Codes provides an excellent methodology to select components and tasks that should be reviewed. The feedback element on the status of change requests to the maintenance technicians is a key sponsorship element in success of the program.

There are other processes in place to identify improvement opportunities within the plant for major failures, safety, environmental and regulatory events. The possibility exists that the PAM Program could be evaluating a task or component at the same time that an existing process is doing the same thing resulting in redundancy of effort. However, this redundancy is expected to have only a minor effect on the goal of ½ FTE for the PAM site Coordinator. Duplicate change requests will be filtered in Engineering or the Health Committee.

Changes that are requested as a result of identification by the Proactive Maintenance Program follow existing procedures and processes. The handling of change requests is very important in the overall success of the PAM program. The tracking of the change requests by the PAM site Coordinator is critical to assure there are no barriers to the PAM process.

The process is well documented in the MAG-CG-510 procedure. This procedure reflects the design of the process, the roles and responsibilities, includes process diagrams and use of condition codes. As the program is finalized, this document should reflect any changes and become the control document. The "Desktop Guide" is an excellent document providing specific instructions regarding application of the program and program tools.

Recommendation 1: Duplicate processes should be mapped in conjunction with the PAM process to fully understand any duplication of effort as well as the follow-up steps to PM change requests and Engineering Evaluation requests. All other links such as to "TOPS" and "PCM" should be designated where appropriate. The mapping process will also bring together the responsible individuals for each of the processes and may identify any conflicts. A review of process diagram AP913 does not indicate where the PAM process is linked.

Recommendation 2: The PAM process flow diagram (Exhibit MAG-CG-510-1) does not show "condition code" completion by technician or code/Crem review by PAM coordinator. The diagram does not show path to PM Change Process that is mentioned in the procedure nor does it show the assigning task type to work order that is well defined in MAG-CG-510-3.

Recommendation 3: Periodic group sessions with maintenance technicians will provide feedback on how the overall success of the program is perceived. These sessions could be a part of the on-going refresher training.

Recommendation 4: During a training session with one of the work teams, they requested that the PAM Coordinators Report be provided to the teams. Providing this report will help continue the support from the teams. During the discussion, it was indicated that the report could be filtered for items submitted from each team. This request should be implemented.

SPECIFIC FINDINGS AND RECOMMENDATIONS:

Finding: Work Management System- All of the work order information including remarks is entered, stored and retrieved from the PIMS system. This system is capable of handling or has been adapted to handle the most of the needs of the PAM program. Where PIMS has not met the needs of the program, a separate program is being utilized to pull data, provide processing and input to the records. This approach appears to be the most efficient method to satisfy the PAM program. Additionally, a separate database (PAM Review Tracking) has been established to track the status of PAM activities and measure benefits.

Recommendation 5: The loop program that accesses data from PIMS is transparent to the user and appears to be integrated with PIMS. While this meets the needs of the PAM program and was quicker and less expensive to implement it may present a problem in the future if changes are made to the PIMS file structure. If this approach continues to be utilized, a procedure should be developed to insure future links to the PIMS data.

Recommendation 6: The PAM Review Tracking database provides a short-term solution for the PAM program but is outside of the info management processes and may be difficult to maintain in the future. A request should be submitted to develop this database as part of the information management systems.

Finding: Metrics- The PM change request indicator is a good indicator but initially was difficult to understand because the total number of change requests established the scaling. This has since been modified to show the total number of change requests as a numeric value.

Recommendation 7: Other indicators may be beneficial such as the breakdown of condition codes and task types. When cost-tracking data becomes available a metric should be established for these values.

Finding: Communication- The process of soliciting input from the maintenance technicians and providing feedback on the disposition of their comments is excellent. This element provides communication and involvement. Providing the PAM Coordinators Report to each work team (see Recommendation 4) will establish a regular path of communication.

Recommendation 8: Additional methods of communicating the activities of the PAM Program could be a newsletter or implementation of a WEB site. Soliciting suggestions from the work teams for the best method of communicating should be considered.

Finding: Training- The training session provided to each work team was exceptional. The information was well presented and apparently well understood. There was considerable positive discussion during the training session.

Recommendation 9: Follow-up training should be considered after the program has been in place for at least 6 months. A critique of the work order close out remarks should be included in this training session.

