AN EFFECTIVE ARCHITECTURE FOR INDUSTRIAL PROCESS MANAGEMENT

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Abstract
Pacific Northwest National Laboratory personnel have developed a cost-effective solution for implementing the use of advanced technologies for monitoring the condition and performance of industrial facilities. A combination of operations and maintenance (O&M) know-how together with the broad technical capabilities of the Laboratory have been combined to develop and demonstrate the effectiveness of a condition monitoring software architecture that has paid large dividends in the reduction of O&M costs in a pilot facility. Additional projects are underway to develop this technology to its full potential.

This advanced architecture was designed to provide each segment of the plant operations and maintenance (O&M) team with understandable information for making safe, cost-effective life-cycle operating decisions. The software will provide plant operators, maintenance technicians, engineering staff and administrators with on-line information to enable high process efficiency simultaneously with cost-effective capital equipment management. The software design provides an information infrastructure based on the Laboratory's holistic model of facility O&M.
The result of this research provides the practitioner with the ability to intelligently select the asset management course of action that minimizes both the cost and risk engendered by the operation and maintenance of real-world process systems.

Introduction
One of the biggest battles our military forces face may well be found in the bases they use to train their personnel. The energy savings bar has been raised. Military leaders are now faced with a mandate to reduce their base energy consumption not by 20%, but by 35% relative to a 1985 baseline by the year 2010[b], and to do so with reduced Operations and Maintenance (O&M) budgets. Many managers are turning to the Energy Savings Performance Contracts (ESPCs) with the hope of achieving their goal and staying within this rigidly bounded budget. Some of these contracts have ended in bitter disappointment. As contractors, hungry for a return on their investment, seek to maximize profits, they do not always have the best interests of the base in mind. The result has sometimes been a rapid decline in the condition of the facility infrastructure, resulting in a similar decline in the ability of the base to meet its mission.

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[a] Operated for the Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RL0 1830.

[b] Executive Order 13123 – Greening the Government Through Efficient Energy Management. Federal Register Part IV, 8 June 1999.

The US Marine Corps has turned to the Department of Energy's National Laboratory system in an effort to maintain base readiness while meeting its energy reduction responsibilities. By applying technology transfer initiatives from the national labs, applied methods for O&M have been paying large dividends in cost reduction while allowing the Marines to maintain control of their own base infrastructure.

This article provides insights into how the USMC has found:

- A new view of managing its facility assets
- A holistic model of process information requirements
- A life-cycle asset management perspective
- A well documented case history of economic success
- A new architecture for condition-based O&M cost reduction

The net result of understanding and carefully implementing the condition based approach to operating and maintaining facility O&M processes has been shown to dramatically impact the bottom line.

Evolution of the Condition-Based Approach

Degradation happens. Savvy maintenance managers have long since learned to subscribe to a rigid preventive maintenance (PM) philosophy because it has been made obvious to them that by not following these precepts, they open themselves up to being blindsided by some very unpleasant surprises. Like how not replacing the oil pump bearing seals every 5 years as recommended showed up as 30 gallons of lubricating oil on the plant floor that almost made it to the storm sewer. So, experience makes us firm believers in following even the unpopular tear-it-down-and-measure-the-tolerances routines of the preventive maintenance (PM) regimen.

But, what are the alternatives to this PM approach? Where are the leaders in O&M research headed and what can we expect from these new ways of doing facility business?

There have been, in fact, four distinct evolutionary steps that we have taken in reaching our current state of proactive condition-based O&M. Each successive step has had a positive effect on the efficiency, reliability, and safety of plant processes.

Corrective Maintenance (CM) is the old "if it ain't broke, don't fix it" story. The perennial run-to-failure mode. It is simplicity itself, requires little forethought, and (at least up to the point of machinery failure) requires the least resources from the O&M crew and their support staff. Many "war stories" are told in which equipment is destroyed by rapidly acting degradation mechanisms, erosion or cavitation in a pump for example, that shorten the life expectancy of a component by an order of magnitude or more. In very simple, and non-critical, components (a light bulb for instance) run to failure may be a cost effective mode for maintaining the equipment. In critical applications, however, (like the safety systems of a nuclear power plant) this risky approach is not tolerable. As long as the consequence of equipment failure is not high, this approach can make some sense.

The CM method of plant maintenance is still, surprisingly, the predominant method of commercial plant operation in the U.S. despite the resulting high product loss, capital equipment loss, total manpower expenditure, and accident severity that result.

Preventive Maintenance (PM) is the art of periodically checking the performance and material condition of a piece of equipment to determine if the operating conditions and resulting degradation rate are within the expected limits. If they are not, a search for the reason for the more rapid degradation must be found so problems can be corrected, or at least mitigated, before the machine fails.

