Nuclear Power Plant Surveillance Issues for Extended Operating Cycles

by
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ABSTRACT

Commercial nuclear power plants are a vital part of the national energy program. Their competitiveness in the electrical generation market has been compromised by low fossil fuel costs and extensive regulatory oversight. One strategy to improve plant competitiveness is to increase capacity factors through the use of longer operating cycles. The MIT project on, "Improvement in Nuclear Plant Capacity Factors Through Longer Cycle Length Operation," is investigating and developing the feasibility and practical application of a strategy to extend operating cycles to as long as 48 calendar months.

One of the primary requirements of any extended operating cycle program is the reconciliation of plant surveillance activities to the longer interval between refueling outages. This thesis builds on previous work by project group members to complete a proposed extended cycle surveillance program that modifies all surveillances at two case study plants to make them compatible with a 48 month operating cycle. This proposed program recommends modifications to those surveillance activities that would currently prohibit longer cycle operations by moving them to an on-line performance mode or by extending their performance interval to 48 months. The few surveillances that are unable to be modified are left as unresolved pending further work, although some thoughts on possible solutions are presented. The results of the case study surveillance program demonstrate that plant surveillance activities are not likely to limit operating cycle extension within the range of 24 to 48 months.

The proposed extended cycle surveillance program differs substantially from current surveillance programs in the nuclear power industry and would have a number of impacts on plant operations. Some of these impacts are discussed, including increases in plant surveillance workloads and lengthening of refueling outage durations for a 48 month operating cycle. Based on this analysis, the proposed surveillance program is found to be feasible and acceptable for nuclear plant operations.

Finally, a more general study of surveillance effectiveness is undertaken. This section examines preventive maintenance activities and provides a framework for how the surveillance effectiveness can be qualified. This qualification includes the efficient allocation of maintenance effort to counter dominant modes of degradation as well optimized surveillance performance intervals to maximize net economic benefit.

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1. Introduction

1.1. Research Impetus

1.1.1. Industry Background

For many years, electric utility companies have operated under the franchise monopoly model in which the government has guaranteed power providers with uncontested geographic markets in exchange for certain service agreements. This compact has been heavily regulated by federal and state law, in addition to the public utility commissions which bear the responsibility of ensuring efficient and equitable service in the monopolistic environment. The enactment of the federal Energy Policy Act in 1992 signaled a dramatic watershed in the future of the American energy industry. The convergence of this policy shift with advancements in power generation and transmission technology is rapidly pushing utility companies into a tumultuous deregulated power market.

While this move towards free market control may eventually lead to a more efficient and diverse power sector, in the short term it represents a real crisis for the established utility companies. The combination of guaranteed market franchise and highly intrusive regulation has produced a unique economic environment. This environment is characterized by almost zero risk capital investment recovery due to regulated rate base costs and guaranteed captive markets, as well as government intervention in contracting, diversification and service requirements. These unique constraints are economically optimized by extremely large, long term capital investment. While electrical demand was increasing at an average of 7% per year and fuel costs were rising dramatically through the 1960s and 1970s,[1] the major utilities incorporated continued growth projections into their investment strategies. The result was the construction of the U.S. fleet of large central station nuclear power plants.

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[1] Bisconti, Ann, Vice President of the Nuclear Energy Institute. Personal Interview. 20 November 1995.

Twenty years later the utility companies find themselves in a dramatically different world. As the growth rate for electrical demand slowed to a crawl and fossil fuel prices actually fell, nuclear plant construction and operating costs soared to unforeseen levels. With the sudden removal of a guaranteed rate base to subsidize these investment deficiencies, the utility companies are finding themselves with millions of dollars of unrecovered capital debt in the form of nuclear power plants. While recent, intense reformation efforts have managed to bring nuclear operating costs in line with conventional plants, the billions of dollars in debt remaining from nuclear construction continues to hang over the industry and threaten its competitiveness in the open market.

1.1.2. Nuclear Competitiveness

Nuclear invested utility companies clearly face a challenge of either making their nuclear plants economically competitive or suffering enormous financial losses. This is a daunting prospect given the relative disadvantages that current nuclear plants face. From an engineering perspective, nuclear plants are technically more complex than comparable coal and gas fired plants and therefore required greater initial capital investment. These larger capital costs were amplified by the higher interest rates during the 1970's and early 1980's, when the majority of nuclear plants were built, relative to the low interest financing of new conventional plant construction. Because of the greater technical complexity, nuclear plants also require larger budgets for manpower and operating expenses. Most importantly of all, nuclear regulatory requirements have exacerbated all of these factors and absorbed an enormous amount of financial and human resources.

The single positive economic factor that nuclear power plants have on their side is their dramatically lower fuel costs. Even with enrichment, handling, and disposal costs, the price of uranium per kilowatt hour is significantly lower than for coal or natural gas. Therefore, the key to improving the competitiveness of nuclear power plants in an open energy market is maximizing the fuel cost advantage. Fuel costs are fundamentally different from the other economic factors mentioned above because they are directly proportional to the level of revenue generating electrical output. While the capital and interest costs, manpower, and operating expenses are generally constant over the life of the plant, fuel costs are dependent on plant operational performance. If the key to nuclear competitiveness lies in exploiting the fuel cost advantage, then the electrical output of nuclear power plants must be maximized.

1.1.3. Capacity Factor

In order to quantify the extent to which an existing power plant is taking advantage of its fuel cost margin by maximizing power production, an appropriate performance indicator is required. Among the several indicators used in the nuclear industry, capacity factor is the most direct measure of power output maximization. The capacity factor is defined as the ratio of the amount of electrical energy produced by a plant in a given time period over the theoretical maximum amount of electricity that the plant could have produced in that time;

$$\text{Capacity Factor} = \frac{\text{Actual Electricity Production}}{\text{Maximum Possible Electricity Production}}. \tag{1}$$

Because nearly all nuclear power plants in the United States are operated at full power as base-load generators, the capacity factor can be thought of more simply as the number of days that the plant is running divided by the number of days that the plant is shutdown over a given period of time. Overall annual plant capacity factors for U.S. units range from less than 20% to more than 90%, with a 1993 to 1995 industry average of 73.54%.[2]

A plant's capacity factor value is a function of three parameters that impact a unit's ability to generate electricity. The first parameter is the plant's Forced Outage Rate (FOR), which is actually a dimensionless fraction of plant forced outage time over operational time. Assuming a non-dispatched base-load plant, a forced outage is defined as any interval that the plant is off-line except for planned refueling outage periods. Forced outages are most often caused by equipment failure or operator error. The second parameter is the Refueling Outage (RFO) length. Light water reactor plants run on an operating cycle in which every 12 to 24 months they shut down to refuel the core and perform maintenance activities. The RFO length is simply the duration of this planned shutdown period. The third parameter is the plant's operating cycle length. The operating cycle

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[2] "Generation by Nation." Nucleonics Week 8 February 1996: 8

length is defined as the planned interval between consecutive RFO shutdowns. The cycle length influences capacity factor because it determines how often the plant will enter a RFO and therefore affects the total number of shutdown days.

From these definitions, it is clear that nuclear power plants can be made more competitive by improving their capacity factors through FOR reduction, RFO length reduction, and operating cycle extension. As shown in Figures 1 and 2, both the FOR [3] and RFO [4] length averages for the nuclear industry have been steadily declining. These capacity factor contributors have received significant attention, both from nuclear engineers and utility managers, and have returned the invested industry effort through increased plant performance and revenues.

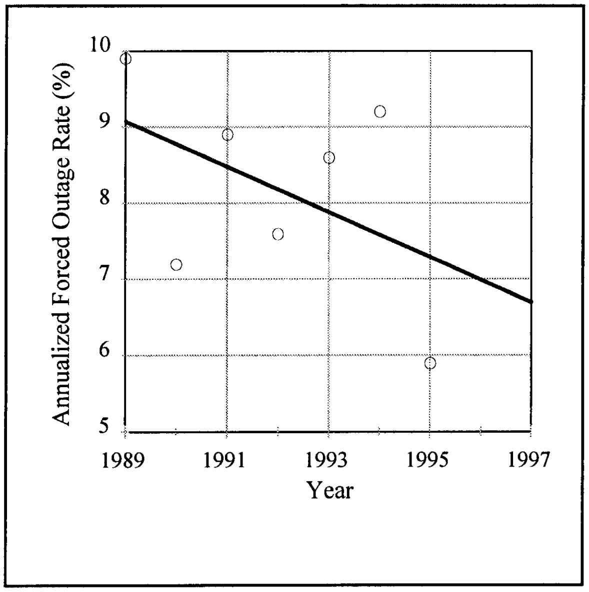

Figure 1: Industry Average Annualized FOR Trend for 1989-1997 [3]

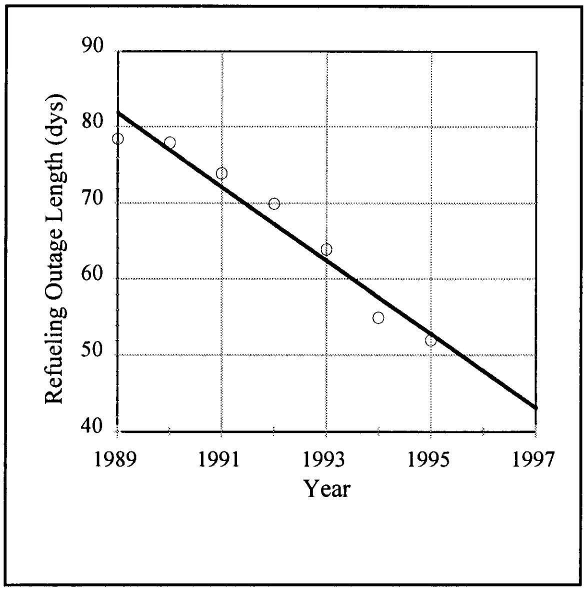

Figure 2: Industry Average RFO Length Trend for 1989-1997 [4]

1.1.4. Operating Cycle Extension

While improvements in FOR and RFO length have been used to increase plant capacity factors, there has been less widespread adoption of extended operating cycles within the nuclear industry. This is most likely due to the fact that FOR and RFO length reduction are purely operational objectives, while operating cycle extension requires modified core designs. The added

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[3] Russell, William T., USNRC. Presentation, MIT Reactor Safety Course. Cambridge MA, 16 July 1996.

[4] Pate, Zack T., INPO. Presentation, MIT Reactor Safety Course. Cambridge MA, 17 July 1996.

expense and complexity of changes to the fuel and core have made the other options more potent targets for limited investment dollars. After years of being the center of focus, however, the marginal benefit of further efforts to improve FORs and RFO lengths is diminishing. The best performing plants have achieved FORs of 1-2% and have cut their RFOs to 20 days.[5] Even if U.S. plants were to adopt the Finnish strategy of using short 12 month operating cycles to reduce FORs and shorten RFOs, continued improvement in these factors is unlikely due to differences in plant design and operation. Both areas of performance, and especially RFO lengths, are approaching the limits of economic and feasible advancement. Operating cycle lengths, in contrast, have not reached nearly the same level of optimization. Most plants were originally designed for 12 month operating cycles, and the vast majority have since moved to 18 month cycles. Subsequently, less than one fifth of the U.S. fleet has attempted to move beyond 18 months[6], despite considerable remaining margin for capacity factor improvement. This available margin for capacity factor improvement through cycle length extension is illustrated in Figure 3. Here the capacity factor versus cycle length curves are shown for various levels of plant performance. As performance levels rise, it is clear that a forward looking effort to further improve nuclear plant capacity factors must examine operating cycle length extension.

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[5] Limerick Generating Station. Research Meeting. Sanatoga PA, 22 November 1996.

[6] Moore, T., et al. "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors." MIT Nuclear Engineering Department, MIT-ANP-TR-036 (June 1996): 20

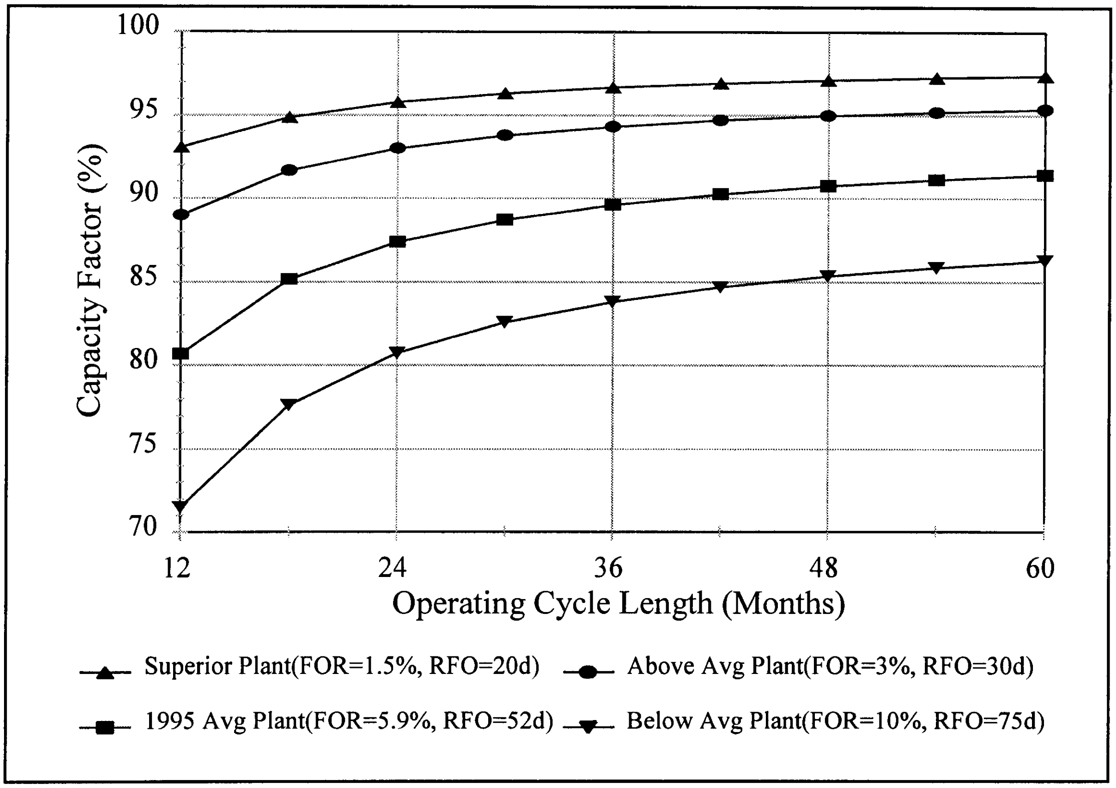

Figure 3: Capacity Factor Versus Operating Cycle Length for Various Levels of Plant Performance

1.2. MIT Extended Operating Cycle Research Project

A research effort has been underway within the MIT Nuclear Engineering Department since June of 1995 with the primary goal of examining extended operating cycles for commercial nuclear power plants and evaluating their technical feasibility. The project is sponsored by the Idaho National Engineering Laboratory University Research Consortium, and has been funded through the end of calendar year 1997. The project group is headed by Professor Neil Todreas, and is based on contributions from nuclear engineering faculty and graduate students, and a variety of nuclear industry and government collaborators.

Implementation of an extended operating cycle beyond 24 months will require both an engineering assessment of its technical feasibility and a determination of its economic profitability. The assessment of technical feasibility can be subdivided into three primary requirements. The first is the development of BWR and PWR reload cores that can facilitate extended cycle operation. These core designs must conform to existing plant and regulatory conditions without incurring cost penalties that negate the benefit of extended operating cycles. Once a satisfactory core is available, it must be shown that the balance of plant components can tolerate the longer operating cycle. Each of the components within the nuclear power plant must be maintained and tested according to regulatory requirements and sound economic investment protection. The majority of this maintenance and testing is currently done during the RFOs. If the operating cycle is extended, the requirements of the components must be reconciled with the longer interval between RFO periods. After demonstrating that the plant and core can run on an extended cycle, an evaluation must be made of plant availability performance. FOR reductions inherent in longer length operating cycles must be found in order to achieve economic profitability from the desired capacity factor improvement. Finally, this complete assessment of technical feasibility must be incorporated into an economic analysis that demonstrates an increase in plant revenue for an extended cycle relative to current operations.

1.2.1. Core Design

The first major area work is that of designing reload cores for existing PWR and BWR plants that are capable of sustaining extended cycle operations at rated power. The purpose of this work is to use state of the art nuclear design packages to evaluate the feasibility and costs of an extended operating cycle core, considering the full range of practical design and economic considerations. The computer codes being used are the CASMO-3/TABLES-3/SIMULATE-3 reactor analysis suite developed by Studsvik. These powerful, licensing level codes allow a high quality analysis of the core design. Additionally, MCNP4A (Monte Carlo N-Particle Transport Code System) is being used to evaluate reactor vessel fast flux radiation embrittlement damage. The PWR design is in its final stages, and the analysis has considered performance factors including maximum enthalpy rise hot channel factor, core critical boron concentration, core reactivity coefficients, and control rod worth.

The design is a $7^{w}/_{0}$ U^{235}, single batch reload core for a 48 month fuel cycle that does not exceed current fuel burnup limits. It uses Gadolinium (Gd_2O_3) mixed with the fuel of selected pins to hold down initial reactivity and control flux peaking, and IFBA (ZrB_2 Integral Fuel Burnable Absorber) as a coating on the poisoned pins to reduce the critical soluble boron concentration. Work is currently underway to complete a similar design for BWR plants.

1.2.2. Surveillance Requirements

The second major area of project work is the reconciliation of plant surveillance activities to the extended operating cycle. The goal in this area is to demonstrate that surveillance activities will not prohibit cycle extension beyond the current 24 month experience and to evaluate the impacts of an extended cycle on the surveillance program. In order to satisfy this goal, a PWR and a BWR plant were selected for case studies. Because economically optimal extended cycle lengths were not available at the beginning of work in this area, a 48 month target cycle length was selected. This length was chosen because, as seen in Figure 3 on page 22, the slope of the capacity factor curves are relatively flat beyond this point and because it represents an ambitious but feasible doubling of current 24 month operations. The complete surveillance programs were analyzed at the case study plants, and any surveillance activity that restricted cycle extension to 48 months was modified. The modified surveillances were compiled into an extended cycle surveillance program. Following this demonstration of the ability of current surveillance programs to be extended to 48 month operating cycles, the impact of the extended cycle surveillance program on plant operations was evaluated.

1.2.3. Availability Performance

A nuclear unit is "available" when it is free from critical failures and able to produce electrical energy at full capacity. The availability of a plant is defined as the probability that it will be in an operational state at any specific point in time. It is therefore an informative performance indicator and plays an important role in the ultimate success of an extended operating cycle effort. There are two primary project objectives in this area of work. These are to determine the level of plant availability required to make the extended operating cycles economically attractive, and to explore strategies to achieve this level of performance. Within this topic it is important to differentiate performance improvement strategies that can be applied to all cycle lengths with equal benefit from those strategies that are uniquely inherent to extended cycle operations. It is hypothesized that maintaining longer steady state periods of plant operation will provide these inherent FOR reductions. To meet these objectives and evaluate the hypotheses, probabilistic risk assessment methods are applied to a wide variety of historical data from the nuclear industry including plant performance records, system and component failure data, and plant maintenance and repair records. While the core designs and surveillance analysis are aimed at determining if extended operating cycles are possible, it is this portion of the project that will establish if longer operating cycles are truly beneficial to the nuclear industry.

1.2.4. Economic Analysis

The goal of the project economic analysis is to quantify the many plant performance factors that are affected by cycle length variations and to use these factors in a simple economic model to determine the optimum operating cycle length. The economic factors are divided into the two basic categories of fuel cycle costs and operations and maintenance costs. In general, a longer cycle length core design incurs added fuel cycle costs relative to current operations, but extended cycles generate greater revenue with lower operating costs to offset the losses. While wide variations in the core designs and economic factor values prohibit an accurate optimal cycle length result to date, the initial results indicate that a single batch PWR core generates the greatest revenue around a 36 month operating cycle, and a single batch BWR core is optimized near a 48 month cycle.

1.3. Thesis Goals

Within the broader scope of the MIT research project on extended operating cycles, the work included in this thesis is directed solely towards the area of plant surveillance requirements. Previous members of the project team made substantial progress in analyzing surveillances at the case study plants, and this thesis builds on that work to complete the extended cycle surveillance program. The primary objective is to determine if the surveillance modification research can be formed into a credible extended operating cycle surveillance program, and if such a program is feasible and acceptable for plant operations. To complete these objectives, this thesis will analyze three distinct questions as described below.

1.3.1. Will Plant Surveillance Activities Inhibit Extended Operating Cycles?

An integral part of an operating cycle extension justification is a thorough analysis of the ability of plant surveillance activities to be reconciled to the longer interval between RFOs. This analysis can be satisfied on a case study basis by creating a complete surveillance program that is coordinated with a significantly longer operating cycle. For this research, a PWR and a BWR plant were used as case studies for cycle extension to 48 months. Previous project group members completed the initial surveillance analysis and modification for the PWR plant and for the regulatory based surveillances at the BWR plant. This thesis will complete the BWR surveillance reconciliation by identifying all non-regulatory based activities, analyzing modification options, and constructing a surveillance program that is compatible with 48 month cycle operation. With this final portion of the surveillance analysis complete, the results of the case study process will be analyzed and formed into a proposed 48 month operating cycle surveillance program. If a complete extended cycle program can be constructed for the case study plants, it will serve as a credible demonstration that surveillance activities will not inhibit the adoption of extended operating cycles.

1.3.2. Are the Impacts of an Extended Operating Cycle Surveillance Program Acceptable?

Following the completion of the extended operating cycle surveillance program, it must be evaluated to determine its effect on plant operations and economics. First, a number of wide ranging general issues related to surveillance reconciliation to longer operating cycles will be presented. More specifically, the modified surveillance program will have a significant impact on surveillance workloads during RFO periods, and the magnitude of this impact will be evaluated. Finally, the increased surveillance workload in RFO periods will be studied to produce an estimate of any possible increase in RFO lengths for the extended operating cycle. The identification and resolution of these secondary issues will demonstrate that the extended cycle surveillance program is not only possible, but realistic and acceptable for plant operations.

1.3.3. How Can Maintenance Surveillance Effectiveness be Evaluated?

Within the topical area of surveillance performance, a more general analysis of the qualification of preventive maintenance surveillance effectiveness will be performed. The goals of this analysis are to present a framework to evaluate the ability of maintenance activities to counter dominant degradation modes and to economically optimize the surveillance performance intervals. This analysis will include the example of 4.16 kV breaker maintenance performed within the electrical distribution system of the case study BWR plant.

2. Extended Operating Cycle Surveillance Program

2.1. Purpose

The objective of this section is to complete the surveillance modifications for the case study BWR plant and create an extended cycle surveillance program. This program will reconcile all surveillance activities at the case study plants to a 48 month cycle and serve as a credible demonstration that plant surveillance activities need not prohibit extended operating cycles. Additionally, the framework for surveillance reconciliation to the extended operating cycle and the general results should prove useful for utilities that are considering the adoption of an extended cycle. Finally, the early identification of those surveillance related issues that require further study prior to cycle implementation will allow adequate time for the completion of efforts to find adequate solutions.

2.2. Methodology

The completion of the 48 month extended cycle surveillance program has required the work of several graduate students within the extended operating cycles research project. This thesis builds on the efforts of those previous project members, and adopts the basic methodology used to reconcile each surveillance activity to the extended operating cycle from the work of Thomas Moore and Jason Maurer.[7] The following is a summary of that methodology, modified and amplified to represent its actual application to this work. It should also be noted that while the case study PWR plant is included in the proposed extended cycle surveillance program, the research conducted for this thesis

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[7] Moore, T., et al. "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors." MIT Nuclear Engineering Department, MIT-ANP-TR-036 (June 1996): 27-54

was conducted exclusively at the case study BWR plant. Therefore, the following methodology has been tailored to reflect the BWR plant data sources and characteristics.

2.2.1. Definitions

The term "surveillance" encompasses many activities performed within nuclear power plants. As used here, it refers to any cyclical maintenance or testing task that is undertaken on plant equipment. These surveillance tasks are initiated for two reasons. The first is to satisfy regulatory requirements. Regulatory surveillances are specifically designed to meet the stipulations listed in the plant's licensing basis and technical specifications, or required by any of a variety of oversight agencies. Examples of this type of surveillance are Emergency Core Cooling System (ECCS) functional testing, Emergency Diesel Generator (EDG) testing, and isolation valve leak rate testing. These surveillances usually involve critical safety functions and are intended to insure the safe and responsible operation of the plant. The remaining surveillances are initiated at the plant or utility level and are intended to protect the capital investment in plant components and maximize operational performance. Examples of this type of surveillance are main turbine maintenance, steam bypass valve overhauls, and condenser waterbox cleaning. While these economically motivated surveillances are equally important from the perspective of the utility company, they are typically easier to modify because there are no external restrictions on performance modes and intervals.

Surveillance activities can also be classified according to their performance mode. A surveillance can be performed "on-line" while the plant is in an operating state and producing electrical power, or "off-line" while the plant is shutdown in a forced outage or RFO. On-line surveillances are typically non-intrusive monitoring or involve redundant systems that can be safely taken out of service. Examples of this type of surveillance include thermography of electrical breakers, vibration testing of pumps, and maintenance on the Residual Heat Removal (RHR) system. Off-line surveillances must be performed with the unit shutdown because they are performed in areas that are inaccessible at power, take vital equipment out of service, or would put the plant in a configuration with unacceptably high risk. Examples of these include in core radiation monitor calibrations, primary pressure boundary valve overhauls, and main feed or recirculation pump overhauls.

2.2.2. Surveillance Resolution Options

The objective of this extended cycle surveillance program is to demonstrate that all surveillance activities can be modified to conform to a 48 month extended operating cycle. The surveillances that require modification are those that are performed off-line at intervals less than 48 months. Without a planned off-line period within that 48 month cycle, these surveillances will not be able to be completed according to current procedures. In order to reconcile the surveillances to the longer cycle, they can be modified in one of two ways. First, the performance mode can be changed so that the surveillance can be performed on-line. On-line surveillances do not require planned outage windows and are generally independent of operating cycle length. The other alternative is to extend the surveillance performance interval. If a technical justification can be made that extending the performance interval will not have an adverse effect on plant operations or component lifetime, it can be deferred until the next 48 month planned RFO.

It is important to note that surveillances were analyzed with a focus on the physical limitations of the system rather than the legal limitations. Surveillances that clearly supported safe on-line performance but whose corresponding technical specification called for shutdown performance were still classified as candidates for on-line performance. If a surveillance's historical record suggested that an extended performance interval was justified, then it was classified as a candidate for interval extension even if legal limitations to a 48 month interval might currently exist. This methodology was adopted in light of the fact that legal obstacles can be overcome if the technical case is made for either on-line performance or interval extension.

2.2.2.1. Unavailability Analysis for Surveillance Modifications

In order to justify the modification of a current surveillance activity by moving it on-line or extending its performance interval, some evaluation must be made of the net effect the modification will have on the safety and economics of the component. While the proposed modifications need not be risk and cost neutral in every case, these factors must be considered to prevent the final proposed extended cycle surveillance program from significantly degrading current safety and performance levels.

The primary parameter relevant to surveillance modifications is the unavailability (Q(t)) of the associated components and systems. The unavailability represents the probability that the equipment will be failed at any specific time (t) given that it was operational at some base time (t_o). Component failure is significant from both safety and economic perspectives. A failed component in a reactor control or accident remediation role can increase the risk of negative impacts within the plant and in the surrounding environment. For all components, failures incur economic costs of repairing the failure, repairing secondary damage caused by the failure, and the possible loss of revenue due to decreased plant electrical energy generation. The goal of all surveillance activities is to decrease equipment unavailability by either resetting the random failure curve through functional testing or improving the shape of the unavailability curve through preventive maintenance.

The specific behavior of the unavailability curve for each component is influenced by a number of factors. For reference, a figurative unavailability plot for a standby safety component is shown as Figure 4. At time t_o, there is some immediate probability that the component will be failed due to pre-existing defects, causing an initial unavailability Q_o. The unavailability curve then increases with time as random failures can occur. This is governed by the exponential function, $Q_{Random} = 1 - (e^{-\lambda t})$, where λ is the component failure rate. At time t_s, the surveillance activity is performed, which can take the component out of service and cause the unavailability to go to a value of 1.0. This surveillance test lasts for a duration of t_t, after which there is some probability (f_o) that the component will fail the test and will be out of service for a repair duration of t_r. Subsequent to the surveillance test and possible repair, the component is restored to an improved state characterized by unavailability Q_1. The value of Q_1 is always greater than Q_o because all possible failure modes cannot be tested and because the test and repair process can introduce its own defects and errors.

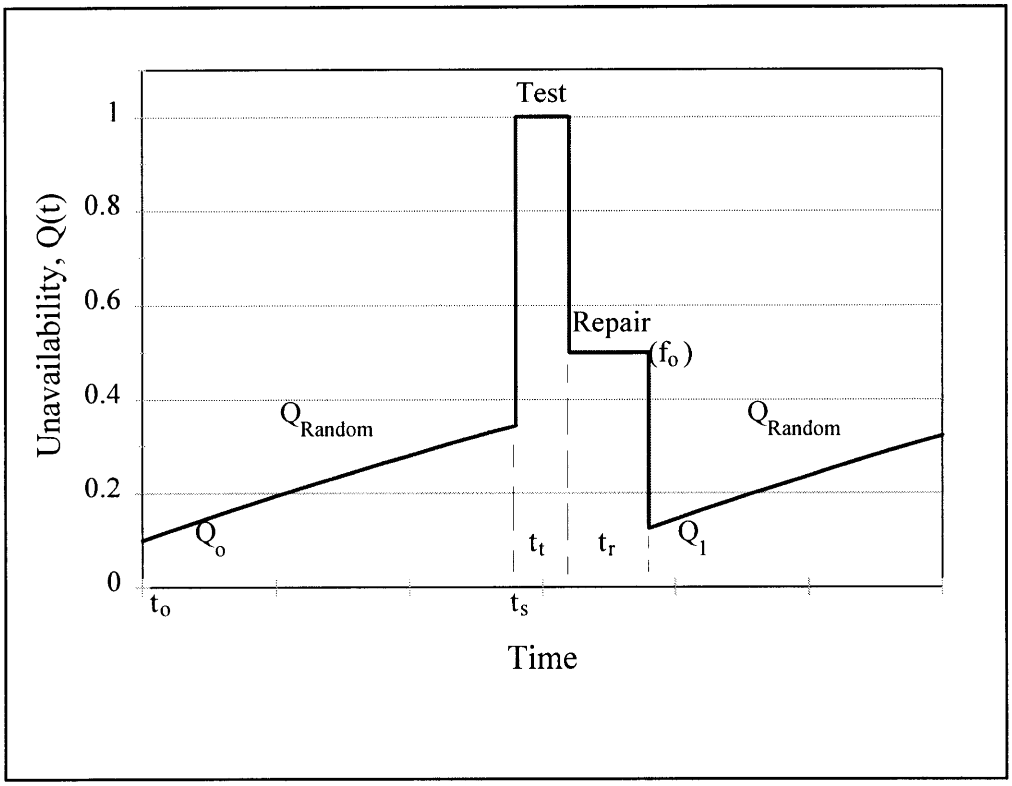

Figure 4: Figurative Unavailability Curve for Standby Components

While Figure 4 is not representative of all surveillance activities for all components, it does introduce the language of unavailability analysis. In the subsequent surveillance program resolution of Section 2.3, it is the type of unavailability consideration discussed here that underlies all modification recommendations. For example, if a surveillance activity is to be recommended for on-line performance, it must be determined if it is an intrusive procedure that requires that the component be taken out of service, thereby increasing the unavailability as shown, or if it is a non-intrusive procedure that can result in decreased unavailability through more frequent testing. For off-line surveillances that are being considered for performance interval extension, an evaluation must be made to determine the likely influence the longer interval between maintenance and testing periods will have on component unavailability. This relationship can be explored by reviewing historical surveillance and failure data at the specific plant of interest and throughout the nuclear industry. If a surveillance modification is recommended, it implies that the unavailability is not expected to change significantly or that any increased unavailability will not have a discernable impact on plant safety or economic performance.

