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SURVEILLANCE STRATEGY FOR AN EXTENDED
OPERATING CYCLE IN COMMERCIAL NUCLEAR REACTORS

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ABSTRACT

The impetus for improved economic performance of commercial nuclear power plants can be partially satisfied by increasing plant capacity factors through operating cycle extension. One aspect of an operating cycle extension effort is the modification of plant surveillance programs to complete required regulatory and investment protection surveillance activities within the extended planned outage schedule. The goal of this paper is to introduce a general strategy for existing power plants to transition their surveillance programs to an extended operating cycle up to 48 months in length, and to test the feasibility of this strategy through the complete analysis of the surveillance programs at operating BWR and PWR case study plants. The reconciliation of surveillances at these plants demonstrates that surveillance performance will not preclude 48 month operating cycles. Those surveillance activities that could not be resolved to an extended cycle are identified for further study. Finally, a number of general issues are presented that should be considered before implementing a cycle extension effort.

I. BACKGROUND

Commercial nuclear power reactors face increasing competitive pressure for economic efficiency, demanding innovative changes to plant management and operational practices. To achieve competitive operation, nuclear power producers must offset their inherently greater capital and manpower costs with the benefit of their lower fuel costs. This is achieved by maximizing the variable amount of power produced in a given period against the fixed capital depreciation and operational expenses. This ratio is quantitatively measured by the plant's capacity factor, which is defined as the amount of electricity actually produced divided by the theoretical maximum if the plant had run at 100% capacity for the full period.

Over the course of a plant's life, it must be shutdown periodically to refuel the core and to conduct maintenance and testing activities. A plant will also inevitably experience forced shutdowns caused by failures of critical components or operator errors. The total of these planned and unplanned shutdown days determine the plant capacity factor. While the Forced Outage Rate (FOR) should be minimized, it is impractical, undesirable from a safety standpoint, and economically inefficient to reduce planned shutdown times beneath some optimal level. Assuming an arbitrary but fixed total shutdown time, the plant capacity factor then becomes dependent on the operating cycle length. Figure One shows capacity factors based on various refueling outage (RFO) lengths and a 3% forced outage rate. Assuming a 30 day planned refueling outage, the current industry target, a 48 month cycle offers 3.3% and 2.0% capacity factor improvements over 18 and 24 month cycles respectively. Economic analysis shows that if the FOR can be reduced sufficiently (from 5% to 3%), extended cycles of 36 to 42 months offer an economic advantage over conventional 18 and 24 month cycles.[1]

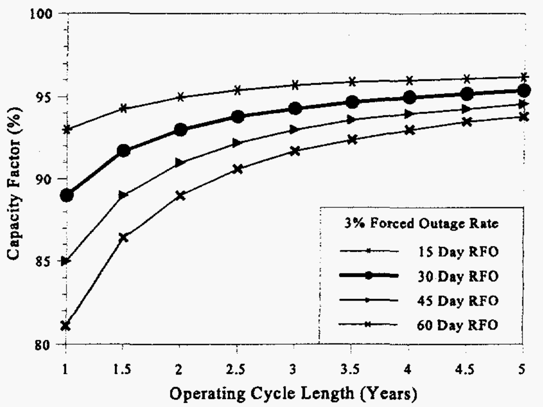

Figure 1
Capacity Factor vs. Cycle Length

To complete a comprehensive operating cycle extension strategy, work must be focused on the three general topics of core design, operational availability, and plant surveillance requirements. While complete BWR and PWR core designs and plant availability improvement are included within the scope of the current MIT research project, "Improvement in Nuclear Plant Capacity Factors Through Longer Cycle Length Operation,"[2] this paper addresses only the issue of plant surveillance reconciliation to an extended operating cycle. It is the goal of this surveillance research to develop the framework for a methodology that will enable utilities to evaluate a cycle extension effort, and to demonstrate that the performance of plant surveillance activities will not preclude operating cycle extension up to 48 months.

A typical commercial nuclear power plant performs thousands of surveillance activities including system testing, equipment inspections, and preventive maintenance. These surveillances may be imposed by a regulatory body, or they may be initiated at the plant level for investment protection of economically significant components. The surveillances can be further divided by their mode of performance. On-line surveillances can be accomplished with the reactor at power, while off-line surveillances require that the unit be shutdown. On-line surveillances are generally independent of operating cycle length, but the off-line surveillance program must be coordinated with refueling outages to ensure that periodic testing and maintenance is completed within the time frame set forth by regulatory and investment protection guidelines.

