The Effects of the On-line Maintenance Work Management Strategy on Nuclear Plant Performance

by

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Submitted to the Department of Nuclear Engineering
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

A determination of the effects of the on-line maintenance strategy on nuclear power plant performance was made, using the key performance indicators of cost of generation, capacity factor, availability and reliability, the number of significant events for the measurable aspects of performance, and establishing the role certain key organizational factors that affect human performance of work process steps for the non-quantifiable effects.

On-line maintenance work management programs are in use at nearly every commercial U.S. nuclear power station. The programs were developed in the early 1990s, primarily as a method of improving work process efficiency and to accomplish work during operational periods that had previously been accomplished during outages, thereby shortening the outages and improving the economic performance of the station. On-line maintenance programs are distinguished from other maintenance work management strategies by a tiered approach to maintenance, a systematic scheduling process that provides long lead times, and highly coordinated work execution. The direct result of this is more efficient use of worker resources and more work being accomplished.

The combined effects of the improved work processes and the changes in plant culture that have occurred concurrently are shown to have yielded measurable improvements in nuclear safety and economic performance. Important non-quantifiable benefits in human performance are demonstrated on the basis of how the processes influence performance shaping factors.

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Biographical Note

Frederick M. Nielsen, a student in the Nuclear Engineering Department since September 1996, received his Master of Engineering in Nuclear Systems Engineering in June 1997. He is employed by the Institute of Nuclear Power Operations (INPO) in Atlanta, Georgia.

Nielsen graduated magna cum laude from the United States Naval Academy (1974 - 1978) with a Bachelor of Science degree in Electrical Engineering. He served in the U. S. Navy as a submarine officer until joining INPO in 1985. During 1993, Nielsen was loaned by INPO to Houston Lighting and Power Company's South Texas Project Electric Generating Station as Electrical Maintenance Manager. He was Assistant Outage Department manager and Work Management Team Leader during his most recent assignment at INPO prior to enrolling in the Massachusetts Institute of Technology.

Nielsen is a Commander in the United States Navy Reserve, serving as Executive Officer of an engineering duty reserve unit. He is a licensed professional engineer in the State of Georgia.

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I am indebted to my wife, Debbie, and children, Christin and Matt, who persevered while being away from a home they love during this period. Because of their support, love, and tolerance, my role as a student was made much easier. I am grateful that they allowed me to back down somewhat from being a husband and a father during these past nine months.

I appreciate very much my company, the Institute of Nuclear Power Operations. The encouragement and support they provided to me from beginning to end humbles me. It is wonderful to be associated with a company that gives so much to its employees.

Most importantly, I am grateful to my God and Savior, to whom I owe everything. "I waited for the Lord on high and He heard my cry" became *my* Psalm while I was here.

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Chapter 1
Introduction

The focus of this thesis is on a relatively recently developed work management strategy for commercial nuclear power stations that makes previously unprecedented use of on-line maintenance and emphasizes a systematic approach to scheduling and work preparation. This strategy, implemented at most U. S. plants as of 1996, has helped improve utility cost of generation through moderating operations and maintenance costs and improving capacity factors. More importantly, human performance and the reliability of important safety systems have improved as a result of this strategy.

The strategy involves accomplishing work that has traditionally been relegated to outage periods while the plant is at power -- for that reason, it is called "on-line maintenance." The Institute of Nuclear Power Operations (INPO) describes an individual on-line maintenance activity in its most basic form, in this way:

> "On-line maintenance is a planned and scheduled activity to perform preventive or corrective maintenance, with the reactor at power, while properly controlling out-of-service time of systems or equipment."[1]

The on-line maintenance work management strategy accomplishes this and other maintenance activities by scheduling the activities months in advance, prioritizing them among scores of other activities, judging the effect of the activities on plant conditions or other work using the plant's probabilistic safety assessment, determining whether the workers require detailed instructions, and coordinating the work with plant conditions.

The on-line maintenance work management strategy has many similarities with predecessor work management programs. The overall mission of the on-line maintenance

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[1] Sullivan, T., *Managing Maintenance During Power Operations,* Letter to nuclear utility executives from Institute of Nuclear Power Operations, February 17, 1995

program is the same as other work management programs. Also, the essential process steps used in preventive and corrective maintenance are nearly indiscernible among this and other work management programs. The key program differences lie in which groups are involved in the steps and when the steps occur. These differences have helped improve the nuclear industry's economic performance and favorably influenced the performance shaping factors and external conditions that affect human performance.

This thesis describes how on-line maintenance work management programs work and the benefits -- both quantifiable and non-quantifiable -- the strategy can provide. It explores the role of the on-line maintenance work management process in the nuclear industry's drive for improved performance. Chapter 2 provides the background necessary to understand on-line maintenance programs, and includes a review of the history of on-line maintenance, and a description of a model on-line maintenance program. Chapter 3 explores the effects of on-line maintenance programs on quantifiable indicators of performance such as cost, outage duration, reliability and availability, capacity factor, and significant events. Chapter 4 describes non-quantifiable benefits of the program in terms of human performance and organizational performance. Conclusions and future work are provided in Chapter 5.

Chapter 2

On-line Maintenance

This chapter provides the background necessary to understand on-line maintenance (OLM) work processes and how they affect plant, human, and organizational performance. The background is covered through an introduction to nuclear power plant maintenance, a history of on-line maintenance, and an on-line maintenance program description.

Before exploring the details of OLM, it is necessary to describe maintenance programs at nuclear power stations in general.

2.1 Introduction to Nuclear Power Plant Maintenance

According to the Institute of Nuclear Power Operations, the purpose of maintenance at a nuclear power facility is to ensure "safe and reliable nuclear power station electrical generation. The maintenance program should ensure that installed station equipment operates when needed and that equipment malfunctions or deficiencies are corrected in a timely manner and rarely occur."[2] More simply stated, the role of the maintenance function at a nuclear power facility is to optimize plant materiel condition. Materiel condition is a qualitative term that describes the overall "health" of systems, structures, and components. When a plant has good materiel condition, its systems are available and reliable.

Optimizing materiel condition of a nuclear plant involves far more than simply repairing broken equipment or conducting tests. Staff organization, processes, programs, and policies, programs, regulations, and plant design all play a role in shaping maintenance effectiveness at power plants. The following descriptions of these areas provide a general overview of their role in current nuclear plant maintenance programs.

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[2] Guidelines for the Conduct of Maintenance at Nuclear Power Stations, INPO 92-001, Institute of Nuclear Power Operations, April 1992, p. i

2.1.1 Station Organization

The first step toward understanding maintenance at nuclear power stations is to understand the key groups involved in the maintenance process. Many groups within even a small plant staff must work together to maintain the plant. Although it is convenient to assume that the maintenance function is accomplished primarily by a maintenance department, it would be inaccurate to do so. Just as the operations department cannot operate a plant without the direct involvement of many interfacing organizations (such as training, engineering, housekeeping, etc.), neither can a maintenance department optimize materiel condition without the direct involvement of many interfacing organizations. The following are the key plant organizations involved in station maintenance:

Plant manager: The individual "responsible for all aspects of safe and reliable station operation, including the safety and well-being of personnel working at the station."[3] The plant manager is responsible for establishing high standards and holding individuals and groups accountable for performance. Operations, Maintenance and Engineering departments typically work directly for the plant manager.

Typical Station Departments

Maintenance: The maintenance department provides the workforce for conducting the actual equipment maintenance. Some maintenance departments are more self-sufficient than others. For purposes of this thesis, the "Maintenance Department" refers to mechanical, electrical, and instrumentation and control (I&C) technicians. These workers are also referred to as "craftsmen."

[3] Guidelines for the Organization and Administration of Nuclear Power Stations, INPO 92-002, Institute of Nuclear Power Operations, July 1992, p. 2

Operations: The operations department operates the reactor and other plant controls. Within the context of maintenance, operations authorizes maintenance work to commence, aligns systems for work, and provides worker and system safety during maintenance by tagging components (breakers, valves, and dampers) to prevent their operation. Operators are frequently the first to identify equipment deficiencies. Because operators best understand system interactions and the relative importance of each piece of equipment, they have a strong voice in prioritizing deficiencies for work.

Engineering: The engineering department provides technical guidance for the staff. Engineers determine the type and frequency of preventive maintenance from equipment manufacturer information and reliability studies. Engineering also has an important say on the priority of equipment deficiencies, and provides technical advice on the effect of conducting maintenance on equipment availability and reliability.[4] System engineers are responsible for monitoring the condition of their systems, and incorporate predictive measures to determine if latent equipment problems exist.

Training: The training department teaches the skills necessary to accomplish the functions of the organizations described in this section.

Non-department Groups

Planning: The planning group develops the work instructions needed by maintenance craftsmen. This includes the step-by-step instructions, drawings required, permits (such as welding, enclosed space entry, etc.), spare parts, setpoints and torque requirements -- nearly every piece of information a craftsman

[4] "Availability" is a term relating to whether or not a component or system is capable of operating. It is essentially the fraction of in-service time within a specified time interval. "Reliability" is a term that refers to whether a component functions successfully upon demand. It is the fraction of successful trials among a specified set.

needs to conduct the work.. Planners provide work instructions commensurate with the difficulty of a job -- work that is within the skill of the craftsman, such as tightening valve packing, does not require detailed instructions.

Scheduling: Scheduling coordinates the work efforts of interfacing organizations. This is accomplished in several phases. A long-range schedule that provides general opportunities for maintenance on pre-specified systems is used for rough planning. Several weeks before work starts, a more detailed job schedule is developed to allow parts to be delivered, tags to be prepared, and scaffolds and other support work to be organized. Finally, a detailed schedule that includes work sequences to coordinate the jobs with other station jobs is developed. Schedulers are sometimes separated into two teams for on-line and outage scheduling.

Work control group: The work control group administers much of the maintenance process by controlling the flow of documentation, from problem identification to work completion. Stations vary widely in how work is authorized, tracked, and closed out -- for purposes of this thesis, a work control center is the hub through which workers obtain permission to start work, work is tracked, operators are kept informed of work status, tags are issued and hung, and work completion is announced. Although the work control center is largely manned by off-shift operators, it can be organizationally assigned to the maintenance or other departments.

Nearly all nuclear power stations have organizations similar to those described here, and these organizations are common to OLM work management programs as well as other work management programs (OLM programs have some other differences that will be discussed later). Other important organizations that will not be discussed in detail include the quality group, materials management (parts), and licensing. Management and supervision are assumed to be part of each of the organizations described above.

2.1.2 Processes, Programs and Policies

The way the organizations listed above interface is a vital part of maintenance. Indeed, poor interfacing is a key factor in many events. The processes, programs, and policies of a nuclear power station are the "software" that makes the staff function safely and effectively. In consideration of maintenance, they include the strategy and tactics employed to ensure high station availability and reliability. Certain programs, such as quality assurance, are required by law. Many procedures, such as operating procedures, are also required by law. The ways (tactics) stations choose to accomplish top-level functions are usually not mandated by regulation.

Although most domestic stations have the same basic organizational structure described in the preceding section, there is wide variation in maintenance effectiveness, largely because of weak interfaces among the organizations. In fact, each organization doing its job well *separate from the other departments* does not mean that the maintenance function is being accomplished well. It takes each organization doing its job well *in concert with the other departments* to make a good maintenance program.

Interfaces among organizations are defined by the processes. Processes are the means used to get groups to work together in an efficient, coordinated manner. Without processes, chaos would reign. Processes can be formally established, as in the case of most on-line maintenance programs, or can have evolved as unwritten "ways things are done." In both cases, the processes used by organizations to accomplish tasks are important to the efficiency and effectiveness of the station.

2.1.2.1 The Basic Work Process

The basic work management process at U.S. commercial nuclear power stations consists of six steps. Although the details concerning which groups accomplish the steps or how much time elapses between the steps can vary dramatically from plant to plant, all maintenance work management strategies adhere to this general model. Each of the steps treated here include appropriate oversight and review of work. The six steps, illustrated in Figure 1, are described as follows:

Problem identification: A problem, such as an equipment deficiency, is identified as needing resolution. Often a work request is prepared at this point to alert the correcting organizations of the need for their action. Some analyses treat this step as a distinct work process that provides input to the work steps that follow.

Prioritization: The importance of the problem is assessed. Prioritization ensures the problem is addressed based upon its importance. The bulk of work should be of low (routine) priority so systematic planning and scheduling can take place.

Planning: The planning step is where *the way the problem will be corrected* is determined. Planners create work order packages that tell workers how to do the work. They also obtain parts and arrange for special permits. The support groups that will be needed for the work are alerted.

Scheduling: The scheduling step establishes when the problem will be corrected. Scheduling ensures the work groups are coordinated and that plant conditions are acceptable for the work.

Execution: The work conditions are established and the work is accomplished during the execution phase.

Closeout: The completed work is tested, systems are realigned, and documentation is processed during the closeout period.

The Basic Maintenance Work Management Process

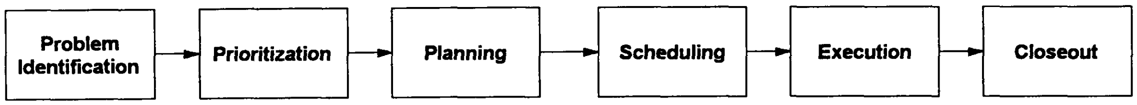

Figure 1 The basic six-stage work management process common to U. S. nuclear power stations

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2.1.2.2 Maintenance Programs

There are two key maintenance programs that are common to all commercial nuclear power plants -- preventive maintenance and corrective maintenance. A brief description of each follows.

Preventive maintenance: Preventive maintenance includes the maintenance actions taken prior to equipment failure in order to extend equipment life and keep it operating within design conditions.[5] In his book on reliability-centered maintenance, A. Smith states that the three reasons for doing preventive maintenance are to prevent failure, detect the onset of failure, and discover hidden flaws that can lead to failure.[6] Many strategies are used in the nuclear power industry to prevent equipment problems -- these strategies are not the subject of this thesis. However, it is useful to be aware that preventive maintenance programs have evolved from many influences, including regulatory requirements, manufacturer recommendation, experience and judgment, tradition, and risk determination.[7]

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[5] INPO 92-001, p. 22
[6] Smith, A., Reliability -Centered Maintenance, McGraw-Hill Inc., New York, NY 1993 p. 11
[7] Ibid. p. 18

Many nuclear power stations have a reliability-centered maintenance (RCM) program as part of their preventive maintenance program. Reliability-centered maintenance uses probability theory in the analysis of equipment performance to focus preventive maintenance programs.[8] RCM has been used by many stations to optimize preventive maintenance programs by increasing, reducing, or sometimes eliminating the amount of preventive maintenance equipment has. By identifying the correct type and amount of maintenance needed for reliable operation, plant staffs can be more certain that maintenance work scopes are appropriate and that work forces are efficiently used.

Corrective Maintenance: Corrective maintenance includes the "repair and restoration of equipment or components that have failed or are malfunctioning and are not performing their intended function."[9] A key objective of most station maintenance programs is to avoid having to conduct corrective maintenance. This aim is similar to the goals physicians have in preventive health care, because cures are harder and more expensive than prevention.

It should be noted that the basic maintenance work process model described in Section 2.1.2.1 is used for both corrective and preventive maintenance. Although, for example, an engineer reviewing an owner's manual to establish a preventive maintenance task for a piece of equipment is performing a significantly different task than an auxiliary operator identifying a leaky valve in need of corrective maintenance, both are essentially taking part in the problem identification phases of the processes they are using. The work planning steps for preventive and corrective maintenance also differ. The basic work process is an important frame with which to compare OLM work management effectiveness with other work management strategies.

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[8] Ibid. p. 27
[9] INPO 92-001, p. 22

2.1.3 Plant Design

Nuclear power plants are designed with built-in redundancy and defense-in-depth of important systems, so that failure of any single component should not affect the safe shutdown of the reactor. This redundancy also provides a degree of flexibility in conducting maintenance, since redundant systems can be taken out of service for work without a significant impact on plant operation. In addition, structural features, such as monorails, hooks and pick points, removable concrete plugs, and access ports are designed into plants in varying degrees to facilitate maintenance.

2.1.4 Regulations

U.S. nuclear power stations are regulated by the U.S. Nuclear Regulatory Commission (NRC), which has the mission of ensuring adequate protection of the public health and safety. The NRC hares this responsibility with its licensees. Federal regulations and the NRC regulatory program are important elements in public protection, but the licensees have the primary responsibility for the safe use of nuclear materials.[10]

Nuclear power plants are licensed by the NRC based upon the plant technical specifications, which describe the plant design basis, safety features, and operating parameters. The technical specifications dictate the systems that must be operational under given plant conditions and specify the amount of time systems can be out-of-service before corrective action is taken. Frequently, the specified corrective action is to shut the plant down until repairs are made.

New rules designed to improve public safety are sometimes issued by the NRC. These can have a significant effect on plant staffs by requiring new or revamped programs. The Maintenance Rule of July 1991, is one such rule.[11] This rule requires that each

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[10] "Mission of the NRC," January 17, 1997, by NRCWEB (nrcweb@nrc.gov).

[11] The Maintenance Rule was established in July 1991 as Section 50.65 of 10CFR Part 50

nuclear power plant develop a maintenance monitoring scheme to measure the effectiveness of maintenance activities on plant structures, systems, and components.

Regulations intended to ensure public safety tend to make maintenance of nuclear power plants more complex than maintenance of non-nuclear power plants. As a result, the maintenance strategies that nuclear power plant staffs employ to optimize materiel condition may seem inefficient when compared with the more straightforward strategies of non-nuclear facilities. For example, work on important nuclear safety systems is frequently deferred until the plant enters a mode in which conditions for the maintenance is allowed. Fortunately, the move toward "performance-based regulations," such as the Maintenance Rule, is providing more flexibility for utilities in plant operations.

2.2 History of On-line Maintenance

Prior to the early 1990s, few domestic nuclear power stations conducted maintenance on-line of important safety equipment. Deficiencies in these systems typically accumulated until outage periods, during which time they were addressed. This strategy was expensive because long outages using contract labor to augment the station's work force were necessary to address the work backlog. The strategy was also not conducive to good materiel condition, because work backlogs would typically grow high during operating periods. It was not unusual for stations to have corrective maintenance work order backlogs in the thousands.

The drive among many utilities to reduce generating costs and improve capacity factors that started in the early 1990's saw the long outages that typified U. S. nuclear plant operating cycles as a prime target for improvement. One way to shorten outages and thereby improve capacity factor is to reduce the scope of the outages. This meant that the amount of work to be done during the outage needed to be restricted. This could be accomplished by conducting as much of the work as possible while the plant was operating -- conducting on-line maintenance. In the words of one outage manager, "You can't allow maintenance work that can be accomplished in non-outage periods to be done during a 30-day outage,"[12]

When on-line maintenance was still a relatively new strategy, the NRC was concerned about the potential for reduced safety in case multiple components were removed from service during the maintenance. The NRC director of Nuclear Reactor Regulation noted in 1994 that, although some plants were limiting the planned on-line maintenance outage window to a single train or system, others "would allow multiple equipment in other systems within a single train to be out of service as long as it did not violate the technical specifications." [13] He cautioned that the technical specifications "do not address allowable outage times for multiple equipment being out of service at the same time." The concern was that, under these circumstances, the plant could be in an unanalyzed condition.

In an effort to provide guidance to the industry for the conduct of on-line maintenance, INPO issued a letter to utility executives in February 1995 which outlined a conservative approach that the industry for the most part has adopted. This guidance was viewed favorably by the NRC. The associate director for technical assessment, Office of Nuclear Reactor Regulation (NRR), said "The letter from INPO was quite good -- good guidance and focus on the kinds of things people should be taking into consideration when they're doing corrective maintenance during power operations."[14]

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[12] Peterson, S., *Countdown*, Nuclear Energy, a publication of the Nuclear Energy Institute, Second Quarter 1994, p. 36

[13] *NRC takes aim at utility trend to perform more on-line maintenance*, Inside N.R.C.: an exclusive report on the U.S. Nuclear Regulatory Commission, October 17, 1994 p. 2,

[14] Hart, K., *NRC finds greater awareness, uneven handling of on-line maintenance*, Inside N.R.C.: an exclusive report on the U. S. Nuclear Regulatory Commission, March 12, 1995 p. 4

INPO's on-line maintenance guidance included the following key points:

- Station managers must ensure that on-line maintenance activities contribute to safe and reliable plant operations.

