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DEVELOPMENT OF POWER GENERATION RELIABILITY AVAILABILITY AND MAINTAINABILITY (RAM) PROGRAMS

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ABSTRACT

Ideal plant designs perform as intended. The goal of Reliability, Availability and Maintainability (RAM) processes is to convert designs into operational task requirements to achieve lifecycle goals. This paper discusses developing Power Generation RAM programs. Given the performance-based nature of ASME RAM standards, different approaches can be used to achieve its goals.

Improved operations and maintenance (O&M) programs offer to manage risk at lower cost. This paper introduces a risk management process to develop, maintain and use better risk-based failure management plans with an approach that is simple and clear. It predicts that software will become a more important RAM program development tool.

NOMENCLATURE

Architect Engineer (AE)
Age exploration
Computerized Maintenance Management System (CMMS)
Conditional overhauls
Conditional (On-condition; condition-directed or condition-based)
Condition monitoring
Distributed Control System (DCS)
Direct (not indirect; immediate – not based on multiple failure)
Drop (data drop card/station to the DCS)
Effective (works virtually always)
Efficient (works cost-effectively)
Equipment Asset Management System (EAMS); CMMS
Failure (dominant failure mechanism/DFM; mode and cause)
Failure analysis (Root cause failure analysis/RCFA)
Fault (direct; indirect): functional failure, faulted
Function: Output (Functional failure)
Hard-time: direct rework/replace tasks
Instrumentation focus (monitoring focus)
Master Equipment List (MEL)
Operations and Maintenance (O&M)
O&M Manual
Objective task orientation: measureable; actionable
Partitioning: differentiation
Partition: a structural hierarchy of parts
Preventive maintenance (PM): scheduled maintenance
Process and Instrumentation Drawing (P&ID)
Reliability Development Software: Rel. Process Software
RAM – Reliability, Availability & Maintainability (Program)
Reliability Block Diagram (RBD)
Registry (MEL)
Scheduled maintenance: Preventive maintenance
Template (Standard template, Custom template)
Time- based
Vender Technical Manual (VTM)
Work blocking (task blocking into work order task blocks)
Work Order (WO); workscope, job plan

INTRODUCTION

Things happen, seemingly uncontrollable. That things go awry is a fact of life. Even small equipment has hundreds of interchangeable parts to manage; entire plants have many more. Translating risk management strategies into industrial work practice reduces daily forced outage risk, and lowers cost. It also takes insight, energy and time. The expectation of favorable outcomes and unwillingness to tolerate failure has never been greater. Experience has shown that effective engineering can control most equipment failures or their effects. With the right plans and design strategies, functional failure can be controlled. Standard approaches can be developed that are effective. Not considering failure risks won't eliminate them, though.

Yet today, designers still have few methods to translate the designer's intentions into activities that run plants. While they can recommend tools to develop planned diagnostic, troubleshooting and scheduled maintenance and conditional responses by identifying failing parts, designers are limited translating their guidance into simple end user's plans. Specialists are better developers of integrated work plans based on risk, experience, standards, manufacturers' guidance and practices. Developers still need special development tools like software to be effective, though.

Along with theoretical knowledge of how equipment fails, performance expectations have escalated. While that raises the bar, it also suggests how to meet higher expectations. The time horizon for mitigating risk influences what you can do in a plant. A risk that never develops into failure over the life of a plant doesn't need a control; that risk should never convert into a fault. Managing risk requires controlling potential failures. Reducing random emerging failures allows more time for planned work.

Insurance is another method of risk control. To self-insure can be effective for frequent, controllable risks. Self-insuring requires self-control. Self-control of operational processes requires understanding and managing direct failure threats. Self- insurance allows organizations to take higher deductibles that may lower costs. However, self-insurance also requires they manage more risks.

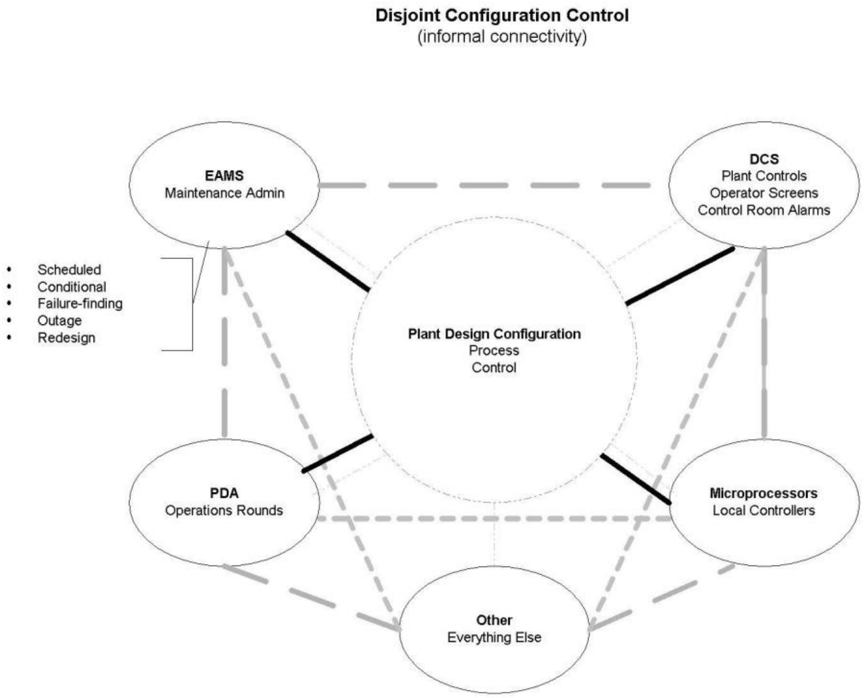

Figure 1 Disjointed Design Configuration

IMPROVING RISK CONTROL

We constantly find better ways to manage risk; risk control techniques improve with time. Control methods include diagnostic technology and failure understanding. Experts need to become involved evaluating both. Better phenomenological aging, diagnostic and performance understanding provide more options for risk control than ever before. The challenge is to translate risk mitigation into common practices, and then integrate those across the facility's equipment.

Enterprise asset management system (EAMS)[i] applications can't develop a risk management strategy or basis – they lack means. That requires access to external documents, spreadsheets, and other process development applications. Is maintaining that detailed information worthwhile over the life of a plant? Very often, experts can recreate it when needed. In some industries laws require that design information be carried. In most however, they don't.[ii] Although maintaining design information offers the benefits of understanding the value basis of work, developing a formal rationale for scheduled maintenance and condition monitoring tasks has never been a requirement or even a goal for most plants. Any understanding has only been implied, in hindsight only understood by experts though subject to many regulatory interpretations.

Work justification could include text documents, spreadsheets and webpages of pdfs. These may be standalone applications for development reference, or entities directly tied into EAMS applications. They provide content like tasks in scheduled maintenance work orders, assessment limits in tests and predictive maintenance as well as decisions to do nothing at all. A relational database information format can easily model relationships, without duplication found in legacy applications. A database application meets many needs very well, combined into an overall process. Software applications will continue to improve offering more efficient methods to implement RAM.