Any proposed operating cycle extension, therefore, must analyze each off-line surveillance activity currently performed at the plant and reconcile it with the increased planned outage interval to maintain regulatory and economic compliance. There are two approaches to achieving this reconciliation. First, an off-line surveillance activity can be modified for on-line performance. Many activities currently completed during refueling outages can be done with the reactor at power given minor adjustments in operating policy, improved training, or equipment modification. If on-line performance is not an option, a technical justification must be made to extend the performance interval of the surveillance activity to four years or more. Such a technical justification can be based on historical performance data and may require increased maintenance, on-line monitoring, or upgraded plant components.

In order to achieve the stated objectives and complete a systematic surveillance reconciliation to a four year operating cycle, a general surveillance reconciliation methodology was developed.[3] This methodology was designed to analyze pertinent characteristics of the surveillance procedures and to categorize each individual surveillance activity according to its potential for on-line performance or performance off-line at extended intervals.

One of the most significant results from the theoretical development of the surveillance reconciliation methodology was the introduction of the concept of limiting plant event frequency (LPEF) to make rigorous surveillance modification decisions. The LPEF is the frequency of any event that limits the ability of the plant to generate full electrical capacity. These events would encompass all operational and economically important components, and would include core damage frequency (CDF) as a subset of economically adverse end states. The complete development of LPEF as a comprehensive performance measure, just as CDF is often used as a comprehensive safety measure, would greatly enhance the economic optimization of plant operations.

II. CASE STUDY PLANTS

To validate the surveillance reconciliation methodology and to evaluate the ability of a typical commercial nuclear power plant to coordinate its surveillance program to an extended operating cycle up to 48 months long, two operational BWR and PWR plants were selected as case studies.

The BWR plant is a General Electric type three design and has been in service since 1972. It is currently operating on a 24 month cycle. The plant's surveillance tracking database is keyed to the performing division within the plant. These divisions, which represent primary technical areas such as electrical, mechanical, and instrumentation and controls, maintain responsibility for their designated surveillances across all system and plant boundaries. To facilitate coordination with the existing database, our BWR analysis uses the same organization and lists surveillances by performing division. Also, within our BWR study, surveillance activities currently performed off-line at intervals greater than or equal to 48 months are considered to be compatible with the cycle extension limit and are administratively categorized for off-line performance at extended intervals.

The PWR plant is a Westinghouse four loop design that has been in service since 1990. It is currently operating on an 18 month cycle. The plant's surveillance program is organized around Standard Technical Specification sections. Our PWR study differs from the BWR in that it includes those surveillances currently performed off-line at intervals greater than 48 months in the complete analysis, making recommendations to move some to the on-line work scope. Because of this difference from the BWR study, there is a minor bias in the relative number of on-line surveillances recommended for each plant type.

III. METHODOLOGY

The surveillance reconciliation methodology was applied to the existing surveillance program of each case study plant, producing a categorization of recommended surveillance modifications consistent with extended cycle operation. Although the recommended surveillance

programs are not carried through to the point of rigorous technical evaluations, they are believed to approximate the results that a utility could expect from a cycle extension project. It is also important to note that all surveillance categorizations are based on technical and not legal limitations. It is assumed that an operating cycle extension to 48 months will stretch the current regulatory requirements in some areas, but NRC personnel have confirmed that given sufficient technical basis, current regulatory limits will not preclude extended cycle operations. NRC Generic Letter 91-04, "Changes in Technical Specification Surveillance Intervals to Accommodate a 24 Month Fuel Cycle," is used as a model for 48 month cycle interval extension requests.

At both case study plants, practical application of the theoretical methodology took the form of targeted queries of the plant surveillance tracking databases followed by expert review and evaluation. After identification of all surveillances that currently prohibit operation on a 48 month cycle, the first step in reconciling each surveillance was to examine the governing procedure to determine what actual plant mode restrictions existed in the text. In some cases specific allowances were made for on-line performance of the procedure, and in many others no restrictions were stated at all. For those surveillances that did not state a mode requirement or that required shutdown conditions, the use of a limiting condition of operation (LCO) was considered and a comparison with similar surveillances was made to identify any inconsistencies or unutilized performance options. Finally, system schematics were studied to determine if alternate test paths existed or if relatively simple system modifications would allow for on-line surveillance completion.