ACKNOWLEDGEMENT

On behalf of EPRI, I would like to extend my appreciation to the employees of Exelon for sharing the information on their Proactive Maintenance Program. Their pride and dedication to improving “what”, “when” and “how” work is done by creating and implementing this program will guarantee the success of the program and the continuous improvement of their plants. The Proactive Maintenance Program in place in Exelon can become the standard for the industry but the employee excellence may not be able to be duplicated.

Attachments:
A: EPRI Proactive Maintenance Project, Exelon Phase, Interim Report, March 21, 2001

Attachment A:

EPRI
PROACTIVE MAINTENANCE PROJECT
EXELON PHASE
Interim Report
March 21, 2001

OBSERVATIONS:

Process- Well-defined, well thought out, process diagrams developed, process understood by site coordinator. *There are other PAM processes in place that aren't indicated on the PAM process diagram (i.e.: response to a maintenance rule or failure of a radiological system). To get a total picture of proactive processes in the plants, these processes should be designated. The PAM process flow diagram (mag-cg-510) does not show "condition code" completion by technician or code/Crem review by PAM coordinator. MAG-CG-510 does not show path to PM Change Process that is mentioned in procedure. Diagram does not show assigning task type to work order (MAG-CG-510) but is well defined in MAG-CG-510-3.*

Procedure- The desktop guide provides a step-by-step procedure for handling responsibilities. The development and utilization of the condition codes is exceptional. The Crem report and utilization is good. Roles and responsibilities are defined in procedure. *Procedure (MAG-CG-510) does not show use of condition codes by technician (sec 5) by review is included by PAM coordinator in sec 7.1.3. The procedure does not detail questions PAM coordinator should consider in determining disposition of task. (i.e.: Should PM task frequency change? Is there a monitoring task that could be used in place of task or to complement task?) How to evaluate task is not defined. Procedure does not state how to select tasks to review. (i.e.: sort based on condition codes, Crem report run and review.) Procedure refers to PM change process. Is this the same as "Eval" process?*

Metrics: *The PM change request indicator is a good indicator but consider showing total tasks reviewed as a tabular number to provide a better scale for other data. Other indicators are probably needed such as breakdown of condition codes and task types. Also, once cost-tracking data is available, a metric showing this data should be considered.*

Cost Benefits: The "Access" database is a reasonable method to track net change in maintenance cost as a result of PAM when it is change to frequency or addition or deletion of task. Whether it is best to embed this in PIMS or just link to PIMS is best decided by IT. Regardless, requirement is that no data should be entered twice. *Benefit from making change as a result of a C! Condition may not be fully credited. Cost benefit program should be modified to include some of the elements of the CBA model used by the PDM group to account for avoidance of failures and any impact on production capacity.*

Communication: The "feedback" element in the process is excellent and should continue to be emphasized. *The best method to communicate PAM activity to general plant population and management still needs to be determined.*

Training: The training element is excellent and seems well received by teams.

OVERALL: The PAM process in place at Limerick and Peach is very good and is the best model seen in the industry to date. The comments included in this document mostly deal with modifying the documentation to agree with the actual process. Key elements that make the process exceptional are the use of the condition codes and feedback processes.

RELIABILITY CENTERED MAINTENANCE

***Anil Kumar** ***G.P.Singh**

SYNOPSIS

Reliable, uninterrupted & economical power generation can be achieved only if power generating units have a low down time & operate within specified regime.

Low down time of equipments can be achieved if maintenance plans are schedule to be condition based and maintenance actions have a diagnostic approach with a view to plan major replacements on the basis of behavioural trend & assessment of residual life.

It is with this objective, the present paper lays emphasis on an integrated approach to plant maintenance optimization plans (PMOP) through a cost effective process (CEP) where in maintenance needs are addressed from the drawing board stage it self. The dynamic process encompasses equipment's selection and layout, so as to facilitate maintenance besides quality control during erection and commissioning and a total productive maintenance approach.

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RELIABILITY CENTERED MAINTENANCE

1.0 INTRODUCTION

Reliability centered Maintenance (RCM) aims at an integrated approach to plant maintenance optimization plan (PMOP). It revolves around the concept of developing a cost effective process (CEP) wherein maintenance needs are addressed from the drawing board stage itself. This dynamic process encompasses equipment's selection and layout in a manner that facilitates maintenance requirements, besides organizing a quality control process during stages of erection and commissioning. This also incorporates a continuous updation of maintenance programs based on equipment's behaviour within the operational regime.