- The effect of the on-line maintenance on plant safety and reliability must be evaluated and managed.

- Planning and scheduling of on-line maintenance must ensure the out-of-service time for important equipment is adequately controlled.

- The unavailability of risk-significant systems must be periodically evaluated to demonstrate the effectiveness of the maintenance.[15]

As OLM programs continue to evolve and mature, more and more utilities are using the results of probabilistic safety assessments (PSAs) as a yardstick for system availability measures. In 1988, the Nuclear Regulatory Commission required nuclear utilities to conduct an independent plant evaluation (IPE) of each of their plants to learn about accident behavior, determine the most likely severe accident sequences, and to quantify probabilities of core damage and fission product releases. The PSA was the product of these evaluations, and is useful in determining the effect of removing equipment from service on nuclear safety (core damage frequency). Some utilities have adopted a "risk monitor," which allows them to determine in real time the effect of the plant configuration and in-progress or planned maintenance on core damage frequency.

Probabilistic safety assessments also highlight the relative importance of specific equipment availability to nuclear safety. Although the Maintenance Rule requires the monitoring of maintenance program effectiveness on important equipment, plant PSAs

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[15] Sullivan, *Managing Maintenance During Power Operation*

highlighted the importance of key equipment availability prior to the rule. The result has been an increased sense of urgency for returning equipment to service when deficiencies exist, and restricting the out-of-service time of important systems during maintenance.

Currently, nearly all domestic nuclear power stations engage in some variety of on-line maintenance. With most of these programs, the balance of licensing requirements from technical specifications, equipment availability optimization, and advantage gained in reducing outage scope is being maintained. Most plants are coordinating on-line maintenance to reduce out-of-service time and optimize system availability.[16]

2.3 On-line Maintenance Work Management Program Description

This section describes in detail a representative on-line maintenance program. The program described is not necessarily the "ideal" program, and programmatic weaknesses that some stations have are not described here. No two nuclear power stations are alike in their approaches to station operation, but stations with well-functioning OLM programs have enough similarities that a composite sketch can be made that is representative.

Before the OLM work process is described, differences between the plant organization covered earlier and a description of the tiered approach to maintenance used by OLM programs is described.

2.3.1 Plant Organization

The general station organization described in Section 2.1.1 applies to stations using the OLM work management strategy. However, most OLM programs also have the following groups and individuals:

[16] Hart, loc. cit.

Work week manager -- the single point of contact responsible for the success of the work week. Six work week managers rotate through a continuous preparation - execution cycle that corresponds with the countdown schedule (described in Section 2.3.4). The work week manager coordinates all activities in his work week to ensure the work schedule is executed successfully. The work week manager also sequences the work to eliminate interference with other jobs or activities and optimize plant defense-in-depth.

Fix-it-Now (FIN) Team -- a small, self-directed work force with the mission of rapidly accomplishing emergent work. The team is led by a licensed senior reactor operator who is permanently assigned as the FIN supervisor. The team is made of the following individuals:

- supervisor -- typically an individual with a strong operations background
- work planner -- prepares paperwork as needed
- reactor operator -- prepares, hangs, and clears tags
- craftsmen -- two from each of the three craft disciplines

Work is accepted by the FIN supervisor during the morning prioritization meeting. He can accept as much work as can be accomplished in a shift, and he has the authority to refuse work. Although much of the work the FIN team accomplishes is minor maintenance, the team is not restricted from planned maintenance. The team is able to "trade" work with the maintenance department when its skills are not suitable to deal with important emergent work.

2.3.2 Tiered Maintenance

OLM programs incorporate a "tiered" response to resolving equipment deficiencies. This means that the complexity or importance of the work dictates the detail of planning documents provided to the workers. The tiered approach to maintenance includes two types of corrective maintenance:

- Minor maintenance: Minor maintenance is defined by INPO as "work that can be conducted safely without detailed written work instructions and without overall plant scheduling."[17] This work has no operational impact and requires no support from other groups that requires advance notice or coordination. Because of this, the lifecycle of a work request that is determined to be minor maintenance differs from a conventional maintenance request in the speed and efficiency with which it steps through the work process. Minor maintenance is usually declared as such during work classification in the prioritization meeting. Minor maintenance consists of "toolpouch" maintenance and "minor work."

  Toolpouch work is that simple work that can be accomplished on-the-spot without affecting plant conditions or other plant activities. No documentation or work authorization from operations is required for this work. Whether or not the work is toolpouch is typically determined on-the-spot by the individual discovering the deficiency.

  Minor work is similar to toolpouch work, but requires an initiating document. It may be that the person identifying the minor work was not qualified to

[17] Minor Maintenance Process Description AP901, Institute of Nuclear Power Operations, Atlanta, GA, 1996, p. 3

conduct it as toolpouch; therefore, the work document is necessary so other resources can be assigned.

- Conventional Maintenance: Conventional maintenance includes all other corrective maintenance work. Formal work documents and scheduling are required, and work authorization must be obtained prior to work start.

2.3.3 On-line Maintenance Work Management Process

As described in Section 2.1.2.1, the work process includes the steps taken from deficiency identification to work package closeout at the end of the maintenance. The OLM work process, shown in Figure 2, is designed so as to optimize the number of handoffs of work packages among individuals throughout the cycle. The key aspects of the OLM work management process steps and their differences from the basic work process of Section 2.1.2.1 are described below.

Problem identification: Equipment deficiencies can be identified by anyone -- a policy that exists in most maintenance programs, OLM or otherwise. In OLM programs, if the work fits in the "toolpouch" category, it will be done on-the-spot with a minimum of work documents. When a deficiency is identified that cannot be corrected immediately i.e., scheduling is required, then a work request is written to document the problem.

Prioritization: Prioritization is the process of determining how important the problem is, and whether it requires immediate attention or can be scheduled later. The OLM work management prioritization step differs from other maintenance prioritization steps because of the groups involved. In the OLM strategy, an operator in the work control center will make an initial determination of the importance of the deficiency and the effect of the deficiency on plant operation. If the problem is not extreme, formal prioritization will be accomplished at the next morning prioritization meeting by a committee made

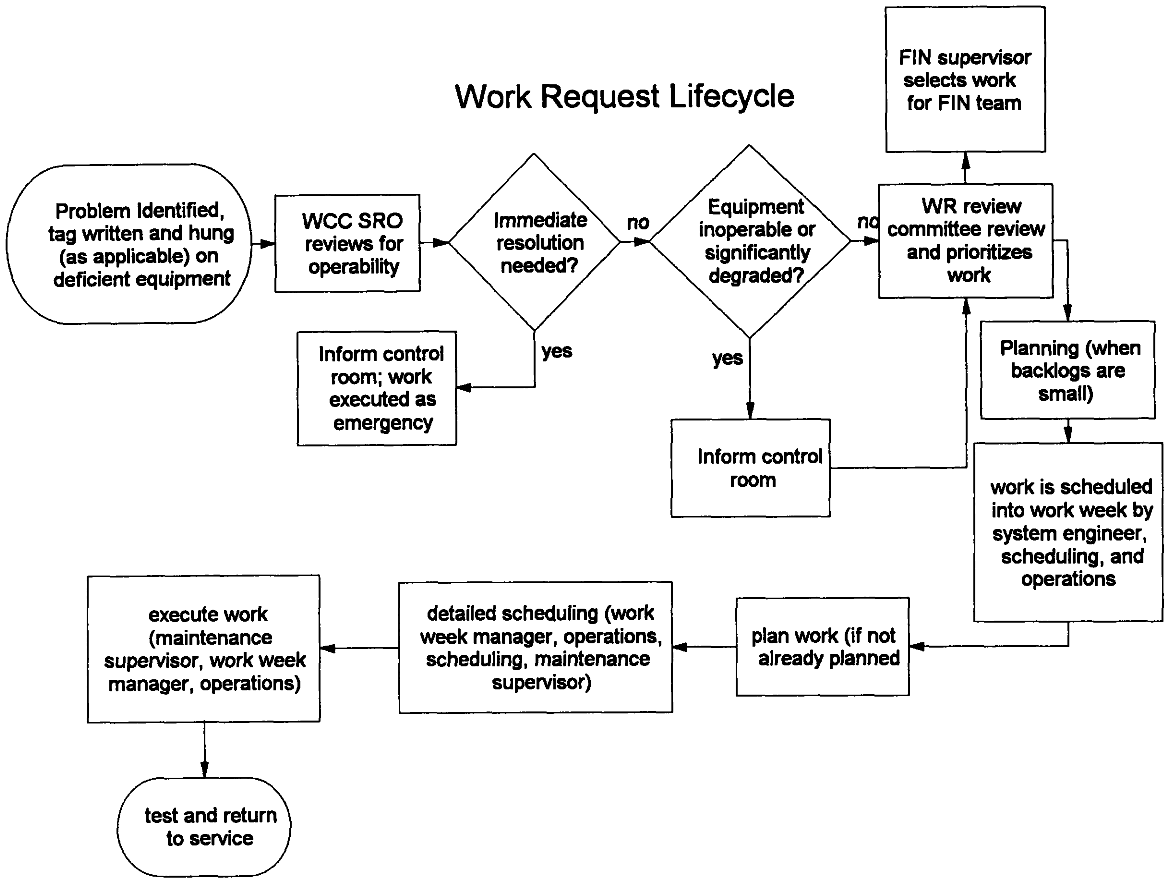

Figure 2 The lifecycle of a work request, showing major decision points and steps in the work process.

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up of a shift supervisor, engineering supervisor, scheduler and the fix-it-now team supervisor. Other strategies typically rely solely on the operator for prioritization.

The station assigns one of four priorities to newly identified equipment deficiencies during a brief morning prioritization meeting after the night shift. Each new work order is reviewed by the fix-it-now supervisor, system engineering supervisor and off-going shift supervisor. The scheduling supervisor is on hand for the meeting, but does not participate in the prioritization decision. Priorities are established by the system engineering supervisor and shift supervisor. Priorities include the following:

Priority 1 -- extremely important, accomplish as soon as possible

Priority 2 -- important, accomplish as soon as practicable

Priority 3 -- routine, accomplish during work window

Priority 4 -- routine, accomplish during outages

Work assigned priorities 1 and 2 can disrupt the work schedule, so whenever possible, the FIN team will accomplish work of this priority to keep the schedule intact.

Planning: Planning is accomplished in one of two sequences in the work request lifecycle. If planning backlogs are small, planning can be accomplished nearly as soon as the problem is discovered -- a desirable situation. If backlogs are high, planning is accomplished after scheduling, in which case the schedule of work dictates the order of work in which to plan. Other work management strategies tend to be dominated by larger work backlogs than OLM programs, and the planning is frequently not accomplished until shortly before the maintenance is scheduled to be performed.

Scheduling: The scheduling step is the strength of the OLM process and is quite different from other maintenance program scheduling strategies. The rolling schedule is the heart of the on-line maintenance program. The focal point of the rolling schedule is a repeatable 13 week (quarter) period established during OLM program development and that uses pre-established work windows set aside for every system in the plant. The rolling schedule should not to be confused with the daily schedule, which consists of the list of tasks to be accomplished.

The work windows in the 13-week schedule are based upon the surveillance program (license basis), preventive maintenance, and the probabilistic safety assessment, which provides the guidance for combinations of components that can be out-of-service. For example, the first week of every quarter may be designated for the Train A residual heat removal (RHR) system, so any preventive maintenance, surveillance tests, or corrective maintenance that needs to be accomplished on Train A RHR is scheduled for that work window. There are several systems permanently scheduled for each work window, none of which significantly alter station defense-in-depth even when accomplished together.

Execute work: Systems are aligned, tags are hung, work start is authorized, and work is accomplished. The work execution phase provides an important test of the effectiveness of the process. OLM work management systems use work week managers to coordinate the work during execution weeks, whereas most other maintenance strategies coordinate work on a maintenance discipline (e.g., mechanical or electrical group) level.

Closeout: There are few programmatic differences between OLM strategies and other maintenance strategy closeout steps.

2.3.4 The Process Timetable

Another important difference between OLM programs and other work management strategies is the timing of the different process steps. The OLM strategy uses a "countdown schedule," shown in Figure 3, to control when the activities that result in assignment of work to work windows take place. This is not an independent process -- it is the way the steps of the process are sequenced in time. The countdown schedule is as follows:

- Ten weeks prior to the workweek, the schedule is reviewed by operations, the cognizant system engineers, maintenance, and scheduling. If maintenance has insufficient resources projected for the workweek to accomplish the maintenance, operations and the system engineer will select which maintenance to defer to the next RHR work window. Scheduling then compiles the proposed schedule and issues it to planning to prepare work documents and order parts, if not already done. Depending upon the size and nature of the work backlog, the work package planning may have been accomplished shortly after the deficiency was identified.

- Six weeks prior to the workweek, the schedule is built based upon agreement of operations, the system engineer, and the work week manager. If planning is not complete for the jobs selected at the 10 week review, the work is considered for the next work window. Also, craft resources are frozen at this point, so resource loading of the schedule for maintenance personnel can be accomplished. Planned vacancies such as vacations or training must be scheduled prior to the six week point. The schedule is reviewed preliminarily by the probabilistic safety assessment engineer, who checks for configurations that may increase plant risk above a predetermined level. This review is of great importance to ensuring the plant configuration required for maintenance is safe.

- At three weeks, the work week manager freezes the schedule and starts coordinating the support activities for the maintenance. This involves assigning work to crew foremen, verifying support activities like scaffolding and fire watches, and sequencing the work so

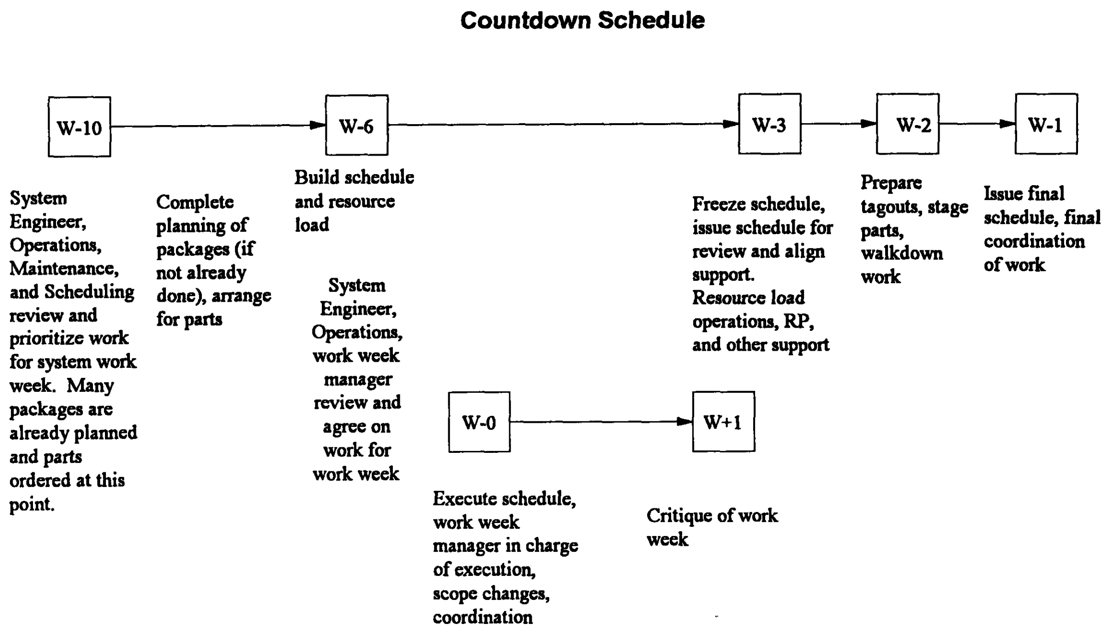

Figure 3 Schematic of countdown schedule. Each activity shown here is accomplished weekly for the future work week.

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that each job can be worked without interference from other jobs or activities. Support resources such as operations and radiological protection personnel are verified available.

- At two weeks, work packages are delivered to crews for review and walkdown, tagouts are prepared by the work control center and the parts are staged.

- One week prior to the work week, the final schedule is issued, final coordination of work is accomplished, and crew foremen certify to the work week manager that their crews can accomplish the schedule as planned.

- During the work week, any changes to the schedule are checked by the probabilistic safety assessment engineer to ensure the changes do not adversely affect plant risk.

- One week after the work week, the work week manager reviews the results of the work week and identifies areas for improvement.

2.3.5 Long-range Plan

A long-range station plan that is based on the company's business plan is maintained. This plan establishes the outage calendar, capacity factor goals, large maintenance projects such as steam generator or turbine replacement, and budgeting targets. The plan covers a five-year period, and is updated annually. Outage durations and the annual budget are based upon this plan.

The significance of the long-range plan to the OLM program is in the up-front establishment of capacity factor, outage durations, and operations and maintenance (O&M) costs. The plan is the utility's means of managing these quantities, which are key to the economic viability of the station. The long-range plan predicts the amount of work that will be accomplished in the future so that appropriate resources can be allocated. This not only involves acquiring parts, but also hiring and training (or releasing) workers. Without the long-range plan, resource allocation is a guess. The long-range plan is the plant's blueprint for success.

2.3.6 Materiel Condition Improvement

Good materiel condition is important to the efficient operation of an on-line maintenance program. The OLM strategy is based on the assumption that most of the work backlog can be accomplished in one calendar quarter, which means that non-outage work is usually less than 90 days old.[18] High work backlogs are undesirable because they tend to mask other deficiencies, and the latent problems appear later, often during maintenance. Although it is good to identify and correct emergent deficiencies during maintenance, when this practice must be exercised frequently, work schedules are severely disrupted and less work gets accomplished than planned, and materiel condition continues to suffer. When materiel condition is poor, a continuous cycle of new deficiencies seems to exist, the work backlog remains high, and emergent work takes its toll on good schedule discipline.

In order to break this cycle and allow the OLM program to function as designed, the work backlog can be reduced during an intensive, focused campaign. Such efforts have been accomplished by many plants with successful OLM programs and, although the effort is usually expensive, the conditions they establish are important to the OLM strategy. One outage coordinator from a station that cut its outage time from 87 days to 22 days in just three years listed two keys to their recent success as being the excellent materiel condition and the aggressive on-line maintenance program.[19] This station adopted a significant materiel condition improvement program two years earlier. At least three other stations making similar dramatic improvements have adopted materiel condition improvement programs.

2.3.7 Plant Culture

Finally, a strong work culture at the station is important, even vital, to success of the OLM strategy. Management styles and the accompanying cultures that are created can mean the difference between strong and weak programs. The following are brief descriptions of cultural characteristics that are important to good operations in any

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[18] If new work is identified after the freeze date for the next work window, the work is deferred into the next open window. This means that a work item could be more than 13 weeks old, even with low work backlogs and good work turnaround.

[19] Michal, R., *Reducing Outage Durations at South Texas Project*, Nuclear News, November 1996, p. 29

organization. It will be seen in Chapter 4 that these, when coupled with a strong OLM work management program, establish conditions that promote good human performance.

- Accountability: Organizations and individuals take meeting commitments seriously.

- Teamwork: An attitude exists that everyone has a stake in problems that arise.

- Resources: The right amount of human and material resources is provided for the task.

- Measuring performance: Performance measures are used to identify shortcomings and trends are followed.