Processes to control risk must integrate. The best are simple, efficient and direct. They cost relatively little to implement in a new plant. In a legacy plant, however, they compete with practice and culture. Because technical understanding has improved while technology costs fell, more options are available today than in the past. Consider diagnostic information for example. More sensors and digital process controllers are available to analyze equipment condition in new plants than ever before. They still require integration into simple tasks that organizational cultures can perform.

TRADITIONAL CONTROLS

Understanding the nature of a risk provides the keys for its control. When we understand a proximate (local) risk, we can design around it. Though that may not eliminate random failure events, it allows us to control their effects.

In traditional programs, organization, culture and values provide control. Tribal knowledge fills content out. We can design control strategies like redundancy and voting logic to select the best operational channels for control. To understand how to control randomness requires knowledge of the aging failure mechanisms[iii] at work. Then we can build strategies around them that operating plant staffs can support.

For a plant, partitioning[iv] provides an early step towards understanding risk. It's an integral part of design. Once we've differentiated plant systems and equipment into parts that deteriorate and age, we can develop specific strategies for their control. Parts with a lifetime must be replaced before they wear out. Parts exhibiting aging-life dispersion must also be controlled. While time-based replacement may be effective, condition assessment often works better at lower cost. Many failure control decisions depend on the approach selected. Cost is one of the most important.

Condition assessment depends on the ability to monitor an aging parameter. When no suitable parameter can be found, other techniques must be used. Those often include failure finding (FF) tests, which demonstrate suitability for continued service. Combined with redundancy and diversity in design, these tests are effective and easy to use.

RISK MANAGEMENT PROCESS

Basic Risk Process Steps

The basic steps to analyze failure risks are:

1. Identify a functional risk (functional failure)
2. Differentiate the proximate (local) failure source
3. Analyze the causes (mechanism); propose solutions as tasks
4. Document analysis (event-chain logic, causes and effects)
5. Decide whether results are acceptable
6. Reevaluate results (to get the same answer)
7. Package results as blocked tasks to perform
8. Use the integrated work blocks of results to operate the plant
9. Integrate

Identify risk

Partitioning takes the plant down into parts, the opposite of design or construction. Partitioning starts analysis. Once done, how and where the equipment is likely to fail can be found.

Differentiate sources

Proximate failure effects depend on functions that equipment contributes based on design. Then with the partition, likely failure event locations can be found. These are the places where failure can be expected over time. Time is the independent variable that drives failure processes.

Analyze

Understanding basic equipment aging processes, how long failures take to occur can be found. Basic physical processes cause proximate equipment failures. In some instances, these are so varied that random failure models are most effective to use. Once analysis is complete, solutions are often very clear. New methods and technologies continuously developed expand options, though.

Document analysis

Documentation allows update of failure mechanisms with new experience over time. Systematic updates based on physical processes allow us to improve our failure understanding to better predict failures. Technology changes and improves, as well.

Review Results

Decide whether results are acceptable. Is the proposed failure control task effective? Will it work; is it cost effective? In many instances approaches can't be used, won't work in the field or have to be abandoned for other reasons, like cost. However, retaining them for future reference, development and reconsideration is ideal.

Reevaluate task effectiveness

Once a mitigation task has been found, how likely it is to be effective in the field? Is it developmental technology or in commercial production? How likely is it to work in the hands of the inexperienced, as well as the skilled? What are the likely consequences if it doesn't reveal incipient failure? All these questions need answering at the component material part level and again, installed in the plant where exact risks are evident.

Package task blocks

Once lists of tasks are developed, an effective machine state or unit "mode" must be found to perform them. Clearly, some tasks take different conditions to perform. You can't inspect the turbine blades on an operating machine. You can't do machine vibration checks on one that is shutdown. It would be foolish to perform tasks inefficiently, one at a time.

Use results to operate the plant

For simple equipment like a manual valve, there may be only one task. For complex ones, there could be five or ten. Very large equipment like combustion turbines and heat recovery steam generator may have hundreds. Thus the great challenge becomes how to integrate all these tasks into plant operations to perform.

Integrated Challenge

Software is one way to put work so that it happens consistently, economically over time. Currently, most plants develop products independently internal to each application. The result is a rough, poorly matched set of varying results. They duplicate requirements that can't be easily maintained over time. (See Figure 1)

APPROACHES TO MANAGING RISK

Overall Design – the Architect Engineer

Overall design of a plant affects its reliability, availability and maintainability. Good plants stem from good design. Design features like redundancy, instrumentation and purposefully installed hardware often reflect standard design practices. These vary from one designer to the next, one culture to another along with other factors like cost. Engineering firms don't codify design – it's proprietary, and some design better plants.

Design costs money, and you get what you pay for. Better engineering design firms command premiums. Better designs cost more. Very often the ability to quantify and codify the exact benefits of a superior design for a plant is difficult; it's intangible. Many companies control design risk by working with Architect-Engineering (AE) firms they know when ordering plants. Owners should understand the quality of their designer's prospective designs. Some factors that influence quality design include:

- Design margins
- Redundancy, diversity and layout
- Maintainability factors like laydown space
- Configuration reviews
- Instrumentation and Controls (IC) monitoring capabilities
- Reference documentation (soft goods): P&IDs, system descriptions, training materials, master equipment list (MEL) databases
- Data systems: plant registry (MEL)-based information
- Vender technical materials and operations and maintenance (VTM/O&M) manuals
- Integrated plans: Instrumentation and controls, especially tied to systems design
- Simple design for operations
- Quality materials and construction
- Test plans (startup and operations surveillance tests)
- Project management

Soft goods like the MEL, VTM and O&M literature provided as an afterthought, assembled quickly at the finish of construction may fall short of needs or expectations. Then their value for operations is reduced.

As-built plant

A well-built plant is a step towards successful operations. Experienced staffs can tell quality construction. Conversely, low-cost construction should cause a prospective owner concern. Uneven flooring, poor fit, cheap[v] materials, poor access, poorly applied coatings, improperly set equipment…. et cetera – the list goes on – will cost commensurately more to operate. Although the unobservant owner may not notice, experienced designers know low cost design and construction.

When an owner engages a constructor, they should assess whether the constructor can do the work. They may do this directly or through a Project Manager.[vi] They should become familiar with the constructor (contractor) well enough to know what they build. The owner should anticipate quality construction will cost more.

Many new designs have not met expectations due to up-front cost cutting. Several examples include:

- B-1 Bomber (first models released without leading flap edge deicing equipment)
- Denver International Airport (designed without luggage handling)
- Kennedy Arts Center Washington, DC (roofing leaks on inaugural opening)

Examples at the other extreme end of spectrum include:

- B-52 (in service over 60 years, expected to go 100)

- US Navy Los Angeles Class fast attack submarines (collision with underwater seamount at flank speed/depth without sinking)
- Empire State Building, New York City (survived airplane crash 1945)

The lesson is that quality design counts. There are many ways to build quality into design that will pay dividends over the life of a plant. Likewise, you can build cheaper plants, but one the owner will pay more to operate one over its life. Ideally, the owner would thoroughly explore those differences before purchase.