2.2.2.2. On-Line Surveillance Performance

In addition to component unavailabilities, there are other factors that influence the decision to modify surveillance performance modes. Performing surveillance activities on-line has a number of advantages. The foremost of these is the reduction of RFO workloads. Given a fixed number of surveillance activities that have to be completed within a 48 month operating cycle, they must be divided into on-line surveillances distributed over the 47 months of operational time, and off-line surveillances scheduled into the 1 month of planned shutdown time. The more surveillances that can be done on-line, the shorter the RFO period can be. Even if surveillance activities are not directly on the critical path for RFO completion, reducing the RFO workload can indirectly shorten outages by freeing human resources to deal with emergent work items that often do enter the critical path. During refueling outages, the number of tasks performed and the increased manning levels generate a degree of fatigue and complexity not experienced during normal plant operations. Senior engineering oversight gets stretched thin when many people are performing many different activities at once. In contrast, on-line surveillance performance can be afforded much greater oversight and planning. Consequently, on-line surveillance performance may result in higher quality maintenance and more precise test execution.

Another human factor advantage associated with performing a surveillance on-line is the increased probability of it being performed by full-time plant employees rather than more expensive outside contractors. The magnitude of the work to be done during a refueling outage and the incentive to minimize the outage length means that outside contractors are often hired to perform a significant portion of the outage surveillances. If a surveillance can be performed on-line, the relatively light daily plant workload facilitates surveillance performance by full-time plant personnel. This results in two direct benefits. The first is the increased attention afforded the surveillance since the plant employee has an ownership stake in the day to day performance of the component or system. The second direct benefit resulting from surveillance performance by plant personnel is increased component and tasking familiarity. Reading the report of a surveillance performed by a contractor can only communicate a certain level of knowledge about the true component condition. Having a permanent employee on-site everyday who performed the latest diagnostic checks of a component and is intimately aware of the results of those checks is extremely valuable. Such a person is more likely to understand potential failure mechanisms and identify trends in component performance.

On-line performance is also advantageous because it allows for more flexibility in surveillance performance intervals and is well suited to condition based maintenance programs. If a component demonstrates poor performance, non-intrusive surveillances may assist in predicting component failure. Failure mechanisms can then be diagnosed and corrected before catastrophic component failure occurs. In this way, on-line surveillance performance provides an enhanced component monitoring capability. This monitoring capability may ultimately result in improved equipment performance. If preventive maintenance and diagnostic checks can be performed whenever a problem is suspected rather than at set intervals dictated by the refueling outages, then problems can be avoided. For example, if the oil can be changed on-line whenever a motor exceeds a certain amount of run time rather than at set calendar intervals, it is likely that the motor will last longer.

While there are many advantages to on-line surveillance performance, it is not risk free. The safety and economic impacts of taking systems out of service for surveillance performance must be carefully considered prior to any on-line work. On-line, Probabilistic Risk Assessment (PRA) based risk monitors can play an important role in surveillance planning. They greatly enhance the ability of plant personnel to identify potentially hazardous system configurations. However, they do not consider economic risks from on-line surveillance performance and they are not substitutes for thorough preparation and training of the workers who will actually be performing the surveillance. Senior management must ensure that everyone involved in on-line surveillance performance understands the possible complications of the proposed work. Surveillance performance can often have a significant effect on other seemingly independent equipment. For example, many instrument calibrations are fairly routine when they are performed during an outage. But, if they are performed on-line, simply valving an instrument in and out of the system can cause potentially dangerous fluctuations in other instruments monitoring vital plant parameters. Workers must thoroughly understand system interdependencies such as these when they perform any surveillance during power operations.

2.2.2.3. Surveillance Performance Interval Extension

For those surveillance activities that cannot be moved to the on-line work scope, the next alternative is to evaluate the surveillance performance interval for possible extension. During the early years of the nuclear power industry, plant engineers had very little operating experience upon which to base component reliability judgments. Consequently, it was not unusual for plants to come off-line every few months only to test vital systems. While the industry has progressed beyond this overly conservative mentality, many current surveillance intervals are still an indirect consequence of that reasoning. Intervals started out as conservatively short and have been gradually extended to meet plant operating cycle length requirements, but not necessarily as determined by component performance. As a result, many performance intervals have not been optimized. This cycle driven interval basis is evident in the non-quantitative surveillance performance extension requirements mandated by NRC Generic Letter 91-04 for utilities going from eighteen to twenty-four month fuel cycles. Extension requests rely on expert opinion and historical surveillance data to make the case that a surveillance interval can be safely extended. This method was chosen because no quantitative methodology for optimizing performance intervals currently exists. An optimization methodology would facilitate justifying the extension of performance intervals for surveillances that currently have overly conservative intervals. If a component has been in service for a significant period and has never failed or been found out of specification, it is reasonable to question whether the performance interval can be increased. Surveillance performance requires time and labor. Resources are poorly allocated if they go toward over-testing a proven component. Frequent testing can also contribute to equipment wear-out.

2.2.3. Data Collection

The first step towards developing the extended cycle surveillance program is analyzing the current plant surveillance programs to identify which surveillance activities require modification. At the case study BWR plant, the current surveillance program is contained within a Unix database called the Master Surveillance Tracking Program (MSTP). The MSTP contains every active surveillance task including related information such as the governing procedure, performance interval, required plant mode, performing division, and completion and due dates. In order to facilitate logical queries of this database, it was downloaded and converted into a Paradox[8] file for further manipulation. With the data in this form, a simple series of queries was used to isolate the surveillance activities that prohibit a 48 month operating cycle. The first step was to extract only those surveillances that are performed off-line. Surveillances performed on-line are assumed to be compatible with any operating cycle length and are not considered further in this analysis. A second query was made to extract those remaining surveillances that have performance intervals of less than 48 months. The surveillances with intervals of 48 months or greater can be performed during RFOs on a 48 month cycle and are also not considered further. This process generated a list of surveillances that are currently performed off-line at intervals less than 48 months and require modification to be made compatible with the extended operating cycle.

Once the surveillances requiring modification were identified, a systematic approach was used to study each of them in depth. The first step was to review the surveillance's governing procedure. A procedure is a management tool used within nuclear power plants to control all work activities. It is a document that gives the background and requirements for each surveillance, and then provides step by step instructions on how to complete the tasks. Plant personnel use the procedure as a guide, signing-off each step as it is completed and recording testing results and equipment data where required. Because of their integral role in plant operations, the procedures are an excellent source of detailed and accurate information about surveillance activities. The governing procedure was studied for each surveillance with the intent of gaining a basic understanding of the nature of the activity. Within the procedure text it was common to find discussion of surveillance performance modes, including a listing of requirements to perform the surveillance on-line. As the procedures were studied, plant and system schematics were examined as well to gain an understanding of the relationship of the affected equipment to the plant as a whole.

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[8] Paradox Relational Database, Version 5.0, Borland International (1985)

The second step in collecting data about the surveillances was to review the historical performance data for the surveillance procedure itself and for the associated equipment. The historical information was accessed through several different computer and micro-fiche databases maintained at the plant. Because of the less centralized and less organized form of the historical data, this was a very time consuming process. For this reason, if a surveillance activity showed a high likelihood of being able to be moved to the on-line work scope following procedure and schematic review, the historical data step was omitted. For those surveillances whose ability to be moved on-line was in doubt, the historical data was analyzed to reveal failure frequencies and dominant failure modes. A judgement was made as to whether the particular surveillance activity being studied was related to evident failure problems and if extension of the surveillance interval might aggravate failure rates.

The third step in the surveillance review process was to interview the associated system engineers at the plant. The system engineers are intimately familiar with their respective systems and offer the most informed insights into system operations, performance, and modification potential. During these interviews, the initial judgements formed from the procedure review and historical data analysis were presented and evaluated. The engineers also offered a knowledgeable view of vendor and industry experiences, including surveillance alternatives used at other plants or under development by industry related organizations. The engineers were able to use their personal experience and professional knowledge to validate or correct the judgements as necessary. The opinions of the system engineers were relied on as the final arbiter of all surveillance modification proposals.

2.2.4. Surveillance Resolution Analysis

Given the extracted list of surveillance activities that are incompatible with 48 month cycle operation and the accrued knowledge from the data collection process, a systematic surveillance resolution procedure is required. This procedure is designed to serve as a framework that compares pertinent data about each surveillance activity, considers the resolution options, and outputs a modified surveillance program that is compatible with the longer cycle length. Due to the inherent advantages of moving surveillances to the on-line performance mode, this option is preferentially used when possible. Those surveillances that are found to be ill suited for on-line performance are then further analyzed to evaluate performance interval extension. If a surveillance activity cannot be performed on-line and cannot be performed at extended intervals, it will be classified as "unresolved" and left for future study. These unresolved surveillances are listed in Table ? on page ? and discussed further in Section 2.4.4.

2.2.4.1. On-line Performance Evaluation

This section presents the process used to evaluate whether or not each surveillance activity analyzed was a candidate to be transitioned to on-line performance. Figure 5 on page 42 is a logic diagram of the process and is amplified by the following explanations of the decision boxes.

Can the surveillance be eliminated?

If performance of the surveillance has no effect on plant safety or reliability, then the surveillance should be eliminated. Additionally, if surveillance performance has only a small effect on plant safety or economic performance and could be compensated for by increasing the frequency of other selected on-line surveillances, it may be possible to eliminate the surveillance with no net effect on the overall Core Damage Frequency (CDF) or economic performance.

Can the surveillance be performed on-line by procedure?

If an on-line performance option already exists in the current surveillance procedure, then a determination must be made as to why the utility currently chooses to perform the surveillance off-line. This could include reasons ranging from economic cost, a perceived risk of operator errors causing unplanned shutdowns, increased man-rem exposure, or no current incentive to perform the surveillance on-line given current plant cycle and refueling lengths. Whatever the reason, action would have to be taken to ensure that on-line surveillance performance does not constitute an unjustified risk.

Is the component accessible at power?

Some components are inaccessible while the reactor is on-line. Inaccessible equipment includes any components inside the bio-shield or located below the reactor and may also include components that are located in high radiation areas where excess personnel exposure costs may make on-line performance cost prohibitive. If a component is not accessible at power either directly or remotely, it may be possible to employ system modifications to permit access. If it is not possible to gain access to the equipment, the surveillance cannot be performed on-line.

Is the component more risk significant at shutdown?

Some surveillances are simply safer to do while the plant is operating. For example, from a risk standpoint, the Residual Heat Removal (RHR) System plays a larger safety role when the plant is being shutdown then when it is on-line. Therefore, surveillances that require the RHR system to be inoperable are safer to perform on-line. In the case of the RHR system, performing the applicable surveillances during an outage could limit the plant's ability to successfully cope with a Loss of Cooling Accident (LOCA) and raise the CDF.

Can the equipment be taken out of service?

Some equipment can be taken out of service while the reactor is on-line, enabling associated surveillances to be completed. Operational equipment can be removed from service if there is redundant equipment that will prevent or mitigate a loss of function. Standby equipment can be taken out of service when it does not unduly increase the plant's risk posture. Many such systems are under regulatory control and require the use of a Limiting Condition of Operation (LCO). An LCO is a regulatory tool that allows for certain standby systems to be removed from service for a fixed period of time. Originally intended to allow for emergent work after a failure without requiring the plant to shutdown, LCOs are now permitted for planned maintenance and testing activities. If redundant equipment exists or can be added, or if the equipment is part of a standby system that can be temporarily taken out of service, the surveillance can be performed on-line.

Are on-line testing substitutes available?

It is often possible that an open and inspect surveillance can be replaced with alternative on-line testing. The availability of such alternatives are dependent on the existence of specific non-intrusive tests that measure component performance parameters equivalent to those evaluated in current surveillance performance. On-line testing methods such as radiography or ultrasonic testing may provide an alternative to many of the open and inspect surveillances resulting from the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI. Other testing substitutes could include vibration analysis, thermography, and state of the art lube oil analysis programs.

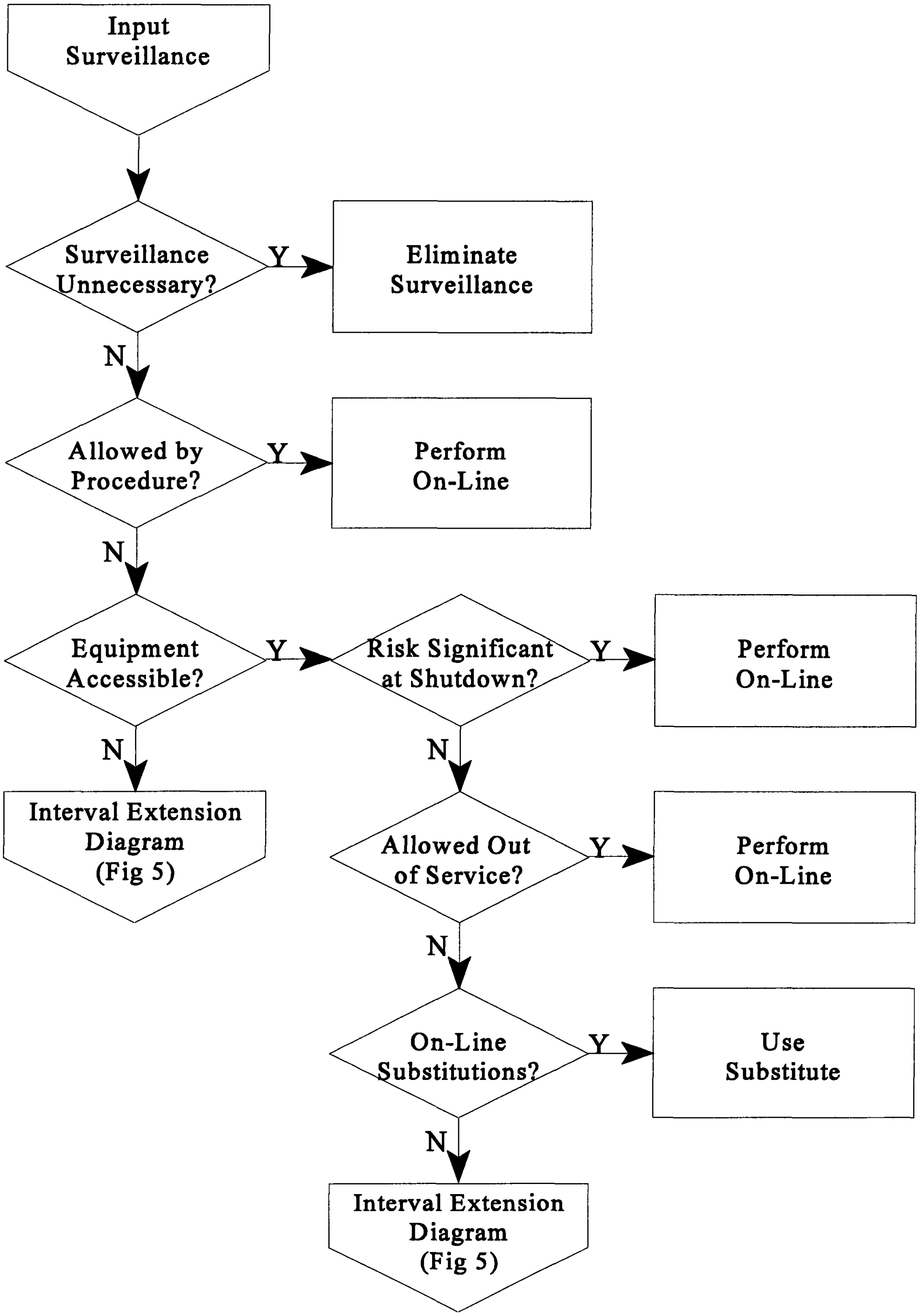

Figure 5: On-Line Performance Evaluation Flowchart

2.2.4.2. Performance Interval Extension Evaluation

If the result of the on-line performance evaluation is negative, the next step is to determine if the surveillance is a candidate for performance interval extension. The performance interval extension evaluation logic flowchart is Figure 6 on page 45. The following items describe the decision boxes in greater detail.

Can the interval be extended based on the historical performance data?

This will be the primary method for justifying extensions of surveillance performance intervals. NRC Generic Letter 91-04 forms the basis for the technical evaluation. The evaluation must consider issues such as surveillance history, corrective maintenance history, preventive maintenance history, time dependent failure modes, and system engineer technical opinions. Based on these factors, If there is no predicted negative impact on plant safety or performance the performance interval should be extended.

Can the interval be extended based on a lack of risk significance?

If extending the performance interval of a particular surveillance has little or no impact on the overall CDF or economic performance, then its interval can likely be extended. Any increase in CDF or the increased economic costs as a result of performance interval extension could be offset by additional on-line testing of other surveillances.

Can the interval be extended by increasing the scope of the surveillance?

If the scope of a surveillance is increased, it may be possible to perform it on a less frequent basis. For example, a particular pump is completely overhauled every ten years, but an inspection is performed every twenty-four months while the plant is shutdown. However, if the pump's material history showed that time dependent failures only occurred at frequencies approaching ten years, than the pump components with the highest time dependent failure rates could be replaced on a more frequent basis than once every ten years, allowing the plant to justify extending the inspection interval for the pump to coincide with the 48 month operating cycle.

Can the interval be extended by performing on-line monitoring?

On-line monitoring programs are increasing in use and sophistication. Some of the current on-line monitoring programs include techniques such as vibration analysis of pumps and turbines, acoustic flow detection and monitoring to measure valve performance, radiography, thermography of breakers and pumps, and lube oil analysis. The application of these techniques may allow for intrusive inspection intervals to be extended. This has the added benefit of reducing the number of times a component must be taken apart for inspection and therefore reducing the human error contribution to component failure rates.

Can the interval be extended by upgrading the component?

Many surveillance performance intervals are based on the failure history of particular components. If a superior component or system exists, performance interval extension might be possible by replacing the existing component with the superior one. Upgrades of components could also entail more elaborate installation and alignment techniques. For example, many pump failures are due to improper or insufficiently precise alignments. An improvement in the alignment of the shaft through the use of a modern alignment technique and proper mounting of the pump could result in improved component performance and reliability which would justify a surveillance performance interval extension.

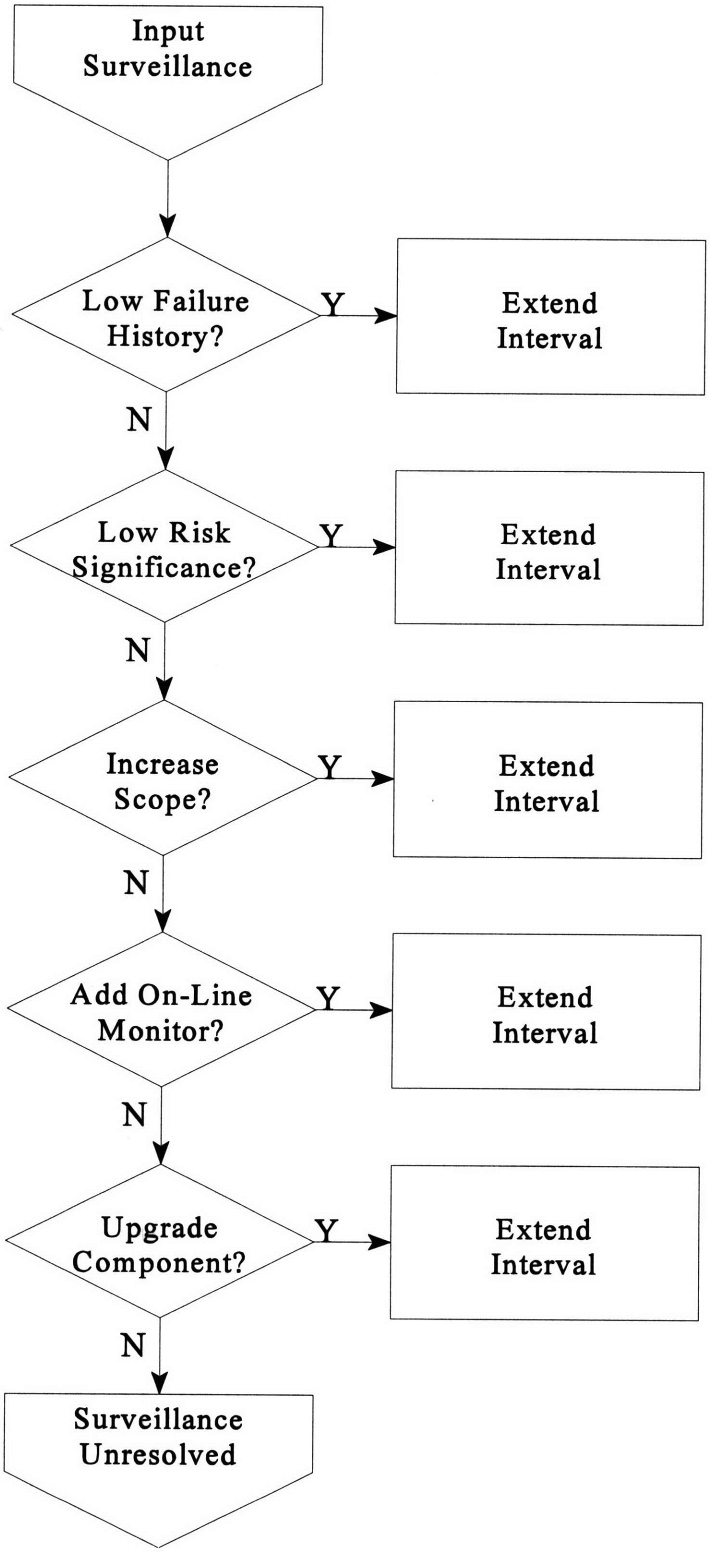

Figure 6: Interval Extension Evaluation Flowchart

2.3. BWR Investment Protection Surveillance Analysis

In order to complete the 48 month extended operating cycle surveillance program, the BWR non-regulatory surveillances must be evaluated. Using the methodology outlined in Section 2.2, these surveillances were identified and reconciled to the extended cycle.

Of the 2694 surveillances currently performed off-line at the candidate BWR, 975 were found to be economic investment protection surveillances. A breakdown of these surveillances by performing plant division is shown as Figure 7. Of the 975 investment protection surveillances, 635 have performance intervals greater than or equal to the 48 month extended cycle goal and do not require modification. Their numbers are carried through the rest of the section to provide a complete picture of the proposed surveillance program and to maintain compatibility with previous work. The remaining 340 investment protection surveillances that are performed off-line at intervals less than 48 months are analyzed below to determine their proposed modification method.

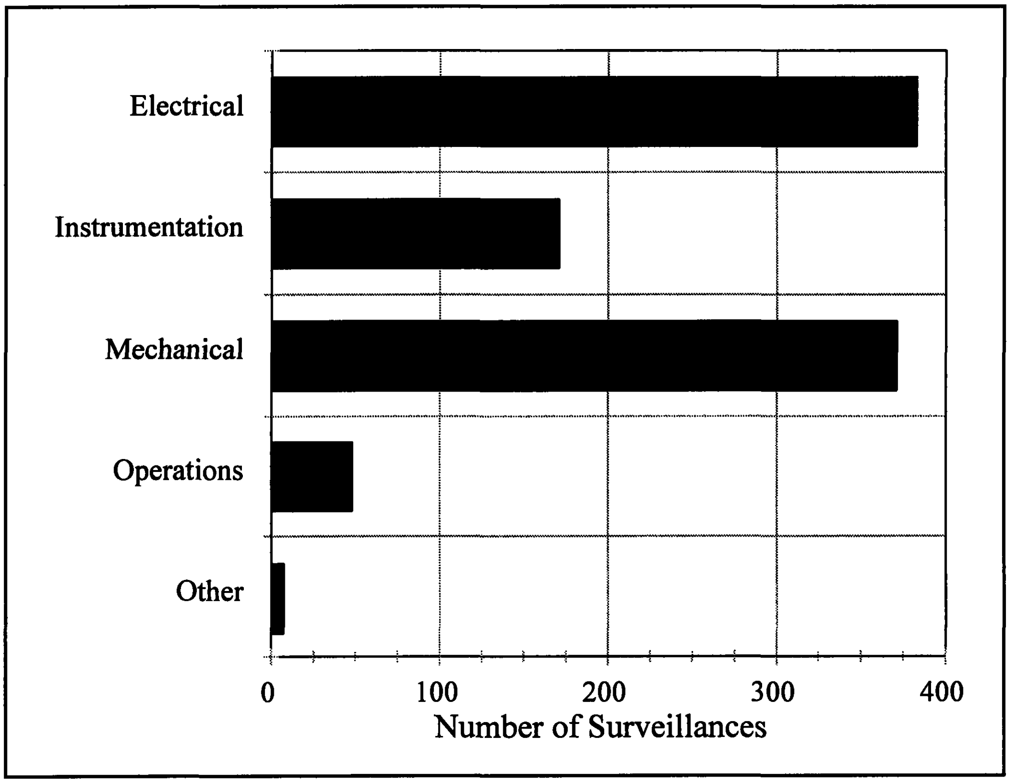

Figure 7: BWR Investment Protection Surveillances by Division

2.3.1. Electrical Surveillances

2.3.1.1. Surveillances Moved On-Line

Relay Logic Circuit Testing:

Of the ninety-two electrical surveillances, thirty-six of them involve the functional testing of relay based safety logic systems. The first thirty-four relay tests cover the actuating logic circuits for the High Pressure Coolant Injection (HPCI) and Reactor Core Isolation Cooling (RCIC) systems. The relay circuits sense certain plant operating conditions and actuate the corresponding emergency cooling systems. A functional test of these relays could be performed on-line within a HPCI or RCIC LCO with the circuits isolated by lifting the leads to the actuated hardware. Simulated signals for each of the pertinent plant conditions could then be generated at the first relay, and the resulting switching logic could be followed through to the output of the actuating signal. Although this testing method is not currently used, both the HPCI and RCIC system engineers and senior Electrical Division personnel concur that there would be no technical barrier to its development. Therefore, all thirty-four HPCI and RCIC relay logic tests are designated for on-line performance.

The remaining two surveillances cover the calibration of stuck breaker relay logic for the 345 kV breakers. When a fault on the 345 kV ring bus is detected, regulatory required relay logic circuits open the appropriate ring bus breakers to isolate the fault. Additional investment protection relay logic exists to detect a failure to open for the two breakers adjacent to the main transformer. Should this failure occur, the relay logic opens additional breakers and trips the main turbine to prevent damage. These surveillances cover only the calibration of the relays, which show negligible drift, and are permitted to be performed on-line in the governing procedure.

Recirculation Pump Motor Generator Tachometer Replacement:

There are two surveillances that govern the replacement of the tachometers on each of the two recirculation pump motor generator sets. These tachometers provide speed feedback from the pump to the motor generator set. They are currently replaced every twenty-four months during refueling outages, and their performance history does not warrant interval extension. Replacement of the tachometers require that the corresponding recirculation pump be secured or its scoop tube positioner locked in place.

The candidate BWR has two recirculation loops, and although it can technically operate with one loop isolated, the plant lacks the supporting instrumentation to allow the safety systems to compensate. As discussed further in Section 3, this is generally not the case within the industry and many plants currently isolate recirculation loops to perform maintenance activities. To maintain generic applicability to the industry as a whole, these surveillances are therefore designated for on-line performance with a power reduction to 50%. The few plants that are not able to perform similar surveillances on-line can incorporate a modest instrumentation upgrade package that would allow recirculation loop isolation.

Electrical Meter Calibration:

There are two surveillances involving the calibration of various electrical meters on panels associated with the diesel generators. These surveillances take very little time and can easily be incorporated into the diesel generator LCOs required for diesel preventive maintenance activities.

Motor Brush Replacement:

This surveillance involves brush replacement for the HPCI turbine auxiliary lube oil pump and can be performed on-line within a HPCI system LCO.

Reactor Protection System (RPS) Cleaning:

There are two surveillances that cover the general cleaning and vacuuming of the RPS equipment and air passages. While the risk of inadvertent reactor trip prevents complete on-line performance, these surveillances can be satisfied by dividing them into two distinct activities. With the installation of simple filter elements, an on-line surveillance can be conducted for light cleaning not requiring disassembly. The filters and on-line cleaning will allow for a second off-line surveillance, that includes complete disassembly, to be extended to a 48 month interval.

Main Turbine Mechanical Pressure Regulator Calibration:

This surveillance governs the calibration of the main turbine pressure regulator. There are two pressure regulators, one mechanical and one electrical, that are used to control the steam flow rate through the turbine. These regulators control the reactor pressure by slaving turbine generator power output to reactor power output. The system senses a change in reactor power as a change in steam line pressure, and adjusts steam flow through the turbine to compensate.

At the candidate BWR, there have been consistent problems with set-point drift for the mechanical regulator, defeating the dual regulator design. To allow for more frequent calibration, the plant has installed isolation valves so that the mechanical pressure regulator can be tested and calibrated with the turbine on-line. The turbine shed is a high radiation area and a hydrogen injection 'turndown,' as discussed in Section 3.2.1.2, should be used to minimize exposure while performing this surveillance. The ability to isolate and calibrate the mechanical pressure regulator on-line, coupled with a hydrogen injection reduction, make this surveillance an excellent candidate for on-line performance.

2.3.1.2. Surveillances for Interval Extension

Electrical Meter Calibration:

The electrical division performs eleven investment protection surveillances that cover the calibration of electrical voltmeters and ammeters in a variety of systems. While there is a high likelihood that on-line calibration procedures could be developed for these surveillances, modern solid state electrical meters exhibit very little calibration drift. Historical records show that the "as found" values prior to calibration are no further from setpoints then the "as left" values. This makes all eleven of these surveillances candidates for performance interval extension.

Relay Calibration and Automatic Transfer Tests:

There are fifteen surveillances to calibrate and test various relays throughout the plant. The majority of these relay circuits detect under-voltage and undercurrent conditions on transformers and buses and automatically switch loads to alternate power supplies. Many of the less risk significant surveillances in this class have had their performance intervals extended from two or three years to four years. There is no technical difference between those that have been extended and those that are still performed within the 48 month goal, and plant engineers are confident that the remaining relay calibrations will be extended once the continued satisfactory performance of the relays is demonstrated.

Transformer, Bus and Breaker Maintenance:

There are three investment protection surveillances that cover the general cleaning and maintenance of the main transformer, various buses and switchyard breakers. These surveillances do not address specific failure modes that are seen in historical data. The static nature of the transformer and buses prevent anything other than long term corrosion and breakdown of insulation. If care is taken to monitor the component conditions carefully during inspections performed at 48 month intervals, degradation rates are too slow for failures to occur within the next operating cycle. The switchyard breaker work, including timing of breaker action, has been proposed for interval extension to 48 months by plant engineers.