Chapter 3

Quantifiable Effects of On-line Maintenance Strategies on Plant Performance

This chapter explores the quantifiable effects of on-line maintenance on plant performance. The performance indicators of interest are costs, outage duration, capacity factor, equipment availability, and number of significant events. An examination of statistics does not necessarily tell a complete story or provide balance. Factors other than maintenance strategies are also at work in the changes apparent in plant performance -- these factors will be mentioned but not discussed. As will be clear from the indicators discussed in this chapter, overall improvement in plant performance *has* been achieved.

3.1 Economics

This section discusses the industry's economic performance and briefly addresses the reasons behind the trends. The cost of nuclear generation is higher than coal generation, but seems to be moderating to within a few mills per kilowatt-hour of coal. With competition among other generation forms looming, nuclear power plants are being pressed to reduce the cost of generation even more.

3.1.1 Elements of Cost

The expectation from the early days of nuclear power that electricity from the power source would be too cheap to meter has not been fulfilled, nor is it likely to be. Since the Three Mile Island accident, foes of nuclear power have not had to look much beyond a nuclear utility's balance sheet in criticism of nuclear power. Indeed, nuclear power has become more expensive over the years, instead of cheaper. Although the fuel costs of nuclear power are much less than the costs of other forms of energy, the capital and operating and maintenance costs overcome that advantage. The cost of electricity can be thought of simply as the amount of money spent in producing power divided by the amount of electricity produced.

Generation costs consist of capital costs, fuel costs, and operations and maintenance costs. Of the three, operations and maintenance costs is the area that can be influenced most significantly by plant managers.[20] Changes in operations and maintenance cost trends influence overall generation costs more than other factors. There are many reasons for high costs of electrical energy from nuclear power. Three dominate:

- High capital costs spawned by the high interest rates and inflation of the 70's and retrofit requirements following the Three Mile Island accident. New requirements and the construction delays that resulted gave rise to huge overnight and time-related costs.[21] These are shown in Figure 4.

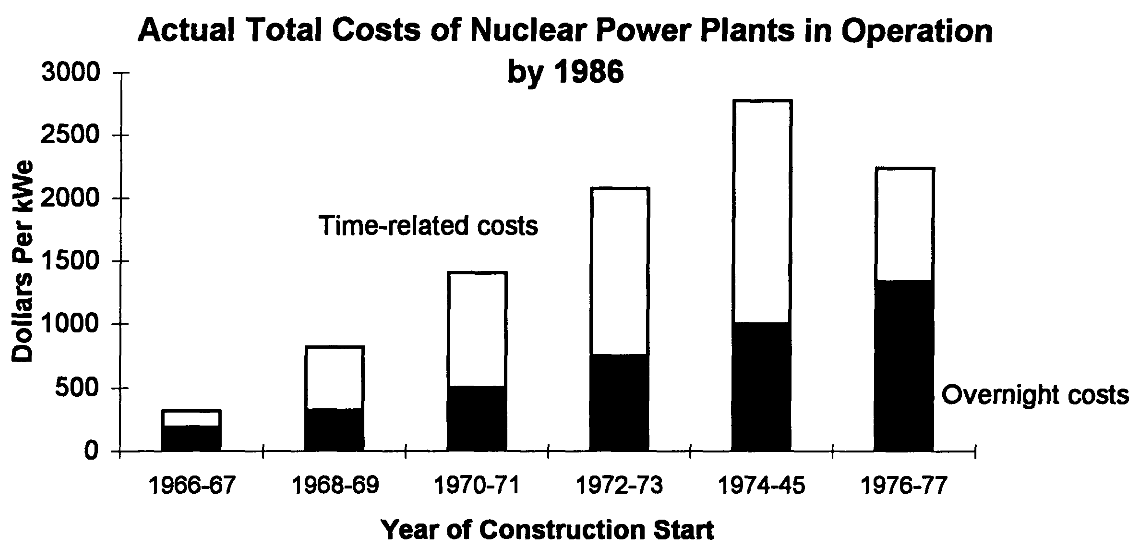

Figure 4 Data from Energy Information Administration

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[20] Byus, L., *Early retirement of nuclear capacity as a competitive strategy,* Nuclear News, April 1994, p.31

[21] Overnight costs are the immediate costs of construction, including labor and materials, with no effect of inflation or financing. These costs represent how much it would cost if a plant could be constructed "overnight." Time-related costs reflect the effects of inflation and financing on a project. The combination of the two costs are the total cost of the plant.

- High operating and maintenance (O&M) costs as a result of expanding staffs and requirements during the 80's, largely as a result of Three Mile Island program upgrades: E. Fuller, former president of the American Nuclear Society, stated in 1993 that "[d]irect labor constitutes 55 percent of the power production costs of nuclear, compared to only 17 percent for coal."[22]

- Long refueling and forced outages durations that lower the capacity factor and, therefore, the amount of energy generated: Outages at nuclear power plants are long and expensive because of the complexity and safety significance of the work being performed. Forced outages frequently result in the plant being fully shutdown for several days to ensure the cause of the shutdown is thoroughly investigated and addressed.

3.1.2 Competition

Until recently, utilities were regulated monopolies with no real source of competition. But in March 1995, the Federal Energy Regulatory Commission (FERC) proposed opening access to the country's interstate transmission network.[23] This was a significant albeit an anticipated step among a series of legislative and statutory initiatives moving the power industry toward wholesale competition.

The road toward competition among power providers began in 1978 when the Public Utilities Regulatory Policy Act (PURPA) was enacted, which required utilities to provide transmission line access to non-utility electricity providers. In 1992, the Energy Policy Act required utilities to make transmission lines accessible to all users. With these acts and statutes, the financial protection provided utilities from being a regulated monopoly was all but eliminated, and the reality of impending competition loomed large.

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[22] Taylor, G., *ROD meeting: Striving for excellence,* Nuclear News, October 1993, p. 31
[23] Zeyher, A., *Competition: Coming soon to a utility near you,* Nuclear News, July 1995, p. 18

States are now considering legislative initiatives that provide for open access competition among power providers.

The process of how the change to utility competition will be implemented is of great concern to utility executives. In a 1995 survey of 285 senior executives of electric utility companies, the top issues facing the utility industry were noted as being competition, retail access and sales, open wholesale transmission access, and improving revenue and earnings. The biggest target for cutting costs was nuclear operations.[24]

In the 1980's, nuclear power operations and maintenance costs (excluding fuel) nearly doubled. In 1981, the annual operations and maintenance cost per installed kilowatt was $43, compared with $83 in 1991.[25] In 1993, Fuller noted that, in the early days of nuclear power, there was a "substantial edge [over coal, gas, and oil] in production costs. That edge deteriorated through 1991 so that now coal production costs 'have become competitive' with those of nuclear."[26]

Actually, coal costs are now slightly *less* than nuclear generation costs. In 1995, the average cost of coal-generated electricity was 1.88 cents per kilowatt-hour; nuclear costs were 1.92 cents per kilowatt-hour.[27] The current costs and production cost trends of these and other generators are shown in Figures 5 and 6. A. Bianchetti writes, "The entry into the market of efficient, small-scale, non-utility generators has established market prices for power, and utilities -- nuclear and otherwise -- face a new era in which efficient operations will be critical for survival."[28]

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[24] *Survey: Utility execs see grim nuclear outlook,* Nuclear News, March 1994, p. 29
[25] Taylor, G., *Rod meeting*
[26] Ibid.
[27] Figenbaum, T., *Can Nuclear Power Survive in a Competitive Environment?* Lecture given at Massachusetts Institute of Technology, Cambridge, Massachusetts, January 1997
[28] Bianchetti, A., *Strategic Management,* Nuclear News, July 1994, p.77

3.1.3 Trends and Causes

Operations and maintenance costs started to level in the early 1990's, evidence of the increased attention utilities were placing on controlling costs. This, along with improving capacity factors, had an important positive effect on the cost of generation. J. Colvin, president of the Nuclear Energy Institute, recently wrote, "Average nuclear production costs are declining and have been for nearly 10 years. Back in 1987, they hit a high of nearly 3 cents per kilowatt-hour, on average. They're now down to less than 2 cents, in 1995 dollars. That's a 34 percent reduction in production costs in less than a decade."[29]

Many utilities have taken or are taking control of costs by "reengineering" work processes and the way outages are conducted to optimize efficiency. In fact, it is primarily through process reengineering that the current maintenance strategies have been born.

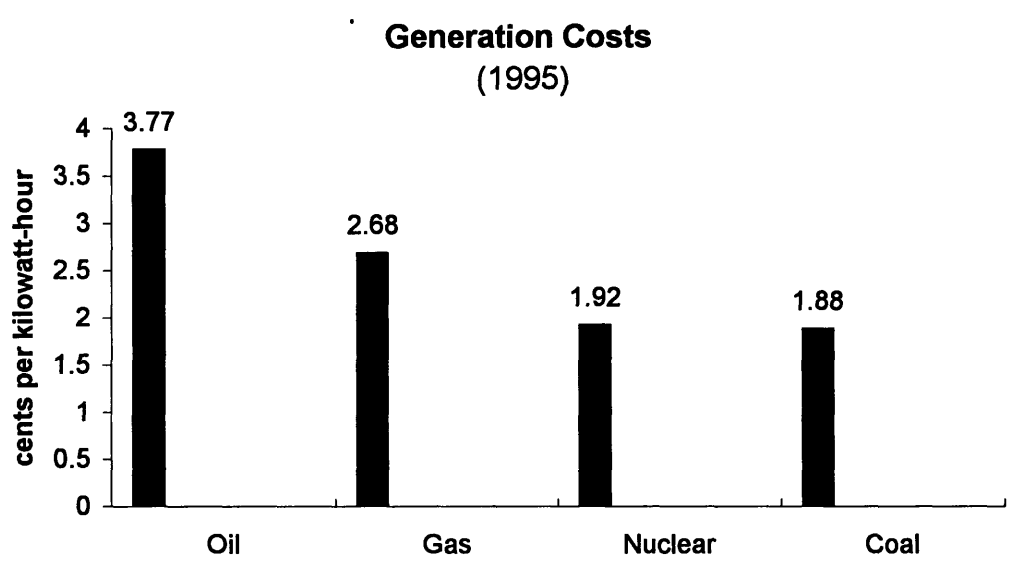

Figure 5 Cost of generating a kilowatt-hour of electricity for various producers. Data from Utility Data Institute.

[29] Colvin, J., *Nuclear power in a competitive environment: Myths and facts,* Nuclear News, March 1997, p. 33

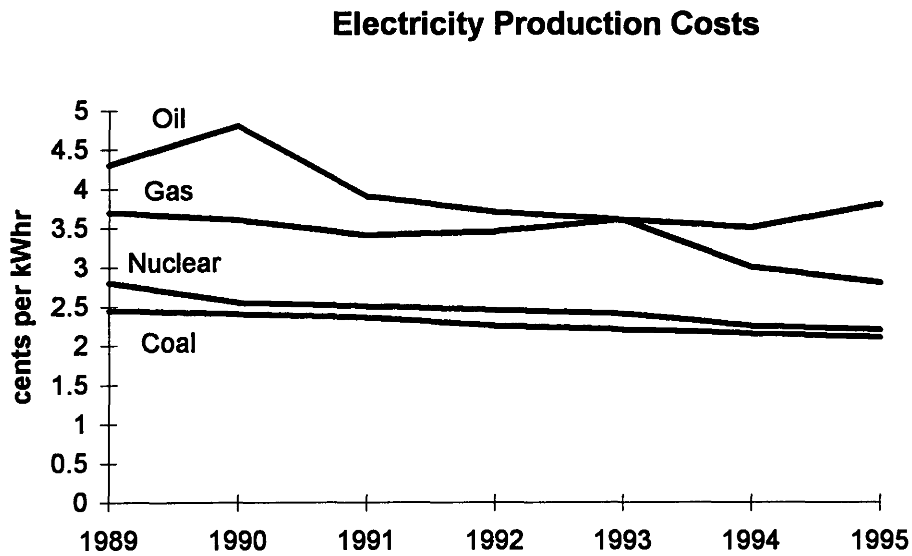

Figure 6 Electricity production costs among various generation types, 1995 dollars. Data from Nuclear Energy Institute, April 1997.

Most of these initiatives were taking place in the early 90s, although some work process improvement programs are still in early stages of implementation.

PECO Energy is one utility that took a calculated approach to manage costs. A strategy to reduce refueling outage length at the two PECO Energy stations, Limerick and Peach Bottom was initiated in 1989. As a result of the innovations, "savings in operating and maintenance costs totaled more than $15 million."[30] The utility essentially reengineered its entire approach to maintenance in its "Refueling Outage Length Reduction Strategy, in which the entire organization was challenged with reevaluating the ways of doing business."[31] PECO Energy's methods will be discussed further in Section 3.6.3.

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[30] *Nuclear News,* July 1995, p. 46
[31] Michal, R., *Innovations of the nuclear industry: Four Stories,* Nuclear News, September 1996, p. 23

One additional situation should be mentioned for completeness -- the role of a favorable regulatory climate. In the 1980's, voluntary entry into a limiting condition for operation (LCO) action statement to conduct maintenance was avoided by most utilities and disliked by the NRC and INPO alike. Gradually, the successes from aggressive change strategies used by some utilities (like PECO Energy) and others that had always conducted LCO maintenance (another name for on-line maintenance) led to more and more utilities adopting the strategy. Guidelines provided by INPO and the measurable improvements in materiel condition that came as a result of on-line maintenance seemed to satisfy the NRC. Also, implementation of the Maintenance Rule provides greater assurance to the NRC that on-line maintenance is not being abused. Without the acceptance of on-line maintenance by the regulator, the improvements in economic performance apparent today may very well not have occurred.

In summary, the timing of the industry's improving costs is tied to a number of conditions working together. The following certainly played a role:

- Impending competition with other producers driving changes in business practices

- Completion of most expensive and time-consuming regulatory mandates such as Three Mile Island modifications and motor-operated valve testing

- Breakthroughs in work management techniques for outages and on-line periods as part of reengineering efforts

- A regulatory climate more supportive of utility innovation

It is against this backdrop of economic incentive and other conditions that we look at the other measurable factors of nuclear plant performance. Some of these factors, such as outage duration and capacity factor, also have a direct effect on economic performance.

3.2 Outage Duration

Outage duration is the measure of time a unit is shutdown for maintenance or refueling, and is affected directly by the amount of work to accomplish. Shortening outage duration is a key strategy for improving capacity factor. A. Chapple writes, "Shorter downtime for refueling outages is one major reason nuclear-generated electricity is becoming more economical every year. The savings [from shorter outages] are significant, since every day a plant is off line costs a utility about $300,000 -- not including the cost of buying replacement power for its customers. That can amount to another $300,000 a day."[32] All in all, outages are huge expenses to the utility, and making them as efficient and short as practicable is economically important.

3.2.1 Outage Description

Refueling outages consist of thousands of individual tasks, including plant modifications, preventive and corrective maintenance, refueling, and testing. Many additional people are typically used to augment the plant staff in an effort to complete the outage quickly. Well-run outages are planned many months in advance to ensure tasks are sequenced properly, people, parts, and tools are available, and reactor safety is maintained.

Outage activities must be carefully scheduled to ensure reactor safety and defense in depth is maintained. Outage activities are organized around five conditions: containment, shutdown cooling, electrical power, reactivity, and reactor vessel water inventory. For example, a task that requires moving large equipment through the reactor building equipment hatch cannot be accomplished while fuel is being moved in the vessel,

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[32] Chapple, A., *Downtime is Shorter,* Nuclear Energy, Third Quarter 1995, p. 15

since containment integrity must be intact during fuel movement, which means the equipment hatch must be closed.

Requirements, such as the ones listed above, greatly complicate scheduling outage activities, but are necessary for reactor safety. In order to optimize efficiency, many tasks must be scheduled in parallel. The longest of the parallel paths is called the "critical path." If the critical path can be shortened, then the outage can be shortened. Losing time along the critical path results in lengthening the outage.

Outage planning centers around pre-outage milestones that include, as a minimum, modification scope freeze, modification design freeze, work scope freeze, and planning freeze dates. Plants that conduct the best outages adhere rigidly to their milestones. Another important aspect of outage planning involves the high degree of participation of work groups in planning and scheduling their own portions of the outage.

In the 1970s and 80s, outages were used to conduct much more maintenance than is currently accomplished. Outage schedules would typically include large blocks of time for "bulk work"-- work that was not accomplished according to an outage schedule. New work, both maintenance and modifications, was often added to the outage work scope with little effective concern for outage duration, and often, the critical path of the outage was not clearly identified or even correctly identified. Work groups were seldom involved in planning or scheduling their pieces of the outage. The result of these habits was an outage with a huge number of activities that were inadequately scheduled, so outages sometimes lasted months.

3.2.2 Trends and Causes

Fortunately, the tide in outage duration began to turn in the early 1990's, as utilities focused increasingly on reducing the cost of generation. Figure 7 illustrates this dramatically. Breakthroughs have been achieved in outage staff organizations, work management, and scheduling techniques, and these breakthroughs are clearly paying off for the utilities that incorporate them in their maintenance strategies. The following are some of the key areas focused upon by stations achieving great reductions in outage duration:

- Commitment to outage planning: Early planning conducted by teams with few additional responsibilities, plus strict adherence to achieving pre-outage deadlines and enforcement of outage scope freeze dates. The discipline necessary to accomplish this typically required a top-level down emphasis on teamwork and accountability. It often was achieved only after a significant restructuring of the plant organization and change of senior managers.

- Optimizing the outage schedule: Schedules are developed by the work groups accomplishing the work, using best job duration historical data (instead of average or longest duration data) that challenges work crews. Schedules are strictly followed, and prompt attention and support is brought to bear on any situation that jeopardizes the schedule.

- Control of outage scope: The number of plant modifications are reduced drastically, and high levels of approval are required to add work after the scope-freeze date has passed. The allowable scope of the outage is tied directly to the long-range plan (which, in turn, is tied to the business plan). In addition, good plant materiel condition is important to controlling outage scope. If new problems surface during maintenance because of latent

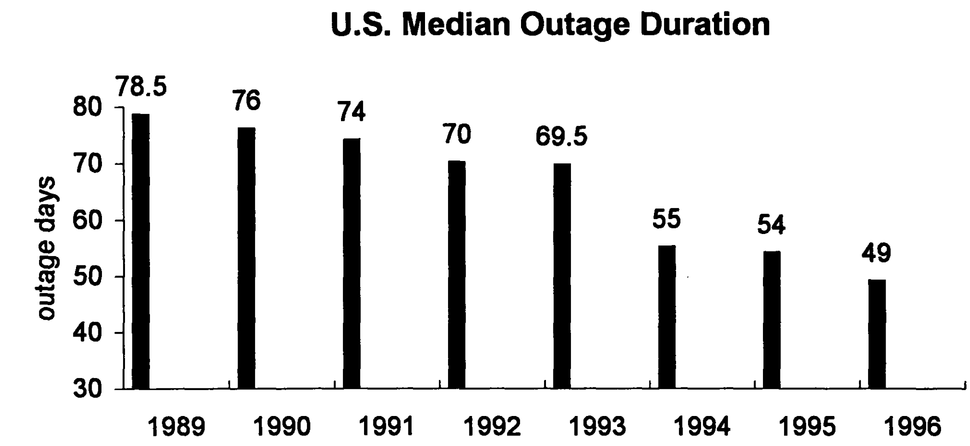

Figure 7 Outage duration data from Institute of Nuclear Power Operations

equipment deficiencies, outage scope grows, schedules are disrupted, and the outage is extended.

- Attention to detail: A dedicated outage manager and staff with no other collateral duties is assigned. A central location for the staff is used as a focal point for coordinating the outage work.