For those surveillances that still could not be moved into the on-line work scope, an analysis was conducted to evaluate their potential for performance interval extension to 48 months or more. Plant surveillance and material history records were reviewed to identify testing intervals that were overly conservative. During these reviews, it was common to find components that had never failed their corresponding surveillances and whose material histories raised no doubts about the ability of the testing interval to be extended. For less obvious cases, plant specific and industry failure histories, applicable testing codes, and expert experience were all combined to form a judgement about the potential for interval extension.

Any surveillance that did not fall into the categories of on-line performance or performance interval extension was left as unresolved and requires further study. In these cases, a broader survey of state of the art testing technologies and alternative testing used within the nuclear industry was conducted. Although some initial thoughts on possible solutions are included in Section Five, the final reconciliation of these surveillances is left as future work for the MIT research project and the nuclear industry.

In all cases, expert reviews of the surveillance categorizations by plant system engineers and department heads were conducted. These interviews were used to incorporate the operational experience of plant personnel and to identify idiosyncrasies not apparent in the surveillance procedures and historical records. Expert opinion was relied on as the final arbiter of the recommended surveillance programs.

IV. SUMMARY OF RESULTS

Upon completion of the analysis of the full surveillance program at each case study plant, the results were tabulated and are presented as Figures Two, Three and Four. Figure Two shows the proposed 48 month cycle surveillance programs as compared to the current plant programs. The BWR plant currently conducts 1115 (29%) on-line surveillances and 2694 (71%) off-line surveillances at twenty-four month intervals. Under the proposed program there would be 1457 (38%) on-line surveillances and 2210 (58%) surveillances performed off-line at 48 month intervals. There are 140 (4%) surveillances that remain unresolved to the extended cycle. The PWR plant currently performs approximately 2000 (44%) on-line surveillances, and 2537 (56%) surveillances off-line during refueling outages every eighteen months. The proposed surveillance program consists of 2625 (58%) on-line surveillances, 1858 (41%) performed off-line at 48 month intervals, and 54 (1%) surveillances that remain unresolved.

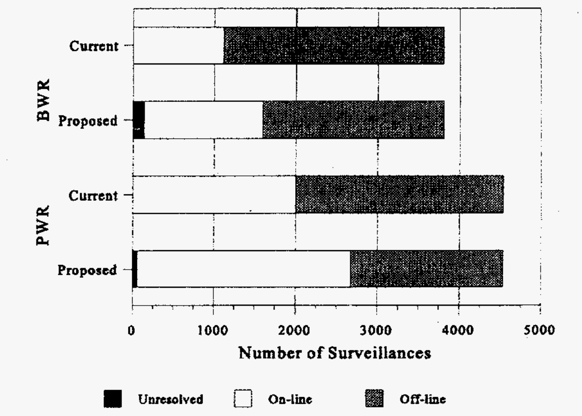

Figure 2
Proposed Surveillance Programs

Reference [3] contains a detailed description of all surveillance activities recommended for modification to on-line performance or performance interval extension. Only those surveillances currently performed off-line at intervals less than 48 months required modification, and Figures Three and Four show the detailed breakdown of these modified surveillances according to the respective plant surveillance organizational structure.