Power Factor Tests:

Four surveillances require the performance of power factor tests on the primary buses and transformers. They are currently required at three year intervals, but a recent in plant review has identified them as candidates for interval extension and a proposal for a 48 month interval has been submitted.

Pump Motor Inspection:

There are seven surveillances performed on the Control Rod Drive (CRD) pump motors and reactor feed pumps which can be extended to 48 month intervals. These tests involve general inspection, internal cleaning, and meggering of the pump motors. An in depth study of feed pump failure mechanisms and maintenance practices was conducted[9], and the results showed that there is

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[9] Moore, T., and N.E. Todreas, "A Strategy for Reducing Forced Outage Rates in Commercial Nuclear Reactors with a Main Feed Pump Case Study." MIT Nuclear Engineering Department, MIT-ANP-TR-044 (1996)

no technical basis for maintenance intervals greater than 48 months. Conversations with the author of the feed pump study and case study plant personnel revealed that the same conclusions should hold true for the vast majority of nuclear industry rotating equipment.

Main Turbine Maintenance:

The final seven surveillances designated for interval extension involve maintenance activities for secondary components associated with the main turbine. Six of the seven cover preventive maintenance on valve and control motors. A proposal has been submitted to extend these surveillances from two to four years. The seventh surveillance involves maintenance of the Thrust Bearing Wear Detector (TBWD). This component measures wear of the turbine thrust bearing and initiates a turbine trip on excessive wear or loss of lube oil pressure. As it currently exists, this is a single point failure system and interval extension may increase the risk of spurious turbine trips. To compensate for the this, the plant is currently considering an upgrade to a two out of three logic system. This will effectively mitigate any increased risk and allow for interval extension to 48 months.

Motor Operated Valve Maintenance:

There is one surveillance performed on a MOV in the Reactor Building Closed Cooling Water System (RBCCW). Engineers at the candidate BWR have an extremely conservative outlook on MOV surveillance interval extension, based on historical performance records. Studies at other plants, including the candidate PWR, have demonstrated that only those valves with high differential pressure and high risk significance would preclude a 48 month cycle. Because this valve has relatively low differential pressure and risk significance, it likely qualifies for an extended surveillance interval.

2.3.1.3. Summary

The electrical surveillance categorizations, including 290 off-line surveillances that had current performance intervals in excess of 48 months, have been summarized in Table 1.

Table 1: BWR Investment Protection Electrical Surveillance Modifications

Performance Mode	Number of Surveillances
On-Line	44
Off-Line at ≥48 Month Intervals	338

2.3.2. Instrumentation Surveillances

2.3.2.1. Surveillances Moved On-Line

Control Room Panel Cleaning:

Fifteen surveillances cover the inspection and cleaning of the various control room panels. The procedures state that, "The preferred plant condition is shutdown to prevent an accidental shutdown or ESF actuation. However, this procedure may be performed on-line at the discretion of the Nuclear Watch Engineer." These surveillances could be resolved in two ways. First, proper training and preparation can effectively reduce the risks associated with cleaning the panels with the reactor at power. Alternately, air filters and light exterior cleaning done on-line can be used to maintain the reliability of the control panel components, with a more thorough cleaning done every 48 months. Both methods will effectively reconcile these surveillances to an extended fuel cycle.

Radiation Monitors:

There are five surveillances involving the calibration or maintenance of radiation monitors. Two procedures calibrate off-gas radiation monitors. The monitors are outside of the high radiation area and are redundant so that their calibration would not affect the off-gas system. The next two surveillances in this category involve the Traversing In-Core Probes (TIP). The calibration of the TIP control unit requires only the utilization of the calibration circuit from within the control room, and the TIP drive mechanisms can be accessed and inspected with the reactor at power. Although both of these activities remove one of the four TIPs from service, the probes are only used intermittently and thus pose no problem to on-line performance. There are allowances in the governing procedure for completing the surveillances with the plant on-line. The final radiation monitor surveillance covers the replacement of the core monitor system test device, which can be easily done with the reactor on-line.

Instrument Calibrations:

Instrument calibrations for a wide variety of systems are covered in fifteen surveillances. Four of these regarding the emergency diesel generators and two regarding the HPCI and RCIC systems can be performed on-line within a LCO for the corresponding system. The majority of instrument calibrations for the turbine generator and auxiliaries are done at four or six year intervals, but one surveillance includes GE recommended turbine protection activities to be performed every two years. While the candidate BWR does not have the capability to perform these surveillances on-line, common digital instrumentation packages do allow for on-line performance. It could also be done with the turbine off-line and the reactor idled at minimal power. There are four surveillances for the HWC system covering instrument calibrations. All four of these procedures allow for the calibrations to be done on-line. Two surveillances calibrate the recirculation system instrument calibrations. While these cannot be completed on-line at the candidate BWR, as previously mentioned and discussed fully in Section 3, most plants do have the ability to isolate a recirculation loop for maintenance activities at reduced power. The final two surveillances in this section cover the Reactor Manual Control System (RMCS) and the reactor level and pressure instruments. Both of these surveillances are allowed to be performed on-line by procedure.

Main Turbine Vibration Testing:

There are three surveillances for vibration testing on the main turbine and the gland seal exhauster. They are not currently performed on-line due to radiation exposure levels within the turbine shed. Rather than extend the interval and degrade this important trending data, these surveillances could be coordinated with a reduction in main steam line hydrogen injection rates, as discussed further in Section 3, or could be automated with permanent vibration monitoring equipment that would both allow on-line performance and increase the data collection rate.

Recirculation Motor Generator Scoop Tube Calibration:

The scoop tube provides the fluid coupling between the generator and motor, thereby controlling the speed of the recirculation pumps. When generator speed is increased, the scoop tube changes position so as to increase the amount of fluid in the coupling circuit and increase hydraulic coupling of the components; the opposite being true when the speed is decreased. Two surveillances, one for each recirculation loop, calibrate the positioner of the scoop tubes so as to ensure accurate recirculation pump control. These procedures require that the corresponding recirculation pump be isolated, but as discussed in Section 3, most plants have this ability and can perform these surveillances on-line at reduced power.

Overhaul Plant Seismic Equipment:

The final Instrumentation surveillance designated for on-line performance is the overhaul of plant seismic equipment. The surveillance procedure makes no restrictions on plant state and this surveillance can be readily accomplished at power.

2.3.2.2. Surveillances for Interval Extensions

Feedwater Heaters:

There are thirty surveillances involving the feedwater heaters and extraction steam controls. The extraction steam system heats feedwater to increase efficiency and decrease vessel thermal shock. Level controllers are used to control the level of condensed steam in each heater with bleeder trip valves and spill valves. Twenty-eight of these are calibrations of the controllers themselves, both for the feedwater heater levels and extraction steam rates. While these can be isolated for on-line performance at reduced power, the historical records and the opinion of the system engineer both indicate that these surveillances can be extended to a 48 month performance interval. The other two surveillances cover pressure transmitter calibration. This equipment shows little or no time dependent drift in historical surveillance records and should easily tolerate interval extension.

Feedwater Control Valves:

The feedwater control valves have nine surveillances covering their preventive maintenance and calibration. Three of them involve preventive maintenance for the feedwater control valve air supplies. While there have been problems with the air supply systems in the past, the system engineer is confident that a longer maintenance interval will not adversely affect their performance, and in fact, suggested that incorrect maintenance done too frequently may have contributed to past problems. The two surveillances for the Bailey positioners, which maintain the correct position of the feedwater control valves, can readily accept a 48 month maintenance interval. The remaining four surveillances are calibrations for the valves themselves and associated instruments. The system engineer expressed confidence that a 48 month interval could be justified for all of these surveillances.

Instrument Calibration:

While many instrument calibrations can be done on-line, there are twelve surveillances that are designated for performance interval extension. Four of these involve the main turbine generator and auxiliaries. A wide variety of turbine instrumentation surveillances were previously completed at two year intervals, but a recent plant review has divided the activities into two, four and six year interval surveillances. The two year interval surveillances were addressed as on-line items above, and the remaining four and six year surveillances are included here. The other eight surveillances in this category cover general instrumentation calibration within the off-gas system, nitrogen supply system, HWC system, and condensate transfer system. They are all designated for interval extension.

Radiation Monitor Calibration / Preventive Maintenance:

There are seventeen surveillances that are performed on various radiation monitoring systems and their drive mechanisms. Twelve of them concern preventive maintenance on the Source Range Monitor (SRM) and Intermediate Range Monitor (IRM) drive mechanisms. These surveillances require drywell access and cannot be performed on-line, but they have shown no historical deterioration over the current preventive maintenance cycle and are likely to withstand a 48 month interval without a significant decrease in reliability. One surveillance for the testing of the SRM discriminator is defined by procedure to be performed only after major refueling outage work and is therefore administratively extended to the longer cycle length. Four surveillances deal with the Traversing In-core Probe (TIP) system, including preventive maintenance on the indexer and isolation valves, friction tests, and flux probe calibration. These surveillances are good candidates for interval extension because they have shown good historical reliability and because their quadruple redundancy reduces risk significance.

Control Rod Drive :

The Control Rod Drives (CRDs) are maintained and calibrated under four surveillances that are candidates for interval extension. The first is the set-point calculation for the CRD air dump system, which has shown little or no historical variation. The second surveillance is the CRD friction and performance test which measures the differential pressure across the CRD pistons. There are also two surveillances to perform preventive maintenance on the CRD backup scram valves. These valves are rarely operated and their maintenance can be extended to 48 months.

Instrument Walk-down:

The instrument walk-down surveillance is a general survey of plant equipment performed just prior to reactor start following an outage. While it would be performed following any unplanned outages, it is administratively categorized for extension to the 48 month fuel cycle.

2.3.2.3. Summary

The instrumentation surveillances, including 56 surveillances that had current performance intervals in excess of 48 months, have been summarized in Table 2.

Table 2: BWR Investment Protection Instrumentation Surveillance Modifications

Performance Mode	Number of Surveillances
On-Line	41
Off-Line at ≥48 Month Intervals	129

2.3.3. Mechanical Surveillances

2.3.3.1. Surveillances Moved On-Line

Diesel Generator Maintenance:

There are five diesel generator preventive maintenance surveillances that can be performed on-line during a diesel LCO. The first two cover all general diesel preventive maintenance activities. Completion of these surveillances takes approximately five days for each diesel generator. Current regulatory limits restrict diesel generator LCOs to seven days and require that planned work not exceed half of this time, but a technical justification can be made to expand the Allowed Outage Time (AOT). Current restrictions on the time that the diesels are allowed to be out of service are based on plant risk level estimates from the plant's Final Safety Analysis Report and more recent plant specific Probabilistic Risk Assessments. The technical justification to increase the time allowed for on-line diesel maintenance could be based on the fact that an equivalent or lower overall risk level can be achieved through increased on-line maintenance. If the combination of the increased unavailability due to on-line maintenance and the decreased unavailability due to a more reliable diesel generator are less than current diesel unavailability, the AOT extension is justified. The remaining three surveillances are for filter and strainer cleaning and can be done during existing LCOs.

Fire Water Tank Inspection:

There are two 250,000 gallon water storage tanks that are currently inspected during refueling outages under two separate surveillances. A complete external inspection can be done at any time and should be adequate to indicate structural problems. Even if internal inspections were deemed necessary, each tank is sufficient for several hours of full load use of the fire water supply system and a city water main is available. Regardless, the risk significance of performing these inspections is independent of whether or not the reactor is on-line.

HPCI and RCIC Preventive Maintenance:

There are four mechanical surveillances of the HPCI system and one for the RCIC system which can be performed on-line within a LCO. The first is the disassembly and inspection of the full flow orifice which is accessible with the HPCI loop isolated. The second is the calibration of the HPCI stop valve balance chamber. The HPCI turbine stop valve uses steam pressure to counter the hydraulic opening force and ensure stable opening of the valve. It is recommended that this adjustment be performed once per refueling outage after stop valve maintenance. Although it is only required following valve maintenance, because the HPCI system and stop valve are subject to on-line maintenance in LCOs, this surveillance must also be included for on-line performance. The remaining two HPCI surveillances are for turbine exhaust check valve preventive maintenance and the booster pump lube oil change. The check valve is a relatively simple component and maintenance takes only a few minutes to complete. Similarly, the lube oil change on the booster pump can be done in under half an hour. These activities can easily be incorporated into a HPCI LCO outage. The RCIC surveillance is the turbine over-speed trip test and maintenance. The over-speed test can be down in a RCIC LCO with the turbine operating on an existing bypass loop. All of these surveillances are classified for on-line performance.

Main Turbine Maintenance:

Four surveillances govern maintenance of main turbine auxiliary components. The first involves the replacement of the Electro-hydraulic Pressure Regulator (EPR). The following is taken from the surveillance procedure:

> "There are two parallel filter groups; one of which is in operation and the other on standby. A manual three-way valve makes it possible to switch one or the other filter unit into service. This arrangement makes it possible to service one filter unit while the other maintains operation without upsetting the electric pressure

> regulator...This procedure may be performed at any plant condition in accordance with good ALARA practices. This procedure shall be performed with hydrogen injection reduced to less than nine CFM, as directed by ALARA."

Therefore the plant equipment and governing procedure clearly allow for on-line performance of this surveillance.

The second surveillance similarly replaces the Mechanical Pressure Regulator, which while not a redundant system, does have isolation valves so that the surveillance can be performed on-line with the EPR taking full control of steam flow. The inspection of the turbine lube oil reservoir is covered under a surveillance that can easily be moved to the on-line work scope. The last surveillance is the "Turbine Front Standard Minor External." This procedure covers the general inspection and greasing of the main turbine auxiliaries, and can be completed on-line with a reduction in HWC hydrogen injection to reduce radiation exposure.

Recirculation Pump Maintenance:

There are twelve surveillances that cover the preventive maintenance of the recirculation pumps and components. These surveillances cover motor generator set coupling calibration and lubrication, internal inspections, and pump motor lube oil replacement and analysis. While none of these surveillances can be completed with the corresponding recirculation loop in operation, most plants have the ability to isolate a single loop for maintenance with the reactor at reduced power. This is discussed further in Section 3.

Feed Pump Coupling Lubrication:

Three surveillances, one for each pump, govern the lubrication of the main feed pump couplings. The procedure requires that the pump be shutdown and isolated, but this can be done with the reactor on-line at 60% power. The lubrication takes approximately one shift to complete.

Condenser Waterbox Inspection:

Four surveillances cover the cleaning and inspection of the condenser waterboxes. These surveillances are currently performed every two years during refueling outages, and the system engineer expressed confidence that they could be extended to a four year interval based on the level of fouling found during past cleaning. The level of fouling of the waterboxes is highly dependent on the local conditions of each plant, and it is not likely that the majority of plants could go for four years without cleaning because of decreased plant performance. The candidate BWR does have the ability to both back-flush and actually enter and inspect the waterboxes with the reactor at 50% power. Back-flushing individual waterboxes with the turbine on-line is likely to enable a 48 month interval for the manual inspection and cleaning. Some plants, including the candidate PWR, do not have the ability to back-flush with the turbine on-line and may have greater difficulty reconciling this type of surveillance to extended cycle lengths.

2.3.3.2. Surveillances for Interval Extension

Feedwater Heater Eddy Current Testing:

There are ten eddy current testing surveillances for the feedwater heaters currently scheduled during refueling outages, but only 10% of the heaters are tested during each outage. Therefore the procedure already supports a 48 month performance interval.

Condenser Inspection:

Three surveillances cover the inspection of the fresh water side of the condenser. Because there have been no associated failures in the plant history, these surveillances are good candidates for interval extension. The system engineer is highly confident that these inspections can be performed at 48 month intervals without problems.

Steam and Drain Trap Preventive Maintenance:

There are eight surveillances to inspect and rebuild steam and drain traps in the augmented off-gas system. These components show no significant degradation during current surveillance performance and system engineers feel that there will be no significant adverse effects if the performance interval is extended to 48 months.

HVAC Inspection:

Two surveillances cover the inspection of HVAC equipment in the condenser bay and drywell. The majority of HVAC inspections are currently performed on-line, but the location of the equipment included in these surveillances preclude access with the plant at power due to excessive heat and radiation levels. These inspections consist primarily of greasing bearings on HVAC motors. Surveillance records show that there have been a number of lubrication related failures of these open bearing motors, and that they probably cannot go without lubrication for four years. However, in response to these failures, the plant has begun to replace the open bearing motors with upgraded sealed bearing equipment. Because of the availability of current equipment that can tolerate the 48 month maintenance schedule, these surveillances are designated for performance interval extension.

Check Valve Preventive Maintenance:

There are five check valve surveillances performed on various systems which can be extended to 48 months. These include the HPCI and RCIC check valves and test line check valve, two valves in the ADS air system, and a valve in the Reactor Water Clean-Up (RWCU) system. In general, check valves have been proven to be fairly reliable and maintenance activities are not directed toward any short term failure mechanisms. The system engineers are confident that they will support a 48 month surveillance interval.

Main Turbine Maintenance:

Eight main turbine maintenance surveillances are candidates for performance interval extension. These include a visual inspection of the turbine-condenser flex joint and inside the servo enclosure. There have been some historical problems with leaks within the servo enclosure, but this surveillance is only an inspection for leaks and there are other external indicators that reveal their presence prior to the visual inspection. Two surveillances cover maintenance of the turbine combined intermediate valves and the main turbine bypass valves. The combined intermediate valve surveillance is currently performed on one of the two valves during each refueling outage, meaning that it will already support a 48 month operating cycle. Although the candidate BWR conservatively maintains the bypass valves every two years to minimize the loss of steam from the turbine, most other plants currently perform this maintenance every four years. It is simply an economic optimization question, and if surveillance interval extension causes valve leakage and subsequently causes a slight reduction in plant electrical output, this cost must be offset by increased revenue from the extended operating cycle. The remaining four surveillances cover hydrogen seal and stator cooling water systems, the generator air test, and the turbine lube oil flush. Both the generator air test and the turbine lube oil flush are required only following major turbine maintenance involving generator depressurization or opening of the turbine lube oil system and therefore are readily extendible to 48 months.

Miscellaneous Surveillances:

There are eight remaining mechanical surveillances that are identified for interval extension. These include drywell airlock maintenance, inspection of the gasket on the spent fuel pool gate, inspection of the secondary containment dampers, inspection of the reactor building vent isokinetic probe, leak checking the SCRAM pilot air tubing, drive water flow checks, and inspection of a fire pump. These surveillances all represent rather simple inspections of secondary components. All surveillance records show no significant failure histories, and the corresponding system engineer was consulted for each surveillance. In each case a determination was made that an interval extension to 48 months can be justified.

2.3.3.3. Summary

The mechanical surveillance categorizations, including 289 off-line surveillances that had current performance intervals in excess of 48 months and did not require modification, have been summarized in Table 3.

Table 3: BWR Investment Protection Mechanical Surveillance Modifications

Performance Mode	Number of Surveillances
On-Line	35
Off-Line at ≥48 Month Intervals	335

2.3.4. Operations Surveillances

2.3.4.1. Surveillances Moved On-Line

Fire Protection Systems:

There are nine fire protection surveillances that can be performed on-line. Each of the four main transformers has a deluge sprinkler system functional test. These surveillances currently require that the transformers be shutdown and that the sprinklers actually discharge water on the transformers. The procedures could be modified to allow on-line performance of the "dry" portion of the sprinkler test, which would test all sprinkler system valves and alarms without the deluge system water distribution system being charged. This on-line procedure would provide a relatively high level of confidence that the system is fully operational. The remaining "wet" portion of the procedure, which tests only the distribution piping integrity, could then be performed every 48 months during refueling outages. The transformer deluge sprinkler system header trouble alarm surveillance and the lube oil reservoir storage area fire protection system functional test are currently performed during each refueling outage. These are both simple alarm indication tests that primarily check that the alarm light bulb is not burned out. The remaining three surveillances test the Cardox CO_2 stations, the turbine fixed dry chemical system, and the transformer air dryer, all of which can easily be performed on-line.

HPCI Tests:

There are two surveillances for the HPCI system which could be performed on-line within a HPCI LCO. These are the HPCI hotwell pump operability test, and the HPCI turbine over-speed test. Completion of these tests require the HPCI system to be aligned on an existing test loop.

Operations Equipment Lubrication:

This surveillance covers the general lubrication of a variety of operations equipment within the condenser bay. While access to the condenser bay is usually restricted due to high radiation levels, this surveillance can be accomplished on-line if it is coordinated with a HWC hydrogen injection rate reduction. This is further discussed in Section 3.2.1.2.

Main Turbine Annual Lubrication:

This surveillance covers the primary lubrication of the main turbine as outlined in GE specifications. The performance interval will not be extended because the utility is unwilling to accept any increased risk regarding the very valuable main turbine, and the procedure requires the complete shutdown of the turbine. The only option that prevents this from being categorized as an unresolvable surveillance is performance during a reduced power window. With the reactor idled at minimal power, the turbine can be taken off-line and the lubrication surveillance performed over the course of several days. While this does cost the utility the value of the fuel burned during this period in addition to replacement power costs, it saves the difficulty and risk of coming to a complete shutdown and may be economically preferable. Reduced power windows are further discussed in Section 3.2.1.1.

2.3.4.2. Surveillances for Interval Extension

Fire Barrier Seals:

While the majority of fire barrier seal inspections are currently done on-line, there are twenty-one surveillances to inspect fire barrier seals in high radiation areas such as the condenser bay, the torus, and the hydrogen recombiner. All of these surveillances are conducted during every outage, but there is currently a proposal at the plant to inspect only 10% of the fire barriers each outage. The fire barrier seals show no sign of degradation over a 48 month interval and will easily support the interval extension.

Fire Protection Systems:

In addition to the “wet” portion of the fire protection surveillances moved on-line, seven fire protection system surveillances are designated for interval extension. There are two surveillances to test the fire hoses and fire hose valves that are in high radiation areas that cannot be tested on-line. Neither the hoses nor the valves have shown any historical degradation problems, and both will support surveillance interval extension. The remaining surveillances in this category cover fire door and damper inspections which show no signs of significant degradation, the turbine fixed dry chemical system test which can be extended with no real decrease in turbine protection, the standby gas treatment spray system test, and the Radiax radio communication system test. The Radiax radio system is used as an emergency communication system, but the signals can interfere with in core radiation monitors and cause spurious reactor alarms. It has never failed a test in the life of the plant and will easily withstand a testing interval extension.

Quality Control:

There are two quality control surveillances, the locked valve lineup surveillance and the refuel outage tag-out audit, which are conducted during a refueling outage by definition and can administratively be extended to the 48 month fuel cycle.

Heating and Ventilation Equipment Lubrication:

This surveillance, called “Standard Heating and Ventilation Equipment Operability Check and Lubrication,” primarily involves greasing the bearings of various unit coolers that are not easily accessible at power. There currently exists a mix of open and sealed bearing equipment at the plant, and although the open bearing equipment now in use could not withstand a 48 month maintenance interval, this surveillance is slated for interval extension because current hardware exists which would allow for the extended fuel cycle.

2.3.4.3. Unresolved Surveillances

Operations Equipment Lubrication:

There is one surveillance that covers the regular lubrication of a wide variety of equipment within the drywell which cannot be performed on-line and which cannot withstand a 48 month cycle. Because the drywell is inerted when the reactor is on-line, these components are not accessible at power. Past surveillance performance records indicate that existing equipment is not likely to withstand a lubrication interval extension to 48 months. While it may be possible to upgrade components, such as with sealed bearing motors that don't require lubrication or with equipment that can be lubricated remotely, these represent significant modifications to existing plant equipment and require further analysis to determine the cost effectiveness of such modifications.

2.3.4.4. Surveillances Subject to Elimination

There are two surveillances that test the drain valves for the four fire protection sprinkler systems. Conducting these surveillances does not contribute to the reliability of the sprinkler systems, does not test system functionality, and does not improve component lifetime. These activities serve no useful purpose and can be eliminated all together.

2.3.4.5. Summary

The operational surveillance categorizations, including one surveillance with a performance interval of 48 months that did not require modification, have been summarized in Table 4.

Table 4: BWR Investment Protection Operations Surveillance Modifications

Performance Mode	Number of Surveillances
On-Line	13
Off-Line at ≥48 Month Intervals	32
Unresolved	1
Eliminated	2

2.3.5. Other Surveillances

2.3.5.1. Surveillances for Interval Extension

Area Radiation Monitor Calibration:

There are three surveillances to calibrate the area radiation monitors in the new fuel storage area, the turbine shed and the turbine basement access area. The surveillance for the new fuel storage area can be extended within the current procedure because it requires only that the monitor be calibrated prior to introduction of new fuel to the storage area. The other two surveillances will tolerate extension to the 48 month interval because there is little or no calibration drift currently seen during surveillance performance.

Miscellaneous:

The final three surveillances cover the Post Accident Sampling System (PASS) jet pump sample, inspection of an access hatch in a high radiation area, and routine inspection of the salt service water piping. All of these procedures support surveillance interval extension to the 48 month cycle without difficulty.

2.3.5.2. Summary

The other surveillance categorizations have been summarized in Table 5. There were no surveillances in this category with current performance intervals of 48 months or greater.

Table 5: BWR Investment Protection Other Surveillance Modifications

Performance Mode	Number of Surveillances
Off-Line at ≥48 Month Intervals	6

2.3.6. Investment Protection Surveillance Summary

Of the 340 investment protection surveillances analyzed, 133 were designated for on-line performance, 204 were designated for performance interval extension, 2 were recommended for elimination, and only 1 was left as unresolved. These results are shown in Figure 8.

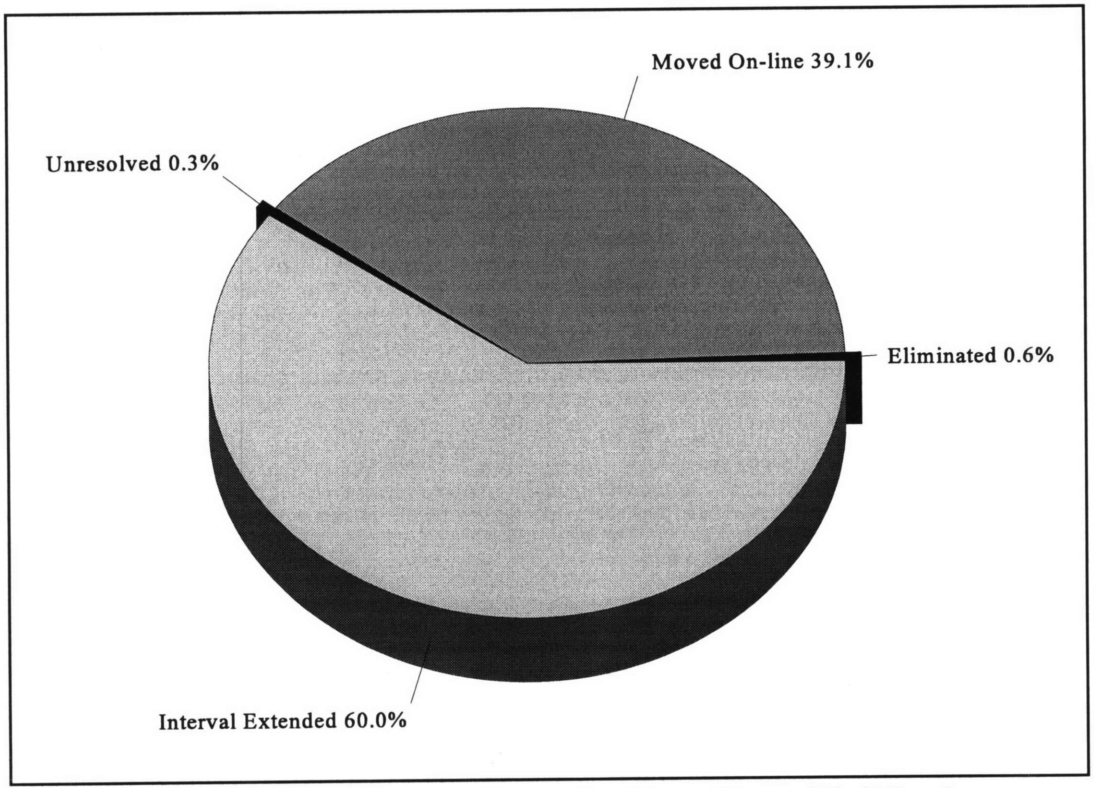

Figure 8: BWR Investment Protection Surveillance Modifications

2.4. Complete Surveillance Program

The BWR investment protection surveillance reconciliation to a 48 month operating cycle, when added to the previous work of other research group members, is the final portion of a complete extended cycle surveillance program. This section will discuss the research at both case study plants and present the comprehensive results.

2.4.1. Variations in Research Methodology

There appears to be fairly wide variation in the organization and execution of surveillance programs throughout the nuclear industry. These differences result from a variety of factors including managerial aggressiveness, technical proficiency, and the design and age of the plant. The candidate BWR and PWR used for this report represent diverse plants from different eras of nuclear and information technology, with contrasting operating and management styles. While this diversity contributes to the generic applicability of the surveillance resolution results, the differences in the structure of each plant's surveillance database led to some differences in the approach used in each case.

At the candidate BWR, the surveillances are primarily catalogued by the division at the plant responsible for the surveillance operation. These divisions, which represent major functional areas such as electrical, mechanical, instrumentation, and operations, perform their designated surveillances across all system and plant boundaries. To facilitate coordination with the existing database, the BWR analysis utilizes this organization and lists surveillance categorization under each primary division at the plant. The BWR database also tracked the specific regulatory body or utility agent that initiated each surveillance. This allowed for the clean separation of all regulatory surveillances, including those satisfying technical specification, NRC, and environmental requirements. The remaining investment protection surveillances were comprised of those initiated at the utility level and preventive maintenance surveillances initiated by the plant itself.

At the candidate PWR, the surveillance program was organized slightly differently. Surveillances were grouped according to whether or not they were technical specification based. For the purpose of this study, surveillances performed to meet technical specification requirements are considered to form the complete set of regulatory based surveillances. Conversations with plant engineers and senior division heads indicated that the number of non-technical specification based surveillances that were regulatory based was extremely small and would not impact categorization results. The use of the technical specifications as the basis for the definition of regulatory based surveillances provides a simple method for further classifying and analyzing these surveillances.

Additionally, there is a methodological difference between the two plant cases regarding the treatment of those surveillances that currently have performance intervals greater than 48 months. The BWR analysis recognizes that these surveillances are already compatible with the extended fuel cycle goal and does not consider them further. The PWR section includes these surveillances in the complete analysis, recategorizing those that can be performed on-line. The result of this difference is that while the BWR section proposes the simplest surveillance resolution program to reconcile operations to the extended cycle, the PWR section goes a step further by attempting to maximize on-line performance. Caution must be taken because the approach used for the PWR pushes more surveillances towards on-line performance and introduces a minor bias in the final surveillance resolution numbers. It is expected that this bias at least partially accounts for the slightly different percentages of surveillances moved on-line for the two plant types.

Despite the differences in how the surveillance databases were arranged at the candidate BWR and candidate PWR, the surveillance resolution methodology presented in Section 2.2 was uniformly applied in both cases. By utilizing the same approach to conduct the surveillance analysis at both plants, the report ensures consistent results and a high degree of confidence that the proposed extended cycle surveillance program is representative of the outcome a typical plant could expect in a cycle extension effort.

2.4.2. BWR Extended Cycle Surveillance Program

The case study plant is a General Electric BWR/3 design with a Mk-1 containment and internal jet pump recirculation flow. The plant has a 670 MW_e capacity and has been in service since 1972. It is currently operating on a 24 month fuel cycle. The plant's equipment and surveillance program are considered to be generally representative of both the BWR design and 1970s era plants.