- Learning from outage-to-outage: Capturing and applying lessons learned are easy. One station improved its outage performance from an average of 87 days to 22 days and received nearly 10 times the number of suggestions during the short outages as during the long outages -- because innovations in reporting suggestions made it easier.[33]

- Teamwork/Accountability: Goals and group and individual roles are clearly defined, and personnel feel accountable for meeting commitments. Opportunities to encourage and reward teamwork are actively sought and

[33]Interview with R. Graham, Outage Supervisor, South Texas Project, January 1996.

rewarded. For example, South Texas Project uses a "we team" concept that discourages finger-pointing or fault-finding under any circumstances. Individuals who slip and say "they" are good naturedly reminded that "they" do not exist at the station.[34]

It can be seen from this list that strong organizational culture features, such as those defined in Chapter 2, are part of strong outage performance. These features will be discussed further in Chapter 4.

3.3 Capacity Factor

Capacity factor is simply the amount of energy actually generated during a given time period divided by the energy that could have been generated over the same period of time. The denominator value makes no allowance for outages, so capacity factor is heavily influenced by planned outage duration. In addition, forced outages also figure prominently in capacity factor measurements. Forced outages will be discussed in Section 3.4.3.

Capacity factor is one of the best overall indicators of plant performance. Plants that have low expenses but do not generate much electricity do not help a utility's profitability. Capacity factors can indeed mean the difference between operating or decommissioning a plant. Nine Mile Point Unit 1 is a case in point. In 1992, Niagara Mohawk Power Corporation committed to operate the plant through its current fuel cycle

[34] The "we team" concept in action was personally observed during the January 1996 outage at South Texas Project. Although the concept may seem like a gimmick, the cohesiveness of the staff at all levels lends great credibility to its effectiveness.

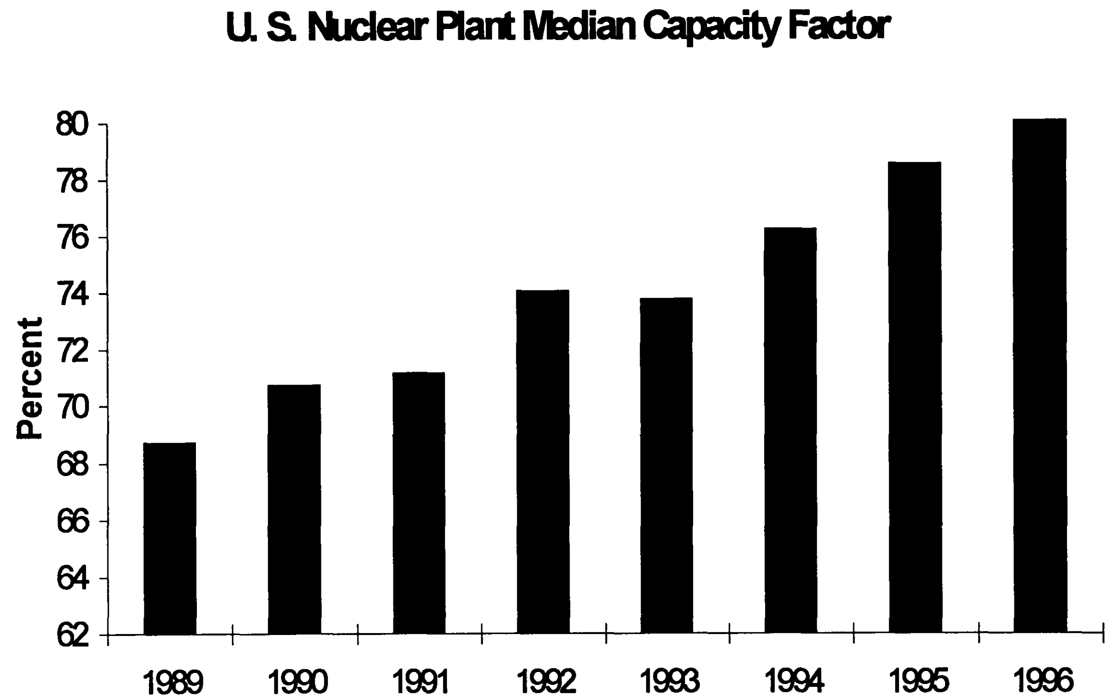

Figure 8 Median U.S. nuclear plant capacity factor from industry data collected by INPO. Median values are displayed to eliminate the data-skewing effect of plants in long-term regulatory shutdown.

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only, then evaluate its continued economic viability.[35] Two years later, in December 1994, it was clear that the 87 percent capacity factor and strong performance over the preceding two years made the plant economically viable, and the commitment to continue operation of the plant was renewed.[36] Although a plant that is poorly maintained may achieve a good capacity factor over a limited period, sustained good capacity performance under those conditions is unlikely.

Industry capacity factors have improved significantly since 1980. In 1980, the average capacity factor was around 58 percent.[37] Compare the 1980 figure to that of the

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[35] *NiMo backs Unit 2 until 1995, maybe not later,* Nuclear News, January 1993, p. 26
[36] *NiMo study shows plant can compete*, Nuclear News, December 1994, p. 22
[37] Figenbaum, *Can Nuclear Power Survive?*

76 percent average in 1996.[38] Figure 8 shows the trend of recent improvements in median capacity factor. Of the 25 plants that had capacity factors less than 60 percent in 1989, only one had a capacity factor of less than 60 percent in 1996 -- the rest had improved significantly. In fact, 11 of these plants had capacity factors of greater than 80 percent, and five of these capacity factors were higher than 85 percent. Figure 9 shows movement of plants in the lower capacity categories to higher categories. Of the 11 plants operating in 1989 with 1996 capacity factors of less than 60 percent, most (seven) also had low 1989 capacity factors (less than 70 percent), although two had 1989 capacity factors greater than 75 percent.

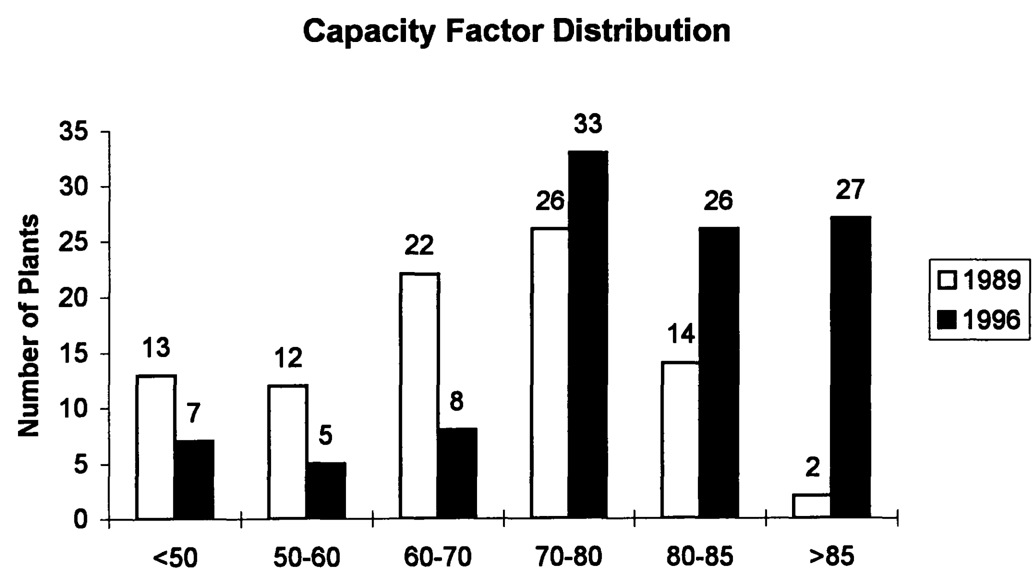

Figure 9 A comparison of the distribution of capacity factors among plants from 1989 and 1996 data. Data from INPO

[38] Use of average capacity factors as indicators of overall industry performance is generally avoided because of the skewing of data caused by plants in extended shutdowns. Average capacity factor is used here for comparison with Mr. Figenbaum's value. Median capacity factor for 1996 is 80 percent.

3.4 Reliability and Availability

Plant and equipment reliability and availability are practical indicators of the effectiveness of a maintenance strategy. This section discusses trends in equipment reliability, equipment availability, and forced outage rate. These indicators appear to be directly affected by quality of maintenance and the plant's maintenance strategy in general. For example, it seems inherently obvious that a well-maintained piece of equipment is more reliable than one poorly maintained. Actually, the indicators must be used carefully for reasons that will be discussed in the following sections.

3.4.1 Reliability

System reliability is the probability that a system operates successfully over a time interval from 0 to t.[39] System reliability depends upon the reliability of the system component parts. Successful system operation over the interval will occur if the minimum number of components needed for operation function reliably. Unreliability is also frequently used as an indicator. Unreliability is simply the complement of reliability -- mathematically it is (1 - *R(t)*), where *R(t)* is the reliability over the time interval from 0 to *t*.)

Reliability can be improved by preventive maintenance. According to R. Ramakumar, preventive maintenance "prolongs the life of components, decreases the number of failures, and increases the [mean time to failure] of the system.[40]
This is important for equipment that *must* be reliable, such as emergency diesels or safety injection pumps. The need for preventive maintenance diminishes significantly for less important equipment, such as a sump pump or chemical proportioning pump, which may run to failure with no real consequence to reactor safety.

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[39] Kumamoto, H., and Henley, E., Probabilistic Risk Assessment and Management for Engineers and Scientists, IEEE Press, New York, NY, 1996, p. 256

[40] Ramakumar, R., Engineering Reliability: Fundamentals and Applications, Prentice Hall, Englewood Cliffs, New Jersey, 1993 p. 129

Clearly, a determination must be made as to the importance of the reliability of any given piece of equipment, and whether preventive maintenance should be used to improve reliability. Two approaches are used to help in these determinations. First, reliability-centered maintenance programs are used by some stations to optimize their preventive maintenance programs. Reliability-centered maintenance considers the actual failure rates experienced by equipment, calculates mean times to failure, and adjusts preventive maintenance tasks and intervals to reflect experience. Some plants also use their PSA to identify the importance of equipment. Then, using the operating experience data from the reliability-centered maintenance studies and with the understanding of the equipment importance, an optimal maintenance strategy can be designed.

Understandably, some systems and components are more important than others in that the consequence of their failure on system reliability is greater than the failures of other systems. System reliability is strongly dependent upon the design of the system. Nuclear power plant design uses "defense-in-depth" to reduce the effect of a single component failure resulting in a system failure. Defense-in-depth incorporates component redundancy and diversity to improve system reliability. Because of this, multiple failures must occur (in most cases) to result in system failure.

The importance of a system or component can be determined analytically using any of or a combination of three methods. First, importance can be determined from the PSA by determining the effect on core damage frequency (or other end-states) of that system *not* being available. This measure is called "Risk Achievement Worth." Similarly, "Risk Reduction Worth" examines the effect on core damage frequency if there is *no* failure rate associated with the system. Finally, the Fussell-Vesely Importance measures the fraction of core damage frequency attributable to a component's failure.[41]

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[41] Chapman, J. and Burns, K., ***Importance Use: Why change analysis is more appropriate***, PSA '95: International Conference on Probabilistic Safety Assessment Methodology and Applications, Seoul, Korea, November 26-30, 1995, p. 177

An example of the effect of the on-line maintenance work management strategy on system reliability can be seen from a recent study of Combustion Engineering plant diesel generators. Diesel unreliability changed "from about 0.020 in the early 1980's to 0.014 in the 1988 to 1991 time frame."[42] The study noted that during the time of this improving reliability, on-line maintenance of the emergency diesels increased. It stated, "while a precise relationship between the [preventive maintenance] process and [emergency diesel generator] reliability has not been established, there appears to be a positive correlation between increased [preventive maintenance] performed in recent years and the enhanced [emergency diesel generator] reliability which has been observed."[43] Diesels were chosen for illustration here because they are one of four key availability performance indicators monitored by WANO.

3.4.2 Availability

The definition of availability, according to Kumamoto and Henley, is the probability of a system operating successfully at time t.[44] The complement to availability -- unavailability -- finds frequent application in equipment performance monitoring.

Availability is influenced by the condition or state of the equipment. Whenever a component is out-of-service, availability decreases. The interesting effect of this is that both too little maintenance (resulting in frequent equipment breakage) and too much maintenance (resulting in excessive out-of-service time) can cause low unavailability. Accordingly, availability should be monitored and managed. The Maintenance Rule requires nuclear utilities to set goals for their equipment, and monitor achievement of the goals to demonstrate the ability of the system to fulfill its safety function. Monitoring system availability is a means of accomplishing this.

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[42] *Joint Applications Report for Emergency Diesel Generators AOT Extension, CE NPSD-996,* ABB Combustion Engineering Nuclear Operations, May 1995, p. 8
[43] Ibid., p. 32
[44] Kumamoto, H., and Henley, E., Probabilistic Risk Assessment: Reliability Engineering, Design and Analysis, IEEE Press, New York, NY, 1992, p. 288

The diesel generator study noted in section 3.4.1 showed that diesel unavailability rose from .007 to .02 as reliability improved from the increased on-line maintenance.[45] This illustrates the tradeoff that sometimes exists between availability and reliability. On the other hand, PECO Energy used a probabilistic safety assessment to establish that the risks associated with Limerick's on-line maintenance strategy were reduced by over 20 percent at both units over a three-year period.[46]

Availability is managed by controlling two aspects of scheduled maintenance -- the frequency and duration of the out-of-service times. The frequency of maintenance is typically no more than quarterly to keep within the 13-week rolling maintenance window program. Duration of maintenance is more difficult to control -- a sense of urgency is needed to move quickly through the repair and return the system to service with no unnecessary delays if availability is to be optimized. This requires teamwork among all involved and a clear understanding that work must progress.

3.4.3 Forced Outage Rate

Forced outage rate over a selected interval is the ratio of unscheduled plant down time to total possible on-line time.[47] INPO reports this indicator as "unplanned capability loss factor," shown in Figure 10. Outage duration and forced outage rate make up the key elements of capacity factor. Unplanned scrams are a leading cause of forced outages. Figure 11 shows industry improvement in the median number of scrams per unit.

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[45] *Joint Applications Report,* p. 8

[46] Based on figures provided by PECO Energy during a presentation to the Joint ACRS IPE/PRA Subcommittee Meeting on Risk-based and Performance-based Regulation, October 26, 1995.

[47] "Forced Outage Rate" is not a "rate" at all , but a ratio. The term is widely used in the industry, however, with the definition as provided.

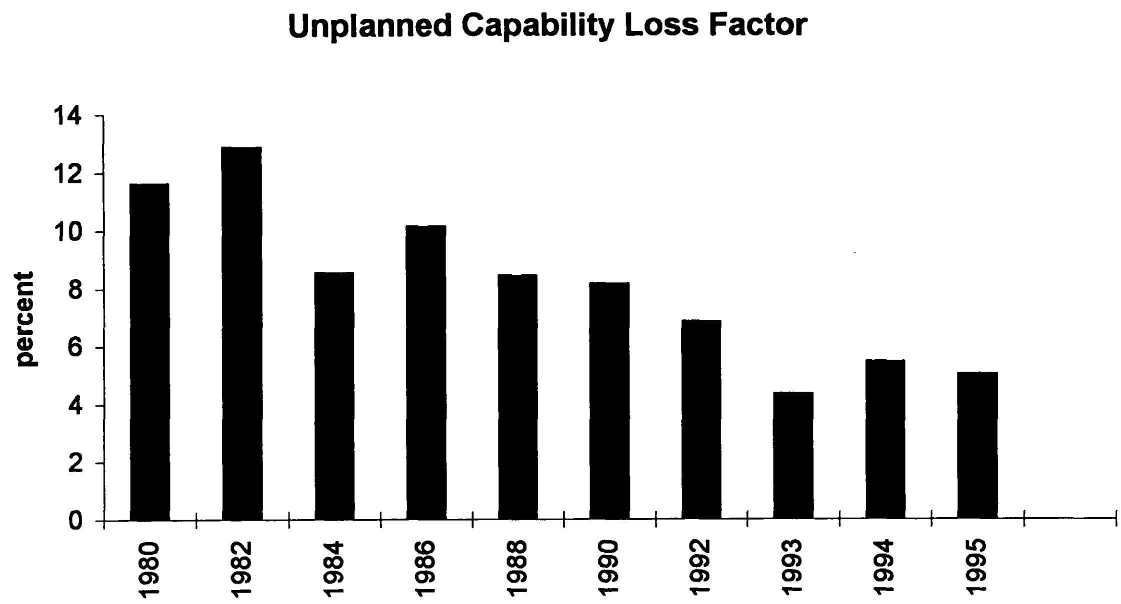

Figure 10 Median values of unplanned capability loss factor. Data from *WANO Performance Indicators for the U.S. Nuclear Utility Industry*, INPO, September 1996.

Forced outage rate is affected by several key factors, many of which can be managed as part of the maintenance strategy. These factors are listed below:

- Maintenance quality: Well-conducted maintenance that solves deficiencies and *introduces no new deficiencies* has a beneficial effect on forced outage rate.

- Human performance: Error-free operation (regardless of the root cause) has a beneficial effect on forced outage rate.

- Materiel condition: Good materiel condition reduces the number of equipment-induced transients. Good materiel condition also provides margin for the plant during transients and flexibility for the operators to respond.

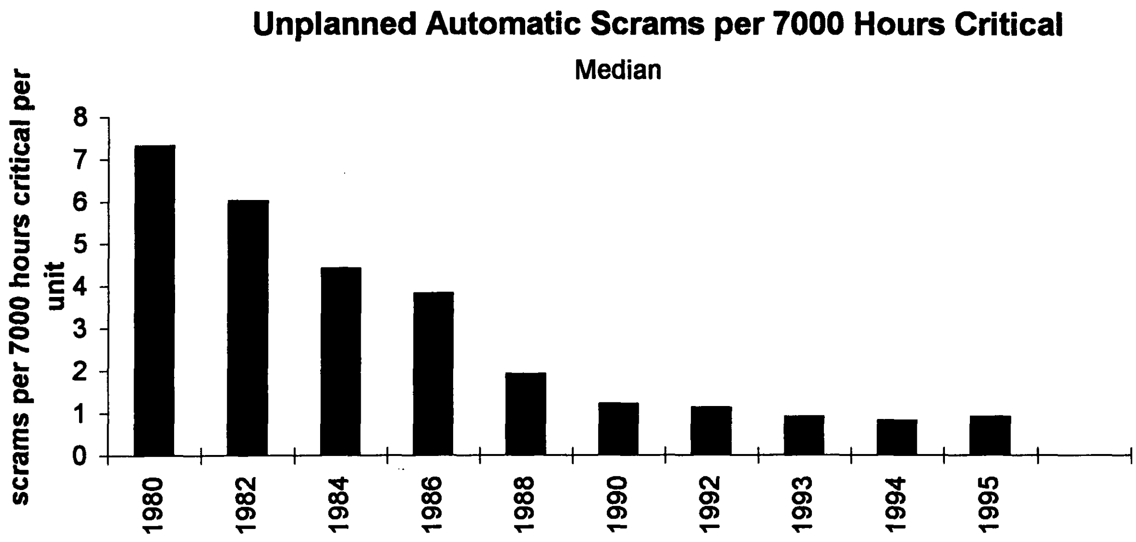

Figure 11 Median values of automatic scrams per 7000 critical hours -- data from *WANO Performance Indicators for the U.S. Nuclear Utility Industry*, INPO, September 1996.

3.4.4 Trends and Causes

The five WANO safety system performance indicators are suitable for demonstrating availability trends at nuclear power plants. The indicators displayed in Figures 12 and 13 show the percentage of plants that have achieved the industry goal for unavailability for the safety system of interest. Although these indicators are not direct measures of reliability, they clearly show that reliability of important safety systems is improving in the nuclear industry.

Trends in safety system performance are improving overall, and the correlation with the amount of on-line maintenance performed, although not specifically measured, is likely to be strong.