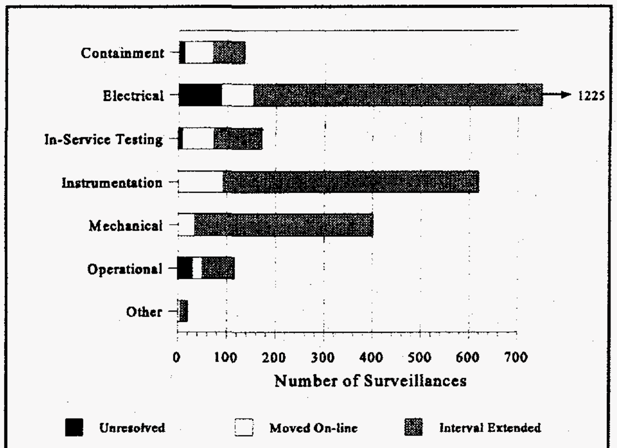

Figure 3
BWR Modified Surveillances

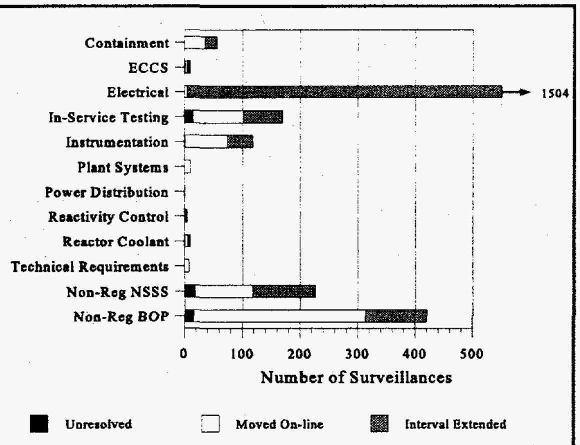

Figure 4
PWR Modified Surveillances

V. UNRESOLVED SURVEILLANCES

All of the BWR and PWR plant surveillance activities unresolved in the case studies are compiled in Table One and discussed here in greater detail. Rather than an indication that the surveillance programs will inhibit a cycle extension effort, the fact that relatively few surveillances (4% for the BWR and 1% for the PWR) remain unresolved after this initial survey is an encouraging result. Having been identified here, these types of surveillance activities can receive more focussed attention to develop engineering solutions that will enable on-line performance or performance interval extension. Possible engineering solutions noted by plant personnel and nuclear industry experts are included below. As an interim solution, the target extended operating cycle does assume a 3% forced outage rate and the majority of these unresolved surveillances can be completed off-line on a hot-list basis during forced outage windows.

Table 1
Potential Barriers to Extended Cycles

Common

- Relief Valve Testing
- MOV Testing
- In-Service Testing
- Battery Discharge Testing
- Condenser Waterbox Maintenance
- Engineered Safety Feature Testing

BWR

- Automatic Depressurization System Testing
- Main Steam Isolation Valve and Feedwater Valve Testing
- Drywell Equipment Lubrication

PWR

- Steam Generator Eddy Current Testing
- Reactor Coolant Pump Maintenance

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 valves are predominately class two containment pressure boundary valves, with a handful of class one primary pressure boundary valves. 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, type 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.

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 a case study plant 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 were found to include just fourteen BWR and three PWR surveillances, greatly reducing the MOV barrier to extended cycles. 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.

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 a surveillance performance hot-list during forced outage windows.

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 storage batteries, on-line monitoring could ensure battery performance.

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 significant economic impact. 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.

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.

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 risk of plant trip is fairly high and alternate solutions are preferable. Both tests are extremely quick and are excellent candidates for inclusion on an outage hot-list, but more complete reconciliation to the four year cycle should be pursued.

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.

Drywell Equipment Lubrication: When a BWR reactor is on-line, the drywell is inerted with gas and all components contained within are 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 and further analysis is required to determine the most economically efficient resolution.

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.

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.

VI. GENERAL CYCLE EXTENSION ISSUES

In conducting the surveillance reconciliation studies at the two test plants, a number of more general cycle extension issues arose. While not fully developed technical evaluations like the surveillance analysis, these are interesting issues that should be considered more completely before final implementation of any extended cycle length.

On-line Surveillances: As indicated in Section Three, the surveillance reconciliation methodology and its application to the case study plants favored on-line surveillance performance over performance interval extension. There are several advantages to on-line surveillance completion. Any surveillance moved to the on-line work scope ultimately shortens the refueling outage length. Reduced refueling outages translate directly into improved capacity factors and increased revenue. On-line surveillances tend to levelize the plant workload which means that plants can utilize full time employees more effectively and can reduce their dependence on expensive outside contractors. There is added value to having full-time employees conduct surveillances in that the level of on-site knowledge and familiarity with plant components will be improved through increased work experience. There are, of course, some disadvantages to on-line surveillances such as increased performance complexity requiring greater personnel training and possible increased plant trip risk.

Surveillances at Reduced Power: In both the BWR and PWR investment protection surveillance categorizations, some surveillances designated for on-line performance require that the reactor power be reduced in order to take equipment out of service. These surveillances cannot be completed with the system on-line, but occur in systems that are redundant or that can be isolated for short periods of time. In order to compare the cost of reduced power operation to a mid-cycle outage of sufficient duration to complete the surveillance activities, an economic analysis was conducted for the reduced power surveillances proposed at the PWR plant.[3] The results indicate that a well planned reduced power window, or several reduced power windows coordinated with periods of minimum electrical demand, can produce savings on the order of three million dollars relative to a mid-cycle maintenance outage.