The PWR surveillance program was analyzed by previous research group members according to the methodology in Section 2.2. Some modifications to the results were made to correct discrepancies between the two plant types and make the data consistent, but primarily this section is included to provide a complete picture of the proposed extended cycle surveillance program. The complete surveillance analysis can be found in the MIT research group's report, "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors."[10]

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[10] Moore, T., et al. "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors." MIT Nuclear Engineering Department, MIT-ANP-TR-036 (June 1996): 65-92

2.4.2.1. Regulatory Based Surveillances

An initial survey of the BWR surveillance program produced a total of 2694 individual surveillance activities performed off-line during planned outages. Filtering by the initiating authority, 1719 surveillances were found to be regulatory based. Of these, 1109 have performance intervals that are greater than or equal to 48 months. These surveillances are currently compatible with the cycle extension goal, and although they do not require performance modification, their numbers are carried through this section to provide a complete picture of the recommended surveillance program. The remaining 610 regulatory surveillances that are currently performed off-line at intervals less than 48 months are further analyzed to determine their possible resolution categorizations.

As stated in Section 2.4.1, the format of the surveillance tracking database at the plant facilitated analysis based on the division at the plant that performs the surveillance. The primary divisions performing regulatory surveillances and the number of surveillances associated with each are represented in Figure 9.

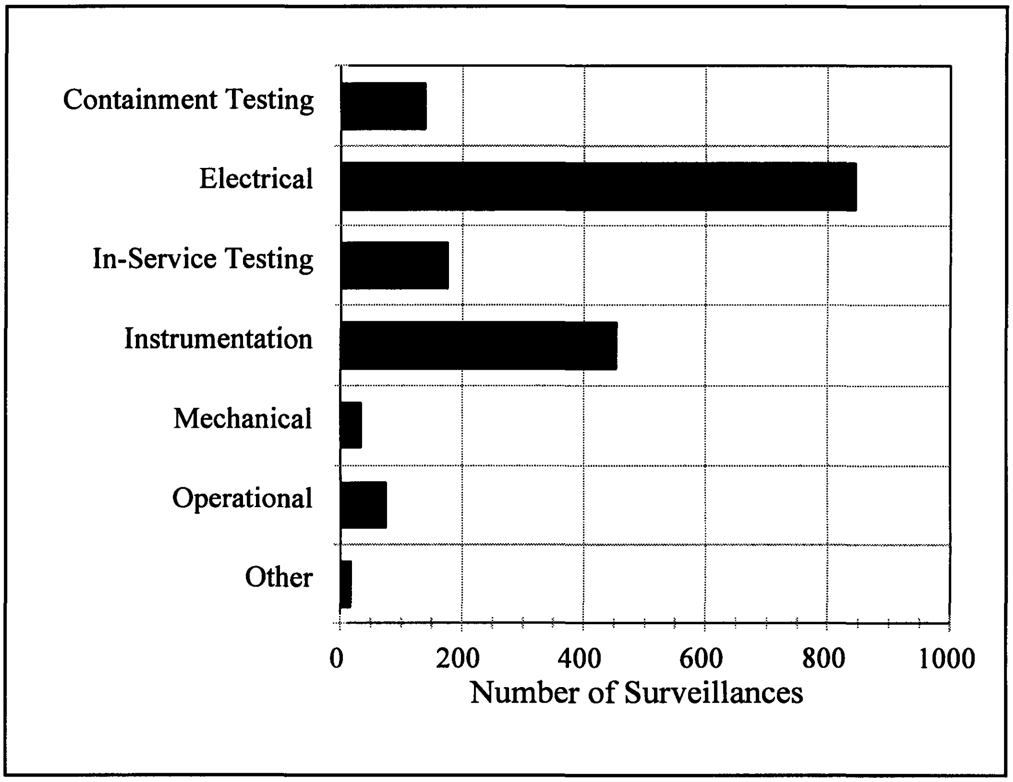

Figure 9: BWR Regulatory Surveillances by Division

Of the 610 BWR regulatory surveillances analyzed, 212 were designated for on-line performance, 332 were designated for performance interval extension, and 68 were left as unresolved. These results are shown in Figure 10.

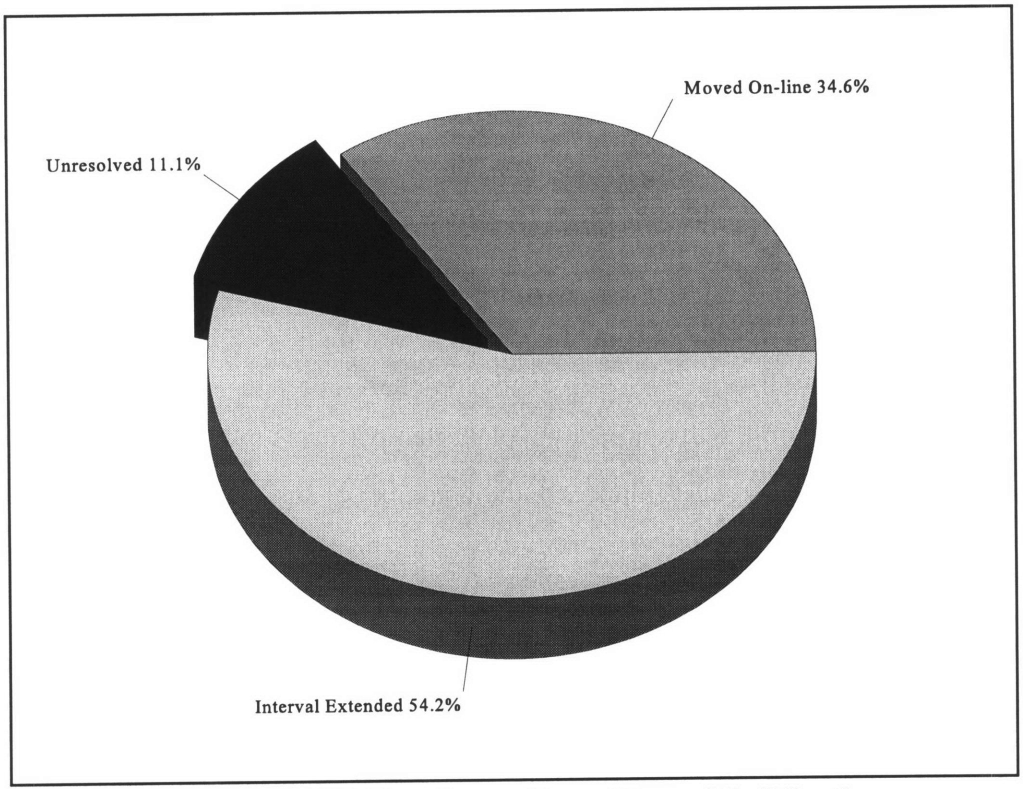

Figure 10: BWR Regulatory Surveillance Modifications

2.4.2.2. Investment Protection Surveillances

The BWR investment protection surveillances are analyzed in detail in Section 2.3

2.4.2.3. BWR Surveillance Program Summary

The modifications of the BWR off-line surveillances are shown in Table 6. The complete proposed program for the extended cycle is compared to the current surveillance program in Figure 11. The extended cycle program increases the number of on-line surveillances by 30.9% relative to current operations (for a total of 38.3%), and increases the number of surveillances performed off-line at intervals of 48 months or more by 30.7% (for a total of 59.8%). The remaining 1.8% are unresolved surveillances, which are discussed further in Section 2.4.4.

Table 6: Modified BWR Surveillance Program

Division	On-Line	Off-Line	Unresolved	Total
Containment				136
Regulatory	59	65	12	
Economic	0	0	0	
Electrical				1224
Regulatory	22	803	17	
Economic	44	338	0	
In-Serv. Testing				173
Regulatory	65	99	9	
Economic	0	0	0	
Instrumentation				620
Regulatory	52	398	0	
Economic	41	129	0	
Mechanical				401
Regulatory	0	31	0	
Economic	35	335	0	
Operations				117
Regulatory	8	33	30	
Economic	13	32	1	
Other				21
Regulatory	6	9	0	
Economic	0	6	0	
Previously On-Line Surveillances (Unanalyzed)	1115			1115
TOTAL	**1460**	**2278**	**69**	**3807**

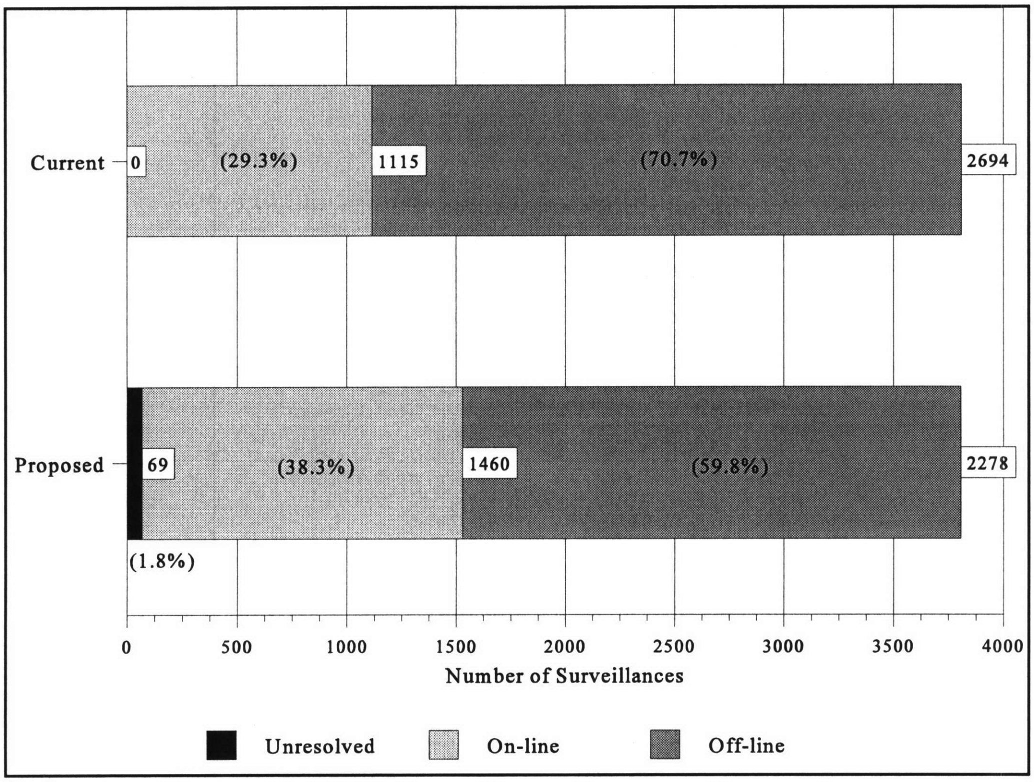

Figure 11: BWR Surveillance Program Comparison

2.4.3. PWR Extended Cycle Surveillance Program

The case study plant is a Westinghouse four loop design with large dry containment. The plant has a 1148 MW_e capacity and has been in service since 1990. It is currently operating on an 18 month fuel cycle. The plant's equipment and surveillance program are considered to be generally representative of both the PWR design and 1980s era plants.

The complete surveillance program was analyzed according to the methodology in Section 2.2. An attempt was made to modify any surveillance that prohibited a 48 month operating cycle by moving it on-line or extending the performance interval. Those surveillances that presented especially difficult technical barriers to on-line performance or interval extension were left as unresolved pending further investigation. The complete surveillance analysis can be found in the

MIT research group's report, "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors."[11]

2.4.3.1. Regulatory Based Surveillances

There are 1772 individual surveillances performed to meet the technical requirements and the technical specifications at the candidate PWR plant. Of these, 571 are currently performed on-line and are independent of operating cycle length. Analysis of the 1201 remaining surveillances currently performed while shutdown are summarized in this section. Of these 1201 surveillances, 278 have performance intervals which are already compatible with a 48 month fuel cycle.

As stated in Section 2.4.1, the format of the surveillance tracking database at the plant facilitated analysis based on the technical specification section that requires the surveillance. These technical specification sections and the number of surveillances associated with each are represented in Figure 12.

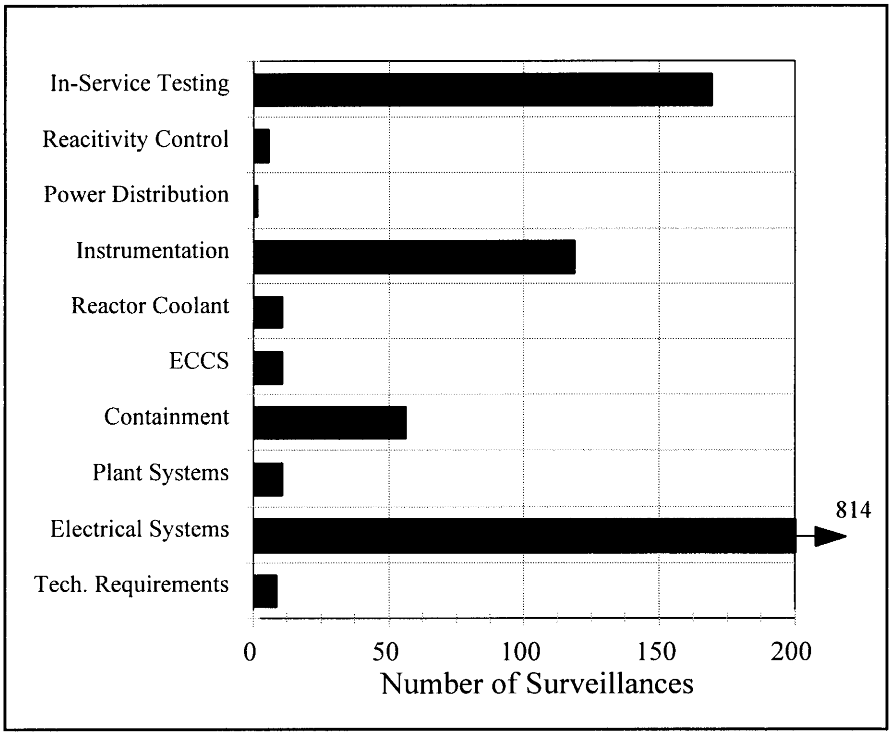

Figure 12: PWR Regulatory Surveillances By Tech Spec Section

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[11] Moore, T., et al. "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors." MIT Nuclear Engineering Department, MIT-ANP-TR-036 (June 1996): 117-147

Of the 923 PWR regulatory surveillances with initial intervals less than 48 months, 228 were designated for on-line performance, 675 were designated for performance interval extension, and 20 were left as unresolved. These results are shown in Figure 13.

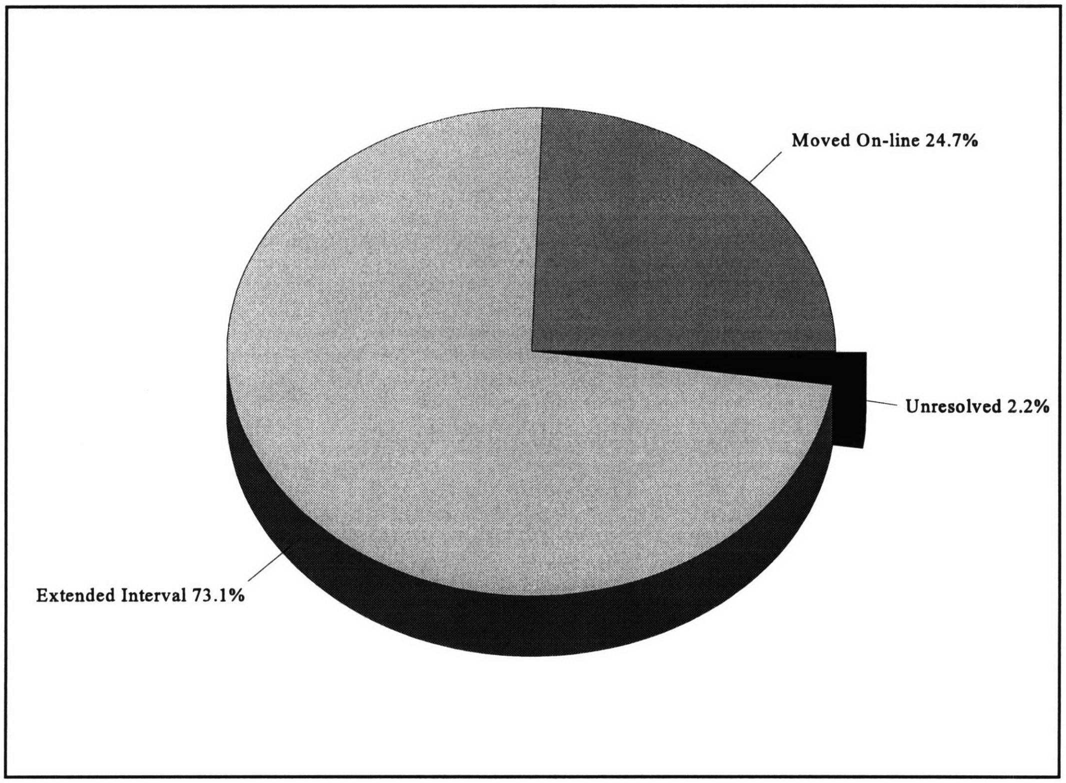

Figure 13: PWR Regulatory Surveillance Modifications

2.4.3.2. Investment Protection Surveillances

To provide a logical framework to analyze the investment protection surveillances, they were grouped by system and placed into three main categories; Nuclear Steam Supply Systems (NSSS), Balance of Plant (BOP) systems, and Electrical systems. Several of the systems were further grouped into larger categories, such as main turbine systems which includes the main turbine generator and all of its associated support systems. Figure 14[12] shows the overall structure adopted

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[12] Moore, T., et al. "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors." MIT Nuclear Engineering Department, MIT-ANP-TR-036 (June 1996): 148

for the investment protection program analysis, and Figure 15 shows the number of surveillances in each category.

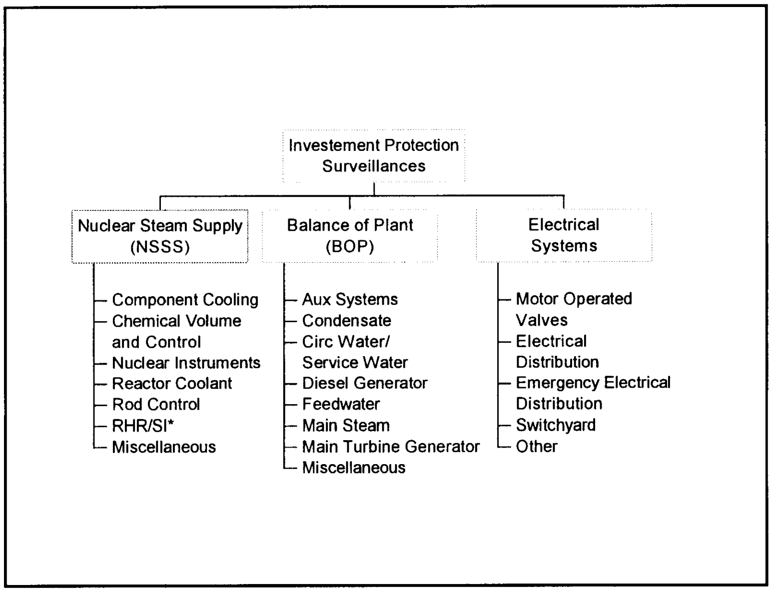

Figure 14: PWR Investment Protection Surveillance Categories

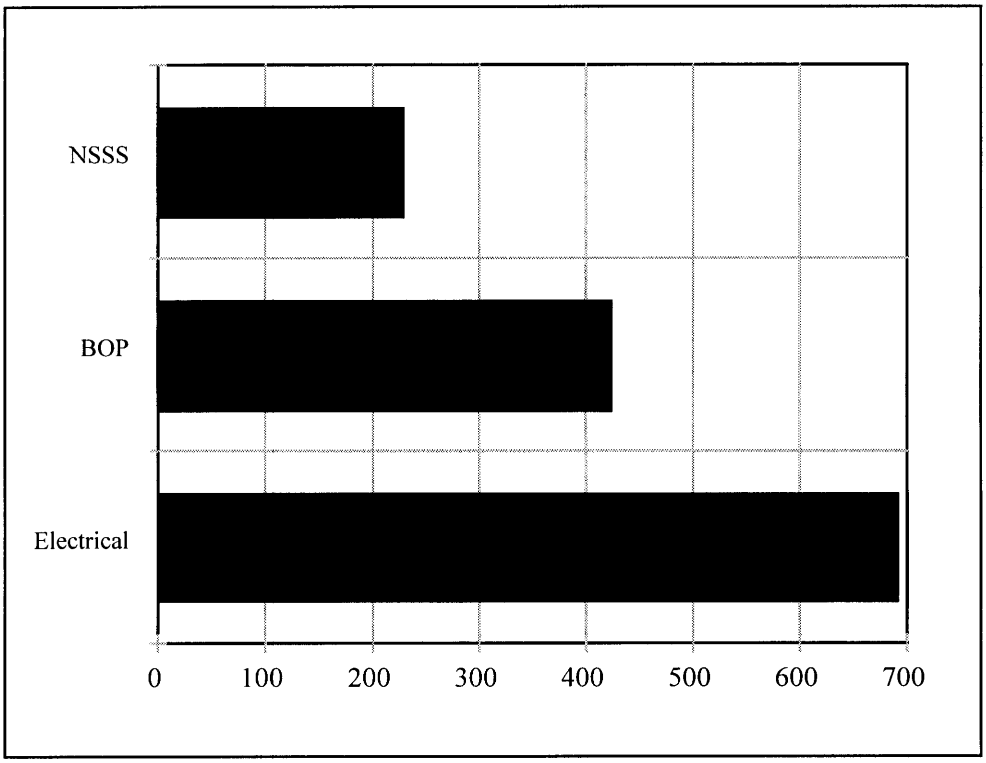

Figure 15: PWR Investment Protection Surveillances by Category

As in the regulatory surveillance section, only those investment protection surveillances currently performed while shutdown were considered in this analysis. There are 1336 individual investment protection surveillances currently performed while shutdown at the case study PWR. Of these, 457 surveillances have performance intervals that are already greater than 48 months and do not require modification.

Of the 879 PWR investment protection surveillances with initial intervals less than 48 months, 397 were designated for on-line performance, 448 were designated for performance interval extension, and 34 were left as unresolved. These results are shown in Figure 16.

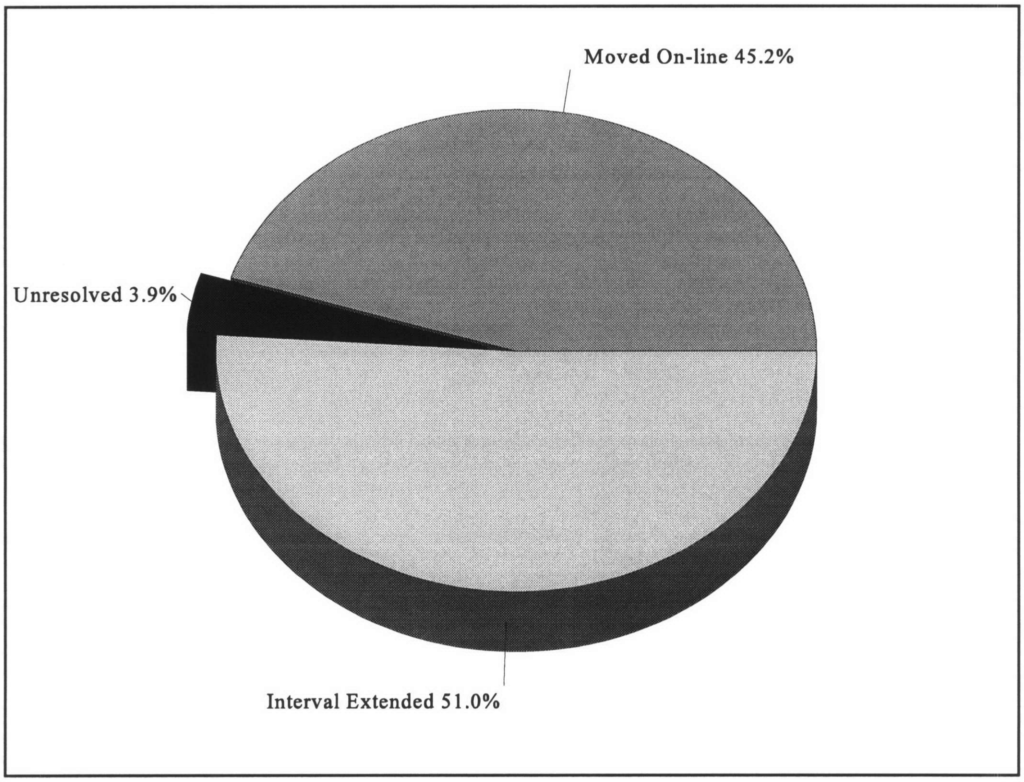

Figure 16: PWR Investment Protection Surveillance Modifications

2.4.3.3. PWR Surveillance Program Summary

The proposed modifications of the PWR off-line surveillances are shown in Table 7. The complete proposed program for the extended cycle is compared to the current surveillance program in Figure 17. The extended cycle program increases the number of on-line surveillances by 51.8% relative to current operations (for a total of 48.9%), and increases the number of surveillances performed off-line at intervals of 48 months or more by 153.8% (for a total of 49.6%). The remaining 1.4% are unresolved surveillances, which are discussed further in Section 2.4.4.

Table 7: Modified PWR Surveillance Program

Tech Spec Section	On-Line	Off-Line	Unresolved	Total
In-Service Testing	87	67	15	169
Reactivity Control	1	4	0	5
Power Distribution	1	0	0	1
Instrumentation	72	44	2	118
Reactor Coolant	5	4	1	10
ECCS	3	5	2	10
Containment	36	20	0	56
Plant Systems	10	0	0	10
Electrical	5	1499	0	1504
Technical Requirements	8	0	0	8
NSSS Economic	100	108	18	226
BOP Economic	297	107	16	420
Previously On-Line Surveillances (Unanalyzed)	1206			1206
TOTAL	**1831**	**1858**	**54**	**3743**

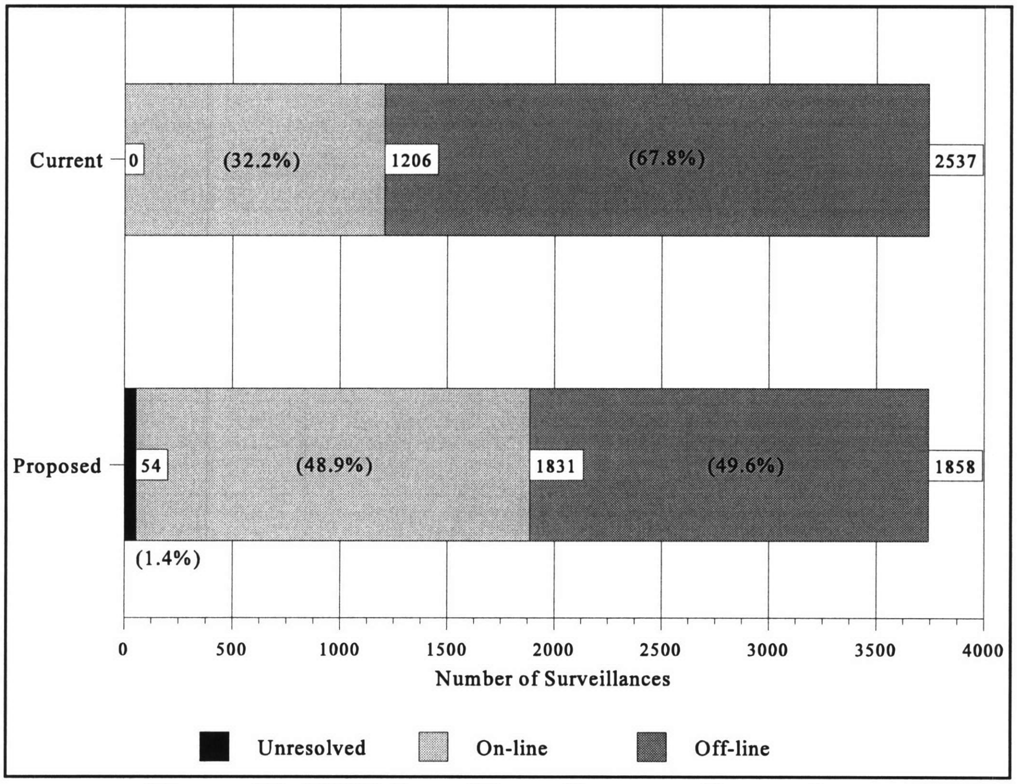

Figure 17: PWR Surveillance Program Comparison

2.4.4. Summary of Unresolved Surveillances

In the complete extended cycle surveillance program, some surveillances could not readily be made compatible with the 48 month operating cycle. These surveillances were labeled as unresolved and are listed here in Table 8. The unresolved surveillances comprise only 1.8% of the total 3809 BWR surveillances and only 1.4% of the total 3743 PWR surveillances.

Table 8: Unresolved Surveillance Summary

Surveillance Category	Initiating Basis	Plant Type
Relief Valve Testing	Regulatory / Economic	BWR and PWR
MOV Testing	Regulatory / Economic	BWR and PWR
In-Service Testing	Regulatory	BWR and PWR
Battery Discharge Testing	Regulatory	BWR and PWR
Waterbox Inspection	Economic	BWR and PWR
Auto Depressurization System	Regulatory	BWR
MSIV Testing	Regulatory	BWR
Operation Equipment Lube	Economic	BWR
ESF Testing	Regulatory	PWR
SG Eddy Current Testing	Regulatory	PWR
Reactor Coolant Pumps	Economic	PWR

The fact that so few surveillance activities were found to be difficult to resolve is a very positive result. With these areas identified now, future work can be marshalled to generate innovative on-line performance techniques or upgrade plant components to tolerate longer surveillance intervals so that these activities will not impede an extended operating cycle effort. Further explanations of the difficulties and initial thoughts on possible solutions are included in the MIT Surveillance Report.[13] Those results are summarized below:

2.4.4.1. Unresolved Surveillances Common to BWRs and PWRs

2.4.4.1.1. Relief Valve Testing

These tests are a regulatory based surveillance requirement common to both the BWR and PWR plants. The valves cannot be tested on-line in most cases due to the risk of system depressurization, and their historical performance records indicate that significant failure rates at current 18 and 24 month intervals could be exacerbated by testing extension. At both plants the

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[13] Moore, T., et al. "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors." MIT Nuclear Engineering Department, MIT-ANP-TR-036 (June 1996): 183-201

valves are predominately class two containment pressure boundary valves, with a handful of class one primary pressure boundary valves. The ASME codes require that 25% of each type of valve be tested every 24 and 48 months respectively, and to satisfy these requirements most valves are replaced with bench tested spares during refueling outages. Although 48 month intervals are currently limited by the ASME code, class one valves rarely fail testing at 18 and 24 month intervals and may be extendable upon time dependent failure mode analysis. The opposite is true for the class two valves, in that despite the fact that the ASME code requires only a 48 month testing interval, most plants currently test valves during every refueling outage and find significant lift check failures. Further analysis of relief valve failures including the valve type, size, system fluid conditions, and environmental conditions must be performed to determine the principal failure mechanisms, relative risk levels, and possible solutions.