PM testing, inspections, servicing, or parts replacement actions are done on a service life (e.g., hours of operation) or purely on a time-in-service basis.. Although accurate failure statistics can allow the testing interval to be optimized, the PM method is expensive, and catastrophic failures can still occur. The PM method is also very labor intensive and risky. Much unneeded maintenance is performed, and incidental damage to equipment is widely reported as a result of poor maintenance practices. A PM system can, however, be a cost-effective strategy when the life span of the equipment is well understood and consistent. An air filter in constant use tends to need replacing with a fairly constant frequency. Studies in the utility industry report reactive-to-preventive life cycle cost savings in the 12 to 18% range.

Predictive Maintenance (PDM) advocates measurements aimed at the early detection of degradation mechanisms, thereby allowing the degradation to be understood and eliminated or controlled, prior to significant physical deterioration of the equipment.

There are many nonintrusive measurement methods that allow us to detect and correct the potential for degradation considerably earlier in the life cycle. Technologies such as vibration analysis, oil analysis, thermography and ultrasonic analysis pushes our problem recognition capability to the leading edge of the degradation envelope.

The application of this technology results in

- a marked increase in equipment life
- earlier mitigation or corrective actions taken
- decreased process downtime
- decreases in maintenance parts and labor
- better product quality
- decreased environmental impact
- energy savings.

The sum of these advantages can add another 8 to 12% to the O&M savings over a good PM program. Also, the root cause for the degradation can sometimes be identified, and consequently, mitigation can be better targeted and repetitive failures become much less likely to occur.

On the negative side, the costly up-front investment in detection and diagnostic equipment, and the high level of staff training, makes this approach a more difficult pitch to an ever wary, cost conscious management. The savings provided by this technology are now largely in terms of avoided cost (a hard concept for management to grasp) and therefore it becomes more difficult to demonstrate and to ensure program funding.

Condition-Based Operations and Maintenance (CBM) is the immediate detection and diagnosis of off-normal equipment operation and the identification of the root cause stressor(s) responsible for this condition. This final evolutionary step, illustrated in Figure 1, is the real key to optimizing high value, critical, O&M process.

Two things should be noted from the outset:

1) operations has now been engaged and integrated into the maintenance equation by becoming responsible for recognizing and correcting the existence of an abnormal condition, and
2) finding the root cause stressors (parameters outside the design envelope) responsible for the off-design condition is now the prime directive.

Figure 1 Condition-Based Operation and Maintenance

In addition to extending the life and performance of critical components, we can be almost certain of absolute reliability – operation without the necessity for failures.

The use of computers and low cost sensors allows us to:

1) continuously automate stressor recognition (what went out of spec),
2) run degradation mechanistic diagnostics (what's going wrong), and,
3) identify a root cause solution (what needs to be done to correct the situation).

The result is that a computerized real-time picture of the problem and a clear understanding of the solution can be computer generated and presented simultaneously to the operations, maintenance, engineering, and administrations staff. Asset management can now proceed using informed decisions based on known conditions, defined degradation rates and, in most cases, accurate estimates of equipment remaining life (prognostics). Predicting and planning now become the bywords of the maintenance group rather than the 2 am brush fire and panic routine. Over the life of the equipment, the savings provided by this proactive paradigm are estimated to be 5 to 10 % above even the predictive approach, including all the initial investment costs. In a balanced approach using reactive, preventive, predictive, and condition-based, maintenance we now find it possible to generate a total production life-cycle cost savings on the order of 25 to 40%. Part of our work at the Laboratory was to demonstrate that these savings are real, rather than simply a wishful projection.

The Proof of Principal Project

In 1990, the United States Marine Corps (USMC) provided the Pacific Northwest National Laboratory (PNNL) with a perfect opportunity to demonstrate the effectiveness of this emerging CBM technology. The Marine Corps produces thermal energy (heating and cooling) for its base facilities using central energy plants. These plants, like so many Department of Defense (DOD) base installations, are being run with minimum staffing and minimal data available to provide cost-effective O&M decisions. This situation results in the creation of significant improvement opportunities for plant O&M cost reduction.