Reliability Centered Maintenance (RCM) is therefore a total forward - backward integration of manufacturer's guidelines and utilities past experience as well as behaviour of the equipment in specific for the continuos upgradation and development of maintenance schedule, techniques and technologies to achieve a life time optimum performance at minimum down time. RCM can provide a platform for longer trouble free runs (TFRs) of the equipments/systems provided a systematic approach is adopted along the following steps.

2.0 APPROACH TO RCM

(a) Equipment design and Selection
(b) Plant layout and sizing
(c) Quality Control during Erection & commissioning
(d) Total productive maintenance
(e) Outage planning & control
(f) System support

2.1 Equipment Design & Selection

The selection of equipment of proven design & performance in similar environmental conditions as well as operational regime is the first step, which not only helps in reduction of maintenance workload but also avoids sudden failures due to incipient problems. Design criteria incorporating ease of maintenance and skill requirement does affect the downtime.
Similarly manufacturer's services after sales e.g. spare availability - quality & cost should be given due consideration. A feedback from similar end user is useful tool during equipment selection.

2.2 Plant Lay Out and Sizing

Layout of the equipment should be such that it facilitates maintenance and thus reduced down time. Adequate access to equipment and its sub-assemblies for dismantling and handling is essential not only to achieve reduced down time but also ensures quality work. Location of wash water pumps & well laid wash lines, material handling wells with adequate mechanized lifting facilities, reclaimation & maintenance bay, planned layout for scrap/wastage disposal yard etc facilitates maintenance with ease and consequently low down time besides encouraging quality work environment.

2.3 Erection & Commissioning

Quality checks during constructions of foundation and equipment erection, leveling and alignment ensures a long trouble free run of the equipment.

Cases of equipment failures/system problems during commissioning are not uncommon. The main reasons being the lack of commissioning checks or shorts cuts to commissioning due to poor commissioning organization or pressing times schedule or both. Units or equipment thus commissioned overlooking minor defects ultimately result into frequent outages, increased maintenance and poor performance. An adequate O&M organisation right from erection and commissioning stage with suitable documentation system for erection protocols, OMIM's, commissioning documents etc provides a base line data-another important step towards reliability centered maintenance.

2.4 Total Productive Maintenance

Total productive maintenance advocates an integrated approach to operation & maintenance at all levels with focus on increased productivity. TPM aims at the equipment with "Engineered for Productivity (EFP)" & not with "Engineered to Perfection (ETP)"

The approach basically

- Identifies areas where productivity can be improved
- Involves all level of personnel in productivity improvement.
- Moves from a reactionary (Breakdown) to proactive (condition based-just in time) work style.
- Creates a base line performance indicator for equipments

- Measures & evaluates engineering efforts and maintenance performance.
- Reduces activities & expenses, which don't improve productivity.
- Increases employee's morale & job satisfaction.

Thus TPM essentially aims to derive desired objective of low down time and low cost along following steps:-

2.4.1 Operation Regime Review & Optimisation

Daily walk down at the area and review analysis of operational parameters of major equipments by a cross functional teams to have a close understanding of equipment behaviour as well as to decide for corrective action needs to be carried out at first level of supervision.

2.4.2 Preventive Maintenance Schedules

Preventive Maintenance schedules drawn on the basis of manufacturer's guidelines need to be updated to specific requirements based on utilities operational experience, equipment behaviors & past data of similar utilities. These schedules could be based on fixed time or running hour’s basis depending upon service conditions & criticality of requirement.

2.4.3 Condition Based Maintenance Schedules

On line as well as off line condition monitoring data's e.g. vibration & signature analysis, oil analysis - routine & wear debris, Infrared scanning (Thermovision) for hot spots/high temperature areas, noise surveys, Thermal imaging of insulations, erosion survey's for pressure parts and wear rate analysis for wear prone components need to be incorporated for a dynamic condition based maintenance schedule. While developing such schedules, influence of major operational regime deviations e.g. number of trips & starts, High heat flux zone operation of pressure parts. Grid operating conditions etc. can not be ignored. Natural aging process of
components subjected to severe duty conditions also need to be considered to formulate plant betterment plans based on metallographic studies of residual life assessment.