2.4.4.1.2. MOV Testing

Both plant types have surveillances involving Motor Operated Valves (MOVs) that cannot be performed on-line in many key systems and that cannot be extended to 48 month intervals based on historical data. MOVs have received widespread attention in the nuclear industry following NRC Generic Letter 89-10, which requested that all MOVs in safety related systems have their design basis reverified, be diagnostically tested, and tested to their design basis condition. A detailed review of the MOV program at the case study PWR by plant personnel indicated that all MOV surveillances can be extended beyond 48 months except for those associated with valves exposed to high differential pressure and having high risk significance. These limiting conditions, which require more frequent maintenance, were found to include just three PWR surveillances, greatly reducing the MOV barrier to extended cycles. When this approach was applied to the BWR plant, a similar reduction in the number of MOVs requiring maintenance within a 48 month interval was found, bringing the number from 83 to 14. Extensive MOV testing research is currently underway throughout the industry, and advances in this area should allow complete reconciliation to the 48 month cycle goal.

2.4.4.1.3. In-Service Testing

Section XI of the ASME Boiler and Pressure Vessel Code requires that all safety related pumps and valves be tested for operability on a quarterly basis. For those tests that are hazardous or not possible on-line, operating plants have requested deferment to refueling outages or designated the surveillances as cold shutdown tests. Cold shutdown tests are to begin immediately upon any shutdown condition more than three months after the previous test and must be completed at least once every operating cycle. Although the current code speaks in terms of operating cycles and not specific time requirements, it is not clear that current deferments and cold shutdown tests would apply to a 48 month operating cycle. BWR and PWR plant engineers offered conflicting opinions on the subject, highlighting the fact that detailed analysis of performance data and evaluation of innovative monitoring techniques is required to resolve the question. If interval extension cannot be technically justified, most of these tests are relatively simple and are excellent candidates for performance during forced outages as discussed in Section 3.3.

2.4.4.1.4. Battery Discharge Testing

The candidate BWR plant does not have a redundant station service battery to allow on-line performance of battery discharge testing, and the batteries are too risk significant to allow them to sit dormant for four years without testing. Many plants do have a redundant battery to facilitate on-line testing, and although this is an option for those plants that do not, it would be an expensive modification. A more attractive resolution of the problem would be to utilize innovative monitoring techniques to evaluate battery capacity. If an accurate correlation between battery impedance and conductance and battery capacity can be developed for large lead-acid storage batteries, on-line monitoring could ensure battery performance.

2.4.4.1.5. Condenser Waterbox Maintenance

The candidate PWR plant is unable to isolate sections of the condenser waterbox for cleaning while at power. The condenser waterbox is the external heat sink for the plant, and degraded performance would have a significant economic impact that could jeopardize extended cycle profitability. The waterbox often uses brackish water, and fowling from marine growth and debris is common. Many plants, such as the case study BWR, have the ability to isolate sections of the condenser at reduced reactor power and to backwash the screens or actually enter for maintenance. Because the PWR plant does not have this option, there is concern that heat transfer may be degraded over the course of a 48 month cycle. Possible solutions include plant modification to allow on-line cleaning and improved chemical and remote cleaning apparatus.

2.4.4.2. Unresolved Surveillances Specific to BWRs

2.4.4.2.1. Automatic Depressurization System Testing

There are two BWR plant surveillances to conduct operability tests of the automatic depressurization system. The first is a manual test of the reactor vessel relief valves, and the second requires the testing of the automatic depressurization system solenoid valves from an alternate control panel. These surveillances can technically be performed on-line, but the associated procedures warn that the risk of plant trip is fairly high and alternate solutions are preferable. Both tests are extremely quick and are excellent candidates for completion during forced outages, but more complete reconciliation to the four year cycle should be pursued.

2.4.4.2.2. MSIV and Feedwater Valve Testing

The BWR MSIV and feedwater valves excluded from Option B of 10 CFR 50 Appendix J may pose a potential barrier to adoption of a four year operating cycle. The integral role these valves play in power production precludes on-line performance, and some engineers have suggested that operating experience and safety significance do not support performance interval extension. Innovative on-line monitoring techniques in conjunction with detailed performance data analysis may enable these surveillances to be reconciled with the extended cycle.

2.4.4.2.3. Drywell Equipment Lubrication

When a BWR reactor is on-line the drywell is inerted with gas. The unbreathable atmosphere, high temperatures, and high radiation levels make all components contained within the drywell inaccessible. Therefore the surveillance that lubricates the various machinery within this space cannot be completed on-line, and the components as they exist may not withstand the lack of lubrication for an entire four year period. Possible solutions to reconcile this surveillance to the extended operating cycle include upgrading plant components to withstand the longer lubrication interval or addition of a remote lubrication system similar to PermaLube cartridges or remote lubrication tubing. Although these are not difficult solutions, they do represent significant modifications to plant equipment. Discussion with various nuclear engineers and managers have demonstrated that there is significant resistance to this type of component upgrade. If less costly maintenance alternatives cannot be found, a rigorous economic analysis must demonstrate the benefit of upgrading the components or installing on-line lubrication systems.

2.4.4.3. Unresolved Surveillances Specific to PWRs

2.4.4.3.1. Engineered Safety Feature Testing

The case study PWR plant performs three ESF tests under six different surveillances, and the BWR has a similar ESF testing program. These surveillances involve the integrated time response testing of actuating logic, valves and pumps associated with safety systems and LOCA response. Current off-line procedures actually inject water into the core, but surveillance modification to test the ESF trains without coolant injection is technically feasible. Because these tests are critical to demonstrate that sufficient cooling water can be delivered to prevent core damage and containment breach in a major LOCA, there may be nontechnical resistance to a modification that eliminates the actual demonstration of core injection or defers it to four year intervals. This safety significance requires that the technical solutions be examined in much greater detail prior to final reconciliation to the extended cycle length.

2.4.4.3.2. Steam Generator Eddy Current Testing

Steam generator degradation in PWR plants has received broad attention within the nuclear industry. Despite a maximum 40 month regulatory limit, existing eddy current testing programs conducted at 18 or 24 month intervals regularly find tube cracks and there have been several tube failure incidents in the operational histories. These factors indicate that performance interval extension beyond current limits is unlikely. Many different studies of steam generator corrosion have been conducted, and the recommended solutions include proper temperature and chemistry control and tube material upgrades to Inconel 690 and beyond. Further study of this issue is required to identify innovative surveillance strategies that will allow for steam generator inspections to be adapted to a 48 month cycle.

2.4.4.3.3. Reactor Coolant Pump Maintenance

The final category of unresolved surveillance involves the reactor coolant pumps. The PWR plant conducts eight surveillances on the reactor coolant pump lube oil system that cannot be performed on-line and that will not likely withstand interval extension. Many of the difficulties in this area stem from the fact that the pump oil reservoir is not accessible with the plant at power. Relatively simple modifications could be made to relocate the tank to an accessible area, allowing for on-line performance of the tests. This option has the advantage of enabling increased lube oil sampling rates as opposed to any performance interval extension approach that could decrease the level of investment protection for the very expensive reactor coolant pumps.

2.4.5. Conclusions

The tables and figures in this section present a picture of the proposed extended cycle surveillance program. While the results are positive for both the BWR and PWR case study plants, there was a noticeably higher percentage of the total surveillances moved on-line at the PWR plant (10.2% more). While this difference is minor and well within the expected variation among different nuclear plants, there may be several explanations for it. First, the two plants were purposely selected to cover a wide range in plant age. The BWR has been in service for 25 years, while the PWR has been in service for less than 10 years. This places the plant designs in markedly different eras of nuclear and management technology. Advances in plant components, such as digital instrumentation for example, could easily explain the greater ability of the newer plant to perform surveillance activities on-line. The two plants were also selected to cover BWR and PWR designs. It is possible that BWR plants are inherently less able to conduct surveillance activities on-line because of the higher percentage of the plant that is subject to steam line radioactivity. Finally, as mentioned previously, there is a difference in the way the research was conducted at the two plants that introduces a positive bias in the number of surveillances moved on-line at the PWR plant.

The work compiled in this section represents the achievement of a primary objective in the MIT Extended Operating Cycles Project Group. With the completion of the extended cycle surveillance program for a 48 month operating cycle, it has been credibly demonstrated that the vast majority of plant surveillance activities can be reconciled to longer cycle lengths. Of the few that remain unresolved, none seem to be insurmountable given the adequate allocation of resources and effort. Therefore, surveillance issues cannot be considered a limiting factor for operating cycle extension in the range of 24 to 48 months.

3. Surveillance Program Impacts

3.1. Introduction

The extended cycle surveillance program of Section 2 has demonstrated that plant surveillance activities are not a limiting factor for cycle extension within the range of 24 to 48 months. While this is a significant achievement, showing that an extended operating cycle surveillance program *can* be developed is not enough. The impact of the proposed surveillance program on plant operations and economics must be evaluated to document its feasibility. While the rigorous economic study is being completed as another topic within the MIT Extended Cycles Research Project, this Section presents some of the pertinent issues identified during the surveillance resolution process. Two of these issues, unresolved surveillance execution during forced outages and the surveillance program impact on surveillances workloads and RFO lengths, are analyzed more rigorously.

3.2. General Surveillance Issues

Over the course of the two years that it took to complete the extended cycle surveillance program, many subsidiary surveillances issues were identified. While significant research effort was not focussed on their complete development and resolution, these general surveillance issues are listed here with initial thoughts and observations. The items discussed here should be considered more fully before an actual cycle extension effort is undertaken.

3.2.1. Altered Plant States

In order to facilitate the designation of some of the plant investment protection surveillances as candidates for on-line performance, realignment of the power plant into altered operating states was required. The two primary altered plant states utilized were reduced power operation and HWC hydrogen injection reduction. Due to the atypical inability of the case study BWR to isolate a recirculation loop at power, the reasons and effects of this are discussed as well.

3.2.1.1. Reduced Power Operation

Of the case study plant surveillances modified for on-line performance, 20% for the BWR and 17% for the PWR require the removal of key components from service that would inhibit the reactor from operating at full power. While the requirement to lower reactor power would have an adverse economic impact on the plant, this tool is used to resolve surveillances that might otherwise prohibit extended cycle operation or require a mid-cycle maintenance outage. Because this concerns only the utility imposed investment protection surveillances, the plants are generally left with wide latitude in determining surveillance performance methods and must make an economic decision of the relative worth of reduced power surveillance scheduling.

If it is assumed that the surveillances slated for reduced power performance would otherwise require a mid cycle maintenance outage to be made compatible with extended cycle operations, the reduced power option offers a number of relative advantages. The time to recover the plant to full power following surveillance performance is significantly reduced. In the case of surveillances that do not require the main turbine to be secured, return to full power can be accomplished in a matter of hours. The reduced power period maintains the reactor and steam systems in a hot condition and reduces the potentially damaging thermal cycling associated with changes of plant state. Also, by avoiding the shutdown state, the plant can avoid cold shutdown operability tests that are required to be completed prior to restart. Finally, there appears to be an increase in component failure rates subsequent to a shutdown when equipment that had been running well is found to be inoperable on startup. For these reasons, reduced power surveillance scheduling could have positive impacts on plant performance and component repair costs.

Conversely, on-line performance of these surveillances does carry some increased risk and costs that should be carefully considered. Adoption of such a strategy would require the plant to attain abnormal operating states and maintain them for several days. Plant operation outside of the normal envelope of experience can sometimes lead to increased operator error. There is also a risk that because the plant is still on-line, error in surveillance execution could cause inadvertent plant trip. Economically, any surveillance that requires the main turbine to be secured incurs additional fuel costs. The reactor is on-line and burning fuel while no revenue generating electrical output is reaching the grid. The economic penalty from burning the fuel may be greater than the savings from avoiding the extra plant startup days following a planned maintenance outage. The reduced power surveillance concept is discussed more fully in the MIT surveillance strategy report,[14] and an attempt is made to quantify these associated economic factors. Table 9 is a summary of the BWR surveillance areas requiring reactor power reduction, and Table 10 presents the same information for the PWR plant.

Table 9: BWR Surveillance Areas Requiring Reduced Power

Description	Power Level	Turbine Secured
Recirculation System		
Motor-Generator Preventive Maintenance	<50%	No
Motor Generator Tachometer Replacement	<50%	No
Motor Generator Scoop Tube Calibration	<50%	No
Pump Preventive Maintenance	<50%	No
Instrument Calibration	<50%	No
Condensate System		
Waterbox Back-flush	<50%	No
Waterbox Drain and Manual Cleaning	<50%	No
Feed System		
Feed Pump Coupling Lubrication	<60%	No
Main Turbine		
Turbine Annual Lubrication	<20%	Yes

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[14] Moore, T., et al. "Surveillance Strategy for a Four Year Operating Cycle in Commercial Nuclear Reactors." MIT Nuclear Engineering Department, MIT-ANP-TR-036. (June 1996): 250-257

Table 10: PWR Surveillance Areas Requiring Reduced Power

Description	Power Level	Turbine Secured
Condensate System		
Condenser Waterbox Maintenance	<20%	Yes
EHC System		
Pressure Transducer Calibrations	<20%	Yes
Emergency Trip System Calibration	<20%	Yes
EHC Power Supply Calibrations	<20%	Yes
EHC Cabinet Cleaning	<20%	Yes
Servo Strainer Replacements	<20%	Yes
Feedwater System		
Steam and Feedwater Flow Calibrations	<75%	No
Feed Control Valve Indication and Stroke	<15%	No
Feedwater Isolation Valve Strokes	<75%	No
Feedwater Isolation Valve Fluid Change	<75%	No
Main Feed Pump Governor Checks	<50%	No
Generator Stator Cooling		
System Pressure Switch Calibrations	<20%	Yes
Lube Oil		
Main Turbine Low Shaft Oil Pressure Cal	<20%	Yes
Low Bearing Oil Pressure Calibration	<20%	Yes
Main Steam		
MSIV Stroke Checks (Tech Spec)	<75%	No
MSIV Maintenance	<75%	No
Circ Water/Service Water		
CW/SW Pump Maintenance	<92%	No
Traveling Screen Inspection	<92%	No

3.2.1.2. BWR Hydrogen Injection Reduction

One of the aspects that differentiates BWR from PWR surveillance resolution results is that the radioactive primary loop encompasses a larger percentage of the plant and therefore radiation exposure is a concern when working on many secondary systems. The steam line radioactivity is mostly attributable to the Hydrogen Water Chemistry (HWC) system. This system injects hydrogen gas into the steam line at the main feed pump in order to arrest Stress Corrosion Cracking (SCC) of the steel components of the loop. SCC is dependent on dissolved oxygen concentrations in the water, and the injected hydrogen gas reacts with the oxygen to reduce the corrosion threat.

A secondary effect of the injected hydrogen gas is to increase the level of radioactivity entrained in the main steam line. The primary mechanism for the activation of the coolant water is the $O^{16}(n,p)N^{16}$ reaction. N^{16} is a γ emitter with a half-life of 7.13 seconds. If there is sufficient dissolved oxygen concentration within the water, a large percentage of this radioactive nitrogen forms NO_3. This is nonvolatile at reactor operating temperatures, meaning that it remains in liquid form and is unable to pass through the steam separators to leave the core. With the HWC system on-line, the added hydrogen reduces the availability of dissolved oxygen, and the majority of the radioactive nitrogen forms ammonia and nitrous oxide. These are volatile at reactor temperatures and become gases that sweep the radioactive nitrogen into the steam line. All components and spaces in contact with main steam are thereby exposed to significant exposure. The 7.13 second half-life of the nitrogen means that the activity of the steam is significant through the turbine and into the condenser, but that the feed system is generally unaffected.

While the HWC system is normally operated to minimize the potential for corrosion in the reactor at just over 900 liters per minute of hydrogen, during a hydrogen injection "turndown" the injection rate is reduced to minimal levels of less than 300 liters per minute. The reduced hydrogen levels mitigate the entrapment of radioactive nitrogen into the steam line and significantly decrease the dose rate in a multitude of steam affected areas. The turndown can be continued for a short period of time, on the order of ten hours, until the water electrochemical potential rises to a threatening level. The length of time that hydrogen injection can be reduced is dependent on core coolant flow rate and flux levels.

The HWC radiation issue was specifically addressed in the BWR investment protection surveillance analysis. Of the 133 surveillances moved on-line, only 9 (6.8%) of them require the utilization of a HWC turndown to make on-line performance a possibility. As many as 43 (21.1%) of the 204 extended interval surveillances are affected by the steam line radiation issue and would be more likely to be candidates for on-line performance if hydrogen injection reductions were fully utilized.

3.2.1.3. BWR Recirculation Loop Isolation

The candidate BWR, like most plants, has two independent recirculation loops. Each loop takes suction from the downcomer annulus and returns water as the driving force for ten jet pumps. Each jet pump acts as a flow multiplier by entraining additional downcomer water to double the core flow. This flow constitutes the forced convection cooling of the core which allows for higher core power than would be possible with natural circulation.

The two recirculation loops are completely independent, and motor operated suction and discharge valves allow the pumps to be isolated for maintenance. While most plants' technical specifications allow for recirculation loop isolation for preventive maintenance, the candidate BWR's licensing basis allows only for a twenty-four hour emergent recirculation LCO to perform corrective maintenance. The following passage regarding single loop operation is taken from the plant's systems reference text:

> "After a pump trip, flow through that loop's ten jet pumps will coast down and reverse. The operating loop's ten jet pumps' flow will increase by 50% due to the lower core pressure drop. Thus at rated conditions, the operating jet pumps will provide 75% of rated flow. However, 22% flow will bypass the core through the idle jet pumps resulting in about 53% net core flow. Indicated core flow will read higher than actual because it still sums all the jet pumps flows even though flow is reversed in ten of them."

The final sentence of the passage reveals the reason that the candidate BWR is unable to undertake planned recirculation loop outages. Each jet pump has a flow meter, and the measured core flow is used to bias the neutron measurements from the Average Power Radiation Monitor (APRM). This biased neutronic data is input into the Reactor Protection System (RPS) and is a critical core safety parameter. With one recirculation loop idled, and reverse flow through it's corresponding jet pumps, the flow biasing of the APRM is inaccurate by more than 20%. This violates the plant's technical specifications and is the reason that planned loop isolation is not permitted.

The majority of plants within the nuclear industry have a logic circuit of "reverse flow summation" that detects and compensate for reverse flow through a jet pump. This ensures the accuracy of the APRM flow biasing and allows for safe single loop operation. Reverse flow summation logic is standard for BWR 5/6s, and an upgrade package has been back-fitted to the majority of older plants. For this reason, despite the inability of the candidate BWR to perform a planned recirculation loop maintenance outage, the recirculation system surveillances that require loop isolation are classified for on-line performance.

3.2.2. Surveillance Program Coordination with Cycle Length

In general, there is wide variability in the structure and execution of each plant's surveillance program. This variability is the result of differing plant and information system ages, system designs, and managerial aggressiveness. These differences are apparent in the existing surveillance programs at the case study BWR and PWR plants, compared in Table 11.

Table 11: Current Surveillance Program Comparison

	BWR Plant	PWR Plant
Current Number of Surveillances Performed Off-line	2694	2537
Current Number of Surveillances Performed Off-line with Intervals Greater than 48 Months	1744 (64.7%)	735 (29.0%)
Current Number of Surveillances Performed Off-line with Intervals Less than 48 Months	950 (35.3%)	1802 (71.0%)

One possible explanation for the markedly different percentages of surveillances currently compatible with the 48 month extended operating cycle comes from the current operating cycle length of each plant. The candidate BWR has been operating on a 24 month cycle for several years, while the PWR is now in transition from an 18 month to a 24 month cycle. Both plants have continuously pursued surveillance optimization programs, pushing surveillance intervals to even multiples of their fuel cycle lengths. Surveillance performance intervals that coincide with multiples of the fuel cycle length minimize both the cost of performing each surveillance and the length of each refueling outage. By coincidence, multiples of the BWR's 24 month cycle meet or exceed this study's 48 month cycle target, while multiples of the PWR's 18 month cycle do not. More than a coincidental anomaly, the fact that the BWR has extended 35.7% more surveillances past a 48 month interval reveals that given economic incentive, surveillance resolution to an extended cycle length can and does occur within the industry.

3.2.3. Odd Length Surveillance Intervals Greater Than Target Cycle Length

An issue that can easily be overlooked is that of odd length surveillance intervals. Odd length surveillances are those performed while the plant is shutdown and that have performance intervals that are multiples of the current cycle length, but whose performance intervals would not be multiples of an extended cycle length. For example, at the case study PWR an electrical surveillances is currently performed every 72 months, which is a multiple of the current 18 month cycle length. If the cycle length is changed to 48 months, a decision must be made as to whether to perform the surveillance more frequently at 48 month intervals or attempt to technically justify extending the performance interval to 96 months. Both options have potential benefits and drawbacks, although 96 months would obviously be a better goal so that the surveillance would not have to be performed during every refueling outage. Another reason to aim for the 96 month performance interval is that some surveillances (such as operability tests of safety system motors) ultimately decrease component life expectancy because of the added wear resulting from surveillance performance. On the other hand, the effort and cost of analyzing all plant surveillance activities that fall into this category is not trivial and should not be taken for granted. Consequently, somewhere in the fuel cycle transition process, economic consideration and engineering attention needs to be given to surveillances with odd length performance intervals. This factor also plays an important role in the surveillance workload and extended cycle RFO length analysis, and is discussed further in Section 3.4.

3.2.4. Surveillance Interval Optimization

The entire 48 month extended operating cycle proposed for the case study plants is based on an evaluation of the technical limits of extending surveillance performance intervals. The basis of the analysis is that since a surveillance interval *can* be extended to 48 months without incurring unacceptable adverse effects, it should be extended to make the surveillance compatible with extended cycle operations. The issue of whether or not the 48 month time is truly the correct performance interval is very complex. A surveillance activity is performed for the two primary reasons of insuring plant safety and maximizing economic performance. For any one component, the safety and economic performance are closely tied to the component's reliability. The economic interests add the further complexities of maximizing the life of the component and minimizing the surveillance performance costs. When all of these factors are considered together, it should be possible to determine an optimal surveillance performance interval. The issue is further complicated by the fact that even if the 48 month operating cycle requires surveillance intervals that differ from their optimal intervals, if the economic costs of the under-optimized surveillances are outweighed by the economic benefits of longer cycle length operation, the 48 month interval is still preferable. A framework for analyzing and optimizing surveillance intervals in the nuclear industry does not currently exist. A summary of work to date in the area and surveillance interval optimization issues comprises Section 4.3 of this thesis.

3.2.5. Utility Level Cycle Length Issues

One interesting factor that has not been otherwise considered in this analysis is the effect that plant operating cycle lengths have on the parent utility company. Especially in the deregulated electricity market, it seems that some consolidation of nuclear generating capacity is likely in the future. Those companies that can master efficient nuclear plant operations will find it profitable to operate several nuclear units as a loosely coordinated team. This approach will allow for the efficient dispersal of some equipment, management and personnel costs over the multi-plant team and give such utilities an economic advantage over single unit operators. One of these shared resources is likely to be an integrated outage team that manages the RFOs for all of the utility's plants. The work of this outage team would be dictated by the operating cycle lengths of the different plants and the number of plants owned by the utility.

For example, the Pennsylvania Electric Company (PECO) currently operates four units in the central East coast region. Each of the units is on a 24 month operating cycle, and the cycle lengths are offset such that the utility's integrated outage team plans and conducts one RFO every six months. This constitutes a demanding pace for the outage personnel, but has the added benefit of maintaining a sharp, constantly practiced outage team that has achieved some of the shortest RFOs in U.S. operating history. PECO managers and engineers feel that they have reached some sort of optimum by operating their four units on 24 month operating cycles.[15] If the utility were to add more units or attempt to operate the units on different operating cycles, the current efficiency point would be lost and there would be some real cost to less proficient outage planning or developing a new integrated outage team structure. It is not clear what the magnitude of this impact might be, but in the closely competitive market of the future, the issue bears further consideration. Other utility level operations that could influence optimum operating cycle lengths should also be identified and explored.

3.3. Unresolved Surveillance Completion

Table 8 in Section 2.4.4 (page 81) lists those surveillances that could not readily be reconciled with the 48 month operating cycle. Barriers to on-line performance and poor failure histories prevent these surveillances from being modified. The compilation of unresolved surveillance activities is intended to identify these areas for further study so that innovative on-line testing methods or component upgrades can make them compatible with longer cycles. In the short term however, there may be a temporary solution that will reduce the impact of the unresolved surveillance problem.

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[15] Limerick Generating Station. Research Meeting. Sanatoga PA, 22 November 1996.

3.3.1. Methodology

The 48 month operating cycle target includes a forced outage rate of 3%. This equates to an average of over 10 days per year (perhaps non-contiguous) of reactor down time in which surveillance activities can be performed. The ability to perform these surveillance activities during forced outage periods, however, is dependent on the time it takes to complete the task and the required preparation and setup. Forced outage windows are likely to vary from the minimum of 2 days, which are required for plant restart, to a week or more. Considerably longer outages are possible of course, but outages outside of the 2 to 7 day range do not occur with a high enough frequency to rely on them for unresolved surveillance completion. When a plant is in a forced shutdown, bringing the plant back on-line as quickly as possible is the top priority. Operators will not begin any non-emergent surveillance activity that has a risk of extending the outage period. Therefore, in order for an unresolved surveillance to be completed in this way, the sum of its preparation and staging time, work time, and system restoration time cannot practically exceed 3 or 4 days at most. This section reviews each of the unresolved surveillance areas for the case study BWR plant and discusses their suitability for completion during forced outage windows.

3.3.2. Results

3.3.2.1. Unresolved Surveillances Common to BWRs and PWRs

3.3.2.1.1. Relief Valve Testing

The term relief valve testing is slightly misleading because in actual practice, the valves are simply replaced with spares and bench tested at a later time. This distinction is important because it drastically reduces the time that the associated system is out of service. Although there is fairly wide variation in the accessability of the relief valves throughout the plant and the complexity of depressurizing their associated systems, no cases could be identified that required significant preparation or staging. The actual removal of a valve is a simple task, and it can be assumed that any relief valve in the plant can be replaced with a previously tested spare in 8 hours or less. If another 8 hours is conservatively assumed for system depressurization and restoration, the total work time is on the order of 16 hours. These surveillances are clearly well suited for completion during forced outage periods.

3.3.2.1.2. MOV Testing

The surveillances included in this area cover the general preventive maintenance and inspection of the MOVs. These valves range in size from 2.5 to more than 60 centimeters and are found in nearly all plant systems. The specific tasks involved in the surveillances are listed in Table 18.

Table 12: MOV Surveillance Time Line

Surveillance Task	Typical Performance Time
As Found Leak Rate Test	8 hours
Leak Rate Acceptable: Inspection, Lubrication and Torque Tests	4 hours
Leak Rate Unacceptable: Removal and Movement to Work Area, Overhaul and Testing, Movement and Replacement.	8 hours / 48 hours / 8 hours
Alternate Leak Rate Unacceptable: Replace with Bench Tested Spare	8 hours
As Left Leak Rate Test	8 hours
	TOTAL: 20 - 80 hours

It can be seen that there is a wide variation in the possible work times that stem from three surveillance scenarios. The best case is that the valve will pass its as found leak rate test and require only in place maintenance, which has a maximum work time estimate of 20 hours. Failure of the leak rate test requires further action. If a valve is small enough, it can be replaced with a bench tested spare just as discussed for the relief valves. This results in a maximum estimated completion time of 24 hours. As the size of the MOV increases, increasing the cost of maintaining replacements, the replacement strategy begins to become prohibitively expensive. In these cases the valves must be removed to a work area, overhauled and tested, and reinstalled. This scenario can take as long as 80 hours to complete. When considering the feasibility of performing these surveillances in a forced outage, it must be assumed that the valve will fail the leak rate test. Therefore, the a priori estimate of work time will be 24 or 80 hours depending on the specific valve. The result is that smaller valves that can be replaced with spares can be readily performed in almost any forced outage, while the larger valves would require a more significant plant failure and are on the outside edge of acceptability for forced outage work.

3.3.2.1.3. In-Service Testing

The in-service testing requirements of interest here are the large number of cold shutdown operability tests that are required following a plant shutdown. These test are listed as unresolved because current regulations allow for the tests to be deferred for the full current operating cycle length of 24 months, but it is not clear that this deferment will apply to the 48 month cycle. This is only an issue if the plant has a perfect run of continuous operation for more than 24 months. Current operational performance and the performance goals for the extended operating cycle make a continuous run of this length highly unlikely. If there are forced outages during the cycle, these tests are intended to be completed in forced outage windows by definition and are designed for such performance in their governing procedures. Typical performance times range from less than one minute to cycle a valve to 8 hours to operate a pump on a test loop.

3.3.2.1.4. Battery Discharge Testing

There are two battery discharge tests performed at the case study BWR. These are the battery service test, which simulates actual emergency loads on the battery and measures the battery response, and the battery performance test, which is a simple continuous discharge of the battery to measure its performance. It is the battery service tests for the 250 V and 125 V station service batteries that are unresolved. These tests use a computer controlled resistance bank to simulate the sequential loads from plant equipment, such as valves and pumps, expected in an emergency situation. The voltage and current of the battery are measured at each stage and must meet certain criteria defined in the technical specifications. The tests follow the Time Line shown in Table 13.

Table 13: Battery Service Discharge Testing Time Line

Surveillance Task	Typical Performance Time
Discharge Sequence	8 hours
First Recharge	16 hours
Stabilization	3 hours
Second Recharge	34 - 72 hours
	TOTAL: 61 - 99 hours

The test consists of the discharge sequence, which last 8 hours, followed by a lengthy battery recharge. The initial charge returns the battery to its required operational voltage, which is measured after the stabilization period, and the second trickle charge maximizes the battery capacity and helps to insure that the battery will maintain the required voltage through the next testing date. While the estimated performance times of 61 to 99 hours seem very long, these tests are more suitable for forced outage performance than they appear. The reason is that once the battery capacity is measured after the stabilization period, it is technically at full rated charge and can be returned to service after only 27 hours. The battery system engineer expressed concern about the reliability of a battery that has not undergone a trickle charge of at least 54 hours, and this recharge would be continued as long as other work items kept the plant off-line. If it was required to put the battery back in service prior to this time, the on-line battery charger could be used to continue the trickle charge with the battery in service.

3.3.2.1.5. Condenser Waterbox Maintenance

The case study BWR actually has the ability to isolate sections of the condenser waterbox for cleaning while the plant is on-line. For plants that do not have this ability, the performance of this surveillance is still very well suited to forced outage windows. The primary threat of waterbox fouling is to decrease the efficiency of the condenser and result in an economic loss through reduced power production. To thoroughly rid the waterbox of marine fouling can take as long as 4 days, but it is not necessary to return the waterbox to this level of cleanliness. If waterbox cleaning is begun, it can be terminated whenever the emergent work of the forced outage is completed. Even the shortest outages of 2 days would allow for significant cleaning and would prevent any loss of condenser efficiency.

3.3.2.2. Unresolved Surveillances Specific to BWRs

3.3.2.2.1. Automatic Depressurization System

The surveillances in this category consist of a test of the automatic depressurization system solenoid valves from a secondary control panel, and a test of the valves themselves. The valve testing can be completed in accordance with the strategy listed for all relief valves earlier in this section. The alternate control panel test requires the simple activation of the valves from a specific panel and can be completed in a matter of minutes. These tests can very easily be completed in even the shortest forced outage windows.