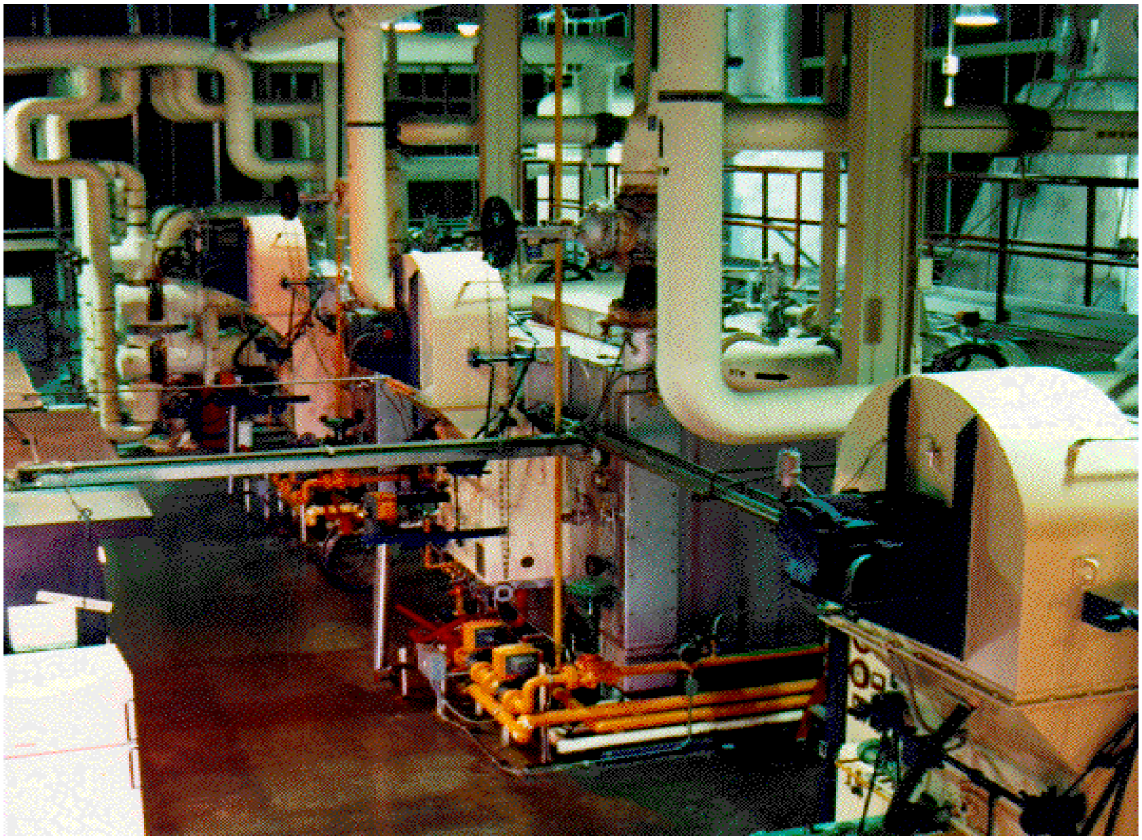

Figure 2 Twentynine Palms Central Heat Plant

The central heating plant (CHP) at the Twentynine Palms, California base was selected as the site for the first implementation of the Decision Support for Operations and Maintenance, or DSOM system. The plant, shown in Figure 2 is a gas-fired 120 MBtu/hr pressurized hot water plant that provides thermal energy (heat) for 20,000 Marines at the Air-Ground Combat Center.

The Decision Support for Operations and Maintenance (DSOM) project was designed to provide a proof of the CBM savings potential by having clear before and after measurements of the actual O&M costs. The project was built around the proactive condition-based approach and integrates:

1) an understanding of degradation mechanisms from the Nuclear Plant Aging Research Program (conducted by the U.S. Nuclear Regulatory Commission),
2) current computer technology,
3) an integral root cause analysis methodology, and
4) the many years of hands-on O&M experience of the Twentynine Palms O&M staff, as well as the Laboratory's Predictive Operations and Maintenance Technology group.