2.5 Outage Planning & Controls

Unit/Equipment outage planning should aim at revival in performance to near original condition. It shall include

- Improvement in performance through betterment action plans, renovation or modernisation.
- Condition based repair & replacement plan.
- Meeting statutory requirement if any.

A careful planning of work & working pattern, assessment of resources requirement - spares, material & skill, tools & maintenance techniques and monitoring of overhauls to meet the schedule time is essential for increased availability as well as reliability of equipment/system.

A post overhaul evaluation in performance improvement is also essential for analysis of cost incurred and gain in value for money spent.

2.6 Systems Support

Approach to RCM becomes meaningful only with the support of top management who acts as authorizations for change. All such supports should be real & visible e.g. with clarity of roles and authorizations of funds etc.

While a well defined and accepted RCM philosophy with bench marking programme for best practices is essential , equally important is the selection of catalysts for the change.

An RCM - believer and go getter in support of such changes with adequate training programme & communication tools has to be established.

3.0 RCM PROGRAM JUSTIFICATION

All RCM programmes can be justified on the basis of

(1) Improvement in availability
(2) Increased reliability
(3) Timely compliance of statutory requirements
(4) Equipment life enhancement
(5) Operational performance improvement
(6) Reduce Maintenance cost
(7) Improved field work quality
(8) Improved product quality
(9) Moral booster to employees
(10) Improved commitment and team work

4.0 PLANT MAINTENANCE OPTIMISATION

Plant Maintenance Optimisation through cost effective process is essential to

- ensure equipment/system reliability and thereby increased availability.
- achieve optimized/increased performance levels with plant betterment plans.
- cater to the requirement of plant aging through renovation and modernisation plans.
- optimize maintenance cost.
- reduce unnecessary/inspections i.e. to eliminate over maintenance.
- update maintenance plans based on plant engineer/contractor's work experience.

The analysis of P.M.O. is required to be done using various maintenance index. These maintenance index as given below can be used to measure effectiveness of maintenance plans/activities.

4.1 Maintenance Work Control Performance Indicators

(a) Job turnover ratio = $\frac{\text{No. of work orders attended}}{\text{No. of work orders raised}}$

(b) Planned Maint.Index = $\frac{\text{Total plant maint. Hrs worked}}{\text{Total maint. Hrs worked}}$

(c) Break down Maint.Index = $\frac{\text{Total break down Maint. Hrs worked}}{\text{Total Maint. Hrs worked}}$

4.2 Maintenance Manpower Performance Indicator

(a) Manpower utilization Index = $\frac{\text{Total Man Hrs worked}}{\text{Total Man Hrs clocked}}$

(b) Manpower efficiency Index = $\frac{\text{Total Man Hrs allowed on job}}{\text{Total Man Hrs worked on job}}$

(c) Over Time Index = $\frac{\text{Total OT Hrs}}{\text{Total work hrs clocked}}$

4.3 Maintenance Reliability Indicators

(a) Mean Time Between Failure = $\frac{\text{Equipment operation Hrs}}{\text{No. of failures}}$

(b) Failure frequency = No. of failures per thousand hrs.

(c) Availability Index = $\frac{\text{Equip. Hrs declared avail}}{\text{Total Equip Hrs}}$

(d) Reliability Index = $\frac{\text{Equipment availability Index}}{\text{No. of failures}}$

(e) Maintainability Index = $\frac{\text{Eqpt. Available hrs. - Equip. down time}}{\text{Equip. hrs}}$

(f) Maint. Efficiency Index = $\frac{\text{Actual Maintenance. Hrs. worked}}{\text{Equip. down time hrs}}$

4.4 Maintenance Cost Performance Indicator

(a) Material Cost Index = $\frac{\text{Total Cost of Spares \& material}}{\text{Total Maintenance. Cost}}$

(b) Job Cost Index = $\frac{\text{Total Cost on Services}}{\text{Total Maintenance. Cost}}$

(c) Maint. Cost Index = $\frac{\text{Total Maint. Cost}}{\text{Total Investment Value}}$

5.0 CONCLUSION

A clear defined RCM philosophy is essential for power generating utilities. Such a philosophy is helpful to identify maintenance needs and assessment of resources in advance for most of the maintenance situations. This ensures an effective maintenance at minimum cost with high degree of availability and reliability so essential for an uninterrupted and economical power generation.