3.3.2.2.2. MSIV and Feedwater Valve Testing

These surveillances are closely related to the MOV testing issue previously discussed. The different actuating mechanism has little effect on the basic valve testing and maintenance procedure. The Time Line of Table 18 is still applicable, although these valves are obviously of the larger type and are not replaced with bench tested spares. The maximum estimated work time of 80 hours may be increased by the added valve size and complexity and the requirement to drain the main steam line. While still feasible for longer forced outages of a week or more, completion of the MSIV and feedwater valve maintenance is not well suited for forced outage completion.

3.3.2.2.3. Drywell Equipment Lubrication

The final unresolved surveillance activity that was considered for forced outage performance is the lubrication of equipment within the drywell. The actual lubrication of the rotating equipment, primarily HVAC blowers, is relatively simple and can be completed in a few hours. The performance time is increased by the requirement to de-inert the drywell and allow heat and radiation levels to dissipate, and to re-inert the space following this and other work. Including these factors the maximum estimated work time is still less than 24 hours, which means that the equipment can be lubricated in practically any forced outage.

3.3.3. Conclusions

The compilation of the total estimated work times to complete the unresolved BWR surveillances during forced outage windows shows a range of a few minutes to more than 4 days. The majority of the activities can be completed in less than 24 hours, providing a 100% margin for work overruns in even the shortest forced outages. Those activities with estimated work times on the order of several days, which would require an expected forced outage duration of a week or more to provide the same margin, must tolerate the longer interval between forced outages of this magnitude. For these surveillances especially, it is restated that the forced outage performance option is merely a temporary solution to the unresolved surveillances. These areas of work should receive further attention from interested academic, government and industry parties in order to develop more complete reconciliation to extended operating cycles.

3.4. Extended Cycle Surveillance Impact on Refueling Outages

In order to validate the feasibility and quantify the operational and economic costs of an extended operating cycle, this section will evaluate the effect of the proposed surveillance program on the plant workload in RFO periods and the RFO lengths within the four year operating cycle. The subsequent analysis is based on data taken from the sample BWR case study plant.

3.4.1. RFO Workload Analysis

3.4.1.1. Methodology

The initial step was an outage workload comparison for various operating cycle lengths. A download of the BWR master surveillance tracking program was used to provide initial data on all active surveillance activities, current performance modes and intervals, and most recent completion dates. This database was then cross-referenced to the proposed surveillance program, producing a compound set of data consisting of actual surveillance activities and completion dates coupled with proposed performance modes and intervals. A simplifying assumption was made that any surveillance activity currently designated or proposed for on-line performance is independent of the operating cycle length and has no impact on refueling outage workloads. These surveillances were removed from the database and are not considered further. It is also important to note that the initial surveillance analysis assumed that any surveillance activity with a performance interval equal to or greater than forty-eight months is already compatible with the extended cycle goal. These surveillances were not analyzed in depth to determine if even longer performance intervals are possible, nor was any attempt made to coordinate performance intervals so that they coincide with planned outage dates. Any surveillance due date that falls between consecutive RFOs is conservatively assumed to fall within the earlier outage.

The resulting compound database, containing 1915 surveillance activities, was imported into a spreadsheet model designed to extrapolate the RFO workload for the proposed four year operating cycle. A base date of February 1st 1997 was used for the beginning of four year cycle operation. A logical expression, diagrammed in Figure 18, was used to set a flag for every surveillance activity that came due within the next sequential four year cycle. The "Interval Test Function" used in the expression returns the date of the beginning of each cycle subsequent to the base date in which a surveillance activity is due. If the output of the interval test function coincides with the date of a RFO, the logical flag for that surveillance to be performed in that outage is set to true. A second expression then updates the latest completion date to coincide with the current outage date, and the model moves on to evaluate the logical flag for the next outage period. All positive flags beneath each outage date are counted, and the final output of the model is the total number of surveillance activities due in each RFO.

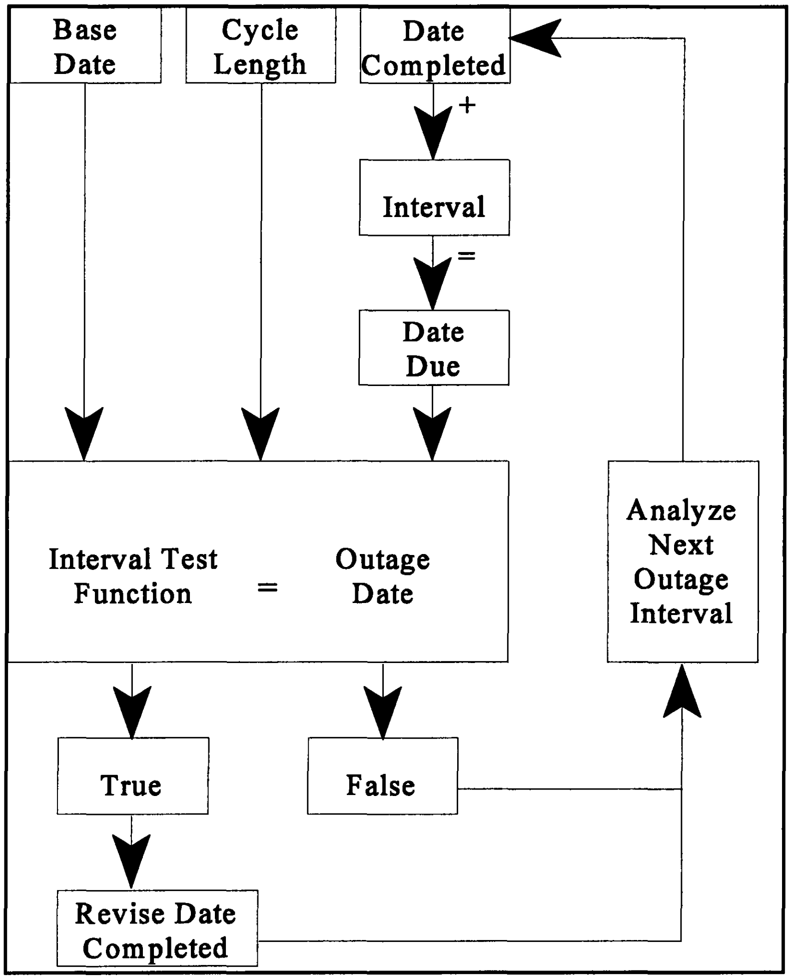

Figure 18: Surveillance RFO Inclusion Logic

3.4.1.2. Results

The spreadsheet model was used to compare the base case, defined as the current surveillance program and operating cycle of the case study BWR, to a number of extended cycle cases. The first case evaluated was a 24 month operating cycle using the proposed extended cycle surveillance program. The proposed surveillance program moves a number of surveillance activities into the on-line workscope and extends all performance intervals to 48 months or more. These changes by themselves, independent of operating cycle length, have a significant impact on the RFO workload and this case was used to quantify that impact so that the cycle length dependent effects could be isolated in subsequent cases.

The spreadsheet model was then used to calculate the number of surveillance activities to be performed in each RFO under the proposed extended cycle surveillance program for operating cycle lengths of 36, 42 and 48 months. The analysis was carried out through the year 2032. The plant's current license expires in 2012, but a license extension of 10 or 20 years is likely. Sensitivity analysis showed that the workload average and proportional lifetime workloads were generally independent of the plant life value used. Figure 19 on page 108 compares the results for the proposed 48 month cycle and the base case and modified 24 month cycles. In order to further quantify these results, Figures 20 and 21 provide the average number of surveillances per RFO and the total number of surveillances performed over the life of the plant for each of the cycle lengths.

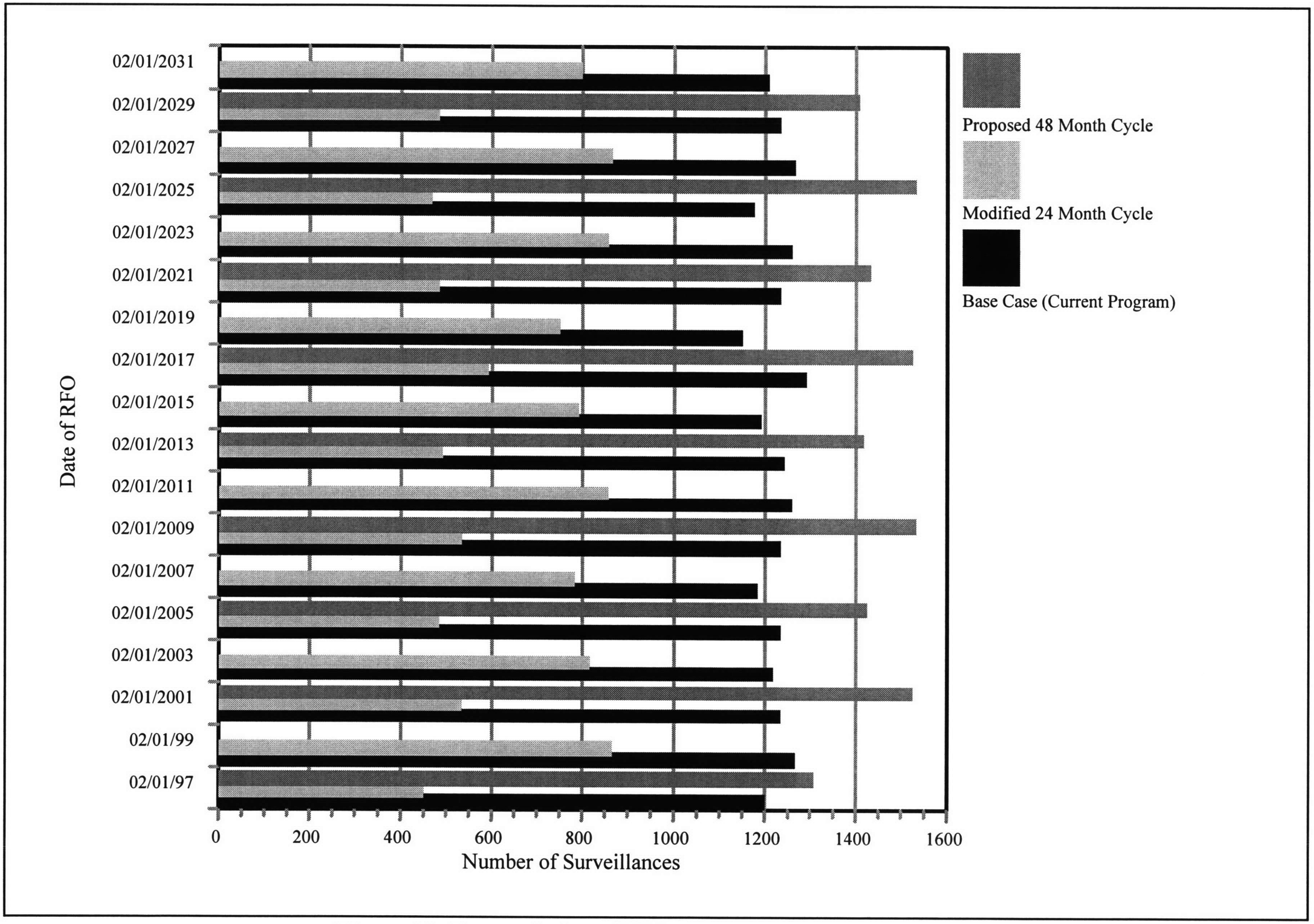

Figure 19: Extrapolation of Surveillance Workloads per RFO

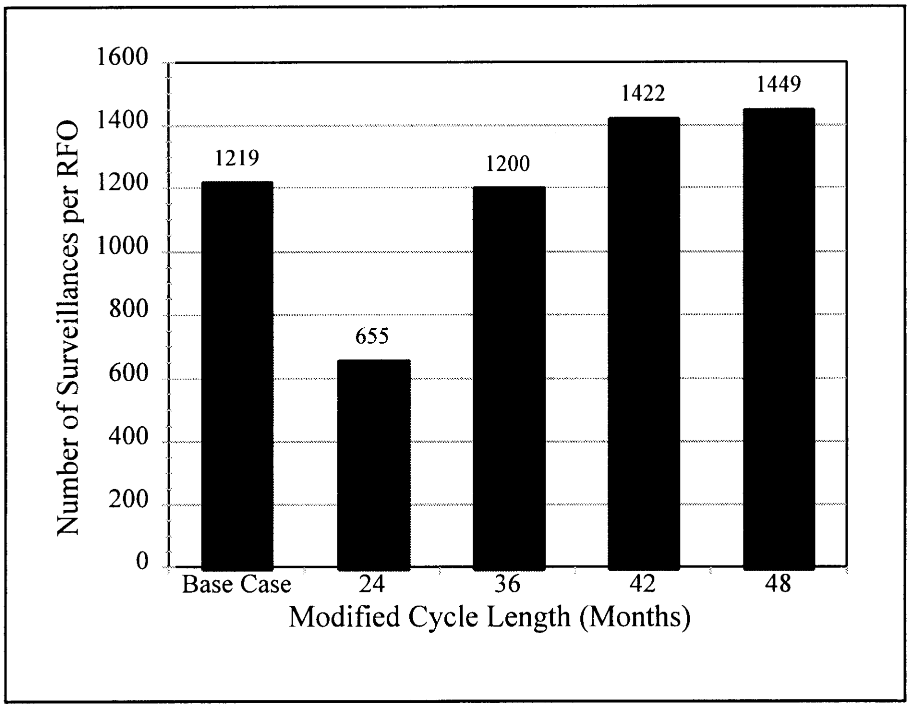

Figure 20: Average Surveillance Workload per RFO for Various Cycle Lengths Compared to Base Case of Current Operations

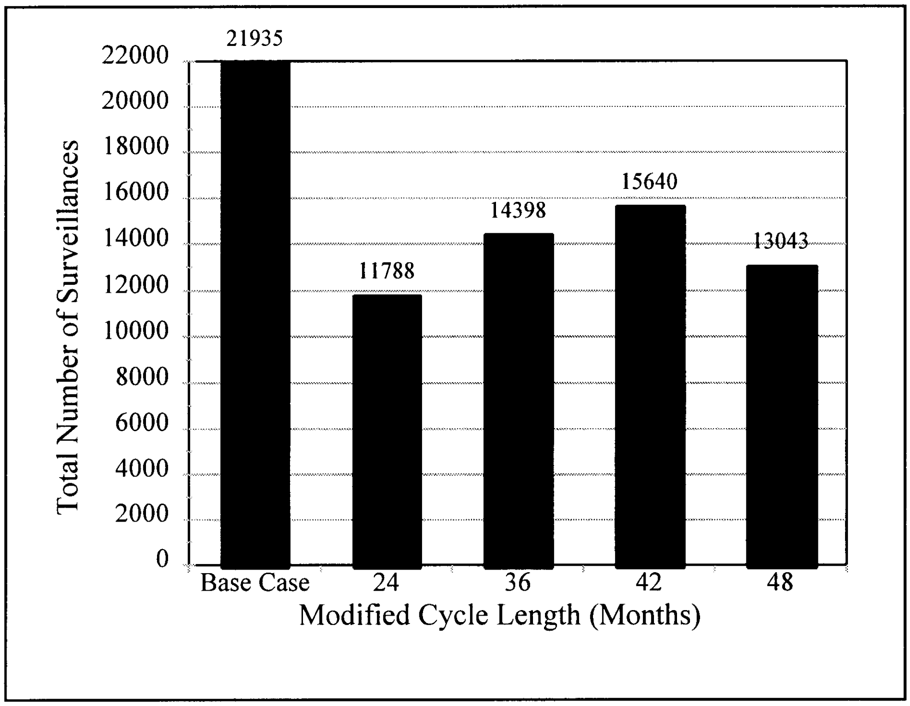

Figure 21: Total Lifetime Surveillance Workload for Various Cycle Lengths Compared to Base Case of Current Operations

3.4.1.3. Conclusions

The above figures reveal a number of interesting points. First, the surveillance program modifications presented in Section 2 have a dramatic impact on the RFO workloads independent of the operating cycle length. Comparing the base case with the modified 24 month cycle in Figure 20, the proposed extended cycle surveillance program reduces the average number of surveillances per RFO by 46.3%. There is a relatively simple explanation for the magnitude of this decrease. The modified surveillance program consists of those surveillances that had an initial performance interval greater than or equal to 48 months, the majority of which are coordinated with whole multiples of the current 24 month operating cycle, and those surveillances that originally had a shorter performance interval but were extended to 48 months. This means that the modified surveillance program is heavily weighted towards 48 month intervals, and nearly all of the surveillances fall on whole multiples of a 24 month operating cycle. The modified 24 month cycle, therefore, performs all of the surveillances that were extended exactly half as often as the base case and continues to catch almost all of the surveillances on whole multiples. This second point is important because, as mentioned earlier, the spreadsheet extrapolation model conservatively requires that any surveillance not falling directly on a RFO be performed in the previous RFO. It is also noted that Figure 19 shows a fairly wide cyclical fluctuation in the number of surveillances performed in consecutive RFOs for this 24 month case. This is a result of the assumed program modifications being instituted instantaneously on February 1st, 1997. It would be more realistic to assume that the surveillance modifications would be phased in such a way to levelize the outage workloads towards the average value. The ultimate conclusion from this point is that, regardless of intentions to extend the operating cycle, there is a wide margin for optimization of surveillance performance intervals.

The second conclusion that can be drawn from this analysis is the influence of operating cycle length on RFO workloads. Figures 20 and 21 both show an increasing trend as the cycle length is increased from 24 to 36 to 42 months, followed by a reversal for the 48 month case. There are two primary reasons for this trend. The upward slope from 24 to 42 months in Figure 20 results from the fact that as the operating cycle length is increased, there are fewer outages to perform a fixed number of surveillance activities and the number of surveillances per outage must increase.

The second factor, which causes the upward slope in Figure 21, is again related to the number of surveillances that are performed on whole multiples of the operating cycle length. As discussed previously, the modified 24 month case is ideally coordinated to take advantage of these whole multiples. As the operating cycle length is extended to 36 and 42 months, the surveillance program moves further and further from this optimal coordination. The result is that more surveillance due dates fall between scheduled RFOs, and anytime this happens the surveillance interval is effectively decreased to move it into the previous RFO. Decreased intervals mean that the surveillances are performed more frequently, and this increases the total number of surveillances performed over the life of the plant.

In both figures, there is a trend reversal for the 48 month operating cycle. This cycle length is perfectly coordinated with the large number of 48 month interval surveillances in the modified program, and is a double multiple of the 24 month base case. The result is that there are far fewer surveillance due dates falling outside of scheduled RFO periods and therefore fewer instances where the interval is effectively reduced.

The results of the surveillance workload analysis are economically significant for two primary reasons. First, there is a direct cost associated with performing a surveillance activity and reducing the total number of surveillances performed over the life of the plant can result in substantial savings. Second, changes in the average number of surveillances per RFO affect the outage work density. Higher surveillance workload densities create human resource management problems and require the reliance on expensive outside contractors to meet outage time restrictions.

The conclusions that should be drawn from this are that in general, extending the operating cycle will increase the number of surveillances per RFO, but by tailoring the surveillance program to a particular cycle length goal, this increase can be effectively minimized. As a more immediate result, the analysis shows that the proposed 48 month operating cycle will cause a modest 18.9% increase in the average RFO workload while significantly decreasing the total number of surveillances over the life of the plant by 40.5%.

3.4.2. RFO Length Estimation

Despite the significance of the workload analysis results, the modified surveillance program may have an even greater economic impact than changing surveillance performance costs. As discussed in Section 1, the length of RFOs has a direct impact on a plant's capacity factor and ultimately it's economic success. If the predicted increase in average RFO workloads results in corresponding increases in RFO lengths, the added time off-line could cost the utility millions of dollars and render the extended cycle economically unattractive. However, the length of a RFO period cannot be directly correlated to the surveillance workload and therefore the change in outage duration is not simply proportional to the estimated workload increase. Forming a reasonable estimate of RFO lengths for the 48 month extended cycle requires a more in depth analysis of outage planning and management.

The task of an outage planner at a nuclear power plant is very complex. The primary objective is to complete all of the required surveillance work and refuel the core within the minimum amount of time possible. Achievement of this objective is constrained by a number of other factors including regulatory restrictions on allowable plant states, the availability and interdependency of plant systems and equipment, and the need to levelize the workload and work density for human resource management and to avoid the need for expensive outside contractors. The magnitude and complexity of these factors require the dedicated efforts of an entire team of engineers and outage planners over the course of several months to develop an efficient outage plan. For this reason, it is beyond the means of this research project to focus the type of effort required to rigorously develop a RFO plan for the 48 month extended operating cycle.

Fortunately however, such a rigorous treatment of the subject is not necessary to meet the analysis objectives. While the task of outage planning is very complex, the majority of this effort is directed towards organizing surveillance activities and human resources within a RFO length goal. While the proposed extended cycle surveillance program does include an increase in RFO workloads, the modest magnitude of the increase allows for a simplifying assumption to be made that the increased workload itself can be compensated for with increased manning and efficient management to negate any impact on the RFO length. This assumption has been discussed at length with outage planners at two different utility companies, and professional opinion supports the conclusion that outage workload increases of the magnitude considered here (≈20%) are not likely to have a significant impact of themselves. There is, however, a threat that the outage workload increases in specific areas of work will lengthen the critical path that determines RFO length goals.

When planning the completion of the large number of surveillance and refueling tasks within an outage, there are many regulatory restrictions, system dependencies, and resource limits that require that specific activities be completed sequentially. Within resource limits and to the extent that they aren't interdependent, all of these sequential chains of work can be completed in parallel. This means that the shortest possible RFO length is the time it takes to complete the longest sequential chain of work, and this chain of work is defined as the critical path. Estimation of extended cycle outage lengths, therefore, requires that this critical path be determined.

Although ideally the critical path should always be the refuel operation, due to its dependence on a large number of plant specific factors, there is not one critical path that will dominate extended cycle outages at all plants. As with the surveillance resolution analysis, the use of a case study plant will allow for a general estimate of the results. Subsequent review and discussion with other professionals throughout the industry will then allow the accuracy and breadth of the estimate to be gauged. The results of this process will be sufficient to estimate the economic impact of longer RFOs on extended cycle economics.

3.4.2.1. Methodology

At the case study BWR plant, the outage planning team uses a number of generic outage kernels from which the final outage plans are developed. Each generic outage kernel consists of an optimized outage plan to complete regular surveillance activities. Four different generic outages are used consecutively to correctly represent longer interval surveillances that need only be included in every second or fourth RFO (corresponding to 4 and 8 year intervals on their 24 month cycle). These generic outages are then expanded to include any emergent work or upgrades that need to be added, updated with current work time estimates, and formed into a final outage plan. These preplanned generic outages can also be used to estimate the critical path of the 48 month operating cycle RFOs.

If two of the four consecutive generic outage plans are combined, the resulting outage would include all of the surveillance activities currently performed at 24 and 48 month intervals. This is functionally equivalent to extending all surveillances performed less than every 48 months to that interval. Once redundancies have been removed, this double-outage plan is therefore comparable to the modified surveillance program presented in Section 2. Further analysis of the combined plan can identify the critical path and estimate its length. This approach will tend to overestimate the work requirements because it does not include the movement of some surveillances to the on-line workscope, but for the reasons stated above, if the resulting critical path is not directly affected by any surveillances moved on-line there will be no impact on the RFO length estimate.

3.4.2.2. Results

The method outlined above was used to combine an "A" and "B" generic outage at the case study BWR plant into a generic 48 month cycle outage plan. The redundant surveillance activities were removed, and the surveillance completion times were updated with the most current estimates available. The resulting outage plan was then analyzed to identify the critical path. This analysis revealed that work on the plant electrical distribution systems was clearly dominant. The work involves the maintenance and calibration of primary electrical components, such as buses and breakers, throughout the 4 kV and 480 V electrical networks. RFO lengths are particularly sensitive to electrical system work of this type because it requires that the downstream loads be isolated without power. The need to have downstream equipment operational restricts the ability of bus and breaker work to be completed inside of the refuel path.

Using the electrical work critical path, the 48 month extended cycle outage length was estimated at 42 days and 2 hours. This represents a 27.5% increase over the equivalent outage under current 24 month operations, which is 33 days long. In order to evaluate the confidence level of this estimate, the method and result was presented to nuclear professionals and outage planners outside of the case study plant. While current outage proficiency varies widely between plants, the response was surprisingly consistent. As a result, the proposed extended cycle surveillance program is considered to result in a 25% to 30% increase in RFO duration relative to current outage performance.

3.4.2.3. Conclusions

The final result of an expected 25% to 30% increase in RFO lengths for a 48 month operating cycle has negative ramifications for the research goal of demonstrating extended cycle feasibility. While the full impact of this result will be explored in the project's economic analysis, it certainly does not seem to be a prohibitive barrier. Current best plant outages are less than 20 days, meaning that even with the extended cycle penalty, well managed RFOs could be completed in 25 to 33 days. This is consistent with the extended cycle assumption of a 30 day RFO.

4. Surveillance Effectiveness

4.1. Introduction

Following the completion of the extended cycle surveillance program and an evaluation of its impact on plant operations, the focus of work was shifted towards surveillance performance in general. The goal is to determine what factors determine the effectiveness of surveillance performance and to develop a framework for effectiveness evaluation.

There are two general types of surveillance- testing and maintenance. Testing surveillances are often imposed by a regulatory body in order to ensure the functionality of components and systems critical to plant safety. The maintenance surveillances can be required by regulations, but more often are initiated by the plant or utility in order to maximize the economic performance of the plant and to protect capital investment in plant equipment. Each of these types of surveillances has fundamentally different objectives and performance characteristics. In order to limit the bounds of this exploration into qualifying surveillance effectiveness, preventive maintenance surveillances are examined independently. This type of surveillance was selected because the greater latitude allowed in economically based surveillance performance creates the opportunity for effective surveillance optimization, and because these surveillances have received significantly less study in industry literature.

4.1.1. Definitions

The first step is to define what is meant by surveillance effectiveness. The purpose of a preventive maintenance activity is to inspect a component, identify areas of material degradation, and to undertake steps to eliminate or mitigate the degradation trend. These steps might include lubrication of moving parts, replacement of worn sub-components, or recalibration of component functions. Therefore, the first measure of maintenance surveillance effectiveness is its ability to target the most significant degradation modes, and further, the ability of the surveillance to systematically counter the degradation processes. While this is necessary for a surveillance to be considered effective, it is not inclusive. An effective surveillance must not only counter component degradation, but it must do so in an economically efficient way. Consider for example, a common light bulb used within a nuclear power plant. It is conceivable that a maintenance surveillance could be devised to test the integrity of the light bulb filament and to replace the filament when it shows signs of wear. Such an approach could virtually eliminate time dependent light bulb failures and would therefore satisfy the first condition of surveillance effectiveness. It is highly likely, however, that the expense and consequence of instituting this surveillance program would exceed the cost of simply allowing the light bulbs to burnout and replacing them as necessary. The second condition for surveillance effectiveness, therefore, is that the activity be performed in a manner that optimizes the net benefit to plant operations and profitability.

4.1.2. Goals

The primary goal of this section is to introduce the pertinent concepts of optimizing the effectiveness of surveillance performance. This will be undertaken in two distinct steps. Section 4.2 will analyze the utility of maintenance tasks relative to their ability to correctly target and counter the dominant areas of degradation. The goal is to develop the framework for a simple analysis tool that will qualitatively rate the effectiveness of a surveillance activity in meeting its objectives. This will be demonstrated through study of the surveillance activities within a specific system and for a specific component at the case study BWR plant. The second step will be to examine surveillance performance efficiency in Section 4.3. The goal here is to define the factors that are required to economically optimize the performance intervals and to discuss a framework for performing the optimization.

4.2. Surveillance Utility Evaluation

An effective preventive maintenance surveillance must be directed at the most prominent failure mechanisms and must produce measurable reductions in the degradation trends that lead to failure. A framework for qualitatively measuring surveillance utility in these terms was developed by using a case study approach of current surveillance performance. In order to meet the goals of this section, the first step was to identify a plant system and component for surveillance analysis. Previous work was already underway to assist plant personnel with surveillance tasks in the 4.16 kV electrical distribution system at the case study BWR plant, so this system was targeted for further work to utilize the background knowledge and resources that had been acquired.

There were three primary objectives for the analysis of the electrical distribution system. The first of these was to study the function, structure, and components of the distribution network to develop a detailed understanding of the system and its relevance to plant operations. Using this background knowledge, the second objective was to study the system surveillance activities and procedures. This was intended to provide insight into how the surveillance activities were created and organized. Finally, a surveillance utility analysis was conducted in which the specific surveillance tasks and their intended maintenance effects were compared to component failure data from the plant and nuclear industry. For the second two objectives, the breadth of work was reduced to manageable levels by studying only one primary component within the electrical distribution system. The 4.16 kV electrical breakers were selected for this role because they are the dominant active component in the system and have significant associated maintenance tasks.

The methodology used is a correlation of surveillance tasks to failure mechanisms and historical data. The surveillance procedure was reviewed in detail, and each independent maintenance sub-task was identified. The tasks were then labeled according to the breaker failure mode that they are intended to prevent. Finally, historical failure records were analyzed to find the relative frequency of each evident failure mode, and a correlation was made between the maintenance tasks and the failure records. Section 4.2.4 presents this correlation as a maintenance utility matrix.

4.2.1. Electrical Distribution System Description

4.2.1.1. Function

The 4.16 kV electrical distribution system at the case study BWR plant is the primary power network. It distributes AC power to all of the plant equipment and systems necessary for normal power operations and emergency plant control. The system is designed so that it can automatically detect faults and power quality degradation and institute a series of load shedding logic and alternate power source transitions to preserve the vital plant loads. Within the overall plant structure, the 4.16 kV system lies between the 345 kV off-site power grid, the 23 kV main generator output, and the 480 V distribution network which powers unit auxiliaries under 185 kW.

4.2.1.2. Structure

The 4.16 kV system draws power from a variety of different on-site and off-site sources. Because of its vital nature, there are five separate power supplies for the emergency buses. The primary operational source is the unit auxiliary transformer, which steps the 23 kV output from the main turbine generator down to 4.16 kV for distribution. During plant startup and shutdown, the system is powered from the startup transformer which converts 345 kV offsite power directly from the switchyard. The startup transformer is also used in the case of plant trip. If the plant has tripped and power is unavailable or degraded from the startup transformer, the normal service buses will be de-energized while the emergency buses switch to the emergency diesel generators (EDGs). If the diesels fail to start or are otherwise unable to accept the emergency bus loads after ten seconds, the buses are transferred to the shutdown transformer which has an independent 23 kV off-site power supply. Should all of these sources fail, as a last resort there is a station blackout diesel generator (SBO DG) that can be manually started and fed into one of the emergency buses. With the exception of this SBO DG, all of the power sensing and source switching operations are automated through the use of relays and breaker interlocks. Regardless of the source, the system distributes the power to six 4.16 kV buses. The first four of these buses carry normal operating loads, while the fifth and sixth buses carry emergency loads for the control rod drives, residual heat removal system, and core spray pumps. Figure 22 is a simplified representation of the 4.16 kV electrical distribution system.