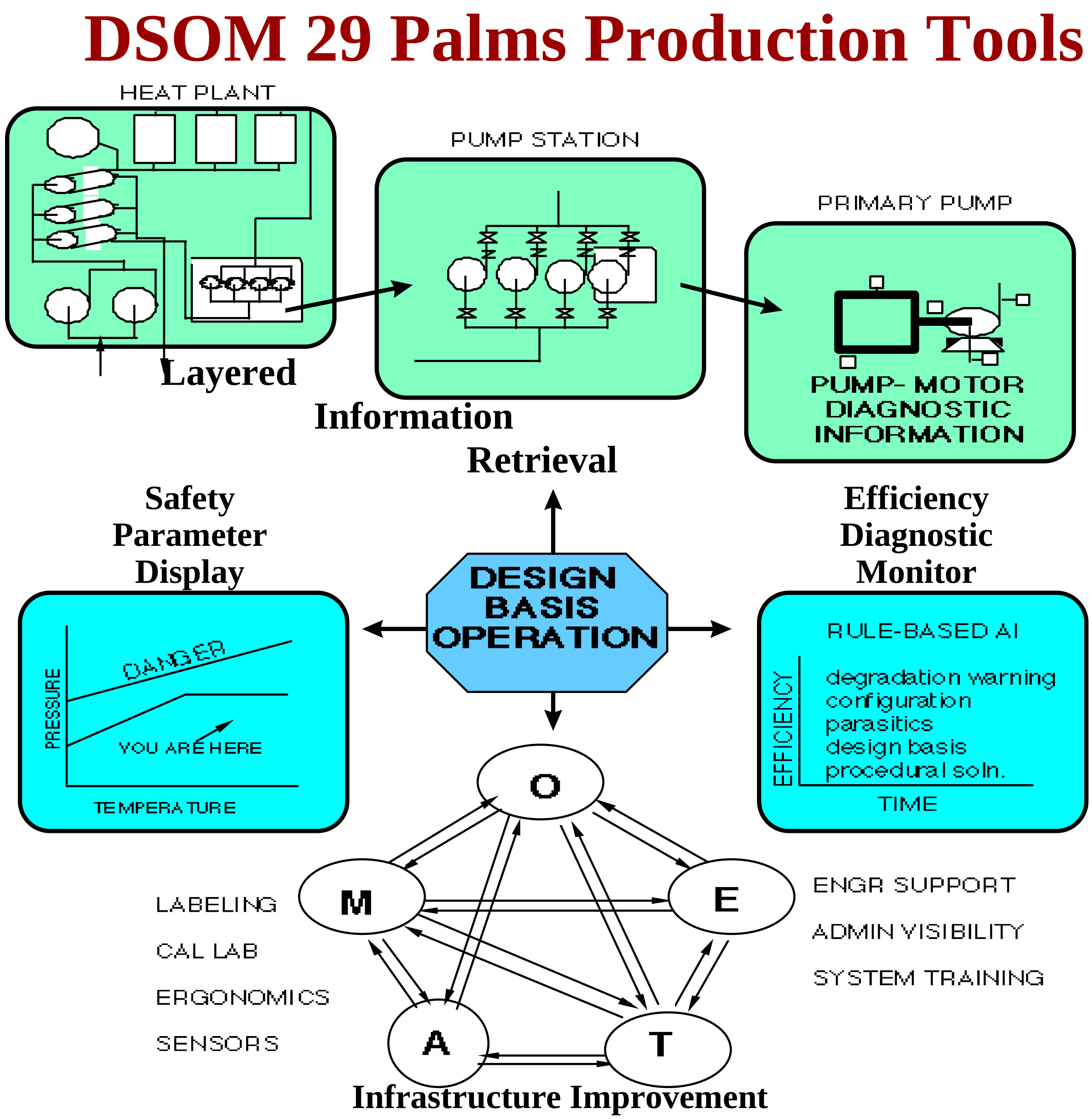

Figure 3 DSOM 29 Palms Operations Tools

The end product is a set of on-line computerized, operations-oriented tools that are based on accurate plant design information and provide the plant operations staff with guidance on cost and safety conscious decisions. The principal operations decision support information tools are shown in Figure 3.

At Twentynine Palms, the DSOM condition-based O&M tool set provides the operations crew with point and click information access to the processes at the plant, system, and component levels. Both the safety and the efficiency of the components and the process are monitored, and root cause solutions are automatically generated and brought to the operator’s attention to regain cost-effective operation. Design basis operation is achieved and maintained by continued vigilance of all O&M infrastructure elements that are required to effectively optimize the process (Operations, Maintenance, Engineering, Training, and Administrative Support, termed OMETA).

Measuring the Economic Incentive

The criteria for success is dominated by the bottom line. To be able to draw an accurate record of change, a detailed baseline characterization was performed (Reference 1). This included not only the common metrics, such as plant overall operating efficiency and maintenance machinery repair records, but also the other OMETA functions that must be integrated to provide the infrastructure required for continued operation

The effect of the 1994 installation of DSOM was an immediate enhancement of the plant's safety, reliability and available capacity. The project increased plant thermal efficiency by 17%, reducing the plant's greenhouse emissions by over 3,000 tons per year, and reduced its gas bill by over a quarter of a million dollars each year. A concurrent increase in plant available capacity eliminated the need for a fourth generator unit, saving an immediate $1M. The more difficult challenge was to show that these rather spectacular savings are actually not as large a reward as the savings on capital life-cycle economics. To demonstrate this, a life-cycle cost projection was performed based on data gathered thus far from the Twentynine Palms project.

When we look at the "life cycle" of the process as "providing sufficient thermal energy to support the base needs for the next 60 years", we must included everything necessary to implement and support plant O&M for the duration (capital equipment, personnel, repairs, and fuel). Based on the documented reactive life cycle costs at Twentynine Palms, the data yields the projected figures shown in Table 1.

Operations and Maintenance Category	Projected Life Cycle Savings
Fuel Savings (operational efficiency)	15 M
Maintenance Savings (condition-based)	16 M
Capital Equipment Savings (life extension)	20 M

Table 1 Economic Results of the Paradigm Shift

Thus we see in clear quantitative terms that the largest single gain from the CBM approach is in avoided capital expenditures. This systematic application of a condition-based improvement process at Twentynine Palms is currently saving the base approximately $480 K per year on its life-cycle heat plant O&M bill and paid back the original research investment in 4 years.