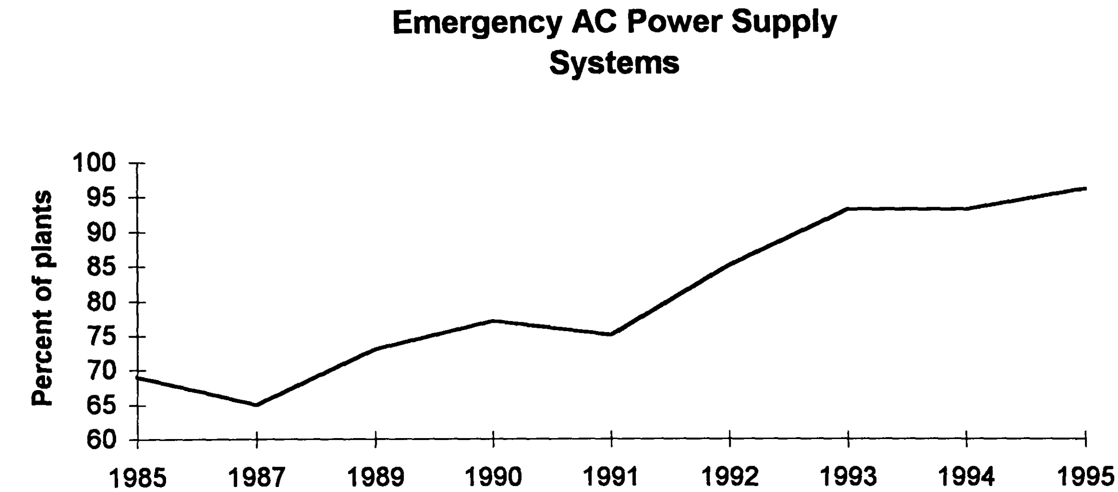

Figure 12 Number of plants exceeding the WANO year 2000 goal for emergency AC power unavailability of 0.025. Data from WANO Performance Indicators for the U.S. Nuclear Utility Industry, September 1996.

3.5 Significant Events

An important indicator of the safety performance of the nuclear industry is the number of significant events that occur per plant. Significant events are unexpected or unanticipated effects of plant operations that threaten or have the potential of threatening public or plant safety. Significant events can include losses of safety functions, significant damage to important equipment, operating under unanalyzed or unsafe conditions, and exceeding Federal limits for ionizing radiation dose. The number of significant events per nuclear plant has decreased dramatically since 1985, as shown in Figure 14.

The improvement in the number of significant events in recent years is influenced by many factors, some of which can be associated with the OLM work management strategy. These include equipment-related effects (good materiel condition, availability, and reliability), and human performance effects. It should be clear that if equipment

Percent of Plants Achieving Industry Year 2000 Availability Goals

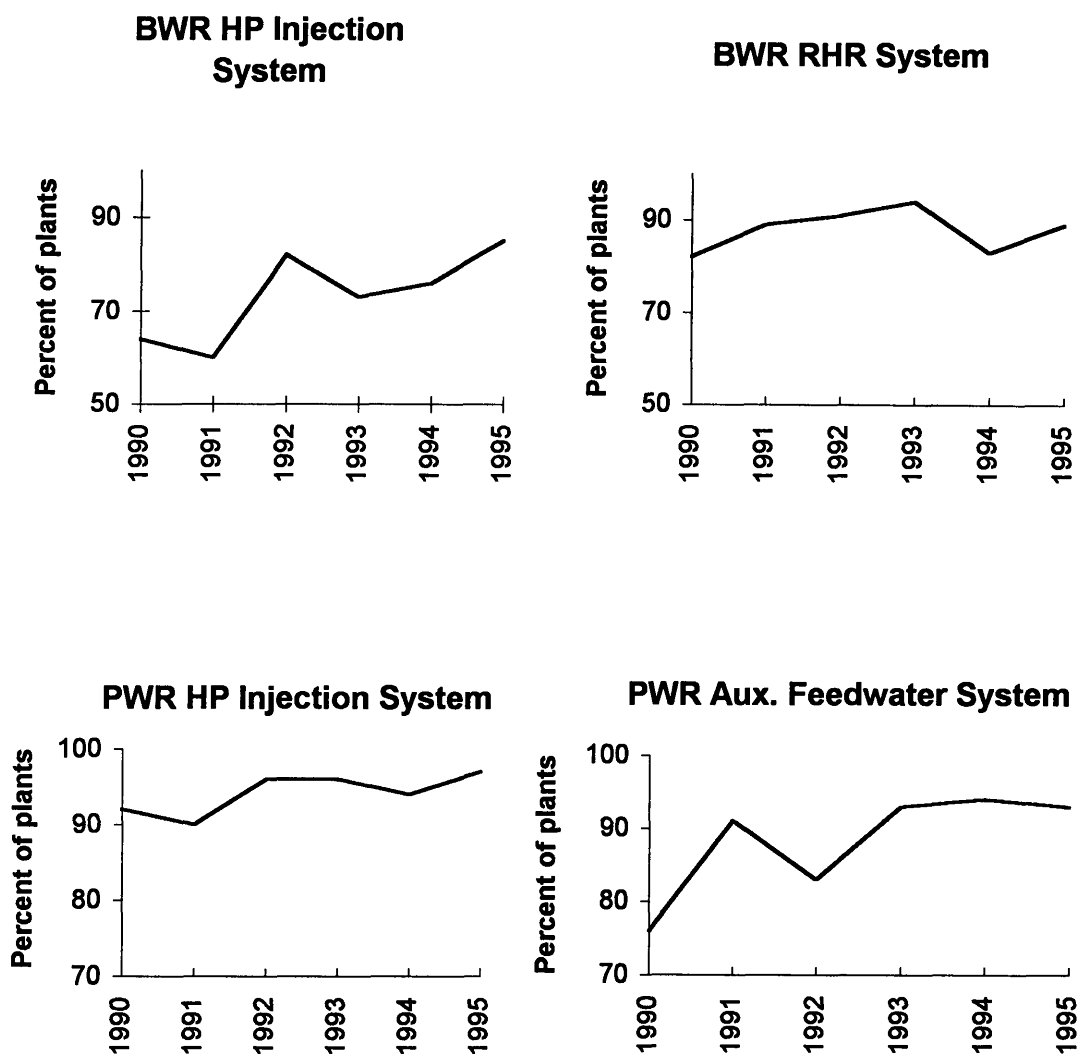

Figure 13 Percentage of plants that have achieved the WANO Year 2000 goals for the indicated safety system unavailability. Unavailability goals are 0.020 except for BWR HP Injection, which is 0.025. Data from WANO Performance Indicators for the U.S. Nuclear Utility Industry, 1996 Mid-year Report, September 1996.

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works well and people do not make mistakes, then problems that result in significant events will not occur. The equipment-related aspects of OLM have been discussed in this chapter; the human performance aspects of the OLM strategy will be discussed in Chapter 4.

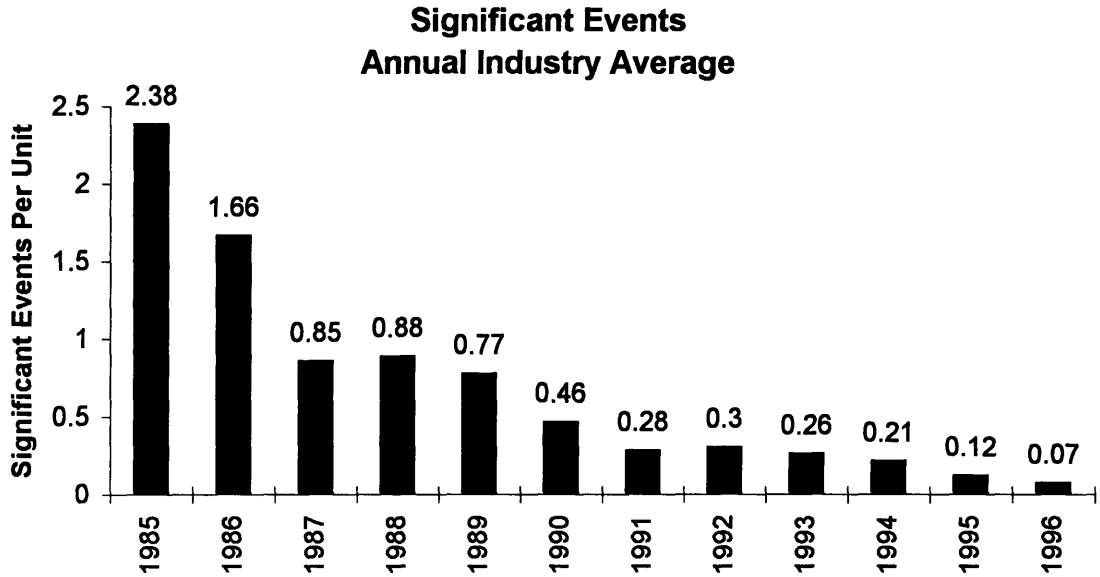

Figure 14 Data from Nuclear Regulatory Commission, Office of Analysis and Evaluation of Operational Data. Plants in extended shutdown excluded from data.

3.6 Three Examples

The following three examples are of stations that have undergone recent rapid improvement in many of the indicators discussed in this chapter. The purpose of these examples is to underscore the role maintenance strategies play in plant improvement. Each of these stations has incorporated most of the key features of the maintenance strategy outlined in Chapter 2. Many of the effects on human performance of the organizational changes apparent in these examples will be discussed in Chapter 4.

3.6.1 Brunswick

Brunswick, operated by Carolina Power and Light (CP&L), is a two-unit boiling water reactor plant located in North Carolina, on the coast near the South Carolina border. In 1993 and 1994, radical changes to plant management and station work processes were made to rescue the plant from a history of poor performance that was not improving. A. Chapple writes, "The late 1980's and early '90s were not kind to

Brunswick. It had a reputation as one of America's worst performing nuclear power plants. 'Up until a couple of years ago, Brunswick was a very cyclical plant--a poor performer, if you will, that would [initiate] a get-well improvement program, but it wouldn't last,' says Dave Verrelli, projects branch chief in the Nuclear Regulatory Commission's Region II office in Atlanta."[48]

In 1992, Brunswick was placed on the NRC's watch list, a list of plants that undergo increased regulatory scrutiny because of performance difficulties. Nuclear News reported that the action was taken because, in the words of the NRC, "Brunswick's performance has declined, and material (sic) condition is degrading because of inattention to maintenance, excessive corrosion, and management's inattention to detail."[49]

Three years later, however, this notoriety was forgotten and the industry was applauding Brunswick's achievements:

- "If you haven't visited Carolina Power & Light's Brunswick nuclear power plant recently, you wouldn't recognize the place. The corroded pipes and rusty machinery, just like the dirty floors, are a thing of the past. Today, Brunswick resembles a modern-art masterpiece, with a rainbow of color-coded pipes lining the walls and ceilings. The freshly painted floors are so clean they sparkle. The area around a control rod drive mechanism is no longer contaminated by radiation and cordoned off. The temporary offices that made the site look like a trailer park are gone."[50]

- The station recently received the highest possible systematic assessment of licensee performance (SALP) ratings in all categories from the NRC. "A number of the improvements CP&L made were in the area of maintenance, resulting as NRC noted, in high reliability and availability of plant equipment

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[48] Chapple, A., *Brunswick's New Look,* Nuclear Energy, 2nd Quarter 1995, p. 18
[49] *Brunswick added to list, Browns Ferry-2 removed,* Nuclear News, August 1992, p. 25

with no automatic scrams on either unit during the period. NRC noted that the establishment of a "fix-it-now" minor maintenance program helped improve efficiencies and significantly reduced the backlog of corrective maintenance."[51]

Brunswick's capacity factors in 1996 were 86.6 and 77.9, both well above the median and one in the best quartile for U.S. nuclear plants. Brunswick's outage durations in 1995 and 1996 were 51 days and 40 days, again both much better than the median for those years.

Although many things worked together to make the changes, some key items are listed here:

- Changes in management style were made that encouraged teamwork and held individuals accountable for performance. Many senior and middle managers were replaced during the change period of 1993 and 1994.

- Sweeping changes in the maintenance work processes were incorporated, making use of on-line maintenance and providing greater flexibility to the workers. Many inefficiencies in the work process, particularly in work planning and work authorization, were eliminated. Fix-it-now (FIN) teams were implemented, which allowed a quick response to maintenance problems. In the words of the maintenance manager, "Before the FIN teams were created, our outage duration for Unit 2 in 1994 was 97 days, for a shroud repair. That was a time when Brunswick was hard-pressed to do an outage in less than 100 days. Then, with the creation of a FIN team, we did an outage for Unit 1 in 50 days, and that was with a torus draindown and some fairly extensive work."[52]

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[50] Chapple, *Brunswick's New Look,* p. 18
[51] *NRC Officials warn utilities to pay more attention to material condition,* Inside N.R.C., June 26, 1995, p. 10
[52] Michal, R., *Gannon: maintenance at Brunswick,* Nuclear News, October 1996, p. 33

- An exhaustive effort to improve materiel condition was made during the extended regulatory shutdown. As a result, fewer deficiencies occur and those that do are easier to identify and resolve.[53]

- A strong desire to learn from others and aggressively adopt good ideas from other stations was instilled in the plant staff.[54] For example, the FIN concept was borrowed from Limerick through visits to that station.

3.6.2 South Texas Project

South Texas Project, operated by Houston Lighting and Power (HL&P), is a two-unit pressurized-water reactor plant located 80 miles southwest of Houston. South Texas' experience parallels that of Brunswick, in that it underwent an extended regulatory shutdown in 1993, was placed on the NRC's watch list, and was poorly regarded. This plant had an average outage duration of 87-days in the seven outages prior to 1994; in 1995 it ran 41- and 26-day outages in the spring and fall, completed a 22-day outage in 1996, and a 17-day outage in 1997.[55,56] The 22- and 17-day outages set records in the United States.

The characteristics of change at South Texas are nearly identical to those at Brunswick.

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[53] When materiel condition and plant cleanliness are good, deficiencies are easy to spot. For example, new oil leaks can be quickly located when there are none to begin with, but they are hard to detect and harder to locate in the midst of many other oil leaks. In addition, a large number of even minor deficiencies can reduce the flexibility a plant would otherwise have to conduct the maintenance, since alternate systems may not be fully capable of being used during the maintenance.

[54] Personally observed during a visit to the plant in November 1994.

[55] Michal, R., *Reducing Outage Durations at South Texas Project,* Nuclear News, November 1996, p. 29

[56] Interview with J. Groth, Vice-president of Operations, South Texas Project, March 31, 1997

- Senior management changes were made in 1993, with new managers from outside the organization hired for their ideas. These new managers have strong team-building abilities.[57]

- According to the outage supervisor, the excellent materiel condition and the organizational lessons learned while conducting on-line maintenance were keys that contributed to the plant's outage success. He said, "An aggressive online maintenance program results in very few corrective maintenance problems as workers get into the systems and into the equipment during the outage."[58] The organizational lessons learned included work process streamlining, schedule discipline, and teamwork.

- A minor maintenance program that allowed work to be accomplished quickly and without unnecessary documentation was implemented. A team similar to the FIN teams previously described was put in place.

- Similar to Brunswick, good ideas were borrowed through frequent visits to other stations by a broad cross-section of the plant staff. Managers and workers alike were sent on idea-gathering visits. As performance improved and other stations began to visit South Texas, the visitors were encouraged by J. Groth, Vice-President of Operations to take away all the ideas they want, but leave some good ideas of their own.[59]

3.6.3 Limerick

Limerick is a two-unit boiling water reactor plant in central Pennsylvania, operated by PECO Energy Company. Limerick was one of the first stations to adopt a

[57] Based on personal observation during frequent plant visits in the 1993 - 1995 period.
[58] Michal, *Reducing Outage Durations*
[59] Based on personal observation during a visit to the plant in 1995.

contemporary on-line maintenance work management strategy. Limerick has served as a catalyst for improvement at other stations, and the recent outage performance is used as a benchmark at other boiling water reactors. The experience at Limerick differs from Brunswick and South Texas in that the plant was not under regulatory pressure to improve. In a way, this makes the improvements more remarkable, because the utility set out to change the status quo on its own.

Limerick initiated its change process from a lackluster performance history -- its three-year capacity factor in 1989 was 62.5 percent.[60] R. Michal writes, "With the average refueling outage length in 1989 well over 100 days for PECO Energy Co. nuclear units, the company set out to achieve a sub-60 day outage by 1994. To accomplish the goal, PECO Nuclear, a unit of PECO Energy, developed the Refueling Outage Length Reduction Strategy, in which the entire organization was challenged with reevaluating the ways of doing business. Initiatives included increasing worker efficiencies, making physical changes to the plant to allow for an easier workflow, and moving tasks to nonoutage periods to be performed more safely and efficiently."[61]

The results of Limerick's efforts are impressive. Its maintenance backlog was reduced by 40 percent. ('You can't allow maintenance work that can be accomplished in non-outage periods to be done during a 30-day outage,' [the outage manager] says.)[62] The nuclear staff (company wide) was able to accommodate a 19 percent reduction in force in 1993 as a result of improvements at Limerick and Peach Bottom. The station was recognized in 1995 with an industry award for cost-saving innovations for its outage length reduction strategy.[63] In 1995, Limerick-2 completed a 23-day outage -- by far the shortest outage conducted by a U. S. boiling water reactor at that time. In 1996, the three-year capacity factors were 84 and 88 percent, and outages continued to improve.

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[60] Three-year capacity factor for Limerick 1 only. Limerick 2 had not accumulated three years of operating history at this point. Data from INPO.
[61] Michal, R., *Innovations* p. 23
[62] Peterson, S., *Countdown*, p. 36
[63] Nuclear News, July 1995, p. 46

Essentially the same types of changes were made at Limerick as at Brunswick and South Texas -- a management philosophy was adopted that encouraged innovation and teamwork, focus was placed improving work processes, and the maintenance backlog was reduced. In the words of C. McNeill, PECO Energy president, during a speech to the Nuclear Energy Institute: "Restructure to simplify work, eliminate unnecessary activities, and reduce staffing. Our Nuclear Effectiveness and Efficiency Program has eliminated approximately 600 positions and will produce annual savings of $31 million."[64] McNeill went on to say, "Safety has increased, something that skeptics can't believe."

3.7 Summary and Conclusions

This chapter has discussed the measurable effects of maintenance strategies. The indicators of capacity factor, outage length, availability and reliability, and ultimately cost of generation can demonstrate over time the effectiveness of the industry's (or utility's) maintenance strategy.

The changes in maintenance strategy adopted by most of the industry and illustrated by Brunswick, South Texas, and Limerick, are manifest in the overall favorable trends in these indicators. The trends discussed in this chapter are industry average or median statistics, and as such, do not reflect the fact that some utilities have either not fully adopted these strategies or not been effective in implementing them. Yet, it is encouraging to be able to conclude that nuclear plants as a whole are becoming more cost-competitive (from capacity factor and economic indicators) and safer (from safety system unavailability indicators).

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[64] McNeill, C., *New rules for nuclear industry's future,* Nuclear News, November 1994, p. 52

Chapter 4

Non-quantifiable Effects of On-line Maintenance Strategies on Plant Performance

In Chapter 3, measurable effects of the on-line maintenance strategy on plant performance were explored. In this chapter, a more elusive aspect of maintenance strategy effects is covered -- the non-quantifiable effects. The area of human performance is the focus of this discussion. On-line maintenance helps improve human performance in many ways: from creating favorable conditions for fewer human failures to contributing to higher worker morale.

The effects discussed in this chapter are difficult to quantify for at least one of two reasons. First, they involve elements of performance that can be affected by multiple influences, and the fractional effect of the "influence of interest" is difficult to determine. Second, quantifiable measures may not yet have been developed. For example, it is difficult to determine the dominant cause of a human failure when both poor procedure quality and an insufficient amount of sleep influenced behavior. Another example of a behavior that is difficult to quantify is teamwork.

Non-quantifiable benefits (or liabilities) of the on-line maintenance strategy are considered in this chapter by exploring how the strategy affects the dominant organizational factor influences on each step of the work process.