Maintenance alone can't compensate cost-effectively for poor design.[vii] It can't correct inadequate design later in operation, either. Organizations that bought cheap designs up front have paid in other ways during operations many times over. Quality design is beyond the scope of this paper, but it's worth noting – design matters. A quality design will pay for itself many times over is the author's and his peers' experience. Furthermore, quality design includes end-user documentation and operating plans. Cost overruns lead to limitations that can cut those luxuries short. The owner of a well-designed quality plant doesn't need to develop scheduled maintenance plans from scratch.

Where projects involve turnkey construction, owners and their agents – especially the project manager – should assure themselves that the constructor can deliver an acceptable plant. They need capable contractors in construction; some stretch beyond what they can deliver. Shaving costs puts more burdens on contractors than constructing a cost-plus design. Building a completely new plant design compounds risk, as does engaging in new technology or untried construction methods.

Owners seek as many products and services from constructors as possible, as a matter of practice. Contractors counter by cutting costs other ways, like reducing the quality of soft goods like documentation. Contractors rarely share proprietary information, though – such as how they perform design or control cost margins. Owners should know what a design involves enough to plan workarounds that manage risk and mitigate unforeseen problems.

Vender Contributions

Documentation

Documentation varies depending on vendor, but its materials facilitate servicing the plant. Vendors providing products "off the shelf" have literature predeveloped based on completed jobs and industry standards. Contractors follow commercial norms and experience producing manuals and technical literature to document their jobs. They persist with traditional methods used with success in the past. Typically subcontractor documents roll up into what they provide to the contractor.

Documentation should explain important process flows. Most vendor literature addresses the theory of how a system works and equipment operates. Where vendors provide custom-designed products, they should also provide design drawings like P&IDs, system descriptions and other engineering drawings as the norm. This is standard practice in custom design contracts.

Equipment

Equipment itself varies greatly depending on the application's functional requirements. Suppliers provide complete equipment to deliver intact. Properly boxed, sealed and delivered with instructions for use, supporting parts and materials make support much easier. Available off-the-shelf, commercial equipment streamlines plant design. Commercial equipment that is in production has met effectiveness tests of utility and cost. It exists in the market at the time as the solution to one specific product need. Commercially available equipment, materials and hardware come with a support infrastructure. Materials available off-the-shelf for application make designing single source items non-competitive.

Support

Equipment needs technical expertise support to address unforeseen problems. Vendors provide technical staff that supports their products in the field. Contract information, local expertise and other support services reduce the cost and risk of problems. Experts in each type of special equipment know details like how it normally wears out, fails and the diagnostic methods available.

Participant Roles

Architect-Engineers (AEs)

AEs are the chief engineering plant designer.[viii] AEs provide basic process design and various additional services. That could include construction. AEs may act as project managers, performing integrating functions. Different contractual arrangements augment their fundamental role – effective design of the plant. An independent project manager lowers risk managing new plant construction. Not vested in the design, they can be objective.

Constructor

As prime contractor, the constructor builds the plant; they may act in other roles as well. They may act as project manager (above). Contracts typically form a tiered hierarchy.

As such, the constructor influences overall quality and conformity level of subcontractors. Typically the constructor manages subcontractors, who provide product descriptions and technical materials (VTM, O&M, Systems Descriptions including MEL, et cetera) for the materials they use and subsystems they construct.

Contractors (including subcontractors)

Subcontractors, or “subs”, perform a substantial amount of the construction of a plant. How well they know their product and integrate that into the design affects the plant that they build. Subs provide most documentation for the plant. AEs and their contractors assemble documentation into manuals they deliver with products that explain how the plant works, servicing it, its parts and how they’re intended to be maintained.

Parts Suppliers

Parts suppliers provide the hardware the constructor and subcontractors assemble in their products. Pieces vary from literally “piece parts” like tube and pipe, to components like motor and air operated valves, to subassemblies skids like major equipment lube oil and hydraulic subsystems. Contracts typically require product technical literature for all the products subs supply in their designs.

What distinguishes the suppliers from contractors is what they supply and how it’s used. Suppliers provide finished products. Typically their products have a specific functional role that they (the supplier) understand well. They are procured off the shelf as complete assemblies. There’s little customization. Products are normally constructed offsite. In contrast, constructors and subs build equipment and subsystems that integrate into plant designs onsite. Their designs require testing integrated products to bring systems and subsystems into operation.

Training

Plant staffs require training operators; training may require simulators. Untrained staffs don’t perform as well, adding cost and risk. Support staffs need training, too, to do their work well. With the complete scope developed for a plant, training can be planned with more certainty. Training for specific designs may be outsourced. Other training may be performed onsite under staff direct control.

Independent Reviewer

An independent reviewer evaluates whether a plant can be built to perform as designed. They evaluate projected plant availability, compared with other similar designs. They evaluate the reasonableness for projected outage durations and costs, based on the technology, degree of cutting-edge design, maintenance services available, comparison analysis and plant maintenance practices. Is what the designer promises reasonable? Will the contracted plant deliver what they propose? Independent plant design reviews add cost but reveal risks. Risks disclosed ahead are often easier to manage.

Design Tools

Text Description

AEs deliver systems descriptions, operational theory and operating instructions at multiple levels as text. Text also includes service guidance. Text guidance from vendors on servicing requires conversion into Scheduled Maintenance Job Plans to use.

Schematic

Schematics include P&IDs, mechanical, electrical, instrumentation and control drawings. Schematics help engineers understand functional parts, physical relationships and how equipment operates. They also reveal how parts could deteriorate, and what’s available to use when they do. They explain the instrumentation and tag-out isolations needed to diagnose and fix equipment.

Block diagrams

Tools like reliability block diagrams (RBD), engineering drawings, fishbone diagrams, Pareto charts, and other image files explain equipment and parts relationships for people who develop work and perform supporting services. Providing these materials helps justify and explain monitoring and maintenance work selections for users of support services. They also facilitate diagnosis and maintenance of equipment.

Information Sites

Technology is changing how work can be performed. Venders offer Personal Digital Assistants (PDA) to access Websites for technical information via document hot links. Work control can also be hot linked, making it more effective. Files can include many formats including documents, drawings and images. Identifying what plant work to perform is a harder issue, though. While documents[ix] are still the most common way of organizing scheduled work content, other methods hold greater promise. While hot-linking PDAs directly to document work content files eliminates pdf paper, databases can organize work content offering even greater information flexibility and control. Many web-linked environments use servers with relational databases for data management. More maintenance systems need to take advantage of information technology (IT), too.