DSOM II at Parris Island

With the success of the Twentynine Palms experiment in condition-based O&M, the USMC incorporating this technology as an integral plank in its Energy Conservation Campaign Plan. Currently, the USMC is applying an advanced version of the Twentynine Palms technology to the thermal and electrical generation systems at its Parris Island South Carolina cogeneration plant.

Figure 4 Parris Island Cogeneration Facility

Software Designed to Fit the Infrastructure

The Twentynine Palms software was designed to provide the operations staff with on-line information to allow them precise control of the combustion, heat transport and hydraulic processes in their plant. Parris Island offered the opportunity to advance this concept by providing preformatted information to not only operations, but to all the facilities staff who are involved in supporting the operation of the plant. In order to fully understand the approach taken in structuring the software design, it is first necessary to define the support infrastructure required.

Plant Functional Decomposition

Careful scrutiny in the commercial nuclear industry shows that any process operation can be broken down into five major functions that must work and communicate together to achieve the process goals. For the case at hand, the process is the generation and transport of electrical and thermal energy at a central heating plant. The major functions that must be accomplished are :

Operations (manipulate the process machinery)
Maintenance (provide upkeep and repair of system components)
Engineering (monitor and improve process O&M performance)
Training (teach people the information they need for equipment)
Administration (provide overall control of goals and resources needed).

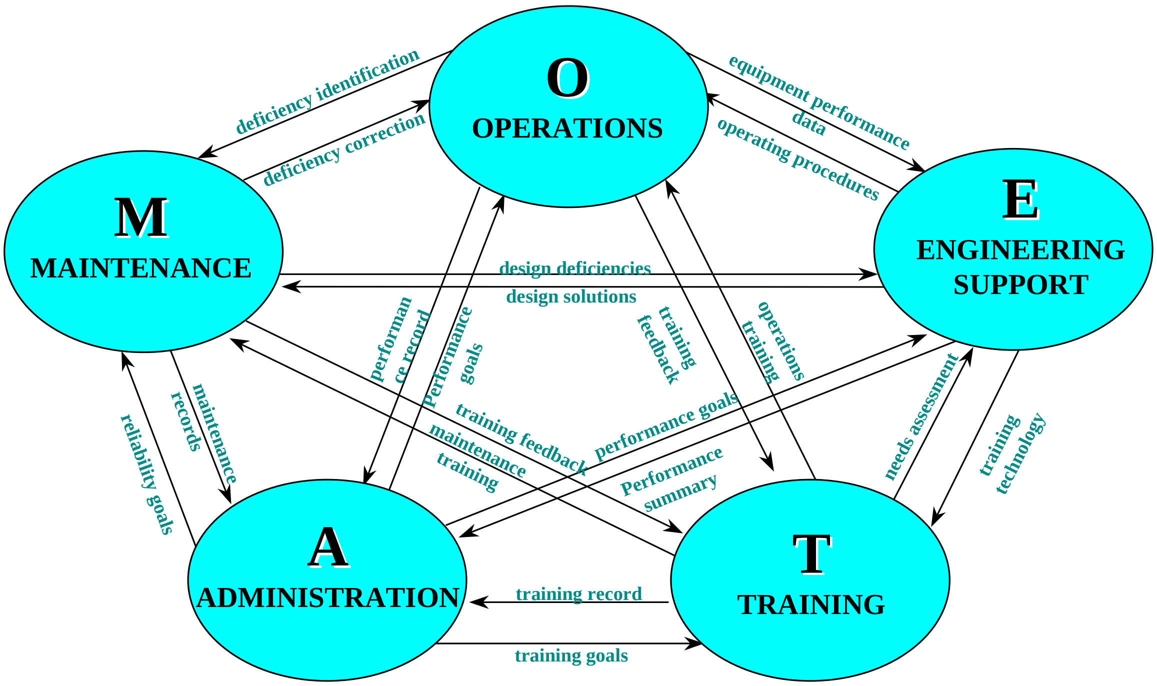

Figure 5 Operations and Maintenance Functional Interactions

We can visualize these five areas as a pentagram structure where each of these five functions are essential to any industrial process.

To illustrate how information must flow between each of the functions for the process to proceed effectively, consider the following example. If, for instance, only the engineering support function were to be inactive, ineffective, or isolated from the other functions for some reason, the following can happen (and in fact has):

- equipment problems identified by the operators would be repaired, but would go unresolved, so chronic plant problems would continue unchecked
- machinery material deficiencies noted by the maintenance technicians would go uninvestigated and the machinery would continue to break repeatedly from the same cause
- the plant administration would not know plant performance level or what resources were necessary to maximize plant life-cycle efficiency and so would loose control of plant costs
- as new technology was added to the plant, training needs would not be recognized, procedures would not be changed and, without operator training, the benefits of installing that technology would soon be lost.