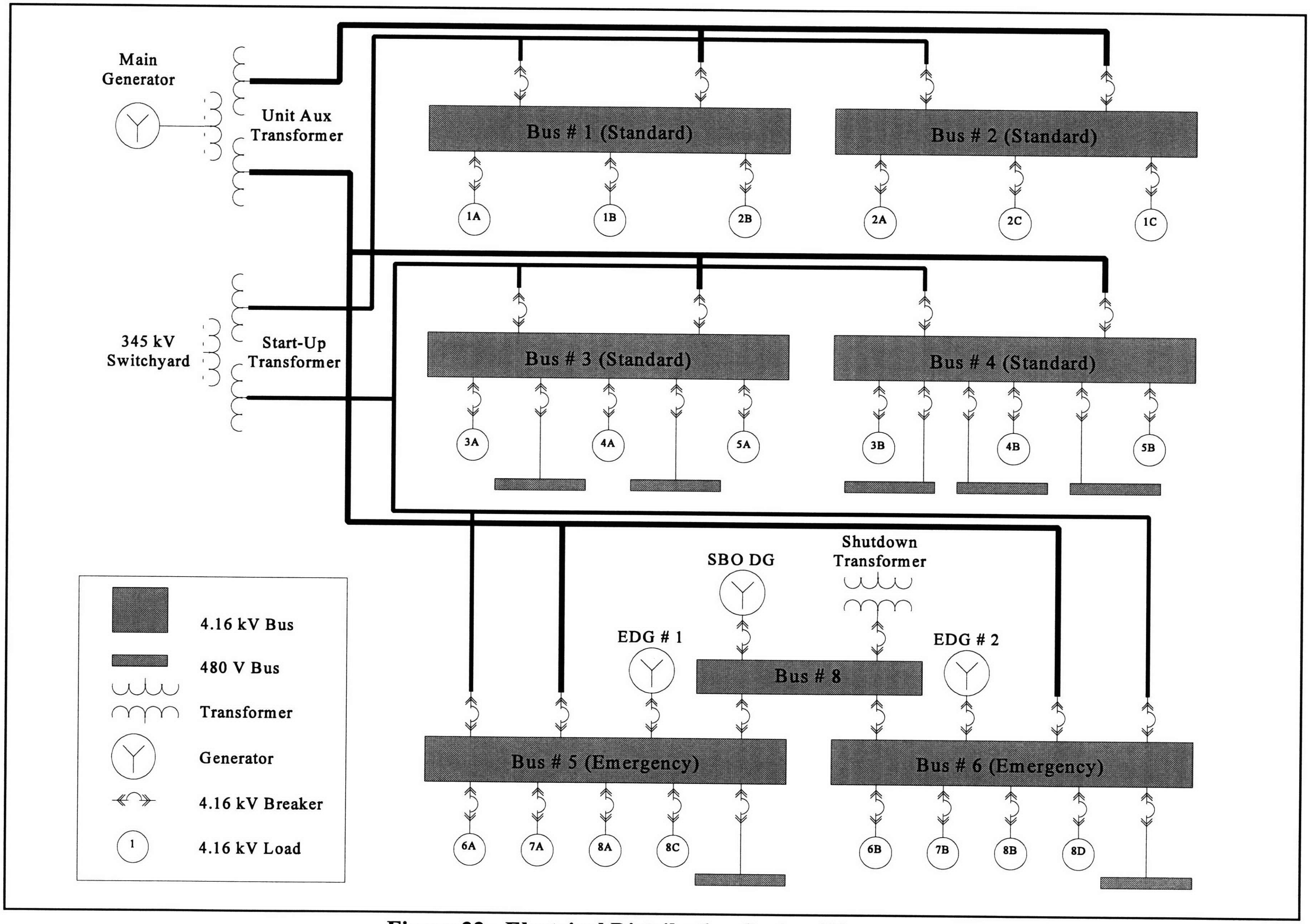

Figure 22: Electrical Distribution System Diagram

4.2.1.3. Components

4.2.1.3.1. Transformers

The three transformers that can provide power to the 4.16 kV system are the unit auxiliary transformer, the startup transformer, and the shutdown transformer. While each of these draws power from a separate source, they are similar in their design and operation. The unit auxiliary transformer is available when the main turbine has been synchronized to the grid, although it can be used by back-feeding off-site power through the main transformer when necessary, such as to allow for startup transformer maintenance during an outage. The startup transformer is located in the plant switchyard and converts power directly from the 345 kV ring bus. They are both three phase, 60 cycle AC step-down transformers, and have forced oil and air cooling systems. A nitrogen blanket fills the area between the top of the oil and the transformer cases. This serves as a fault detection mechanism because a pressure sensor can detect changes in nitrogen pressure resulting from a major fault. The shutdown transformer is actually located off-site at a utility substation of a nearby conventional plant and is therefore not maintained as part of the system. In addition to these primary transformers, the 4.16 kV system also feeds a number of 4.16 kV to 480 V step-down transformers to power the 480 V electrical distribution system buses.

4.2.1.3.2. Buses

The distribution network consists of 4 standard service buses, 2 emergency service buses, and a tie-bar bus to route SBO DG and shutdown transformer power to the emergency buses. The buses are located in the plant's turbine building, and consist of insulated three phase bus bars running above associated switchgear cabinets. The loads associated with each of the buses are listed in Table 14. The load numbers in the table refer to the codes shown in Figure 22 on page 121.

Table 14: 4.16 kV Bus Loads

Bus	Number (Fig 22)	Equipment	Power Rating
Bus #1	1A	Reactor Feedwater Pump A	3.7 MW
	1B	Reactor Feedwater Pump B	3.7 MW
	2B	Condensate Pump B	1.5 MW
Bus #2	1C	Reactor Feedwater Pump C	3.7 MW
	2A	Condensate Pump A	1.5 MW
	2C	Condensate Pump C	1.5 MW
Bus #3	3A	Recirculation Pump A MG Set	3.4 MW
	4A	Condenser Circulating Water Pump A	932 kW
	5A	Turbine Auxiliary Oil Pump A	186 kW
	---	(2) 480 V Load Centers - Standard	1 MVA
Bus #4	3B	Recirculation Pump B MG Set	3.4 MW
	4B	Condenser Circulating Water Pump B	932 kW
	5B	Turbine Auxiliary Oil Pump B	186 kW
	----	(3) 480 V Load Centers - Standard	1 MVA
Bus #5	6A	Control Rod Drive Water Pump A	186 kW
	7A	Core Spray Pump A	600 kW
	8A	Residual Heat Removal Pump A	600 kW
	8C	Residual Heat Removal Pump C	600 kW
	---	(1) 480 V Load Center - Emergency	1 MVA
Bus #6	6B	Control Rod Drive Water Pump B	186 kW
	7B	Core Spray Pump B	600 kW
	8B	Residual Heat Removal Pump B	600 kW
	8D	Residual Heat Removal Pump D	600 kW
	---	(1) 480 V Load Center - Emergency	1 MVA

4.2.1.3.3. Breakers

The 4.16 kV electrical distribution system contains 45 breakers used to control power flow to system components, prevent the spread of damage from electrical or mechanical malfunction, and to provide continuous power to vital loads through automatic transfer logic. The majority of these breakers are the General Electric Magne-Blast type. The primary sub-components of the breakers are listed in Table 15.

Table 15: 4.16 kV Breaker Sub-Components

Main Contacts	Blowout Coils	Closing Spring	Closing Coil	Air Blast Cylinder
Arcing Contacts	Arc Chute	Opening Spring	Trip Coil	Recharging Motor

The main contacts carry the major load current. They open before and close after the arcing contacts, which prevent arcing damage to the main contacts and are designed to be easily replaced. The Magne-Blast breakers operate on the principle that an arc can be interrupted in air by sufficiently elongating and cooling it. This is accomplished by means of a strong magnetic field produced by the blowout coils, which lengthen the arc and force it into contact with a cool dielectric material in the arc chute. The arc interruption is assisted by a stream of air emitted by the air blast cylinder as the breaker opens. The breakers are what are know as stored energy breakers. This means that as the closing spring pushes the breaker closed it also mechanically charges the opening spring. The closing spring is charged by the electric recharging motor. The closing and trip coils are solenoids that pull the mechanical latches from the mechanism and allow the springs to operate the breaker. Although a number of minor sub-component deficiencies have been identified in the Magne-Blast design, the breakers are generally very hardy and catastrophic failures are extremely rare.

4.2.1.3.4. Relays

There is a complex system of relay circuit logic designed to sense unacceptable power conditions on the emergency buses and to automatically institute corrective actions. The relays sense bus under-voltage and over-current conditions, and prevent damage to downstream equipment by attempting to maintain adequate voltage on the bus. This is achieved by a load shedding process in which non-essential loads are shed from the buses, and if necessary to maintain vital loads, the bus is transferred to an alternate power source.

The relays themselves are based on the use of resistance coils and induction disks. When the voltage through the relay is no longer adequate to hold the resistance spring in an under-voltage relay, or when the current through the relay causes the rotation of an induction disk in an over-current relay, contacts are closed. This in turn leads to an appropriate alarm and a signal to other breakers and relays. The cumulative signals from all of the system relays allows the specific fault condition to be uniquely identified and corresponding corrective steps to be activated.

4.2.1.4. System Surveillance Activities

There are four primary surveillance areas performed within the 4.16 kV electrical distribution system. These correspond to the four types of components that make up the system. Each of the surveillances is comprised of a series of tests and maintenance activities designed to demonstrate that the component is operating properly and to insure that the component will not suffer a failure before the next scheduled repetition of the surveillance. These tests and activities are derived from a variety of sources including the plant's technical specifications, OEM guidelines, and nuclear industry operating experience.

4.2.1.4.1. Transformer Surveillances

There are associated surveillances for each of the system transformers, including the 4.16 kV to 480 V step-down transformers fed by the 4.16 kV buses. These surveillances include a number of activities that can be divided into the four general categories of general inspection, functional testing, calibration, and preventive maintenance. General inspection activities are visual surveys of static sub-components to identify degradation or mechanical failures. Functional testing is used to verify that alarms and active sub-components, such as cooling fans, are operating correctly. Those sub-components that have associated condition sensors, such as the pressure sensor for the nitrogen blanket or the actuating sensor for the cooling fans and pumps, are calibrated to specifications. Finally, all components are cleaned, lubricated or overhauled as necessary to maximize component life and reliability. The transformers are currently inspected at 2 year intervals during each RFO, and complete overhauls are conducted at 8 year intervals.

4.2.1.4.2. Bus Surveillances

Due to the static nature of the buses, these surveillance activities consist primarily of general inspections. The bus cabinets are opened and the bus-bar insulation is examined for signs of cracks or other degradation, and an insulation resistance test is conducted. The buses also have potential transformers located in pull out drawers above the switchgear. These transformers are provided to measure and indicate that the proper voltage is present and available on the bus. When the bus is energized, transformer power is used for meter and relay functions, synchronization, voltmeter indication, and the potential lights mounted on the switchgear and control panels. The pull out drawers are inspected and cleaned, and each of the subsidiary functions are verified and calibrated. All bus surveillances are completed off-line, with a 2 year interval for safety related buses and a 4 year interval for standard service buses.

4.2.1.4.3. Breaker Surveillances

There are three types of surveillances associated with the 4.16 kV breakers. These are, in order of significance, breaker cycling, breaker preventive maintenance, and breaker overhaul. Breaker cycling is a simple functional test of the breaker completed by manually opening and closing the contacts several times. This periodic cycling, performed on-line every year where possible, is also recommended by the breaker OEM as a method to increase reliability. The preventive maintenance surveillance includes opening the breaker cabinet and performing a complete inspection, replacing obviously worn parts, lubricating key components, and testing to insure that breaker sub-components are operating correctly. This is designed to target the most prevalent time dependent failure modes and keep the breakers in good operating condition. The specific tasks of the preventive maintenance surveillance are broken down in detail in Section 4.2.2.1. This surveillance is currently performed every 2 years for safety related breakers and every 4 years for non-safety breakers. For the comprehensive breaker overhaul, the component is removed and transported to the OEM. The breaker is completely rebuilt, and any worn sub-components are replaced. Overhauls are performed at 4 year intervals for safety related breakers and at 8 year intervals for non-safety breakers.

4.2.1.4.4. Relay Surveillances

There are two surveillances in this category, one for the standard service portion of the system and one for the emergency portion. The surveillances outline the calibration and functional testing of all protective relays associated with the 4.16 kV buses and breakers. This includes both the sensing and signaling of each individual relay and the comprehensive relay logic circuit. Simple on-line functional tests are performed monthly for safety related technical specification relays and maintenance is performed during current RFOs every 2 years, while non-technical specification relays are maintained and tested off-line at 4 year intervals.

4.2.2. Breaker Preventive Maintenance Surveillance Sub-Tasks

The first step in completing the qualitative analysis of surveillance utility is to identify the specific sub-tasks performed within the surveillance procedure. Once each of these sub-tasks were identified, the nature of the tasks were reviewed to determine the intended benefit derived from their completion. It was assumed that if the tasks are broken down into small enough steps, each one will be directed towards preventing one primary failure mode or type of failure mode. Finally, the complexity and time requirement to perform each sub-task was estimated and a relative ranking of surveillance effort to counter each failure mode was produced.

4.2.2.1. Sub-Task Identification

The breaker surveillance procedure outlines step by step instructions for the preparation, maintenance and restoration of the breaker to service. Many of the sub-tasks in the procedure are merely preparatory steps or administrative management items. Any sub-task that did not include a direct preventive maintenance objective was disregarded.

Each sub-task was then associated with a specific failure mode it is intended to counter. The failure modes were determined from the historical failure records, OEM manuals, and the experience of 4.16 kV system engineers at the case study plant. Table 16 lists the results of this analysis.

Table 16: 4.16 kV Breaker Maintenance Sub-Tasks

Step	Maintenance Sub-task	Associated Failure Mode
1-1b	Inspect position switch operator	Control Switch Failure
1-7	Measure contact resistance	Contact Failure
1-8	Inspect and clean interrupters	Internal Mechanical
1-10	Inspect arc chutes	Internal Mechanical
1-12	Inspect / replace contacts	Contact Failure
1-13	Inspect wiring and terminal connections	Internal Electrical
1-14	Inspect nuts, bolts and cotter pins for tightness	Internal Mechanical
1-15	Check torque on spring charging motor	Charging Motor Failure
1-16	Check trip latch screw tightness	Trip Latch Failure
1-17	Inspect trip latch cam, latch and roller surfaces	Trip Latch Failure
1-18	Sub-component lubrication	Lubrication Related Failure
1-19	Inspect and smooth control relay contacts	Relay Failure
1-20	Inspect / refinish breaker stud bushing insulation	Primary Ground
1-21	Plunger gap calibration	Breaker Misalignment
1-22	Inspect breaker insulation and dampness	Primary Ground
1-23	Operate the trip coil plunger	Trip Latch Failure
2-5	Interference block measurement	Interlock Failure / Misadjustment
2-6	Interference plate measurement	Interlock Failure / Misadjustment
2-6	Auxiliary switch rod measurement	Interlock Failure / Misadjustment
2-6	Lifting rail to stop bolt measurement	Elevating Mech. Failure / Misadjustment
2-7	Charge breaker springs	Spring Failure
2-12	Operate breaker via control switch	Control Switch Failure

4.2.2.2. Relative Maintenance Efforts

The targeted breaker failure modes were then listed in order of relative maintenance effort. The level of effort was evaluated based on the number of separate maintenance tasks performed within the procedure correlated to each failure mode, and the relative complexity and time requirement of the tasks. This determination was based on hands-on experience performing the maintenance procedure in addition to the opinions of case study plant Electrical Division personnel. In order to make the maintenance effort ranking useful in the surveillance utility analysis, the surveillance sub-tasks were grouped by their associated failure modes and a list of the relative effort directed toward countering each failure mode was generated. This ranking is shown as Table 17.

Table 17: Circuit Breaker Failure Mode Ranking by Maintenance Effort

Effort Ranking	Failure Mode
1	Trip Latch Failure
2	Interlock Failure / Misadjustment
3	Internal Mechanical
4	Contact Failure
5	Control Switch Failure
6	Lubrication Related Failure
7	Relay Failure
8	Internal Electrical
9	Breaker Misalignment
10	Elevating Mechanism Failure / Misadjustment
11	Charging Motor Failure
12	Spring Failure
13	Close Latch Failure
14	Latch Switch Failure / Misadjustment
15	Secondary Disconnect Failure
16	Blown Fuse

4.2.3. Breaker Failure Data

The second step in completing the maintenance surveillance utility evaluation was to use historical failure data to determine the dominant failure modes of the 4.16 kV breakers. Historical data for the General Electric Magne-Blast breaker was collected from plant records and from the Nuclear Plant Reliability Data System (NPRDS).

Precise failure modes were not always identified in the failure data, and the descriptive summaries were interpreted to allow for failure categorization. Access to plant personnel assured that the failure modes of all plant breaker failures could be identified, while the NPRDS data was inconclusive for many of the failures reported.

4.2.3.1. Case Study Plant Failure Data

Historical records for breaker failures at the case study plant were collected through the on-line computer database systems. Each breaker failure was reviewed and discussed with plant personnel to determine its probable root failure mode. Plant failure data was readily available for the time period from January 1990 through December 1995. The number of breaker failures attributed to each failure mode were normalized by this time period to produce the average number of failures per year at the case study plant. These results are shown in Table 18.

Table 18: Breaker Failures at Case Study BWR

Failure Mode	Average Number of Failures per Year
Breaker Misalignment	0.084
Charging Motor Failure	0.167
Control Switch Failure	0.167
Elevating Mechanism Failure / Misadjustment	0.084
Interlock Failure / Misadjustment	0.084
Internal Electrical	0.025
Internal Mechanical	0.025
Lubrication Related Failure	0.167
Relay Failure	0.333
Trip Latch Failure	0.025

4.2.3.2. NPRDS Reported Failure Data

The breaker failures reported in NPRDS were collected using a query on the GE Magne-Blast breaker model numbers. There are 28 nuclear plants using this type of breaker, and accurate failure data was available from January 1991 through December 1995. The total number of breaker failures attributable to each failure mode were normalized by the number of plants using the equipment and the time range of the data, producing a value of the average number of failures per plant per year. While this method of determining relative failure mode frequencies is very simplistic, it is adequate for the purpose intended in this analysis. Normalizing the data in this way incorporates the assumptions that there are the same number of breakers in service at each of the 28 plants, and that the operating time of the breakers was equivalent in all cases. These assumptions are surprisingly accurate. Discussions with BWR plant and GE personnel indicate that variation in the number of breakers used in the plants should not be expected to exceed 15% to 20% because of the specific application of these breakers to the plant electrical distribution networks and the fairly standard structure of these systems in most plants. The assumption that the breaker operating times are equivalent can also be justified on the basis that the electrical distribution network of a nuclear plant is virtually always energized, regardless of plant operating state or level of performance.

Table 19: Breaker Failures Reported in NPRDS

Failure Mode	Average Number of Failures per Plant per Year
Blown Fuses	0.071
Breaker Misalignment	0.054
Charging Motor Failure	0.063
Close Latch Failure	0.063
Contact Failure	0.036
Control Switch Failure	0.063
Elevating Mechanism Failure / Misadjustment	0.027
Interlock Failure / Misadjustment	0.116
Internal Electrical	0.134
Internal Mechanical	0.027
Latch Switch Failure / Misadjustment	0.045
Lubrication Related Failure	0.071
Relay Failure	0.295
Secondary Disconnect Failure	0.045
Spring Failure	0.036
Trip Latch Failure	0.089
Other / Unknown	0.634

4.2.3.3. Relative Failure Frequencies

In order to complete the surveillance utility matrix, the data from the case study plant and from NPRDS had to be integrated into a single list of the relative frequency of each failure mode.

Both data sources have been normalized to represent the average number of failures per plant per year, which is equivalent to a component yearly failure rate. If actual failure rates were used, the two data sources could be integrated using Bayesian updating.[16] While the cursory nature of the data does not allow this complete treatment to be used here, the concept is useful. The NPRDS data is taken to be an industry wide generic data source, while the case study plant data is considered to be specific data for the case at hand. The integration of the two sources, therefore, must account for the greater statistical mass of the generic data as well as the more precise applicability of the plant specific data. This was accomplished by creating a weighted index to rank the failure frequencies. The Likelihood function of the plant specific data points given the generic data was used to determine the agreement of the two sources and assign relative weights. If the likelihood function value was high, the plant specific data is closely related to the generic data and the greater statistical mass of the generic data should dominate. Conversely, if the likelihood function value is low, there is a greater probability that the plant specific environment differs from the industry average and therefore the plant specific data should be weighed more heavily. The weighting function derived in this manner is shown below:

$$\text{Weighted Index} = \frac{(N\cdot G) + (\frac{P}{L}\cdot S)}{N + \frac{P}{L}} \qquad \textbf{(2)}$$

where N is the number of plants included in the generic data, G is the generic failure number, P is the number of plants included in the specific data, S is the plant specific failure number, and L is the likelihood function of S given G.

Integrated in this way, the combined relative failure frequencies were used to produce the list of failure modes in descending order of prominence in Table 20 on page 135. The index is simply a ranking factor and has no associated failure probability value. It is also noted that this ranking is

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[16] Apostolakis, G., et al, "Data Specialization for Plant Specific Risk Studies," Nuclear Engineering and Design (1980): 321-329

based purely on relative failure probabilities. No effort was made to include the failure mode severity and calculate the true importance ranking of the failure modes.

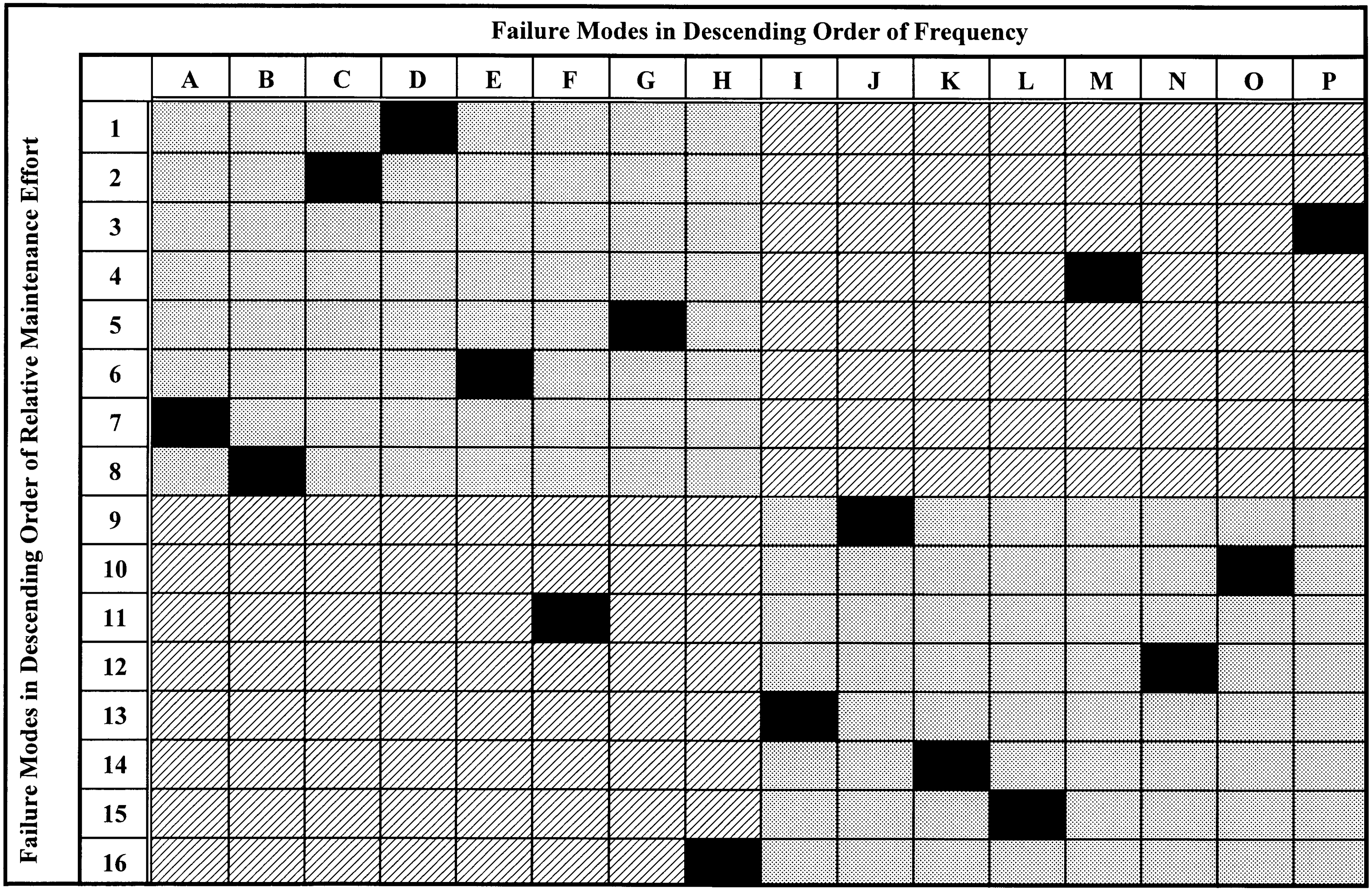
Table 20: Ordered Failure Modes by Frequency

Failure Code	Failure Mode	NPRDS Failures	Plant Specific Failures	Weighted Index
A	Relay Failure	0.295	0.333	0.311
B	Internal Electrical	0.134	0.025	0.131
C	Interlock Failure	0.116	0.084	0.116
D	Trip Latch Failure	0.089	0.025	0.087
E	Lubrication Related Failure	0.071	0.167	0.079
F	Charging Motor Failure	0.063	0.167	0.071
G	Control Switch Failure	0.063	0.167	0.071
H	Blown Fuses	0.071	0	0.069
I	Close Latch Failure	0.063	0	0.061
J	Breaker Misalignment	0.054	0.084	0.056
K	Latch Switch Failure	0.045	0	0.043
L	Secondary Disconnect	0.045	0	0.043
M	Contact Failure	0.036	0	0.035
N	Spring Failure	0.036	0	0.035
O	Elevating Mechanism	0.027	0.084	0.030
P	Internal Mechanical	0.027	0.025	0.027

4.2.4. Surveillance Effectiveness Matrix

The results of Sections 4.2.2 and 4.2.3 are combined into the surveillance utility matrix of Figure 23 on page 137. The matrix is composed of failure mode frequency codes (Table 20, Page 135) across the top and failure mode maintenance effort codes (Table 17, Page 129) down the side, both in descending order.

By correlating the relative frequency of each failure mode to the level of effort dedicated to preventing that type of failure, an evaluation of the utility and effectiveness of the surveillance procedure is possible. If the level of effort dedicated to each failure mode was perfectly correlated to the significance of that failure, the data points would fall in a straight line from the top left corner to the bottom right corner of the matrix. In general, points in the top left or bottom right quadrants represent appropriate surveillance efforts. Data points in the top right quadrant indicate that too high of a maintenance priority is being given to a failure mode that has a low probability, and data points in the bottom left quadrant indicate that the level of maintenance is too low for a higher probability failure mode.



Failure Modes in Descending Order of Frequency

Failure Modes in Descending Order of Relative Maintenance Effort

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	░	░	░	■	░	░	░	░	▨	▨	▨	▨	▨	▨	▨	▨
2	░	░	■	░	░	░	░	░	▨	▨	▨	▨	▨	▨	▨	▨
3	░	░	░	░	░	░	░	░	▨	▨	▨	▨	▨	▨	▨	■
4	░	░	░	░	░	░	░	░	▨	▨	▨	▨	■	▨	▨	▨
5	░	░	░	░	░	░	■	░	▨	▨	▨	▨	▨	▨	▨	▨
6	░	░	░	░	■	░	░	░	▨	▨	▨	▨	▨	▨	▨	▨
7	■	░	░	░	░	░	░	░	▨	▨	▨	▨	▨	▨	▨	▨
8	░	■	░	░	░	░	░	░	▨	▨	▨	▨	▨	▨	▨	▨
9	▨	▨	▨	▨	▨	▨	▨	▨	░	■	░	░	░	░	░	░
10	▨	▨	▨	▨	▨	▨	▨	▨	░	░	░	░	░	░	■	░
11	▨	▨	▨	▨	▨	■	▨	▨	░	░	░	░	░	░	░	░
12	▨	▨	▨	▨	▨	▨	▨	▨	░	░	░	░	░	■	░	░
13	▨	▨	▨	▨	▨	▨	▨	▨	■	░	░	░	░	░	░	░
14	▨	▨	▨	▨	▨	▨	▨	▨	░	░	■	░	░	░	░	░
15	▨	▨	▨	▨	▨	▨	▨	▨	░	░	░	■	░	░	░	░
16	▨	▨	▨	▨	▨	▨	▨	■	░	░	░	░	░	░	░	░

Figure 23: Surveillance Utility Matrix

4.2.5. Conclusions

This analysis of the utility of the 4.16 kV breaker surveillance is embodied in Figure 23. The utility matrix shows that the surveillance maintenance sub-tasks are fairly well coordinated with the relative probability of component failure modes. There are four outliers evident that should receive further analysis and corrective action. The first two outliers, at points 11-F and 16-H, represent the charging motor and fuse failure modes. The location of these points in the bottom left quadrant indicates that the surveillance maintenance tasks may place too little emphasis on preventing these failure modes given their probability of occurrence. The second two outliers, at 4-M and 3-P, are for the contact and internal mechanical failure modes. Their location in the upper right quadrant indicates that too much effort may be expended to maintain these components given their relatively infrequent failure.

This method of surveillance evaluation is a useful tool for plant operations in that it provides a measure of the utility of preventive maintenance efforts. While the basic method shown here is sound, the method could be improved in several ways. First, the failure probability data sources could be expanded and the actual component failure rates rigorously calculated. Bayesian methods could then be applied to tailor the industry failure rates given plant specific data. This improved failure rate data should then be used to calculate the failure mode importance factor of each mode identified. This would incorporate the significance of the failure mode such as its economic or safety risks. Finally, the determination of the level of effort applied to counter each failure mode could be more rigorously determined by using an economic cost value of the maintenance work.

4.3. Surveillance Efficiency Evaluation

The second condition of surveillance effectiveness is that it be performed in an economically efficient manner. Surveillance efficiency is a wide ranging concept, and complete resolution of this issue might include such things as an analysis of worker training practices, replacement part procurement, and countless other factors that impact the cost of performing the surveillance. While these more rudimentary aspects can be approached using conventional management techniques, a more interesting level of surveillance economic efficiency is optimization of performance intervals.

The majority of surveillance performance intervals currently used within the nuclear industry were simply determined by the plant operating cycle length and the associated available maintenance windows. Only in recent years have economic pressures begun to force utilities to move more surveillances on-line and extend off-line performance intervals to reduce operating expenses. Even these current efforts fall significantly short of true economic optimization of the surveillance intervals. Current efforts suffer from the same shortcoming represented in the proposed extended cycle surveillance program constructed in Section 2-- they attempt only to measure the limiting interval length before adverse operational effects are seen. It is reasonable to assume that the interaction of surveillance performance costs and benefits will create economic optimum points and limits that are radically different from the simple operational limit. Previous work by project group members has provided a framework for determining surveillance performance requirements to maintain specific levels of plant safety or performance[17], but this top down approach does not incorporate the actual economics of performing specific surveillance activities.

Evaluation of economically optimal performance intervals requires that the many different factors that contribute to the worth of a surveillance activity be identified and understood. While the compilation of these contributors is a daunting task itself, it is not enough to merely list them or even to quantify their magnitude. If the goal is to calculate an optimal surveillance performance interval, the time dependencies of the factors must be understood as well. It is in this respect that the thoughts presented here might have a meaningful contribution to the achievement of the ultimate optimization objective.