Traditionally, technical information hasn't changed much. Images provided as pdfs, design drawings or documents look the same. What has changed is the ability to access, organize and control it. With more organized content provided in standard formats, there is more opportunity to standardize information use even more. Operator screen reviews, alarm checks and rounds supplement applications of EAMS scheduled maintenance tasks.[x]

Reliability Plans

Only designers know why they put items into a facility's design. Most knowledge is explicit, but some is implied. Some designers occasionally add features by policy. Sometimes this is not well-thought out. Take Control Air inline check valves as an example. The Fort St Vrain nuclear plant had these valves installed throughout its Control Air system. When moisture appeared, they corroded and bound up. Eventually, most were removed to free up air flows. Design policy can have unintended consequences introducing unnecessary components with unanticipated failure modes.[xi] Simple design is often the best design policy.

Developing reliability plans reveals the design's capability the plant will have to maintain. Ready access to equipment to perform work is one aspect; adequate maintenance laydown space is another. Weatherization adequacy is a third. Independent design reviews add objectivity. Designers reviewing their own designs tend to downplay potential problems. Performing reliability reviews before awarding a contract protects owners, especially on innovative designs. History has many examples where new technology introduced risks that were evident only later in hindsight that failed commercially.[xii] Supercritical boilers introduced in the 1950 exceeded material limits. Ensuing problems caused high outage rates that limited supercritical applications many years. Another example, the deHaviland Comet – the first jetliner – suffered a spate of metal fatigue-related crashes during its introduction. Still, Boeing credited success of their Boeing 707 to that unfortunate experience.[xiii]

Maintenance Tools

Tools automate maintenance performance and tracking, improving upon historical practices like paper and early spreadsheets. EAMS software manages performing maintenance development and improves access to maintenance history. Records underpin condition-based maintenance, performing root cause failure analysis (RCFA) and design improvement. These tools are underutilized, today. Companies made huge investments to buy and install EAMS tools, and then underutilized them. Loading maintenance scheduling software is prerequisite to implementing effective preventive maintenance (PM)[xiv]. Failure to fully develop the EAMS scheduled maintenance program considerably reduces its planned maintenance effectiveness.

Software

Software tools that support the EAMS include plant maintenance development software. This provides the transition from OEM O&M manuals into final EAMS plans. It promises to integrate all maintenance plans in one location for comprehensive failure management. Plan integration reduces the complexity and chance of development errors of commission and omission.

Maintainability Considerations

Maintainability determines how quickly maintenance jobs can "turn around." Many issues how quickly a plant can be maintained. Many depend on design, support hardware and other systems that support maintenance:

a. Access: ease of access to work locations, ability to work safety without special rigging and tools.

b. Laydown: Availability of space to disassemble and store major assemblies like turbines, compressors, valves and pumps.

c. Tools: Need for special tools and tooling

d. Training: Availability and execution of specialized training to support scheduled activity and condition directed work

e. Tag-outs: predeveloped tag-outs for anticipated work.

f. Spare Parts: Availability of parts for specialized equipment. Having a spares strategy.

g. Contingency Parts and Contracts: Predevelopment of Standard contracts for work

h. Plans: Predeveloped plans for anticipated routinely performed scheduled and condition-based maintenance.

Having a comprehensive list of all plant equipment broken down to a level that identifies the expected service life of each is one primary RAM benefit. This list of equipment makes maintainability planning easier. One goal of RAM is to develop enough detailed equipment wearout and aging information to develop effective maintainability plans.

LEGACY APPROACHES

Traditional methods: literature research

Traditional maintenance development methods include literature research and following vendor's guidance. Inspection, tests, performance codes and standards fill that out. One problem is the ease with which organizations can overperform maintenance. Risk calculus should limit work done on equipment that doesn't matter. Using risk to focus and limit scope of work can be difficult in regulated environments, which are prescriptive. The deterministic view that every equipment failure matters at the same level of risk overprescribes work. In fact, most equipment failures don't directly cause function failures, and equipment functional failures infrequently cause critical system functional losses. Overprescribed maintenance quickly inflates cost. Diluting maintenance resources by treating items that don't cause direct failure risks increase other failures. Nuclear industry equipment reliability programs[xv] suffer this characteristic[xvi], which greatly inflate nuclear maintenance costs.

Craft direction

Craft-directed maintenance depends heavily on conditional assessments, where operators identify degraded, broken-down equipment. Where condition assessment methods and equipment loss risk prioritization are well thought out, skilled craft can perform effective conditional maintenance. By and large, this is the traditional model for fossil power plants. Its benefit is maintenance timed towards need. Its weakness is dependence on highly-skilled craft, available on demand. Success requires a very small fraction of "time-out" aging failures and effective means to prioritize emerging work. By time-out failures, we mean failures that occur with certainty after a certain period of time; they "time-out." Aside from lubrication, always presumed to have performance benefit[xvii], aging life limit cases cover many instances of wearing/corroding parts. That's only starters. Elastomers exhibit aging life limits based on Arrhenius aging, as do eroding switchgear contacts, canisters of service gas, CEMs calibration ("Cal") gas and SF6 gas charges in high voltage breakers that deplete. The gradual accumulation of deposits on turbine blades, compressors, pumps and actuators in hydraulic systems is another. These comprise a long list of equipment attributes that exhibit time-out failures for some constituents.

However, fewer than 10% of total failure modes sampled exhibit aging mechanisms that time out.[xviii] Scheduled maintenance can be very effective identifying the relatively few aging failures that time-out (cited 7%[xix]) for timely maintenance with a conditional response. Assuring that programs capture equipment failures before time-out requires using hard-time rework, replacement and overhaul activity or conditional assessment with risk margin. Condition assessment, e.g., predictive monitoring, must be performed at a fractional interval of the time-out period. If you combine the relatively few equipment failure cases manageable by hard-time tasks with diagnostic predictive assessment for equipment that lacks well-defined aging with operational tests for standby equipment, you have a full-coverage maintenance program. Use of well-established diagnostics like vibration monitoring improves outcome certainty reducing the need for predictive-fault finding task overlap.

Scaling to larger plants

Plants have a significant problem in common with banks – how to scale their results. While developing a solution for a single account at a bank or a PM plan in a single plant equipment item is simple, it's not so easy to scale that up in larger plants with thousands of equipment "accounts." Banks had a similar problem before the advent of business computers and associated software fifty years ago with customer accounts. Even a paltry 0.01% error rate in accounts created large headaches – and huge costs. The number of tagged items in large generation plants creates a performance coordination challenge. A typical three-generator combined cycle gas turbine (CCGT) plant has well-over five thousand component location codes. In nuclear units, ten times more components are tagged. Since coding practice varies, developing coding tags within equipment skids leads to a higher level of tagging, greatly increasing the number of tagged components to manage.[xx]

For larger plants a solution to large RAM program size is automating the program development process. Past legacy processes like rounds and maintenance management trouble reports, tag-outs and work orders have been converted into digital software format. Since the well-established trend to automate maintenance hinges on the EAMS, scaling comes down to planning the processes that load the EAMS with work. Loading analysis in orderly fashion depends on using the EAMS MEL and its partition to build scheduled maintenance tasks and WOs. The digital rounds PDA programs and integral online screens complement the EAMS used today to monitor plants. All need to integrate in the administrative control system, fitting with the plant's monitoring, alarms and surveillance scheduled maintenance plans. All must have an efficient integrating strategy to organize effective plans. All will evolve to use maintenance development software even more to build and load their work plans and databases.