Similar scenarios could be generated should any of the other functional entities be missing or not operating effectively.   Each of the five functions must, therefore, be effectively performed by some responsible organization/individual to allow the process to continue in a safe and efficient manner.

Subfunctional Areas

As anyone who must work in the O&M arena can tell you, the pentagram graphic provides an over-simplified, single plane view of a very dynamic 3-dimensional hierarical network. A much more confusing, but realistic, depiction is provided in Figure 6.

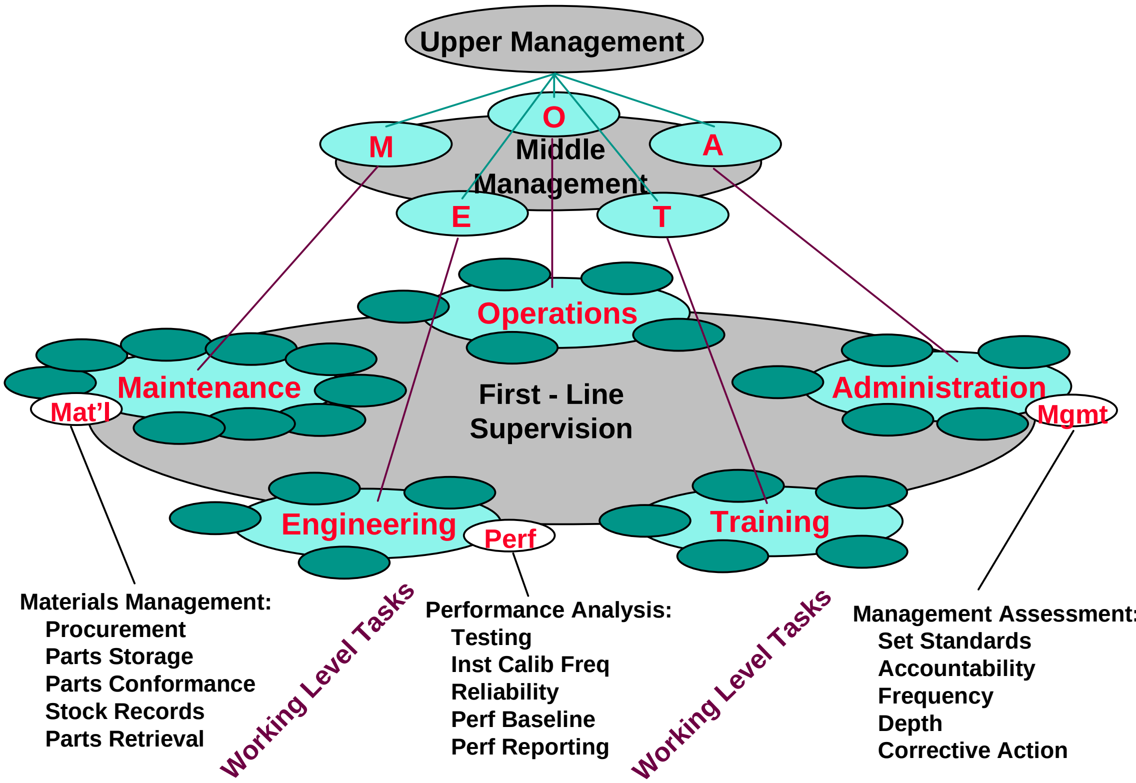

Figure 6 Functional Hierarchy

Here we can see that each of the five major functions can be broken down into specific functional areas of responsibility. Each of these areas must be accomplished in order to make the system perform well at the major function level. Continuing with the engineering function as an example, we find that five different responsibility areas fall into the circle of the plant engineer. These areas include:

Plant Modifications -	produce solutions to problems or upgrades for higher efficiency for the plant process
Performance Monitoring -	provide the basis for understanding, reporting, and improving plant efficiency and reliability
Support Organization -	ensure effective implementation and control of plant engineering support needs
Document Control -	ensure documents provide accurate, as-built information sufficient to support plant O&M requirements
Procedures -	ensure procedures provide appropriate direction for plant efficiency.

Although it is not mandatory that these functional areas be performed specifically by the plant engineer, it is essential, even in small process organizations, that responsibility for each area of performance is assigned and effectively accomplished by cognizant personnel. Again, as in the previous discussion, should any of these areas be even partially dysfunctional, that impairment is transferred to some degree to the efficiency, reliability, and safety of the entire plant.

Task Level Structure

Finally, the level of the individual tasks can be examined. The task level provides a working description of the requirements for each individual in accomplishing basic functions related to the success of the process goals. Again, a description of this level is best accomplished through example.