Surveillance Program Management: All of the surveillance modifications proposed in this report are dependent on the ability and willingness of plant managers to shape their surveillance programs given sufficient economic impetus. When possible, plants prefer to extend surveillance intervals to whole multiples of their operating cycle length. This reduces and levels the surveillance workload during refueling outages and minimizes performance costs. Data from the case study plants demonstrate this effect. Simply because the first whole multiple of the BWR's 24 month cycle meets our 48 month target while the PWR's 18 month cycle does not, the BWR plant has 34% more surveillances currently scheduled at or beyond the 48 month hurdle. This is a clear indication of the margin available for surveillance resolution to a 48 month operating cycle.

Surveillance Impact on RFOs: Implementation of a 48 month operating cycle would have subtle effects on surveillance scheduling and RFOs. First, consider a surveillance that is currently performed with a 48 month frequency so that it falls into every other RFO at the BWR plant. Following cycle extension to 48 months, continued performance at a 48 month frequency would require that this surveillance be included in every RFO. While this does not change the total surveillance workload, it does increase the workload per RFO period. As a second example, consider a surveillance that is currently performed during every fourth RFO at the PWR plant (every 72 months). On a 48 month cycle this surveillance would either have to be performed every 48 months, thereby increasing the overall surveillance workload, or it would have to be analyzed for interval extension to 96 months, which decreases the total surveillance load but would still increase the workload per outage. In order to estimate the impact of the proposed surveillance programs on RFO length, a quantitative analysis of these effects was performed for the case study BWR plant. The analysis calculated the average outage workload over the remaining life of the plant, conservatively assuming that all surveillance intervals that fall between extended cycle outages would be performed in the earlier outage. The results indicate that while the extended cycle does provide a 40% reduction in surveillance workload over the life of the plant, because there are fewer RFOs, the workload per RFO increases by 20%. While RFO planning is an extremely complex task, a simplified estimate of resulting RFO lengths predicts a 25% to 30% increase in RFO duration.

Data Availability: The technical justifications for surveillance interval extension will certainly require historical performance data when considering a 48 month operating cycle. Previous cycle extension efforts to 18 and 24 months have been based primarily on expert judgements and some material condition histories. Due to changing regulatory expectations, it is not likely that expert judgement alone will be sufficient to justify the interval extension of surveillances from 24 to 48 months. Unfortunately, there is a general deficiency in the quality and availability of the type of data needed to complete such rigorous technical evaluations. At many older plants, the data has been collected for years but is not compiled in any accessible format. Newer plants tend to have more efficient computer-based data systems, but the breadth and depth of these programs are still only marginally adequate. Ultimately, the lack of data availability and trending is a problem that can be solved if it is given a high enough priority by management. Continuing economic pressure to optimize plant operations will drive some resolution of this problem, but for the short term, data availability may pose a significant obstacle to any extended operating cycle effort.

Management Impact on Cycle Extension: In general, there are clear differences between the best and worst performing plants which result from a proactive versus reactive management policy. The best plant managers proactively search for problems and impending failures, implementing innovative solutions before negative impacts are felt. Many other plant managers are caught in the vicious circle of constantly reacting to the negative impacts of existing problems. Complete dedication to proactive maintenance and operation is vital to the successful implementation of an extended cycle. It is therefore logical that the best performing plants would derive the most benefit from undergoing a cycle extension effort, while poorer performing plants would only exacerbate existing problems and would be better off concentrating on improving their current cycle length performance. An analysis of 1995 operational performance data supports this conclusion. Of those plants currently operating on the "extended" cycle length of 24 months, 35% are in the top quarter of best performing plants, while 44% are in the bottom quarter. This bipolar relationship demonstrates that good plants have seen positive results from cycle extension, while poorer plants have further degraded their performance.

VII. SUMMARY

The proposed extended operating cycle is a substantial change to current industry practices and would stretch existing operational and regulatory experience. This paper has demonstrated that it is not beyond the limits of existing power plant capabilities to operate on cycles as long as four years. As market deregulation and competition from conventional power producers continue to increase, the concept of significant cycle extension will be a legitimate competitive alternative.

This paper has examined the feasibility of surveillance strategies to achieve operating cycle extension in existing plants. A surveillance reconciliation methodology was applied to two case study plants, an operational BWR and PWR, to evaluate the methodology and gauge the ability of current surveillance programs to conform to an extended cycle. The final results showed that the vast majority of current surveillances can be moved on-line or can be performed at the extended cycle intervals. The few surveillances that may be barriers to an extended cycle are identified for further study and compiled in Section Five. Finally, several more general operating cycle extension issues are discussed including technical concerns and management approaches.

ACKNOWLEDGMENTS

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