Scalability depends on strategies using building blocks, just as designing a plant does. To do it well requires standardizing, understanding individual systems' and components' risk, how to monitor that risk, integrate work and roll it up to the plant level. The only long-term solution to improved scalability is improved methods to develop and implement maintenance plans. That means computer databases and their associated software. Scalability depends on automation software for technical and cost effectiveness.

FILLING THE GAP

Operations certainty improves plant income opportunities in the generation market, today. New roles for power plants are emerging with changes in regulation of the grid. Alternative energy sources like wind and solar require fast starting backup when the energy supply falls – clouds accumulate or winds fall. Although every situation is different, where reliability or availability influence generation, income growth is possible, and can often be significant. Demand equivalent forced outage rate ($EFOR_d$) measures production losses for fast start plants. Where ancillary services like voltage support come into play, there is also potential income benefit. Contracts use EFOR_d[xxi] for payments. Non-traditional services required by the North American Electric Reliability Corporation (NERC) like voltage regulation mean more income in the open access markets managed today. Reducing cost is a primary reliability program benefit. Improving work also generates cost reductions. Cost-based decisions must sustain overall income generation to uphold net production benefits, though.

Systematic approach

A systematic approach to scheduled activity will benefit plants today, just as it has the airline industry. Our knowledge of maintenance has never been better. In addition, breakthroughs in understanding as a result of the airlines, government and basic research have created several new maintenance paradigms. The vast computing resources of relational databases, data servers, and the Internet put information content at the user's fingertips easier than ever before.

While a variety of methods can develop maintenance programs at the equipment level, they still need to roll up as integrated programs in a plant. Today, they do not. Programs need applications to promote standardization, reducing the tedious complexity and needless customization common in current generation programs.

The biggest challenge plants have today is to assure their programs are effective. Tracking their results shows performance. Discretionary programs don't get performed as intended. When programs aren't performed as planned, results are skewed.[xxii] Outcomes confuse developers, who wonder why their programs aren't effective. Then managers question the fundamental value of programs at their plants.

Improved implementation

Plants need maintenance programs that are:

- Simpler
- Standardized
- Integrated
- More intuitive, automatic, with less unnecessary duplication
- Cost effective, directly and indirectly

Simpler

Simple task formats and applications cost less and support consistent use.

Standardized

Limited customization standardizes work. Use of repetitive elements wherever possible improves human factors and lowers cost. Identical work processes simplify methods and improve outcomes.

Integrated

All the parts needed fit together well. Programs exhibit symmetry – simplicity in approach is evident. Applications and their software integrate well.

More intuitive, automatic, with less duplication

Users understand multiple levels of the programs, like the traditional newspaper inverted writing style – top down. They are able to query the material, with ready access to view information. They can pursue that according to their interest and need, not wading through volumes of detailed information to find answers to simple questions – the O&M manual approach. Efficient tools streamline and facilitate processes.

Cost effective, directly and indirectly

The program is cost-effective and helps reduce costs. It reduces the labor of delivering maintenance by minimizing duplication, promoting learning, and saving experience, reducing the need for unplanned, unbudgeted costs.

Reducing the direct labor needed directly improves work and lowers cost. Improving support infrastructure contributes indirectly to efficiency, improving work effectiveness by reducing overheads, while improving productivity.

- Processes are more efficient
- The most modern tools are used
- Redundancies, duplication and repetitive work are reduced
- Program fit with users is improved
- Maintenance exhibits better logic and flow

The promise of new EAMS systems was eliminating waste. They haven't, because key work elements have never been developed. Work practices and culture remain. While reducing repetitive custom work content from the ground up improves work, most new EAMS systems have not. Other legacy systems struggled being effective for similar reasons. To reduce costs requires developing and implementing new paradigms that assure new processes deliver what they should, addressing maintenance culture.

Integration of support systems

Human Element

Better analysis and failure mitigation strategies promise to integrate operations and maintenance with design. However, current operations depend on subjective guidance to identify and perform equipment maintenance. For example, pipe thinning from corrosion in coal plants happens in many places. Better materials and design can reduce that risk, but in the meantime it must be managed. No plant has enough resources to monitor pipe thinning everywhere, though in the past some tried. Monitoring should be based on risk – an awareness of where thinning will most likely occur. Then weak spots where thinning exceeding specifications can be found and removed efficiently – based on objective measurement criteria.

Software Systems

Primary software processes include:

1. EAMS work order management application software
2. Monitoring screens and DCS application software
3. Personal digital assistants (PDAs) application software for operator rounds inspections
4. Microprocessor controls embedded locally in common equipment, which may or may not be 'dropped' into the DCS
5. Risk management/work development process software

Degraded equipment requires conditional response. Users must understand how to address general performance degradation like unmonitored failure mechanisms, low-risk equipment work and installed redundancies. They must coordinate how to perform appropriate conditional maintenance based on risk. Then they can avoid functional failures – the highest priority shortfalls to address. Risk management/work development software addressing item (5) above alone remains.

Overarching paradigm

Information organization and development needs an overarching paradigm. Traditional methods are text-based, like a book. Although traditional methods translated into pdfs were fine in their day, they do not improve legacy processes. A revolutionary paradigm like Google's Internet search engine is needed.[xxiii] Such a paradigm would improve information content access, without having to filter unorganized text content. Today that requires organized search like a search engine. Because of lack of structure, current methods are tedious and require technical experts to use.

Better support methods

Software Limitations

Software makes a consistent technical justification feasible on a large scale. Software can link EAMS, PDA, DCS and maintenance development systems. Software promotes consistency, cost effectiveness and speed. It allows referencing requirements like codes and standards, while facilitating age exploration. Software makes maintenance development and control possible over plant life.