In the engineering function, we found that one of the area responsibilities was Performance Monitoring: provide the basis for understanding, reporting, and improving plant efficiency and reliability. At the working task level this is further resolved as:

- Instrument calibration frequency determination
- Component, system and process testing
- Process performance baseline analysis
- Performance analysis (relative to the baseline)
- Machinery reliability analysis
- Process performance reporting.

These are the basic elements that the engineer must be capable of achieving to accurately determine the adequacy of the performance of the process. In large plants, several “Results Engineers”, as they are sometimes called, devote their entire energies to providing these basic building blocks. In smaller processes, these tasks and, other area functions fall into the province of the plant engineer. The level of detail of these tasks is usually less explicit in smaller plants, but the task elements themselves must still be performed. The result of the deletion of any of these elements is reflected in or reduces control of both the economics and safety of the process.

It is at the task level that the information flow, or lack of it, really makes itself apparent. Pick one of the tasks from the engineer’s list. Let’s say machinery reliability analysis. It is obvious that without the information of the operators regarding availability on demand (pump would not start, valve would not close), a detailed listing of maintenance data on failures (mean time to failure, resources necessary to repair), and the resource availability information of the administrative support group, the completion of this task is virtually impossible. The same is true for all of the other 220 identified task level entries in the infrastructure listing. The importance of accurate, timely information cannot be under-estimated in the effective operation of a process plant.

Design of the Software to Implement Information Exchange

The PNNL DSOM project staff fully appreciate the importance of the forgoing argument. Twentynine Palms was focused on the immediate needs of the operators. Parris Island afforded us an opportunity to extend the infrastructure information net to the full extent of the OMETA team.

In fact, the integration concept extends beyond the thermal and electric generation on the site, including the demand side management and waste treatment facilities. The basic idea is shown in Figure 8.

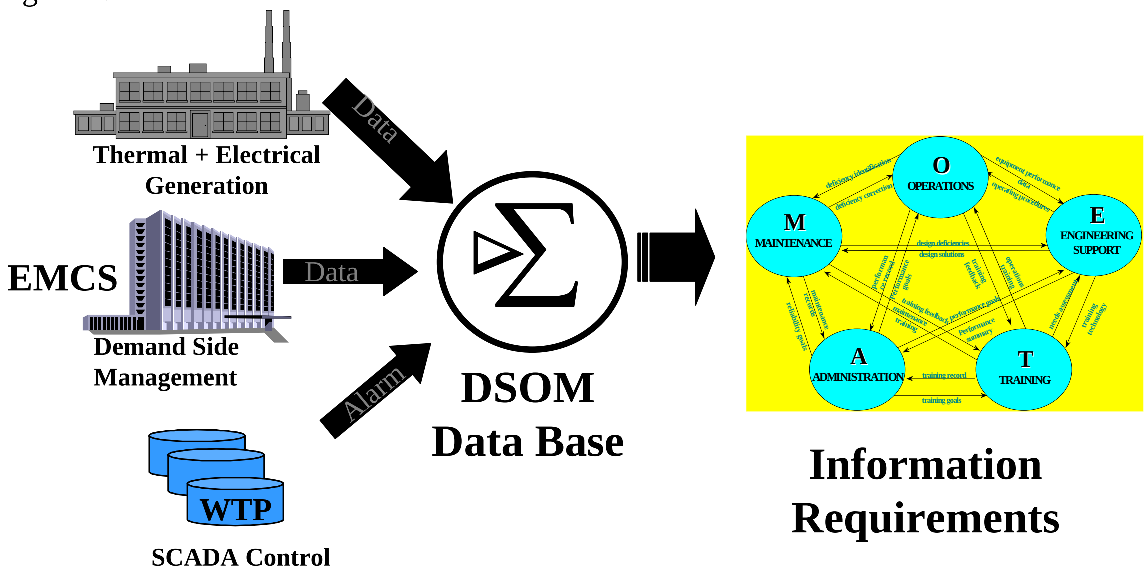

Figure 8 Parris Island Information Integration Model

Data generated in the central energy plant (CEP), building energy management and control system (EMCS), and alarm information from the site waste treatment plant are all routed to a central data base in the DSOM computer. That data base can then be queried by the population of users, and, depending on the identified function of the user, the data is displayed in a from customized to the users' need. The CEP operator gets the information he needs regarding the operational status, the maintenance technician finds status and failure information, the engineer can access design and performance data, and the administrator has the plant efficiency translated into readily understandable asset management terms (see Figure 9). This structured interface not only provides each of the plant functions with data it can relate to and understand, but will allow other functional disciplines to "see" the plant through the perspective of their coworkers. A unique cross-training benefit.

And what of the training function? This function has been physically decoupled by requiring that it be performed in a different, non-networked computer. The potential for collisions between a training scenario and real plant operations was not left to chance.