4.1 Background: Organizational Factors, the Work Process, and Human Performance

This section establishes the background necessary for further treatment of non-quantifiable effects of the OLM strategy. This background includes a definition of the work process model that is used as the framework for examining non-quantifiable effects and a discussion of general influences on human performance.

4.1.1 Work Process Analysis Model

A work process is defined by Davoudian et. al. as a "standardized sequence of tasks designed within the operational environment of an organization to achieve a specific goal."[65] These authors developed useful work process models of corrective and preventive maintenance for analyzing the effects of organizational factors on PSA parameters. They then established a matrix of the organizational factors that influence each of the work process steps. Tuli et. al., weighted each organizational factor of this matrix to show the relative importance of each of the key organizational factors in the various work process steps for both corrective and preventive maintenance.[66]

The matrices developed by Tuli et. al. are shown in Tables 1 and 2. The Davoudian et. al. work process steps, shown in Figure 15, is also reflected in these matrices. A description of the organizational factors of the matrices are provided in Appendix I. Note that the sum of the importance factors in each work process step column is 100.

This thesis uses the work process described in Chapter 2 to discuss both preventive maintenance and corrective cycles, although, according to the Davoudian et al. definition, they are different processes because the goals of preventive and corrective maintenance differ. However, because the major steps are the same for both preventive and corrective maintenance, the Chapter 2 model is used here with the understanding that the functions within the steps differ.[67]

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[65] Davoudian, K., Wu., J., and Apostolakis, G., *Incorporating organizational factors into risk assessment through the analysis of work processes*, Reliability Engineering and System Safety 45, (1994) pp. 85-105

[66] Tuli, R., Apostolakis, G., and Wu, J., *Identifying Organizational Deficiencies Through Root-Cause Analysis*, Nuclear Technology Vol. 116 December 1996, pp. 334-359

[67] The differences between the corrective and preventive maintenance processes are within the problem identification, planning, and scheduling steps. The differences include both when the steps are performed and by which groups the steps are performed. Scheduling differences are very subtle.

Weighted Organizational Factors Matrix for the Corrective Maintenance Work Process [68]

	Prioritization	Planning	Scheduling	Execution	Return to Normal	Documentation
Centralization	5.7	3	3.7	4.3	12.1	17.1
Communication - External		3.4				
Communication - interdepartmental	4.5	3.4	3.9	2.7		
Communication - intradepartmental	4.5	3.4	5.8	3	6.2	
Coordination of work		15.5	18.9	9.2		
Formalization	5.3	4.9	4.8	10.6	10.6	42.3
Goal prioritization	15.7		11.1			
Organizational knowledge	5.7	4.4	6.5	2.1		
Organizational learning	13.2	7.6				
Ownership				6.4		
Performance evaluation				5.5		
Personnel selection	7.4	11.2	9	9.2	13.7	
Problem identification		9.3		9.4	14.9	
Resource allocation	6		5.1			
Roles - responsibilities	5.8	8	5.4	4.7	6.5	13.5
Technical knowledge	16.8	14.6	13.2	11.9	12.6	
Time urgency	9.9	11.5	12.8	8		
Training				12.9	23.4	26.9

Table 1

The Chapter 2 work process differs slightly from the Davoudian et. al. processes by including a step for "problem identification" and lumping the "return-to-normal" and "documentation" steps into one "closeout" step. Davoudian et. al. consider the problem identification step to be a separate work process. The problem identification step, however, is an important part of the OLM work process, and there are discrete benefits derived from the way the OLM work management strategy executes this step. The lumping of the other two steps serves to simplify treatment of the work process and therefore, the discussion of benefits, without affecting the completeness of the discussion. The organizational factor matrices is used for comparing the effects of the OLM work management strategy on the basic process steps.

[68] Davoudian et.al., loc. cit.

Weighted Organizational Factors Matrix for the Preventive Maintenance Work Process[69]

	Scheduling	Planning	Execution	Return to Normal	Documentation
Centralization	4.7	3	4.3	12.1	17.1
Communication - External	2.8	3.4			
Communication - interdepartmental		3.4	2.7		
Communication - intradepartmental		3.4	3	6.2	
Coordination of work		15.5	9.2		
Formalization	8.1	4.9	10.6	10.6	42.3
Goal prioritization	17.3				
Organizational knowledge	3.4	4.4	2.1		
Organizational learning	11.7	7.9			
Ownership			6.4		
Performance evaluation			5.5		
Personnel selection	7	11.2	9.2	13.7	
Problem identification	10.3	9.3	9.4	14.9	
Resource allocation	4.6				
Roles - responsibilities		8	4.7	6.5	13.5
Technical knowledge	18.9	14.6	11.9	12.6	
Time urgency		11.5	8		
Training	11		12.9	23.4	26.9

Table 2

4.1.2 Human Performance

People make mistakes for many reasons. If the causes of the mistakes can be identified and eliminated, the frequency of mistakes and associated consequences will be reduced. In order to better understand what causes human failure, the modeling approach called ATHEANA ("a technique for human error analysis") is useful.[70] ATHEANA is a new method for human reliability analysis being developed for the NRC that addresses

[69] Davoudian et. al., loc. cit.

[70] Cooper, S., Bley, C., Parry, G., Wreathall, J., Roth, E., Luckas, W., and Thompson, C., *Knowledge-base for the New Human Reliability Analysis Method, "A Technique for Human Error Analysis,* "American Nuclear Society's International Topical Meeting on Probabilistic Safety Assessment: Moving Toward Risk-Based Regulation, Volume II, September 29, 1996, p. 679

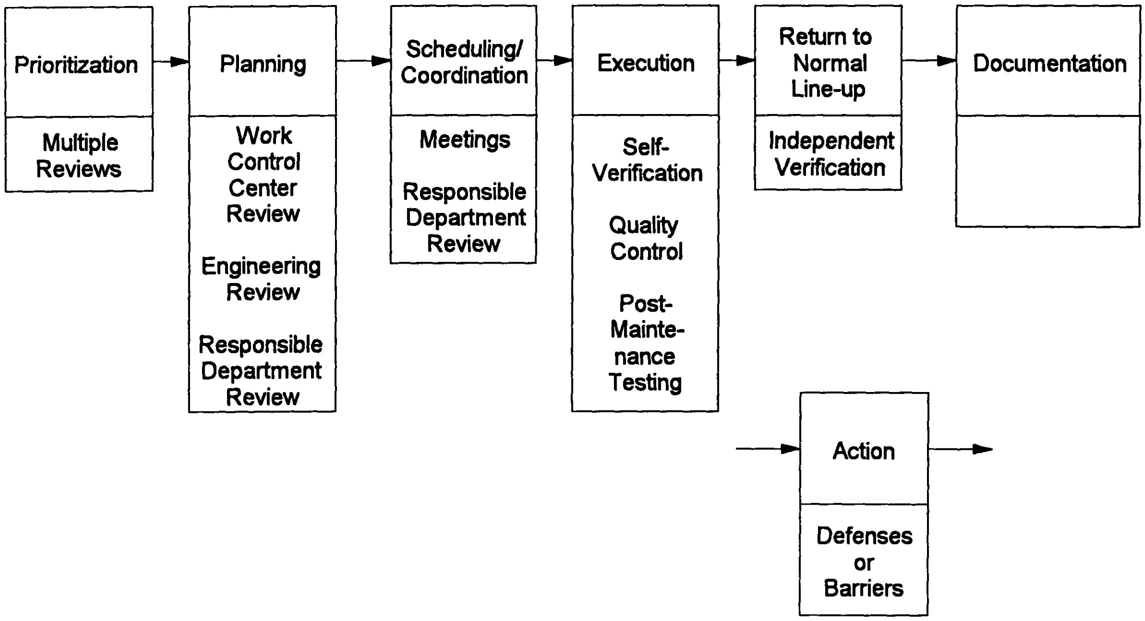

Figure 15 Davoudian et. al. work process, showing defenses and barriers to human failures built into each step.

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errors of commission and dependencies, and represents "more realistically the human-system interactions that have played important roles in accident response."[71] The underlying assumption of ATHEANA is that "people commit serious mistakes, actively decide to pursue the wrong course of action, when conditions coalesce to make error very likely."[72]

Cooper et. al. further state that "ATHEANA's premise is different [from other human reliability analysis methods]; it is assumed that operators behave rationally and perform very reliably except under certain combinations of plant conditions (typically unusual or unfamiliar accident conditions) and PSF's [performance shaping factors] that

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[71] Ibid

[72] Bley, D., Cooper, S., Parry, G., Wreathall, J., Luckas, W., and Drouin, M., *Trial Application of a Technique for Human Error Analysis (ATHEANA),* American Nuclear Society's International Topical Meeting on Probabilistic Safety Assessment: Moving Toward Risk-Based Regulation, Volume II, September 29, 1996, p. 686

virtually guarantee operator failure (i.e., error-forcing contexts)."[73] The plant conditions and the performance shaping factors, then, are of great interest in the discussion of maintenance strategy effects.

Performance shaping factors "represent influences on both the occurrence, and the type of human error mechanisms during, for example, operations, testing, and maintenance activities."[74] Performance shaping factors include human-system interfaces, such as layout and types of displays, procedures, component labeling, and administrative controls. The organizational factors listed in Tables 1 and 2 are important performance shaping factors.

Plant conditions also have a large effect on human performance. These are defined in the ATHEANA context as "the specific features of the plant and its operating state that lead not only to the tasks being performed, but also the circumstances under which they are performed. [They] represent influences related to operating configuration and parameters including equipment/instrumentation availability, core reactivity, and reactor coolant system temperature, pressure and inventory."[75] A shutdown reactor, for example, requires many more manual operations than a plant operating at full power, so there is more opportunity for human failure.

With this background and having defined some essential nomenclature, an in-depth discussion of the non-quantifiable effects of OLM work management strategies can proceed.

4.2 The Non-quantifiable Effects of the OLM Problem Identification Step

The problem identification step involves recognizing the deficiency and making the deficiency known. In corrective maintenance, this involves finding and reporting

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[73] Cooper, S., et. al., loc. cit.

[74] Wreathall, J., Luckas, W., Thompson, C., *Use of a Multidisciplinary Framework in the Analysis of Human Errors,* Springer's meeting on Probabilistic Safety Assessment and Management '96: ESREL'96 – PSAM-III, June 24, 1996, p. 784

[75] Ibid., p. 785.

deficiencies; in preventive maintenance, this involves determining the appropriate maintenance to conduct. (The organizational factor matrices assembled by Davoudian et. al. do not include the problem identification step as part of the work process.)

4.2.1 Preventive Maintenance Task Identification

Preventive maintenance task identification is perhaps the most significant step of the preventive maintenance process even though it may only be accomplished once in the lifetime of a component. This step corresponds to the problem identification step of the corrective maintenance process. In the OLM work management program, system engineers have the prime responsibility of identifying the types of preventive maintenance tasks that are necessary to keep their systems reliable and available. The OLM 13-week rolling schedule -- the key to program effectiveness -- is based upon the safety-related equipment surveillance requirements and the preventive maintenance tasks identified by the engineers. Without the emphasis during the program design stages of establishing the right amount of preventive maintenance on the right kind of equipment, the OLM program would not be as effective.

The key non-quantifiable benefit derived from strong preventive maintenance is good materiel condition. Although it is arguable that materiel condition *is* quantifiable (backlogs can be counted, failures can be counted), the definition of materiel condition can be broadened to include preservation, leaks, cleanliness, lighting, etc.[76] Materiel condition defined (more completely) in this way is much more difficult to quantify, and yet it is not hard when visiting two different plants to conclude that one plant's materiel condition is better than the other without looking at any statistics.

The non-quantifiable effects of good materiel condition include the following:

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[76] INPO 92-001, Section VIII.

- fewer hidden problems emerge when systems are opened up, so work scope does not frequently expand -- this in turn makes problem identification for operators easier because deficiencies stand out more

- greater confidence is placed in systems functioning properly

- greater trust exists among work groups -- maintenance workers can more accurately estimate time to complete work because fewer hidden problems exist, and operators have greater confidence in specified job durations

Many stations with strong OLM work management strategies optimized their preventive maintenance programs during the OLM program design stage. These optimization programs use reliability-centered maintenance (RCM) and the PSA to establish the optimum preventive maintenance for equipment. The RCM process examines the reliability of the components in question, and determines failure rates. The PSA is used to determine the equipment importance, using either the Fussell-Vesely importance, Risk Achievement Worth, or Risk Reduction Worth, to establish the effect of the equipment on plant safety.

4.2.2 Corrective Maintenance Problem Identification

The OLM program problem identification step for corrective maintenance is similar to other maintenance strategies with one significant exception -- the minor maintenance toolpouch work provision allows on-the-spot correction of certain deficiencies. Toolpouch work provides a significant degree of latitude to the worker to make choices that are not subject to review, so the organizational factors that affect this aspect of the work process step are goal prioritization, technical knowledge, organizational knowledge, ownership, and personnel selection.

The benefit of the OLM strategy problem identification step over other work management strategiesis is that minor deficiencies never enter the formal work process, so more focus can be provided for the deficiencies that *are* in the system. Clearly, the effect of immediate correction of minor problems is to improve efficiency and reduce the cumulative effect of the minor problems.

There is a also a greater risk of error with this approach. More latitude is given the worker to use his judgment and skills instead of using detailed work instructions with procedural steps that may not be fully applicable. Although the steps of the work process of an on-line maintenance program are clearly specified (formalized), the instructions provided to craftsmen are less formal than those typically provided under other work management processes. An example of a problem that this latitude caused is provided in Appendix II Case 3, which describes a safety function at a plant that was disabled because of a human failure during minor maintenance. Fortunately, human failures because of the extra latitude provided to workers are rare.

4.3 Non-quantifiable Effects of the OLM Prioritization Step

The organizational factors matrix for corrective maintenance indicates that goal prioritization, organizational learning, and technical knowledge are the most important contributors of organizational factors to the prioritization step.

The effectiveness of OLM work management prioritization step is strongly influenced by goal prioritization and technical knowledge, two of the three significant factors of the matrix. The goals of the OLM maintenance program to optimize materiel condition are clearly stated, and help drive the appropriate prioritization of work. Indeed, if work is improperly prioritized, the wrong work will be accomplished and schedules could be disrupted -- a situation that adversely influences efficiency as well as materiel condition. OLM programs are effective at prioritization because of the clearly stated goals and the team approach used to prioritize. The OLM program roles and responsibilities of operators and engineers differ from other maintenance strategies, in that there is a much higher degree of joint responsibility and teamwork required of them. Because of this, coordination among organizations is also an important factor of the effectiveness of the step. The result is a better prioritization of the deficiency.

Whereas in most of predecessor maintenance programs, operators established work priorities based upon their knowledge and experience of the equipment important to operations, in OLM programs, there is a team approach taken. This team approach is a strong aspect of the strategy. The operator brings his knowledge of equipment importance, and the engineer brings his understanding of the system's overall condition, complete with knowledge of the accumulated effect of other deficiencies and test data of which the operator may not be aware. Because of this, the technical knowledge of the engineers and operators that set the priorities are important. In addition, training -- particularly integrated plant system training for engineers -- is also a contributing organizational factor.

Better prioritization and the up-front teamwork between operations and engineering creates better conditions later on in the process. For example, operators are less likely to change or inflate priorities (a very real problem in predecessor work management strategies) because of the team establishment of the priority. The more complete prioritization that comes from considering the cumulative effect of system deficiencies also helps to improve overall materiel condition by placing the focus on the appropriate maintenance. The end benefit is, again, better materiel condition.

4.4 The Non-quantifiable Effects of the OLM Planning Step

The planning step involves the preparation of work instructions, acquiring parts, obtaining permits, and notifying support groups. The organizational factors matrix for the corrective maintenance process emphasizes the importance of work coordination, personnel selection, technical knowledge, and time urgency for this step in both the preventive maintenance and corrective maintenance work processes.

In OLM programs, coordination of work, personnel selection and technical knowledge are the three organizational factors emphasized by the matrix that have the most effect. The planner exercises a high degree of discretion in preparing work instructions for the craftsman, and plants, in general, choose highly experienced individuals for the job. Coordination of the planner's work is important to avoid planning backlogs that would adversely affect the readiness of the work packages for work. On the other hand, OLM programs are designed with long planning lead times, so urgency is not a significant influence on the effectiveness of planning. In fact, because time is usually not an issue, better quality work packages can be prepared.

As a result of the planning lead time built into the OLM program, there is greater worker confidence in planning (and thus improved cooperation and teamwork), there is more time to plan because emergent concerns do not dominate a planner's day, and package quality is better, which can result in fewer human performance errors.

On-line maintenance programs provide non-quantifiable benefits over predecessor work processes because of the systematic approach to planning and scheduling of the work. The benefits provided include increased focus during maintenance of important equipment and greater trust in work schedules. Predecessor work management programs often experienced problems because scheduled work did not have work packages ready. The OLM work management process only puts work on the daily schedule that is fully ready.

One additional comment must be made. Planners are given the latitude to plan packages in consideration of craft skills. Predecessor maintenance programs used highly detailed work packages that sometimes masked important work steps or sequences -- simpler work packages are thought to reduce worker errors. The latitude planners now have can result in packages of *insufficient* detail, so there is a *risk* of *more* worker errors. Experience, however, shows otherwise.

4.5 The Non-quantifiable Effects of the OLM Scheduling Step

The key organizational factors that influence the scheduling step, according to the organizational factors matrices, are coordination of work, goal prioritization, technical knowledge, and time urgency. Of these, coordination of work and goal prioritization are the most important contributors to OLM work management programs. Similar to the planning step, time urgency is not a key factor in the OLM process. Technical knowledge is also a *significant* factor, because sound judgment is needed to ensure nuclear safety when scheduling work on-line or during outages. OLM programs have a high degree of programmatic protection built into the 13-week rolling windows, which tends to complement the importance of high technical knowledge.

The coordination of work organizational factor is stronger in the OLM scheduling step than in other programs because of the role of operations, engineering, maintenance, and the work week manager in developing the schedule during the 10 weeks prior to the work week. This results in schedules that protect the worker from mistakes by providing the correct plant conditions, correct parts and work instructions, adequate support, and adequate time for the job. The synergism that exists as a result of the multiple groups represented in the scheduling process is the key distinction between the OLM and other work processes as they relate to the coordination of work organizational factor.

Goal prioritization is also stronger in the OLM program scheduling step than in other programs, also because of the representation of different groups in the scheduling process. As a result, the needs of the station as a whole (instead of the desires of individual departments) are considered during scheduling. This creates favorable conditions for schedules to remain constant, which allows better planning and coordination of work.

Organizational factors not considered significant to the scheduling process in the matrix that *do* influence OLM scheduling are ownership and centralization. The degree to which schedulers and, indeed, the entire maintenance program staff (operators, planners, craftsmen, etc.) feel ownership for and commitment to the schedule to (1) make it workable and (2) execute it fully, largely determines how effective the OLM program is. Centralization is key to this. The schedule is developed by representatives of the groups affected by the schedule, so the schedule becomes a *plant* schedule, not just a maintenance department schedule.

4.6 Non-quantifiable Effects of the OLM Execution Step

The execution phase, along with the scheduling phase, is an area where the OLM work management process provides great non-quantifiable benefit. The execution phase is where the strengths of the OLM work management strategy are put into action by the worker, and where program weaknesses will be manifested by error.