Third generation EAMS software tools evolved from various earlier CMMS forms. EAMS software today can merge purchasing, planning and scheduled maintenance performed with corrective maintenance work requests, outages, and tag out boundaries. What it can't do is develop and maintain effective maintenance logic; it has no way to develop and maintain the basis. Of course, performing scheduled maintenance and monitoring initiates most work. A work justification basis explains why work is done. It organizes discrete tasks around equipment, based on design risks and total scope of work. EAMS software alone lacks the sophistication to subdivide a plant into component parts, track them and their failures, integrated into a complimentary work plan. To maintain a basis requires an equipment analysis for how parts contribute functions and fail. Third generation EAMS software on the

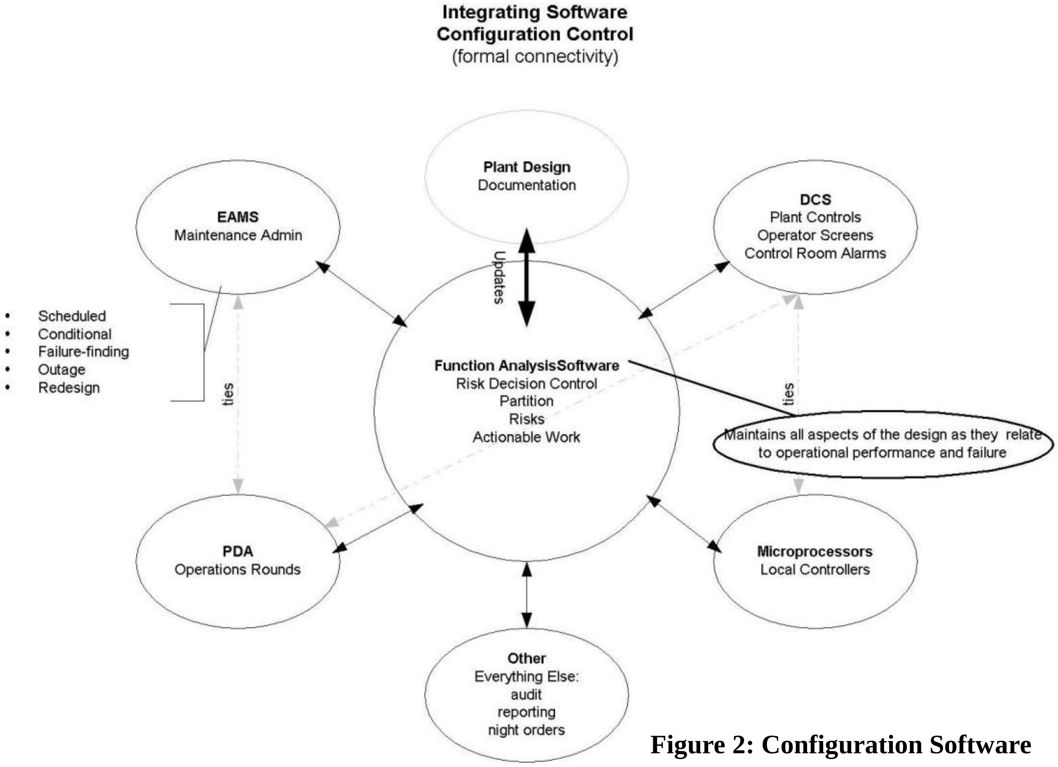

Figure 2: Configuration Software

market today has come a long way, but it still has far to go.

Every time the plant configuration changes, equipment risk changes, too. Like an automobile, the moment you change a flat tire with a spare, the risk from a new flat tire changes; it's greater. Until the car's configuration is restored, risk has changed. Plant configurations change often, even when they're base-loaded. All plants change modes multiple times from just starting up to shutting down. Ideally, software would capture dynamic changes, allowing users to reevaluate risk on demand. Like other processes, risk control needs flexibility. Work development processes today lack dynamic flexibility. Basis development software fills the gap so all software applications can more effectively support the plant.

Integration

Today, better methods are available to develop basic tasks. Specialists can develop maintenance processes many ways, including:

- Literature search
- Fundamental principles
- Equipment experts
- Empirical learning
- Reliability-centered maintenance (RCM)
- Failure analysis (including root cause failure analysis RCFA)
- Combinations of the above

Briefly summarized:

1. Literature search: OEMs provide an operations and maintenance manual with most equipment they sell off the shelf. That information explains the equipment in isolation (per this standard). The owner and their agent must decide how that applies to them.

Other research can take advantage of similar equipment when no other options are available. Often this is the case in older plants that lack many of the original manuals. With the Internet, more manuals than ever are provided accessible via open access, and research is more viable than ever before. O&M manual content is more developed, consistent and complete. O&M manuals carry the legal weight of formal Purchase Order specifications and contracts, as well as tort law product liability burden to be accurate, complete and correct.

2. Fundamental principles: Based on techniques like failure modes and effects analysis (FMEA), basic programs can be developed from scratch. In instances where no other information is available, they allow developing a program where nothing else has ever been done. Analysis of related failure experience can develop observed failures, empirically. For new equipment these may be necessary, but information should be available through the equipment supplier. That should provide a starting point to develop a standard template. Comparison analysis can also develop a basic plan. Doing that requires positioning to find similar parts to use.

3. Equipment experts. While methods like PMO or RCM work well enough, they can never replace expert guidance. Experts have irreplaceable insights and knowledge that others don't. Original equipment designers know why they designed equipment is as it is. Program reviews during initial design offer the best chance to capture those insights. Original designers ideally would perform risk analysis like RAM as part of the design process. Since that isn't always feasible, someone like them should review design and develop those analyses.

4. Empirical learning: Unexpected results, including failures, contain valuable guidance to help avoid future events. Where operators have access to experience, they should use it. They should maintain their own failure history and equipment experience for this purpose. (Most have a computer work order system termed an EAMS.) Unexpected events like a skipped hard-time PM with no consequence can be a source of opportunity and learning.

5. Reliability-centered maintenance (RCM): these concepts introduce a systematic approach to failure that follows design. Considerations during design make scheduled maintenance integration with plant operations easier. RCM ideas include those of the original DOC/DOD document[xxiv] of the same title, as well as the classic seven-step methods.[xxv] RCM has become a phenomenon beyond what many saw only as a tool. It can't take the art and skill out of maintenance development, though. In calculus, there are many ways to integrate; scheduled maintenance is similar. RCM is just one way to develop scheduled maintenance. To limit ourselves in math to integrate one way would be silly. Yet, some seek that for scheduled maintenance. Others ignore equally important aspects of the original Nolan and Heap RCM work.[xxvi] Age exploration, conditional overhauls, objective (actionable) task orientation, instrumentation focus by role and work blocking are several. All are critical to effective maintenance, yet RCM purists systematically ignore these in modern application development. Doing so creates unnecessary risk and costs.

6. Failure analysis: where failures persist, root cause failure analysis (RCFA) is needed to root them out. It's expensive, though, so you can't apply it to everything – nor would you want to. Most failures don't require RCFA, particularly with trained craft available. RCFA use should be qualified by risk and cost.

5. Combinations of the above: For large complex equipment with safety risk, many considerations above will apply concurrently. There may be several, tens, or even hundreds of conflicting guides. Sifting through them all may require

substantial numbers of experts and time, especially at nuclear plants. Maintenance development systems need to organize and resolve all potentially conflicting information.

Furthermore, scheduled maintenance and rounds identify developing problems; they need to be applied so they address problems early. Problems are best addressed organizationally while still small. Once they grow larger, they can't be ignored; they also grow more complex. The best world class operating organizations address problems early, while they're still small. Reliability analysis should focus on identifying single faults to address failures while they are simple. Organizations that identify and correct equipment faults while they're simple and small prevent problems from growing large. Statistically, complex multiple failure problems are harder to correct. Correction at that time reduces scheduled maintenance value as a proactive cost-reducing tool.