A Universal Translator

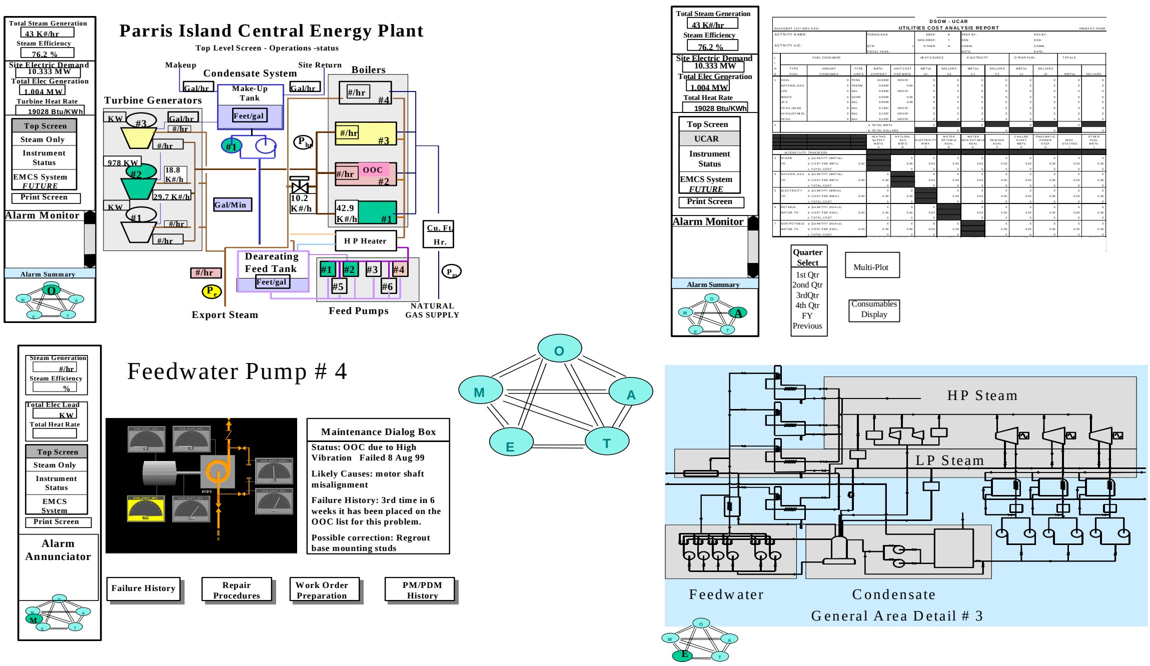

Figure 9 DSOM II Functionally Tailored Multi-User Interface

The integration of the functional OMETA areas is expected to pay great dividends in the form of reduced cost, better communication, and an improved understanding of the team effort that is required to meet or exceed today's commercial operating standard. The administrative task of process assessment will now be possible as never before due to the open exchange of information. The admin decisions that are necessary to provide the O&M team with the resources to achieve the commercial efficiency goals will become clear due to the visibility of cause and effect provided by the program.

Conclusions

A new approach to integrating the information needs of the total infrastructure necessary to support the operations and maintenance of a major process plant is being tried at the Parris Island USMC base in North Carolina. This approach provides a level of customized information access that was previously not possible by parsing a common data base into information specific multi-user interfaces. By including all the functional requirements of the total infrastructure, large paybacks in efficiency, work flow, and aware decision making are expected to be gained by this process.

Besides contributing substantially to meeting the goals of the 1999 Executive Order, this technology is reducing environmental pollution, and enhancing the reliability of USMC thermal energy systems as well. It is estimated that, if applied USMC-wide, proactive condition-based O&M would save the U. S. taxpayer approximately $12.2 M per year on USMC base energy alone. Twentynine Palms has clearly demonstrated that fuel savings is only the first chapter in the condition-based plant asset management handbook. The second chapter on process integration is about to be written in Parris - Parris Island that is…

REFERENCE

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After receiving a bachelor's degree in mechanical and a master's in nuclear engineering from Penn State, Don worked for the Knolls Atomic Power Laboratory in operations and maintenance at the Naval Nuclear Training Center in West Milton New York. He certified as a senior reactor operator and served as the maintenance manager for the submarine prototype facility.

Joining EG&G Idaho in 1978 as a senior scientist, he analyzed thermal-hydraulic phenomena for the Loss-Of-Fluid-Test (LOFT) facility. He was the principal analyst for the confirmatory LOFT simulation of the Three-Mile Island accident.

In 1985 Don joined the Battelle Memorial Institute at the Pacific Northwest National Laboratory (PNNL) where, for the past 15 years he has been performing research and development in the field of predictive operations and maintenance. As a staff scientist, he is the principal investigator for the Laboratories' Decision Support for Operations and Maintenance (DSOM) program, an enterprise wide condition-based approach to O&M information management.