The key organizational factors that influence the execution process, according to the organizational factor matrix, are formalization, training, technical knowledge, problem identification, and coordination of work. Of these, training, technical knowledge, and coordination of work are the most important contributors to OLM work management programs. Training and technical knowledge represent the skills the craftsman needs to accomplish his job correctly. Coordination of the work establishes the plant conditions necessary for an error-free job.[77]

The formalization of the execution phase of the OLM work process is also important to human performance. The carefully scripted work coordination provided by the work week manager provides the foundation of the execution phase. Interestingly, much of this formalism is transparent to the worker. The worker is provided a "clear path" to problem-free work in the ideal OLM work setting, with work conditions established through the careful scheduling, an absence of interfering activities because of the coordination of the work week manager, and work packages with the appropriate level of detail through the flexibility of the tiered maintenance approach. Thus, a "top-level"

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[77] "Plant conditions" here refers to the conditions of J. Wreathall described in Section 4.1.2.

view of the OLM process would reveal a high degree of formalism. A worker, on the other hand, would say that there is less formalism than the predecessor work management process.

Ownership, too, is a significant factor for the execution phase of OLM work management programs. This is because of the latitude that workers have, particularly in conducting minor maintenance. For this to be successful, there must be, in addition to strong technical skills, a high degree of ownership and feeling of accountability for doing quality work. The self-verification barrier shown in the Davoudian et. al. work process is a key part of OLM programs.

The elements of the OLM program that provide the most significant non-quantifiable benefits in the execution phase include work optimization, creating focus, resource loading, schedule discipline, and worker latitude. These are discussed in the following sections.

4.6.1 Optimizing Work

The optimization of work (a coordination of work organizational factor) takes place in the scheduling step, but its effect on human performance is strongest in the work execution step. The OLM work process is designed to optimize work by distributing it over a broader period of time than other work management programs. When large amounts of work take place at the same time, conditions for human failures are greater than during periods of lower activities. For example, a Swedish study of outages concluded that "the outage period seems to be a significantly more vulnerable window in the management of a nuclear power plant than the normal power production state. Thus, an increased focus on the outage period and human factors issues, addressing the synergetic effects or work demands, organizational factors and coping resources is an important area for improvement of safety in the nuclear power industry."[78] The OLM program shifts work from high density work periods (outages) to low density work periods (on-line) thereby reducing the vulnerability of the outage window described in this study, and providing plant conditions that are better for human performance.

There are three significant effects of optimizing work in the OLM work management strategy: relieving job congestion, relieving control room congestion, and reducing the number of contractors doing maintenance. These are described below:

4.6.1.1 Job Congestion Relief

The improvements in outage plant conditions brought about by the on-line maintenance work process revolve primarily around the reducing the large number of 'events' individuals must deal with during the outages. The thousands of jobs being accomplished in a compressed time creates stress, distractions, and, as a result, human performance is adversely affected. Shortening outages improves this. For example, J. Groth, South Texas Project vice-president of operations, stated after the station completed a record-setting 17 day outage that the outage was the least stressful outage the station has ever completed.[79]

The relief from "job congestion" provided by a well-functioning on-line maintenance program is an important benefit. Outages include huge amounts of work, which can adversely affect human performance. "[G]iven the large amount of activity that takes place during an outage, the large work force involved, and the many and rapid changes in plant configurations and personnel assignments that can occur, the demands on plant personnel can be quite heavy. The excessive overtime that is often required to complete the outage on schedule can compound the problem and introduce stress that is

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[78] Jacobsson Kecklund, L., and Svenson, O., ***Human errors and work performance in a nuclear power plant control room: associations with work-related factors and behavioral coping***, Reliability Engineering and System Safety, accepted for publication

[79] Interview with J. Groth, Vice-president of Operations, South Texas Project, March 31, 1997

unique to [outages]."[80] For example, in one small machinery room there may be several different jobs progressing, none of which are related, but all of which interfere with the other in terms of access to equipment, power supplies, tools, hoists, etc. -- these conditions can contribute to human failures.

4.6.1.2 Control Room Congestion Relief

Moving work out of the outage and into on-line periods relieves the control room operators of distractions that interfere with their jobs. The control room during an outage is much different than a control room during full-power operation because of the number of alarms that are lit on the control boards from systems in abnormal lineups, the number of systems that require manual rather than automatic operation, the fewer system operation options because of equipment being out of service, and the abnormally high control room traffic.

The Swedish study cited earlier found that there is a "130 [percent] increase in the number of telephone calls coming into the control room on an average morning shift and for certain critical work tasks the increase is about 280 [percent] for the morning shift in the annual outage condition as compared to normal operation."[81] This study also included a list of the extra demands on operators (control room and auxiliary) during outages. These extra demands adversely affect coordination of work and create time urgency -- conditions which are adverse to good human performance. The portion of this list that relates to control room operators and how the on-line maintenance work process affects each item follows:

- Many extra documents in addition to orders and instructions: By reducing the number of outage activities, the amount of outage paperwork is reduced. In

[80] Barriere, M., Luckas, W., Whitehead, D., and Ramey-Smith, A., An Analysis of Operational Experience During Low Power and shutdown and a Plan for Addressing Human Reliability Assessment Issues: NUREG/CR-6093, June 1994, p. B21

[81] Jacobsson-Kecklund and Svenson

addition, much of the paperwork is handled by the work control center in the typical on-line maintenance program and the control room is not bothered with it.

- Delays in activities from late work permits: On-line maintenance work processes are centered around the scheduling of planned work packages only -- work that is not yet planned will not be scheduled.

- High attention demands: On-line maintenance work processes improve this through the reduction of outage work scope and the shifting of much control room decision making to the work control center.

- High demands on performing several activities simultaneously: On-line maintenance work processes improve this through the reduction of outage work scope.

- High demands on mental capacity: On-line maintenance work processes improve this through the reduction of outage work scope and the shifting of much control room decision making to the work control center.

- Time pressure: On-line maintenance work processes improve this by better scheduling and use of the implementing work groups to determine what is needed to accomplish each task. As a result, time pressure is self-imposed by the work group instead of by an external group.

- Many people and disturbances in the control room: On-line maintenance work processes improve this through the reduction of outage work scope and the shifting of much control room decision making to the work control center.

- Demands on high information capacity simultaneously: On-line maintenance work processes improve this through the reduction of outage work scope and the shifting of much control room decision making to the work control center.

The on-line maintenance work process improves outage operations not only by reducing the amount of work control room operators must deal with, but also by eliminating much control room traffic from workers seeking work authorization. Many on-line maintenance work management programs incorporate a work control center to shield the control room from distractions -- nearly all work is processed through the work control center.

4.6.1.3 Fewer Contractors

There is benefit (beyond the immediate effect on expenses) in not having to hire contract craftsmen. Long outages typically require significant manpower. Work schedulers "resource load" schedules by assigning craftsmen according to the estimated man-hours of work for each task. When there is more work than craftsmen to accomplish it, then contract labor is hired to fill the gaps. Frequently hundreds of contract craftsmen are hired temporarily to work during outages. For example, during Clinton Power Station's first outage in 1989, 900 contractors were brought on site for five months.[82] The initial concern with this is usually the cost of this much labor. However, consideration should also be given to the following:

- Contract labor is not as familiar with station equipment or procedures as permanent employees, so chances for error are greater.

- Contract labor does not "own" the plant in the same way permanent employees do, so quality of work may not be the same.

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[82] Michal, R., *Augmented resources cut contractor dependence,* Nuclear News, May 1994, p. 47

- Contract labor is usually not involved in the planning or scheduling of the outage work, and will therefore be less familiar with the jobs than permanent employees.

- Contract labor may not have the same sense of urgency to complete the tasks as rapidly as permanent employees.

4.6.2 Creating Focus

The OLM program influences the coordination of work organizational factor in the work execution phase by providing more focus on important work than other work management programs provide. Focus is created in both the scheduling step and the by the work week managers. The OLM work process scheduling step creates focus through systematic scheduling of the work in work windows. The effects of the focus are better quality work, optimized equipment availability, and fewer human failures.

Focus is important to good human performance especially when risk-significant work is being accomplished. Work on important equipment must be accomplished rapidly and the system returned to service as soon as possible. In order for this to happen without adversely affecting an individual's performance, good coordination of many different work groups must take place. For example, as soon as the system is aligned for maintenance and tagged out by operations, the maintenance crew must be standing by, ready to start work. If problems arise, they must be elevated quickly to the proper authority for rapid resolution. When the work is completed, the system must be realigned by operations and tested, then returned to service. The coordination necessary for these things to occur does not just happen -- it must be predetermined, widely communicated, strongly supported, and even rehearsed in some cases.

In strong OLM programs, risk-significant work is generally allocated time during which no other work that may interfere or distract is scheduled, so that the staff can focus on accomplishing that work alone. Probabilistic safety assessments are used in scheduling the work to determine the effect of other concurrent work to total risk. The adverse effect of two incompatible activities is illustrated in Appendix II, Case 4, when a significant amount of reactor coolant was drained from the reactor because of two simultaneous incompatible actions. In OLM work management programs, the work week manager is responsible for the coordination of the work and ensuring handoffs from group to group are crisp. Although these work process attributes certainly could have been part of predecessor work processes, they generally were not.[83]

There is a strong sense of single-point accountability that work week managers feel for their work weeks, which results in higher quality work being done with good schedule adherence. As discussed in other sections, maintenance done as part of the OLM strategy is highly coordinated. The work week manager is the focal point of this coordination.

The work week manager's role in creating focus is to enhance teamwork. The work week manager helps provide understanding among workers of the consequences of errors while doing maintenance on-line. This understanding comes from clear communication of the schedule of activities, their effects on safety, and the responsibilities of all involved in accomplishing the work.

4.6.3 Resource Loading

Resource loading is the process of matching the available resources with the required work. This affects the coordination of work organizational factor in the execution phase by ensuring workers with requisite skills are selected, providing them with tools and procedures, and establishing the right plant conditions for them to conduct the work. In an on-line maintenance work management program, it is more likely that the proper elements for a successful task are aligned than in other strategies. This is because

[83] This claim is personal opinion, but is based upon experience gained from visits to over 35 nuclear plants.

of the advantage provided by longer lead times for planning scheduling, and resource allocation.

Individual human performance is affected favorably by the way resources are assigned to tasks in the OLM work management strategy. Other work management systems typically schedule work based upon average (or even full-strength) maintenance man-loading. This is usually accomplished two weeks in advance of the work week. The scheduling of work often does not account for changes in available man-power that comes from vacations or training. As a result, over-tasked maintenance groups either are unable to accomplish the work or must double up on jobs, which puts pressure on the worker to hurry.

In comparison, OLM work processes tend to more fully integrate the scheduling of resources with the scheduling of tasks, and vacations and training are considered when establishing available manpower numbers. As a result, adequate resources are usually available, so pressure on the individual to "hurry on to the next job" is rare, and individual performance is better.

Resource loading as just described is not necessarily unique to on-line maintenance work management strategies. The likely reason that predecessor work management programs do not resource load in this way is that strict schedules (necessary for on-line maintenance) were not important (in the 1970s and 80s) when the maintenance programs were initially being developed.

4.6.4 Schedule Discipline

The discipline created by the work process from executing work under tight work windows to manage availability is a non-quantifiable benefit that carries over into outages. In essence, on-line maintenance work windows become practice outages -- an organizational learning factor. As R. Graham at South Texas Project said, "LCO outages conducted during a unit's entire operating cycle allow the focus to be put on planning techniques and the organization discipline of schedule adherence, which also have application to refueling outages"[84]

A typical difference between on-line maintenance programs and others is the daily schedule that workers use during the execution phase. Stations with strong work management programs use well-designed daily schedules that specify both when a job is scheduled and its duration. This kind of schedule is certainly not unique to on-line maintenance programs; however, the importance of schedule adherence in controlling unavailability makes schedules such as these important. Some stations also include a chart showing core damage frequency during the different schedule times as a further reinforcement of the importance of the work.

The result of good daily work schedules is well-informed workers who are able to rely upon the schedule instead of finding out while obtaining work authorization that their jobs are canceled because plant conditions are wrong.[85] Operations involvement *as a partner* in the prioritization of work and detailed scheduling of the work helps the accuracy of the schedule.[86] This is quite different from predecessor work processes, in which operations participates in the work process more as an authority or approval point than a partner. With operations as a partner in the scheduling process, schedules can be built with a strong operations influence *up front.* The end result is good schedule discipline.

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[84] Michal, R., *Reducing Outage Durations,* loc. cit.

[85] Although it may seem like a rare situation in which work is canceled because of conditions being wrong, it is not (under predecessor work processes). Indeed, schedule adherence under older work processes in which operations is minimally involved are frequently low, and sometimes the shift supervisor would refuse to allow work start even though the work was scheduled and conditions were favorable.

[86] Operations involvement in work prioritization of work is not unique to on-line maintenance work processes, but their involvement in work scheduling in predecessor work processes was very limited.

4.6.5 Worker Latitude

Great reliance is placed upon individual initiative in the on-line maintenance work management strategy. When the organization has properly attended to individual training, procedures and policies, (technical and organizational knowledge organizational factors), the plant receives the benefit that the efficiency of the strategy can provide. On the other hand, initiative that is exercised improperly causes problems.

4.7 The Non-quantifiable Effects of the OLM Closeout Step

The closeout process, which includes system testing, return to service, and documentation, is strongly influenced by centralization, formalization, technical knowledge, and training in the organizational factors matrices. The OLM work processes are influenced in the same ways. The non-quantifiable benefits of OLM come in the return-to-service phase of this step. The emphasis of OLM programs on equipment availability (goal prioritization and ownership organizational factors) encourages workers to be cognizant of the importance of not delaying return to service, and the work week manager keeps the closeout process moving. Other work management programs can allow delays in the return-to-service process for lack of understanding (or commitment) of the workers to restore the equipment or lack of a central point of management (like the work week manager) to keep the work moving.[87]

4.8 Non-process Effects of the OLM Work Management Strategy

Strong OLM work management programs tend to have strong, cohesive organizations that positively influence performance. Without strong leadership and careful adherence to good management principles, plants with OLM work management programs are not likely to be effective. This section discusses some of the non-process attributes that characterize organizations with good OLM programs.

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[87] Many predecessor work processes relied upon the control room to move work along. This is not as affective as having a work week manager, because of the many other responsibilities assigned to control room operators.

4.8.1 Human Resources

In the model on-line maintenance program discussed in Chapter 2, human resources are assigned *organizationally* (strategically) as part of the business plan/budgeting cycle. There is an advantage to the on-line maintenance program over other programs, mainly because well-performing on-line maintenance programs programmatically address resource issues and integrate them fully with business goals. As a result of better assignment of resources, mission-level commitments are able to be kept, trust is built, and workers and organizations are not forced to 'stretch' in accomplishing their missions.[88]

4.8.2 Communication

Stations that have strong work management programs (whether or not they are on-line maintenance programs) in general tend to communicate well both vertically and horizontally. None of the on-line maintenance program distinctives *cause* better communications or better performance in comparison with other work management programs. However, communications *are* typically good at stations with strong on-line maintenance programs.

Many stations that underwent significant process changes were careful to keep workers informed of the reasons for the changes being made -- vertical communication -- during the transition. For example, D. Helwig, then site vice-president of Limerick, said, "We communicated very directly with the work force about the economic imperative we face as a company and as a generating station. All of the workers here understand that it is important that this plant operate well and that we reduce our outage time."[89] Officers at South Texas Project held frequent small meetings with employees to discuss the

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[88] Predecessor work management programs typically schedule work without a full consideration of whether or not resources to accomplish the work are available. Strong on-line maintenance work management programs schedule work after resource have been committed.
[89] Peterson, S., *Countdown*, p. 36

imperatives for change during that station's transition period in 1993. Strong vertical communications still exist at these stations, certainly in large measure because of the communication efforts of management during the transition period.

South Texas Project and Limerick also have strong horizontal communications among work groups.[90] On-line maintenance programs need close coordination among work groups to make the work process function efficiently, but so do other work management programs. Well-functioning on-line maintenance programs seem to have *better* communications, perhaps because of management emphasis on teamwork and accountability.[91]

4.8.3 Culture

Culture is a term that refers to the underlying principles that govern the organization, that is, the personality of the organization. When applied to individual behavior, it is characterized by the sense of ownership for programs and equipment that employees have, the sense of urgency they feel for accomplishing tasks well, and their commitment to safety and "doing the right thing." Strong on-line maintenance programs appear to be strong in cultural areas, but the cultural strength is not likely caused by the program -- rather, the programs are strong because of the culture.

Most plants that have strong on-line maintenance work management programs also went through a cultural change during implementation of their programs. The three plants described in Chapter 3 all experienced cultural shifts as part of their change processes, and their maintenance programs are strong and effective as a result. In some cases, such as with Brunswick and South Texas Project, the cultural change involved altering the collective self-image plant employees had from being a "problem plant" to "world class" performer. Both plants (and others in similar situations) have used, to varying degrees,

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[90] Interview with W. Truax, Outage Manager, Limerick, February 1995, and personal witness at South Texas Project.
[91] Teamwork and accountability are strongly emphasized at South Texas Project and Limerick.

reengineering and change management methods to build teamwork, employee participation and buy-in. The results in terms of cultural change and morale improvement have been profound.[92] Cultural features (described briefly in Chapter 2) that tend to be present in stations with strong OLM work management programs include the following:

Accountability: An OLM program depends upon developing and meeting complex schedules, and the plans of one organization are based on the commitments made by many others. Successful OLM programs involve many individuals and organizations that must provide a deliverable or be at designated locations at the right time prepared to do the task at hand. This strong sense of accountability is demonstrated throughout the organization. For example, meetings are attended by the people who are supposed to be there, they start on time, the meeting agenda is clear, and action items from the meeting are well-defined and acknowledged by the person with execution responsibility. Another example of strong accountability is in high schedule adherence. Jobs are started when scheduled and completed on or ahead of schedule. This is possible because of groups are accustomed to meeting commitments.

Qualification: Individuals are well trained and possess the qualifications necessary to make decisions with few of the layers of review that characterized operations at nuclear facilities a decade ago. For example, toolpouch maintenance relies upon individuals who note deficiencies and decide if it is within their capacity to repair *and* within the limitations of toolpouch maintenance. The latitude to rely heavily upon individuals while providing only limited oversight depends upon a highly trained workforce. The workforce has a greater appreciation for integrated plant operations and the effects of activities on safety than was necessary in previous maintenance programs.

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[92] Based upon personal observation during visits to both plants both before and after the changes.

Teamwork: The time-sensitive nature of on-line maintenance requires close coordination among the groups involved that comes through strong teamwork. An attitude exists that problems that arise are everyone's problem instead of "not mine." Recall the "we team" concept at South Texas Project.

Resources: Management seeks to know what resources are necessary to achieve business goals, and provides them. This is evident in a good balance between a "young" work backlog and suitable maintenance department workforce. Other evidence of this may be a capable information system, and facilities for efficiency-enhancing groups such as the a conveniently located Work Control Center.

Measuring performance: Aggressive performance measures are used to identify shortcomings. Schedule adherence, system unavailability, and work backlog are the key performance measures used as overall measures. Other indicators are used by individual organizations so group performance can be improved. Performance measures are chosen that discourage indicator management.[93] Trends are followed and analyzed.

As in other aspects of the discussion of non-quantifiable effects, defining the precise relationship between the on-line maintenance work management strategy and the cultural changes that have recently taken place at many plants is not practicable or even necessary. It probably is valid to conclude that there *is* a relationship -- that the cultural changes reinforce the effectiveness of the maintenance strategy and vice-versa.

To illustrate the interdependence of culture and program effectiveness, again consider toolpouch work. Unless a worker has a strong sense of ownership for his plant and its materiel condition, he is unlikely to take the initiative while walking through the

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[93] Sometimes performance indicators are "managed" by controlling the circumstances that influence the indicator instead of allowing the indicator to show process deficiencies in the overall mission. As a result, the "good looking" process may actually interfere with interfacing processes.

turbine building to stop, pull out his screwdriver, and tighten a loose deck grating. But because this kind of culture *does* exist, the toolpouch work concept works effectively and, as a result, maintenance backlogs are kept from growing, materiel condition remains high, and worker satisfaction is high.