Effective tasks: In the past, tasks never received critical reviews. Tasks were implemented and used that were not effective. Ineffective tasks were rarely dropped from active work lists. Critical reviews by qualified staff should approve all tasks, culling ineffective ones. Ineffective task removal should be documented to avoid unintended reuse.

Building structure at the right levels: A systems-based approach allows rolling up tasks to high plant level. Turbine efficiency monitoring, for example, reveals much about overall turbine condition. Conversely, it's also more difficult to diagnose a single problem at a high level, like picking a needle out of a haystack. Knowing turbine efficiency is off 1% from design could – and probably does – reflect many little problems. The higher the monitoring task level, the more troubleshooting is needed to trace performance back to its physical equipment source. Experts must balance high-level tasks for early warning with detail tasks on local hardware that will fail. High and low level tasks combine to make a more effective program.

Experts know their equipment; in ambiguous situations they can zero in on problems. They can also build structured programs that users can apply at appropriate levels. Experts include:

- Operators
- Journeymen/Craft
- Diagnostic Experts/Technical support
- Process developers
- Engineers

- Operators: Operators perform short term rounds and monitoring tasks within their skill. They should also perform longer term tasks like area checks (leaks, environments, alarm checks….) and inspections that fall under their competency levels.

- Journeymen: Skilled crafts perform tasks that require special skills. These include predictive maintenance, conditional assessments and time-based parts replacements (including overhauls).

- Diagnostic Experts: For diagnostic activities that require expertise, qualified experts should be used. Experts can be developed in-house or hired by contract. Each has advantages and costs. Acquiring a new technology like thermal imaging, however, does not automatically qualify its users to be expert in its use.

- Process Developers: Process developers are the people who convert new processes into software models for use. Most can model developed processes adequately. Few can develop the new processes that support paradigm shifts. Integrating software is a paradigm shift.

- Engineers: Diagnosing problems, developing statistical reliability-based plans and other advanced tasks require engineers. Engineers can analyze, develop process limits, set intervals, assure tasks comply with standards and insure programs meet specified guidance. New process development also requires engineers.

Backstop processes

Building blocks

No task is 100% effective all the time. Sometimes overlap is needed. Processes that overlap equipment failure coverage need to be cost effective. Usually, tasks require no overlap; redundant coverage is undesirable. The exception is direct safety threats, where failure avoidance is needed at all costs. A task that works effectively 97% (e.g., for a large fraction of uses)[xxvii] is often better than less-effective multiple-layered tasks.[xxviii] In the sole case of safety, multiple tasks are acceptable to ensure complete coverage. In this case, the goal is to achieve high certainty controlling risk; costs are not the primary concern. Identifying tasks that manage aging-risk can't be emphasized enough. Managing critical safe life limits avoids failures that are otherwise certain. Those easy tasks to find when addressed offer fast returns.

Automation

Integration of activities into delivery methods need to be effective and low-cost, which means automated, planned and budgeted.[xxix] Since a plant operating on a conditional maintenance model (failure avoidance) budgets around equipment failures, getting scheduled maintenance budgeted is no small task – it's a cultural shock. Planning explicit scheduled maintenance up front by budgeting funds plans and assures their performance. Without funding, maintenance is sporadic at the time of need. It's unlikely that funding will be available to perform maintenance checks and tests that complete with failure equipment. Despite the best intentions, the program for the plant becomes effectively run-to-failure (RTF). Funding complete programs is the solution. Where funding is not available, organizations find "RTF" effectively is the low cost solution. Money will always be found to restore an asset after the fact and preserve its life; the approach is just generally not low cost. Planned programs, however, make budgeting automatic.

Software

Software automates analysis processes. Highly-repetitive partitioning, identifying loss risk, standardizing response plans for many components concurrently develops scope of work. Applied contextually at plants on many items at once, it becomes rote work. Intervals must be based contextually on specific service and environment. Risk management software used to develop and maintain scheduled maintenance and monitoring plans manages equipment failure risk cost effectively and requires less planning to use.

Software makes processes feasible by speeding work and standardizing response. The problem with some plant modeling software today is that it models past processes too faithfully. The missing link in modern software is risk management. Software that identifies dynamic risks to control would help operating staffs. These are not yet in widespread use, though. It's as if plants still attempted to manage risk like secretaries created typewritten documents manually in the past. Plants lack integrated risk management software with PDA routes and EAMS scheduled maintenance. Combining this with incomplete EAMS installations, little has changed today from the distant past.

Better implementation tools

Summary

EAMS developmental software for scheduling and planning provides the main tool to manage condition-based maintenance, today. Diagnostic O&M products continue to be developed. Many attempt to integrate design with maintenance. New control systems embed more maintenance diagnostics. Unless maintenance is actually delivered as planned, software value diminishes. Integration of condition assessment practices requires an integrated approach to operate and maintain a modern plant. Operating systems and processes need to perform scheduled maintenance, first, as a priority. Then conditional maintenance software can be supported by complementary response-driven corrective maintenance plans.

Screens

DCS screens linked to local microprocessor drops off equipment offer diagnostics that predict its condition. PDA rounds put operators in equipment areas performing real-time visual monitoring. Combining the ability to read local alarms external to the DCS and SCADA systems also reveals monitoring instrumentation values and local equipment alarm states.

Scheduled Maintenance Activities

Well-developed scheduled maintenance plans orchestrate planned response. A well-integrated plan reveals a distribution of maintenance work statistically by technology and approach. Deviation outside expected norms suggests program weaknesses. For example, absence of hard-time tasks signifies incomplete programs or overdependence on predictive technology. Absence of failure finding tasks on redundant or standby equipment signifies high risk of unmonitored on-demand failure. Once identified, risks can be explored. The result leads to more reliable plans.

Scheduled Maintenance Strategy

For years, developers have sought to integrate programs at a higher level. Consider calibration. As scheduled maintenance, tasks are either hard-time or predictive, depending on how you approach the work – reset of zero and span, or checks that assure they are in specifications. The former is time based, the latter conditional. It's splitting hairs, but category depends on work approach. Types of scheduled maintenance include:

- Conditional Assessment (Predictive Maintenance/PdM)
- Hard-time (replacements/rework)
- Overhauls (multiple intrusive hard-time tasks with inspections)
- Calibrations
- Failure finding tests
- Redesign
- Rounds (monitoring)

Rounds cover short term condition assessment and area checks performed around the entire plant. Where longer performance intervals are necessary, rounds with the skill limits of operators can be applied. Activity based on aging degradation can meet the need as well. Operations create variations in equipment use. Equipment use can cause apparent random failures.[xxx] Different plant configurations operating different switchgear, for example, results in different aging. A breaker that operates more, ages more, too. Prediction consistent with operational plans is more certain than simple time-based activity by itself. Conditional maintenance includes:

- Operations mitigation
- Functional test
- Condition-directed maintenance
- Redesign
- Scheduled maintenance plan revision development

All depend on appropriate relative risk-ranking.