4.3.1. Economic Factors of Surveillance Performance

The basic concept of economic optimization implies that there are positive and negative factors that must be balanced to produce the maximum net economic benefit. This definition is the

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[17] Masui, Hideki, "Quantitative Methodology for Surveillance Interval Extension at Nuclear Power Plants." Master's Thesis, MIT Department of Nuclear Engineering (1996)

basis for the approach used here to explore optimizing surveillance performance intervals. The completion of a surveillance activity incurs a number of fixed and variable costs while producing specific economic benefits. The first step, therefore, must be an attempt to identify these factors.

4.3.1.1. Maintenance Performance Costs

It costs money to complete a surveillance activity. The costs might include tangible expenditures such as replacement parts and labor costs, as well as less tangible side effects such as increased plant risk posture or the risk of maintenance errors. In the broadest terms, the surveillance performance costs can be categorized as shown in Table 21.

Table 21: Maintenance Cost Categories

Deterministic Costs	Material Costs
	Human Resource Costs
Probabilistic Costs	Plant Impact Risk
	Maintenance Error Risk

Each of these areas is discussed further, with particular emphasis on the change of the magnitude of the costs with respect to time. It is important at this point to define a time reference. Because the goal is to determine the optimum length of time between repetitive surveillance performance, the time base is defined as the completion of the surveillance activity. The time axis referred to in subsequent discussion runs continuously from this point until it is reset by the next sequential execution of the surveillance tasks.

4.3.1.1.1. Material Costs

There are a number of direct material costs associated with performing a surveillance activity. Using the example of the 4.16 kV breaker maintenance, material costs include the value of the tools used to disassemble and test the breaker, the cost of replacement contacts or latches, and the cost of lubricants used within the breaker to prevent binding. These material costs can further be divided into fixed and variable portions. The fixed costs are those expenditures incurred regardless of the component condition, which might include the value of the tools, a certain amount of lubricant, and any parts that are replaced automatically during the course of the surveillance. Variable costs are dependent on the condition of the component found when the surveillance is executed. They are primarily composed of the cost of the sub-components that require replacement. The time dependent nature of the material costs are represented in Figure 24. A linear component degradation curve is used for simplicity, although the nature of this curve will vary with each component and complex shapes are possible. The magnitude of the y-intercept is the total of the fixed costs as a fraction of total replacement cost, and the variable costs determine the slope of increase with time as degradation increases. The upward slope continues until the level of degradation reaches the point that complete component replacement is necessary, after which all material costs are fixed.

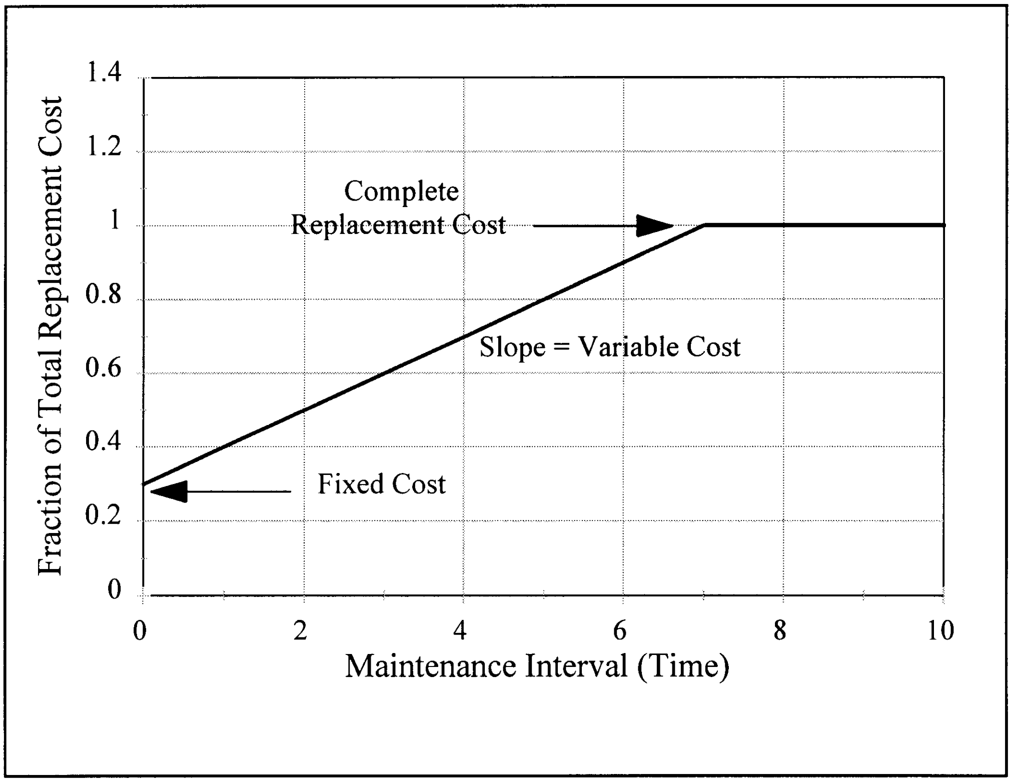

Figure 24: Figurative Material Cost Trend versus Maintenance Interval

4.3.1.1.2. Human Resource Costs

Execution of a surveillance activity incurs the cost of labor for the workers, which is complicated by issues such as regular plant personnel versus outside contractor utilization and radiation dose costs. Like the material costs, the human resource costs also have fixed and variable components. The fixed portion is the cost of performing the basic surveillance steps independent of the component condition including system lineups, work preparation, and automatic surveillance tasks. The variable human resource costs increase as the level of component degradation increases, requiring greater work depth and duration. Figure 25 is a representation of the time dependent nature of the human resource costs. As with Figure 24, the magnitude of the y-intercept represents the fixed cost while the slope of the line represents the variable costs. The human resource plot differs from the material cost plot in that the human resources costs to perform maintenance can exceed the value of the human resource costs of replacing the component. Returning to the example of 4.16 kV breakers, it is relatively simple to rack out a breaker and replace it with a completely new component while there are considerable work and time requirements to perform a complete breaker overhaul.

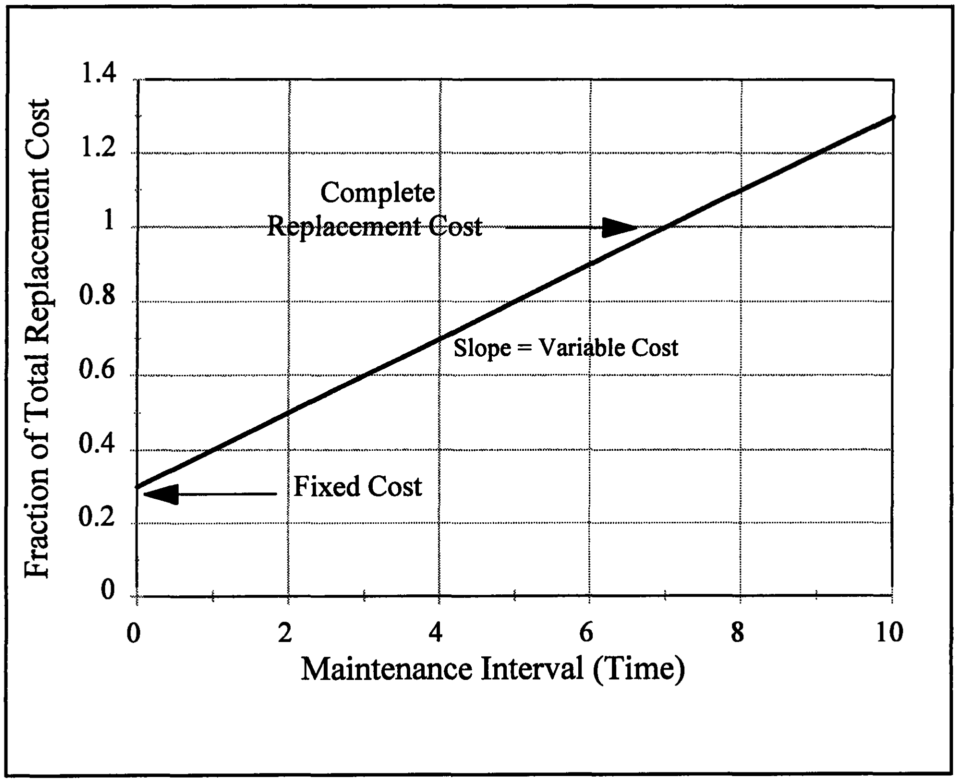

Figure 25: Figurative Human Resource Cost Trend versus Maintenance Interval

4.3.1.1.3. Plant Impact Risk

When a surveillance activity is performed, it often requires changes to the plant operating status or risk posture. These changes are most often the result of taking the corresponding system out of service, although they can be caused in a variety of ways. One example from the electrical distribution system is that when certain breakers or buses are maintained, alternate power sources must be used. The establishment of the alternate sources costs time and money, and these temporary sources are not likely to be as reliable as the primary system so there will be an increase in overall plant failure risk. The plant impact costs are variable in nature. As shown in Figure 26, there is an increasing probability of plant impact as the maintenance interval is extended, while the cost of the impact is independent of the maintenance interval and remains constant. The cost of the risk due to plant impacts is the product of the probability of the impact and its associated risk. In general, this type of cost is characterized by extremely high costs of plant impact coupled with relatively low probabilities.

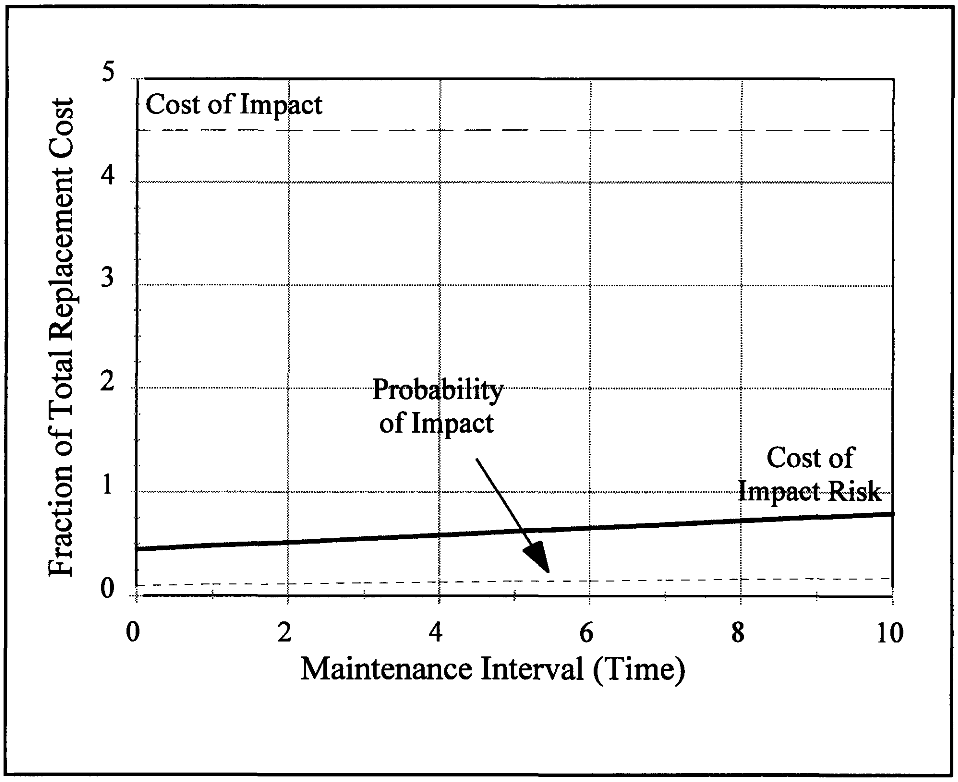

Figure 26: Figurative Plant Impact Cost Trend versus Maintenance Interval

4.3.1.1.4. Maintenance Error Risk

Any time that a component is opened and work is undertaken there is an associated risk of maintenance error. This error can be introduced in any stage, from human error in performing calibrations or returning the system to the proper lineup to material errors in the form of defective replacement parts. The cost of the risk from maintenance error is time dependent because as the level of component degradation increases, so does the required maintenance depth and complexity and this generates a higher error rate. This is represented in Figure 27, where an increasing probability of error with longer maintenance intervals, coupled with a constant cost, combine to form the cost of the risk of maintenance error. Compared to plant impact risk, maintenance error risk is characterized by modest costs associated with higher probabilities of occurrence.

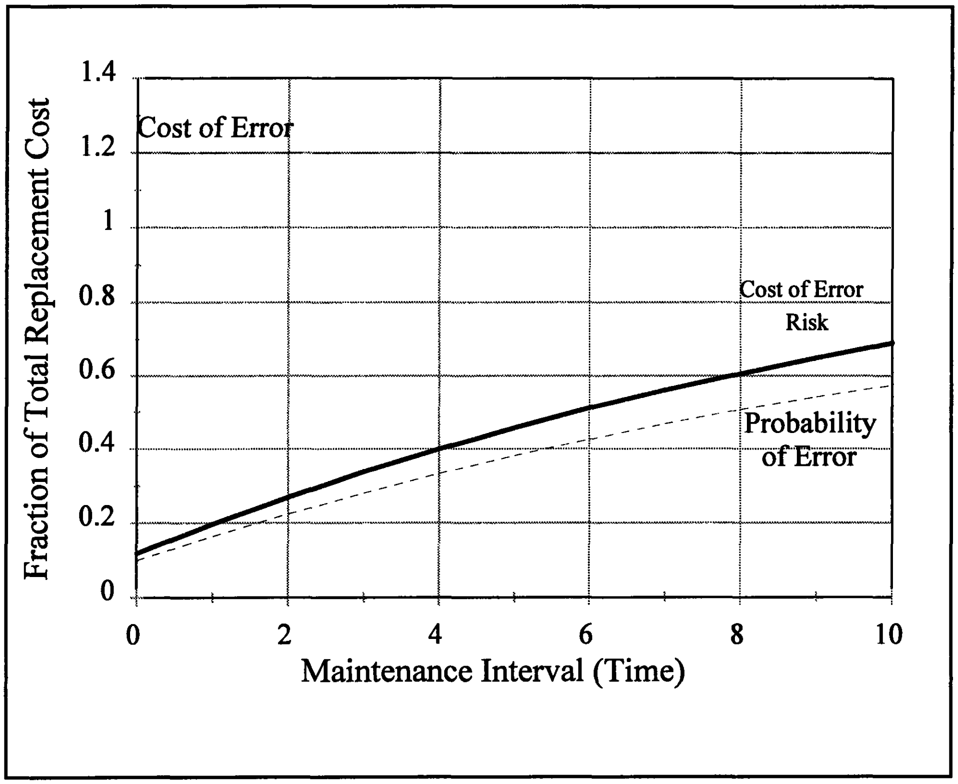

Figure 27: Figurative Maintenance Error Cost Trend versus Maintenance Interval

4.3.1.2. Maintenance Performance Benefits

Preventive maintenance surveillances are conducted to provide economic benefits from the improved reliability and life of components. These benefits can be thought of as the value of the avoided cost of not performing any maintenance. Using this definition, the contributing factors are listed in Table 22. As in the preceding Section, each of these factors is then discussed in greater detail and representative curves of time dependency are shown.

Table 22: Maintenance Benefit Categories

Deterministic Benefits	Component Lifetime Benefit
Probabilistic Benefits	Component Failure Benefit
	Related Failure Benefit

4.3.1.2.1. Component Lifetime Benefit

The total cost of each component within a nuclear plant can be distributed over the life of the component to provide a levelized value. It is reasonable to assume that any well designed maintenance effort will increase the useful life of the component and therefore decrease its levelized "cost." Therefore, the difference between the maintained and unmaintained component cost is a direct benefit of performing the surveillance activity. This effect is time dependent in that if higher maintenance intervals are assumed to result in reduced degradation, the more frequent surveillance performance will result in greater savings. This trend is shown in Figure 28, where a decreasing multiple of the unmaintained component life is achieved as maintenance intervals are extended.

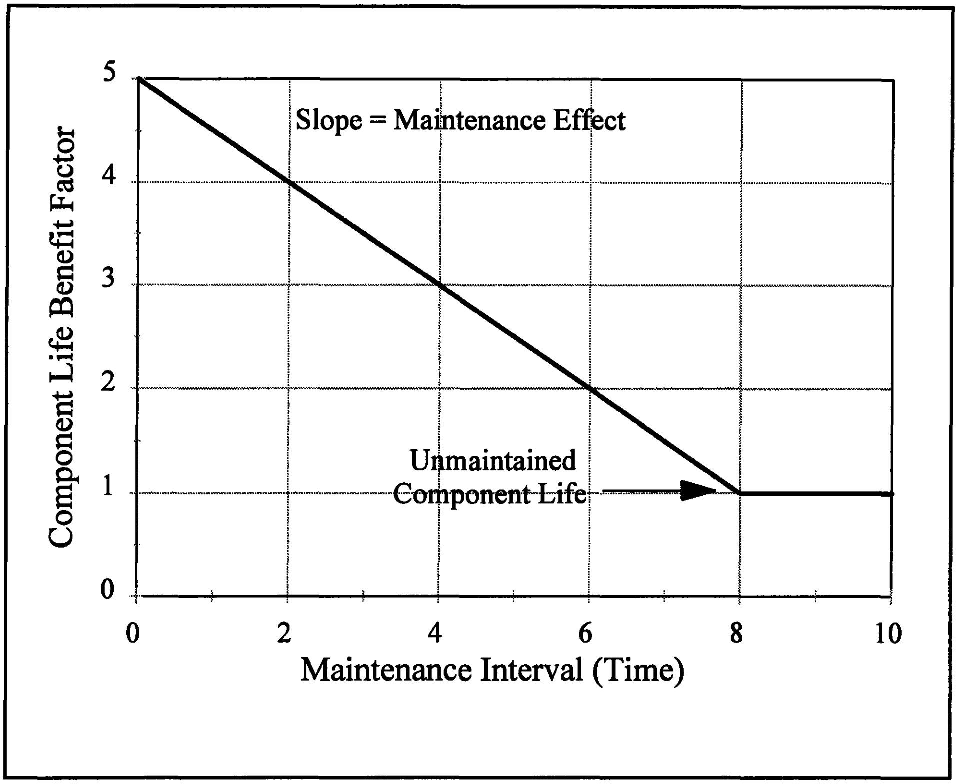

Figure 28: Figurative Component Life Benefit Trend versus Maintenance Interval

4.3.1.2.2. Component Failure Risk Benefit

Separate from the component lifetime issue, there is a real cost associated with repairing the damage resulting from a component failure. Anytime a component suffers an operational failure these costs are incurred. They are made up of the material and human resource costs of performing the repair work, amplified by an emergent work premium. Performing maintenance activities decreases the component failure rate and provides economic benefit in this area. The difference in failure risk costs for maintained and unmaintained components are a direct benefit for the surveillance activity. This benefit is time dependent because the failure rate curves increase non-linearly with time. This effect is show in Figure 29.

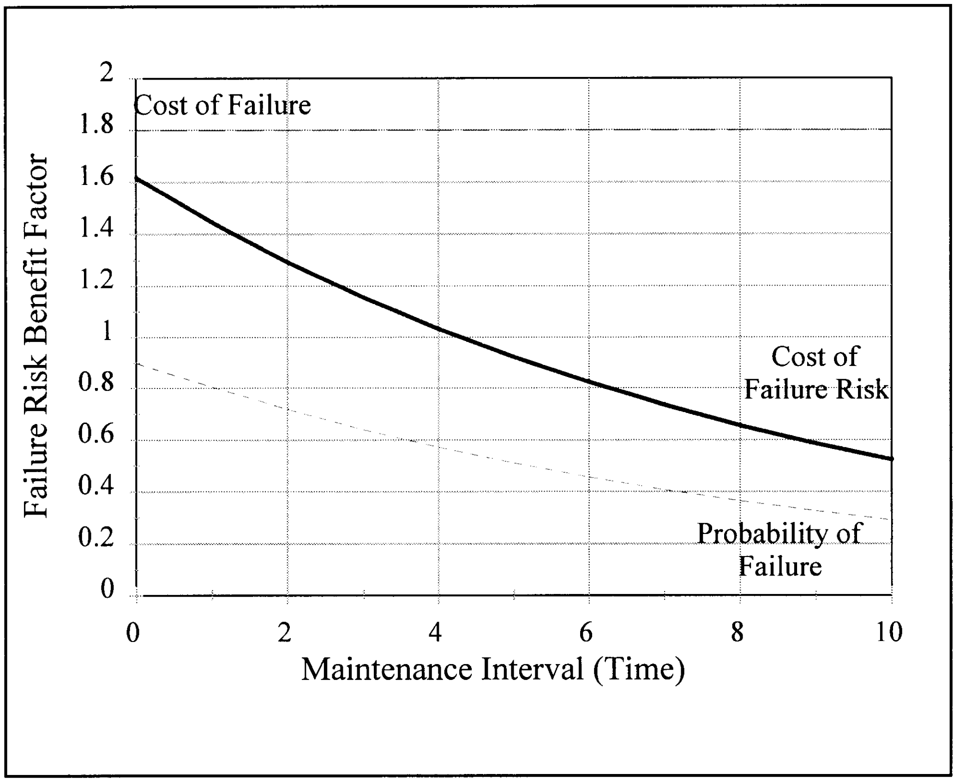

Figure 29: Figurative Component Failure Benefit Trend versus Maintenance Interval

4.3.1.2.3. Related Failure Risk Benefit

When a component does fail in a running plant, it often has implications that extend far beyond the individual component or system. Failure of Components critical to plant operations may cause severe reactor transients or require the activation of standby equipment. The risk associated with these secondary failures can be large. The performance of maintenance activities has the added benefit of avoiding related impacts subsequent to component failure by decreasing the component failure probability. While the risk of component failure varies with time, the risk of secondary failures initiated by component failure is constant as shown in Figure 30.

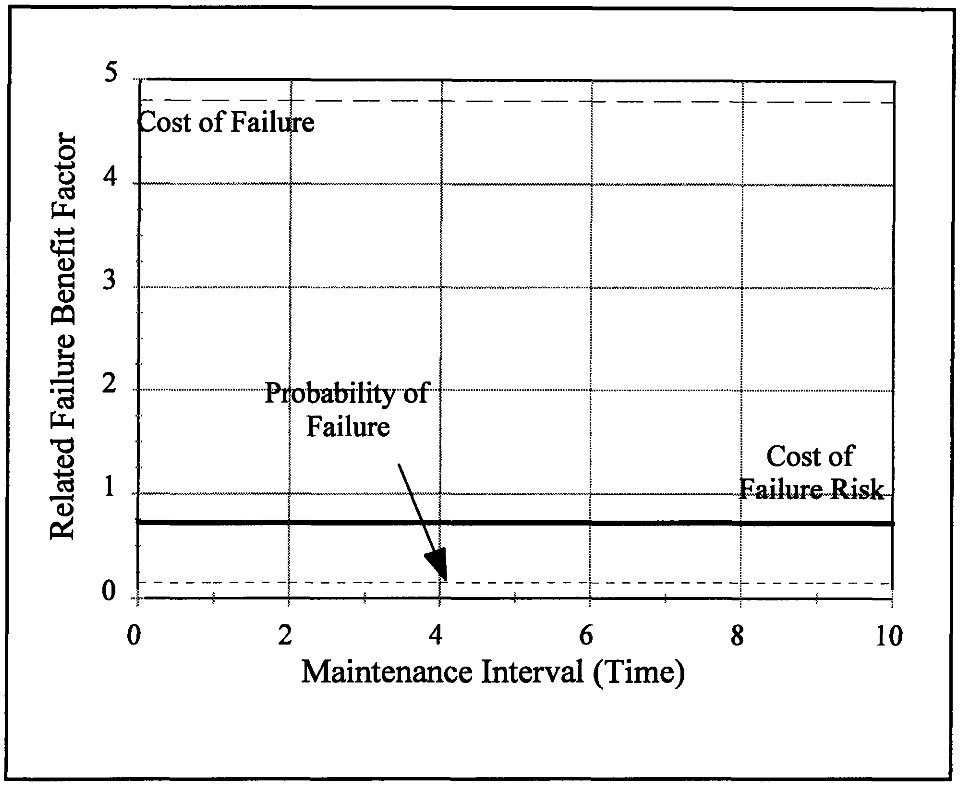

Figure 30: Figurative Related Failure Benefit Trend versus Maintenance Interval

4.3.2. Surveillance Interval Optimization

While the preceding discussion provides only an elementary basis for interval optimization, it does provide a basic structure for the problem and offers some insight into the nature of the important contributing factors. Completion of the optimization problem would require further work in a number of areas. The list of contributing factors would need to be expanded to include each of the secondary factors and their time dependent behavior. These secondary factors could then be combined into accurate cost versus time curves based on actual dollar values specific to every surveillance. After these curves have been generated, they would then be coalesced into a cost function dependent on time. The optimum maintenance performance interval would exist at the minima of this cost curve (or conversely, at the maxima of a benefit curve). A figurative example is shown as Figure 31.

The complete characterization of these factors is a task that is extremely complex and demanding, but the margin for economic benefit through surveillance program optimization is large and warrants further study in this area. The thoughts presented in this section are by no means intended to complete the task, but through the identification of important contributing factors and the presentation of an optimization framework, it is hoped that this work will contribute to the ultimate objective.

5. Conclusions

5.1. Overview

As the nuclear power industry faces a period of dynamic economic, operational, and managerial evolution, there is a demand and an opportunity for innovative developments. As part of a larger research effort, this thesis contributes to the study of a nuclear power plant operating strategy based on the adoption of extremely long operating cycle lengths. One requirement to demonstrate the feasibility of such a strategy is a detailed analysis of nuclear power plant surveillance activities. This thesis has presented such an analysis, specifically answering the critical questions discussed below.

5.2. Will Plant Surveillance Activities Inhibit Extended Operating Cycles?

Surveillance activities and approaches vary widely within the nuclear industry. In order to determine if these surveillances will be a limiting factor in the adoption of extended operating cycles, a case study approach was used. The rationale is that if the surveillance programs of two "typical" case study plants can be made compatible with a significantly longer operating cycle, this will demonstrate that the majority of nuclear units should not expect surveillance related issues to limit their operating cycle lengths.

Previous work by other research project members has made substantial progress in developing the demonstrated extended cycle surveillance programs. In Section 2.3, the investment protection surveillances at the case study BWR plant were analyzed in detail. The reconciliation of these surveillances to a proposed 48 month operating cycle completed the background work for the comprehensive surveillance program. Section 2.4 integrates the BWR investment protection surveillance resolution with previous work at the case study BWR and PWR plants to form the final proposed surveillance program.

The results of this case study demonstration illustrate that current surveillance requirements at nuclear power plants *can* be made compatible with operating cycle lengths of at least 48 months. The vast majority of surveillance activities can be performed with the plant on-line or can be performed at intervals of 48 months or more. The few surveillances that could not readily be modified in either of these ways comprise only 1.8% of BWR surveillances and 1.4% of PWR surveillances. These unresolved surveillance activities are discussed in Section 2.4.4 where the specific complications are shown and possible solutions are introduced. Having been identified here, future work can be targeted at the resolution of these issues and innovative surveillance performance techniques or component advancements should prevent them from restricting the adoption of extended operating cycles.

5.3. Are the Impacts of an Extended Operating Cycle Surveillance Program Acceptable?

The structure and nature of a plant's surveillance program has wide ranging effects on operational management and performance. Given the many modifications proposed for the surveillance programs of the case study plants in Section 2, the extended cycle surveillance program should be expected to have significant ramifications. Section 3 identifies some of the most important of these secondary effects and evaluates if their impacts are acceptable for efficient plant operations.

While there are a number of different issues discussed in Section 3.2, the dominant effect resulting from the surveillance program resolution to a 48 month operating cycle is the alteration of surveillance workload levels during plant refueling outages. Section 3.4.1 compiles the surveillance requirements at the case study BWR and extrapolates them through the end of plant life for various operating cycle lengths from 24 to 48 months. The results show that the average surveillance workload per refueling outage on a 48 month cycle is 18.9% greater relative to current plant operations. This moderate increase in surveillance density should be expected to incur some increased costs for added human resources and outage planning, and more importantly, may increase the length of refueling outages on the 48 month cycle. Section 3.4.2 produced an estimate of the outage growth, predicting 25% to 30% longer outages relative to current operations.

To balance these economic penalties of the extended operating cycle, a number of advantages were also shown. Foremost is the potential for increased capacity factors as described in Section 1.1. Operating on a longer cycle length increases the interval between refueling outages and therefore decreases the total number of outages required over the life of the plant. If the plant is not required to shutdown for refueling as often, it can produce more electrical energy and derive greater revenue with fixed operating expenses. Refueling outages also incur a significant cost for planning, material requirements, and additional manpower. The avoided outages on the 48 month operating cycle, therefore, generate significant savings in and of themselves. Finally, Section 3.4.1 found that the 48 month operating cycle resulted in a 40.5% reduction in the total number of surveillances required over the remaining life of the case study BWR plant. This reduction could produce a number of benefits including reduced material and manpower costs and improved plant performance through the avoidance of human errors in surveillance completion.

The positive and negative impacts of the proposed extended cycle surveillance program are complex, and the net economic cost or benefit to plant operations could not be calculated from the available data. It is clear that there are no negative impacts of an obviously limiting nature, and that the magnitudes of the positive and negative factors are generally equivalent and offsetting. While further work is required to quantify the result, it is concluded that the impacts of the proposed extended operating cycle surveillance program are generally acceptable.

5.4. How Can Maintenance Surveillance Effectiveness be Evaluated?

There are significant inefficiencies in current surveillance programs that offer lucrative margin for improvement. The final goal of this thesis was to identify what factors are important in the evaluation of the effectiveness of a maintenance surveillance activity, and to discuss a framework for the optimization of performance intervals.

Section 4.2 develops a surveillance utility matrix as a tool to evaluate the effectiveness of a specific maintenance activity. The matrix provides a correlation between the relative effort put forth to counter specific component failure modes and the frequencies at which the failure modes are seen. The result is that surveillance inefficiencies such as expending significant resources to counter very rare failure modes or neglecting more common failure modes can be identified and corrected. When applied to an example surveillance, the maintenance of the 4.16 kV breakers at the case study BWR plant, the surveillance utility matrix demonstrated its usefulness. The results showed that the breaker surveillance shows good correlation with relative failure probabilities, with the exception of four specific outliers that should be reviewed and corrected.

The concept of rigorous surveillance performance interval optimization within economic and safety constraints is a very complex task and a complete solution was not attempted. Section 4.3 provides some insights into the quantification of pertinent surveillance cost factors as functions of surveillance interval. These factors, with further refinement, constitute a surveillance cost curve that can be minimized to find the optimal surveillance performance interval.

5.5. Conclusions

The adoption of an extended operating cycle on the order of 48 months is beyond the current horizon for the nuclear power industry, but the credible demonstration of its feasibility and economic advantages may help to bring it into focus. This thesis has presented an analysis of nuclear plant surveillance issue reconciliation to extended cycles as a primary part of that demonstration. The results indicate that surveillance issues are not likely to inhibit operating cycle lengths, and that a feasible extended cycle surveillance program can be developed without overwhelming adverse effects on plant operations.

While the level of work presented here is not adequate to absolutely justify the adoption of extended operating cycles, these results have shown that further study is warranted. If the United States nuclear industry is to survive the current period of increased competition and remain a profitable energy generation contributor, it must have the foresight to stretch beyond current operational experience and seek innovative ways to maximize its inherent potential.