Finally, morale seems to improve along with cultural changes and the accompanying improvements in performance. Clear evidence of this is the enthusiastic testimony of one manager at South Texas Project, who stated that his whole life had changed as a result of the improvements that had been made at the plant -- he now has significantly more time with his family, he seldom receives calls at home, adversarial relations at work "are history," and on and on. The story of this manager is not isolated. Clearly, the successes of the programs undergoing change are reinforcing, and these successes create believers and strong supporters who will resist any 'decay' back to the way things were.

Chapter 5
Conclusions and Future Work

The on-line maintenance work management strategy is proving to be of great value to the industry. The move to this strategy, plus changes in organizational factors and management styles that have accompanied the move, have made plants safer through better equipment condition and human performance, and have improved the economic viability of the plants as well. Although difficult to tie all of the effects discussed in this thesis solely to the on-line maintenance strategy, it seems clear that the strategy does play a significant role in the benefits.

Table 3 summarizes the effects of the on-line maintenance strategy on the various categories of measurable performance discussed in Chapter 3. The categories described in this table all have a clear role in the economic performance of the plant. Chapter 4 discusses the key organizational factors that influence human performance in the work processes (Tables 1 and 2), and points out how OLM work management can result in improved human performance.

5.1 The Value of On-line Maintenance Programs

The issues that must be addressed when drawing conclusions about programs such as OLM work management center around the value of the strategy. First and foremost, the program must not jeopardize nuclear safety. Second, the program must provide an economic benefit. Both of these issues must be favorable for the program to be worth pursuing.[94]

The easiest of these issues to address -- economic benefit -- was addressed in Chapter 3. Economics was one of the driving factors behind the changes from the work

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[94] A program may be for the <u>sole purpose</u> of improving nuclear safety, in which case economic considerations may not be important.

Measurable Benefits

Category	Direct Benefit	Direct Cause	OLM Work Process Influences
Outage	Shortened outages	redistribution of work	13-week rolling schedule
		improved materiel condition	initial materiel condition effort,
			13-week schedule
			strong preventive maintenance
			tiered maintenance
			13-week rolling schedule
	Fewer events	Better human performance	job congestion relief
			control room congestion relief
			fewer contractors
Capacity Factor	Shortened outages	(previously discussed)	(previously discussed)
	Few forced outages	Better human performance	daily schedule
			work week manager focus
		quality work	tiered maintenance
		materiel condition	(previously discussed)
Reliability	High reliability	materiel condition	(previously discussed)
Availability	Optimized availability	lower down time	work week manager
		good materiel condition	(previously discussed)

Table 3 Summary of quantifiable effects on plant performance from the on-line maintenance strategy

management programs of the 1980s to the on-line maintenance strategy of the 1990s. The effects of the combination of maintenance strategy and improvements in organizational factors that have in many cases accompanied the changes show that there is an economic benefit to the on-line maintenance strategy.

The first issue -- nuclear safety -- is more important. The on-line maintenance work management strategy can degrade or enhance nuclear safety. Case 3 of Appendix II describes how workers went beyond program guidelines and inadvertently disabled safety systems by taking initiative. Safety system unavailability can also be increased by plants that are overzealous to move too much work out of the outage and into on-line periods. These are some of the challenges to nuclear safety that must not be taken lightly.

Fortunately, the nuclear industry takes nuclear safety very seriously, and the improvements in safety are well represented by the reductions in the number of significant events, as described in Chapter 3. The program weaknesses that allowed some of the problems described in the case studies in Appendix II do not seem to be widespread. If a cause and effect relationship between both the changes in maintenance strategy and organizational factors and nuclear safety can be assumed, then to conclude that nuclear safety is enhanced by these programs is valid. Furthermore, the reliability of safety systems has shown improvement over the same period of time that on-line maintenance programs were being implemented in the industry, as discussed in Chapter 2.

The validity of this conclusion is further advanced by what we know about the non-quantifiable benefits to human performance -- the on-line maintenance work management strategy enhances this performance area by improving both performance shaping factors and the plant conditions that influence human performance.

We can therefore conclude that there is both economic and nuclear safety benefit to the on-line maintenance work management strategy. These benefits make a well-implemented program, such as that described in Chapter 2 and in the three examples of

Chapter 3, worthwhile. In addition, well-implemented programs help gain the confidence of the public, the regulator, and plant staff.

5.2 Future Work

This thesis has focused on the effects of a work management process on plant and human performance. Clearly there is much more work to be done in the study of work processes. Because most of the serious events at nuclear power plants are caused by human failures (of the 13 events at power reactors that have resulted in fuel damage, only one of them was not related to human failure), this attention is warranted.

5.2.1 Other Work Processes

More work is necessary in investigating the effects of other work processes on plant performance. The outage work processes, for example, differ from the preventive maintenance and corrective maintenance processes that dominate the OLM strategy. Many stations that have not achieved good outage performance require focus on their outage processes. In addition, more study of the steps in the OLM work management strategy would be worthwhile. For example, the details of the scheduling step could be examined to determine an optimal countdown schedule.

5.2.2 Allowed Outage Time Optimization

Work in investigating enhancements to technical specification allowed outage times for safety systems is needed. There may be safety benefit in expanding the amount of maintenance done to safety systems on-line that is currently limited by technical specifications. Research in this area should use probabilistic safety assessments in support of any suggestions to change current practice.

5.2.3 Organizational Factors

More work is needed in studying the effects of organizational factors on human performance in the context of specific work steps. Previous work has used general work process models; there would be value in using more specific models or focusing on smaller portions of the process.

5.2.4 Combined Influences

There are many combined influences on plant and human performance, as has been indicated. Future work to isolate these influences and gauge their effect is needed. For example, determining whether a strong culture is more important than a well-designed process would be valuable. In addition, there is need to study in detail the influences at plants that have undergone significant change in both process and culture. Finally, determining why some plants have been unable to effectively implement change would be a worthwhile study.

Chapter 6

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Appendix I: Definitions of Organizational Factors[95]

The organizational factors listed here shape human performance. Each step of a work process can be influenced by several organizational factors. The degrees to which each of these organizational factors affects the work process steps has been proposed by Tuli et. al. and are shown in the matrices included in Chapter 4.

Organizational Factor	Definition
Centralization:	The extent to which decision-making and/or authority is localized to one area or among certain people or groups.
Communication - external	The exchange of information, both formal and informal, between the plant, its parent organization, and external organizations.
Communciation - interdepartmental	The exchange of information, both formal and informal, between the different departments or units within the plant.
Communication -- intradepartmental	The exchange of information, both formal and informal, within a given department or unit of the plant.
Coordination of work	The planning, integration, and/or implementation of the work activities among individuals or groups.
Formalization	The extent to which there are well-identified rules, procedures, and/or standardized methods for routine activities as well as unusual occurences.
Goal Prioritization	The extent to which plant personnel understand, accept, and agree with the purpose and relevance of plant goals.

[95] Jacobs, R., and Haber, S., *Organizational processes and nuclear power plant safety,* Reliability Engineering and System Safety, 45: 75 - 83

Organizational Factor	Definition
Organizational Knowledge	The extent to which plant personnel have an understanding regarding the interactions of organizational subsystems and the way in which work is actually accomplished within the plant.
Organizational Learning	The use of knowledge gained from past experiences, from the plant and other plants, to improve future performance.
Ownership	The degree to which plant personnel feel personally responsible for their actions and the consequences of the actions. Pride in the organization.
Performance evaluation	The assessment of personnel work-related behaviors.
Personnel selection	The identification of plant personnel with the requisite knowledge, experience, skill, and abilities.
Problem identification	The drawing upon knowledge, experience, and current information by plant personnel to identify problems.
Resource allocation	The distribution of financial resources, including actual and personnel perception.
Roles-responsibilities	The degree and clarity of work and plant personnel activity definition.
Technical knowledge	The depth and breadth of requisite understanding of plant personnel regarding plant and system design, including phenomena and events bearing on plant safety.
Time urgency	The perception of schedule pressure during task completion.
Training	The degree to which plant personnel are provided with the requisite knowledge and skills to perform the task safely and effectively.

Appendix II -- Case Studies

This Appendix includes brief descriptions of actual events as examples of how different aspects of on-line maintenance programs may have influenced the circumstances surrounding the event in a different way. No attempt has been made to analyze root causes of these events -- these events only serve to demonstrate that the various factors that affect human and organizational performance are real and therefore can be influenced.

Case 1 -- Containment Breach During Refueling[96]

Overview

On October 30, 1996, during refueling operations at a pressurized water reactor, containment was breached during core alterations when a valve used for containment isolation inadvertently opened as power was removed from a holding relay during maintenance preparations. This situation went uncorrected for 30 minutes in spite of alarms in the control room indicating the change in valve position. Contributing to the event was an incomplete understanding of the effects of maintenance on plant conditions, distractions in the control room from a large number of other outage activities, and mixed responsibilities between the outage control center and the control room.

Containment closure was required while core alterations were being made. Although the secondary manways of one steam generator were removed to support maintenance activities, containment closure was established by closing isolation valves outside containment on the main steam line, main feedwater line and auxiliary feedwater line.[97] Additionally, operations performed checks during each shift to verify containment closure.

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[96] Licensee Event Report No. 96 - 011, Docket No. 50-285

[97] Containment isolation can be lost through a steam generator with open manways if steam and feedlines are not isolated.

An electrician requested a tagout of the solenoid valve for the auxiliary feedwater pump inlet so the valve could be replaced. The outage control center tagging coordinator created a tagout to close the inlet valve and pull the fuses for the solenoid. When the electrician requested the control room to release the equipment for maintenance, a licensed operator recognized that the solenoid valve was tagged in the closed position, but that the valve would fail open on loss of power. The operator sent the electrician back to the outage control center with instructions to add a tag to hand jack the solenoid valve closed prior to pulling the fuses.

Tags to hand jack the solenoid valve closed were added to the existing tag out modification, and the solenoid valve was hand jacked closed. The electrician was then allowed to pull the fuses for the solenoid valve. When the fuses were pulled, the solenoid valve stayed closed, but the valves to the main steam supply to the auxiliary pump opened because these are controlled through the relay in the control circuit of the inlet solenoid valve. When the fuses were pulled for auxiliary feedwater inlet solenoid valve, the relay deenergized and opened contacts in the main steam supply to auxiliary feedwater pump control circuits, opening the valves and providing an audible alarm and print out in the control room that the main steam supply to auxiliary feedwater pump opened. The opening of this valve breached containment.

This condition went uncorrected for approximately thirty minutes because of activities in the control room. Once it was recognized that a potential containment closure problem existed, override switches were used to close the main steam supply valve. At first, it was believed containment closure had been maintained because the auxiliary feedwater pump inlet solenoid valve remained closed. However, it was later discovered that warm up lines were still open, constituting a containment breach. During the time that this condition existed, two fuel assemblies were loaded into the core.

Discussion

This event illustrates several important issues that have been discussed theoretically in previous sections. On-line maintenance program elements can reduce the effect of these issues. The issues include the following:

Outages are periods of high activity levels. The volume of activities can distract control room operators, which indeed happened during this event. This, then, was a plant condition that contributed to the human failure of overlooking the alarm and missing the effect of the tagout on the slaved relay. Eliminating as many tasks as possible from outages can improve this situation. On-line maintenance strategies are capable of creating outage work scopes in which *only* work requiring shutdown conditions is accomplished.

The division of responsibilities between the outage control center and control room was not optimum, and created opportunity for error. In this case, the control room had responsibility for approving tags that the outage control center prepared. This situation increased the cognitive and administrative load of the control room operators. Although from the few facts presented here it cannot be stated with certainty that the tagging error was made because of these conditions, some stations move all outage preparation activities, including preparing tagouts, to outage control centers so operators are not interrupted from monitoring complex operations such as refueling.

Case 2 -- Loss of Decay Heat Removal Because of Improperly Scheduled Maintenance[98]

Overview

On September 12, 1995, during a refueling outage, decay heat removal was lost when a decay heat pump suction isolation valve automatically closed as a result of an improperly scheduled preventive maintenance activity.

While electricians were changing out emergency safeguards actuation system relay coils as preventive maintenance, the decay heat pump suction isolation valve closed when its relay coil was removed. As a result, decay heat removal cooling was lost, but was quickly restored by attentive operators in the control room after less than a minute.

The preventive maintenance task of changing out the relay coils is normally performed at power. In this case, the task had been partially completed on-line, but left open to complete during the outage. Because it was a partially completed task, it was not reviewed for outage risk. Also, it was not recognized that removal of the relay coil would cause an actuation. This is because ordinarily, two relays are necessary for equipment actuation for equipment maintained in this fashion. However, this particular circuit requires only one relay to function.

Discussion

This event illustrates two points. First, plant conditions were not optimum for conducting the kind of work that initiated the event. The work was normally accomplished on-line, and conducting it during the outage was more risky because there was a need for decay heat removal under existing plant conditions -- defense-in-depth was threatened. Second, a review of the work in context with existing plant conditions and

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[98] Licensee Event Report No. 950912-1, Docket No. 50-289

other work was not performed, so the risk of the maintenance was not recognized. (Failure to recognize the difference between the relay configuration of the suction isolation valve and other installations was also a factor, but this problem would not be influenced by the type of work management system.)

The on-line maintenance work management program may have influenced this problem in two ways:

- Work that can be done on-line is kept out of the outage.
- Reviews of work for risk are conducted while the schedule is being developed and whenever the schedule is changed.

Case 3 -- Loss of Containment Pressure Sensing Capability Because of Improper Maintenance Control[99]

Overview

In March 1994, following the refueling outage of a pressurized water reactor, containment pressure sensing lines were mistakenly capped by two maintenance workers during a containment closeout inspection. The workers acted on their own initiative to cap four of the sensing lines, and the imprecise communication between the workers, their supervisor, and system engineering did not reveal which of these containment penetrations had been capped. As a result of this change to plant configuration, the control room had inaccurate indication of pressure in containment. The problem was discovered four days later, during containment venting, when no indication of containment pressure change was detected.

The walkdown being conducted by the workers involved installing caps on specified lines. The workers were working from a work list of lines and penetrations that required caps. During walkdown, the pressure sensing lines were found to not have caps, and the workers felt that they were authorized to install caps on these lines in addition to the caps specified. The following problems contributed to this event.

- Communication between the workers and their supervisors was not clear, and there was no follow-up by the supervisors after the job to determine what containment penetrations had actually been capped.

- Some confusing information was provided in work documents. The work list of open lines was inaccurate in that it identified four abandoned lines and a spare penetration for capping; in actuality, there were only two open lines needing caps and no

[99] Licensee Event Report No. 94-003-00, Docket No. 50-249, April 22, 1994

penetrations requiring caps. Also, there were no unique identifying marks on the penetrations -- a "map" of the outside containment wall vertical pipe chase was provided, which required the workers to transpose it to reflect an inside containment wall aspect.

- The expansion of the original scope of the walkdown was outside the guidelines for conducting minor maintenance instruction. The minor maintenance instruction excludes making alterations or configuration changes to plant equipment.

Discussion

This event illustrates the following key points:

- Workers must have a firm understanding of program guidelines, and work within them. In this event, the minor maintenance guidelines were violated in that configuration changes were made. In actuality, the workers did not recognize that expanding the scope of work in choosing to cap these pipes was *not* minor maintenance. Strong on-line maintenance work management programs that place high reliance upon workers making maintenance decisions in the field emphasize a thorough understanding of program guidelines. The more latitude workers are provided, the more important knowledge of and adherence to guidelines becomes.

- Clear communication is vital. In this event, communication between the supervisors and workers about expanding the work scope was inadequate, the identification of the pipes capped was miscommunication to the system engineers, and the quality of work documents was low.

- Ownership is important to effectiveness of programs that provide worker latitude. The worker's error may actually be an example of taking ownership, in that the self-initiative exercised was an attempt to improve efficiency. However, the supervisors' failure to check on the work done may indicate insufficient ownership. Strong on-line maintenance programs emphasize ownership through fostering teamwork and individual accountability.

Case 4 -- Loss of Reactor Coolant During Incompatible Operations Evolutions[100]

Overview

In September 1994, at a pressurized water reactor during the early stages of an outage, two incompatible activities were accomplished concurrently that resulted in a draindown of 9,200 gallons from the reactor coolant system to the refueling water storage tank. The draindown occurred when a recently-maintained valve was stroked to seat its packing while another valve in the system was being positioned to recirculate a train of the residual heat removal system. The operation of both of these valves concurrently created a flow path from the reactor coolant system to the refueling water storage tank, causing a rapid loss of primary coolant. The problem was immediately recognized and corrected; however, if immediate action had not been taken, suction from the on-line residual heat removal pump would have been lost.

The B-train of the residual heat removal was being placed into a recirculation mode to sample and adjust the system boron concentration. This was necessary because minor check valve leakage was diluting the boron concentration in the B loop. Placing the B-train in recirculation involved an auxiliary operator opening a manual 8-inch valve that isolates the reactor water storage tank from the common emergency core cooling system pump suction header.

Meanwhile, the packing of the "A" hot leg recirculation loops 2 & 3 isolation valve had just been completed, and control room operators stroked the valve twice to seat the packing and test the motor operator.

No problem was noted during the first stroke of the "A" valve because the auxiliary operator had just started opening the manual valve. However, when the "A"

[100] Licensee Event Report No. 94-013-00, docket No. 50-482, January 4, 1995

valve was stroked the second time, the manual valve was fully open, completing the draindown path. The operators immediately closed the "A" valve, but the stroke time was such that a significant amount of coolant was drained.

The following problems contributed to this event:

- The materiel condition of the check valve caused the slow dilution of the "B" train, which made it necessary to recirculate the system per station instructions.

- It was not recognized by the operators that stroking the "A" valve and putting the "B" train in a recirculation mode were incompatible.

- Administrative controls were not effective in preventing this event. Controls of valves that can contribute to an inter-system loss-of-coolant accident were not in place.

Discussion

This event illustrates the following key points:

- The cumulative effect of work activities can have a significant effect on plant operations. Either of these activities alone would have been inconsequential, but became a problem when accomplished together. Strong on-line maintenance programs provide for the review of the cumulative effects of system lineups and activities. On-line maintenance programs also attempt to reduce the number of jobs accomplished during periods of high work activities (such as outages) by moving work scope into on-line periods.[101] Some stations have computer software ("risk monitors") that allow for rapid review of the effects of lineups on the current plant situation.

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[101] In this case, the problem probably was not discovered when the plant was on-line. The packing leak was more likely discovered when the system was put into operation after shutdown, and the packing adjustment had to be made during that time. Nevertheless, the point is still valid -- reducing the number of jobs accomplished in parallel through scope control can reduce the adverse cumulative work effects.

- Materiel condition of the plant is wide-ranging in its effects. In this case, a small materiel condition discrepancy in the check valve created a condition (low boron concentration) that directly influenced an operational decision, and thereby became part of an event initiator. Strong on-line maintenance work management programs (and the strong organizational factors that frequently accompany such programs) are able to improve materiel condition, as discussed in Section 4.3.1.2.

- Maintenance of a residual heat removal system valve during a critical period when the system was needed contributed to risk. In this case, it may well be that the packing leak was not recognized until the system was lined up for service, that is, the problem was not identifiable during operations. Even so, it is valid to say that had the maintenance of the valve not been necessary, the draindown would not have occurred. Many strong work management programs avoid work on important systems when the importance of their trouble-free operation is high.

Case 5 -- On-line Maintenance During Heavy Weather Conditions[102]

In May 1995, a pressurized water reactor, while at power, elected to conduct maintenance on a diesel generator while a tornado watch was in effect. Although control room operators were aware of the storm and had ensured that the maintenance was suspended until the storm had bypassed the plant, transmission lines, which are part of the station's defense-in-depth, were still at risk. As a result, maintenance was conducted on a key source of electric power while a contingency power source's availability was threatened.

This is an example of how a station can have a strong on-line maintenance program, as this station did, and yet still overlook an aspect that results in a non-conservative decision being made.

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[102] This situation was personally observed.