EAMS systems provide the capability to sort through many equipment problems in resource-limited environment. Effective prioritization depends on ranking risk and using that to plan work done. It's a discipline, one that requires great skill. To do that well requires training. Without guidance, people do not know what to do, regardless of what designer's expected. Parts and service contracts cost. Those must be planned, scheduled and funded to have resources available for simple repetitive response.

CONCLUSIONS

Best possible operations

Ideally operations would be perfect – only in reality they never are. How close to the ideal can we get? Using the airline industry as a model, Power Generation can greatly improve. Though the airline industry's situation doesn't directly apply in generation, it suggests what to do. Quality of operations is based on how the owner defines them. Owners should provide more explicit goals today for operations. Market generators have specific goals; traditional rate base situations often lack guidance. As it is, performance that passes for optimum can get better. In fact, generation performance can get much better, if performers have clearer expectations, more organization and specific guidance on what to do.

Fewer surprises

While perfect operations aren't possible, fewer problems with better outcomes are. Interruptions to planned operations – outages, reductions, workarounds that require overtime and callouts – are surprises. Events causing unplanned expenses and income loss are disruptive and costly. In worst case scenarios, a plant becomes uneconomic, and plant investment must be written off. Confidence falls and jobs are lost. Inevitably, old uneconomic plants must be shutdown. The tragedy of ill-conceived programs, however, is sporadic operations that cause criticism on other grounds. Then licensed, economically viable plants with net book value must be paid off. When a plant must be shut down on political grounds, that outcome affects not only the owner's investments, but the entire service territory of those who benefit from the plant as well.

Best outcomes

Cheaper, less capable designs can't achieve as much as quality designs. Still, the costs of quality design must be amortized over the life of a plant. Owners have to balance cost of an investment against its payback. Doing that requires assumptions about the future. Often those fall back on accounting paradigms and gut feelings. Sometimes new analysis would improve guidance.

Operating plants that continue to operate safely with lower costs generate reliable income. They put their owners in a better competitive position long-term to survive. Plants with erratic performance and unpredictable income generate lower gross margins and less income. They may be difficult to defend on political grounds. They are more difficult to operate successfully. Today's high-stakes generation environment presents owners with political risks. If plants can shift towards a more technically-based, standardized risk-oriented, planned work environment, much better outcomes are possible at lower cost. The tools are available today; they simply require installation and use. Organizations need better alignment with a more structured, software-based risk management approach.

Reasons to change

Many objections block better maintenance programs. They include:

- It's too expensive
- It's too complex
- It's too hard to understand and execute
- It's counterintuitive, it should be spontaneous; no work should be involved
- It's different; we don't understand why change is needed
- It's something we do already
- There's no budget for it
- It should have come with the plant
- Why formalize it as a plan? Anyone can do it – in fact we already do, sort of.

The fact that maintenance plans were never very complete in the past reflects a lack of available tools. Culture played a role. Information access and processes limited work practices to simple training and faith in operators and craft workers. We can do much better, now. Results will vary depending on the investment in a plant. It's a matter of deciding whether a plant justifies improving processes, now. In many instances, the answer is yes. The availability of new software tools to implement these basis development steps makes their application simpler and easier to perform than ever before.

Individuals manage operating risks as a part of their work. How individuals manage operating risks is up for review. Even in the same roles, individuals vary considerably in approach. We manage risks in our private lives – houses, boats, cars, personal computers, and many mechanical contrivances – and we manage them pretty well. In the power industry, managing risk should be objective and professional. We need to produce more at less cost, while we reduce undesirable emissions, public-employee safety hazards and support resources used. By applying similar rules to those that we apply intuitively everywhere else, we can be more effective and lower cost. An organizational context is involved. Being rigorously consistent, using newer tools available today, we can develop plans that come closer to achieving the maintenance ideal – perfect conformance to design-projected reliability. Availability and reliability that exceed the owner's and designer's goals – the Holy Grail of plant operations – becomes an achievable goal.

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[i] Computerized maintenance management systems (CMMS) used to be the term for these applications before they moved to the Internet.

[ii] Due diligence and tort law always apply.

[iii] Failure mechanism: a failure mode and its cause

[iv] The opposite of design integration; differentiation

[v] Use of the term "cheap" is not intended to denigrate low-cost designs. For cost, many design compromises are made. Cheap implies the designer failed to recognize equally effective alternatives for the same cost, and the long-term operating consequences of these choices.

[vi] The owner, an AE or constructor can serve as the Project Manager.

[vii] Inadequate "poor" design considerations like inadequate heating, cooling and ventilation, excessive environmental moisture, corrosion exfoliates not anticipated….[there is a long list] creates a difficult operating environment that maintenance is ill-prepared to address. We suggest readers review more extensive discussion of this subject in other maintenance reliability texts, particular Nolan and Heap and various RCM texts. Numerous papers published by the authors discuss this.

[viii] "The engineer"

[ix] Including pdfs

[x] like Maximo, Ventyx or SAP (this does not endorse any of these products)

[xi] Mode: a way of failing; a failure mode

[xii] Consider Union Carbide's 1986 Bhopal, India plant disaster.

[xiii] Boeing's engineer's learned from that experience introducing the Boeing 707, the first commercially successful jetliner, four years later.

[xiv] Preventive maintenance, the same as Scheduled maintenance.

[xv] Equipment reliability programs base work on the component; all of the same type of components get the same plan.

[xvi] INPO AP-913, Equipment Reliability, Institute of Nuclear Power Operations (INPO), for example, is ineffective for differentiating risk, in the author's opinion.

[xvii] Because lubrication aging is a time-out phenomena

[xviii] Nowlan and Heap, same as below. These aircraft component failure studies have been confirmed in other industries, including the authors'.

[xix] "Reliability Centered Maintenance," Nolan and Heap, United Airlines Department of Commerce (DOC)

[xx] ASME Power Division, Reliability Availability Maintainability Committee is developing a tagging standard.

[xxi] See IEEE 762, Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity (2006), http://ieeexplore.ieee.org

[xxii] Clearly, the degree of program execution is central to understanding the risk – and consequent failures – from incomplete work.

[xxiii] In 1999 on market entry to the Internet, Google's new improved "search" paradigm revolutionized search engines.

[xxiv] Nowlan and Heap, same as above.

[xxv] Smith, Anthony, Reliability Centered Maintenance, Mcgraw-Hill, 1992. Obviously this has to summarize.

[xxvi] Nowlan and Heap, same as above.

[xxvii] Two standard deviations with a normal model

[xxviii] Failure mathematics shows optimum results

[xxix] Automation's goal is to reduce direct labor costs.

[xxx] An invariant time parameter must be found. These are parameters like tonnage, mileage and number of operations that correlate with generalized time.