EXTENDING THE LIFE OF NUCLEAR POWER PLANTS: TECHNICAL AND INSTITUTIONAL ISSUES

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ABSTRACT

Managing nuclear power plant aging is one of the important technical issues which needs to be addressed by utilities in order to extend the operating life of some of the early LWR power stations. Plant managers must understand complex aging phenomena, identify aging effects, anticipate failure, and mitigate the aging process.

Typically, the age-related design limits of crucial components are not known, and this information usually does not appear to be easily available from the equipment vendor. Electrical cables, insulation and instrumentation are most susceptible to age-related degradation. material degradation due to corrosion is the main costly problem affecting a small but important portion of piping and major equipment.

Upgrading the plant, replacing aging equipment, and implementing good maintenance, surveillance and spare parts inventory control programs are actions a utility can take to extend the life of operating nuclear plants.

Considerable institutional uncertainties are associated with nuclear plant life extension. These spring mainly from the absence of clearly defined policies by the U.S. Nuclear Regulatory Commission stating the technical and procedural requirements for plant life extension.

From precedents established to-date, it is reasonable to expect plant operation to be permitted for most plants for a total of 40 years after start of commerical operation. As a large share of the net discounted benefits of extended life operation may be derived from the first decade of additional life, the basis for utility investments for life extension is thus assured.

In planning for life extensions beyond ten years it is useful to consider that the plant would be operated into the future indefinitely, and that it should be maintained so as to maximize efficiency and safety.

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TABLE OF CONTENTS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

By the year 2000, eight commercial nuclear power plants will be approaching the expiration date of their operating licenses. When a nuclear power plant reaches the end of its license life, it must be either decommissioned or its license extended. As the cost of replacing retired plants becomes more prohibitive, utilities are considering the latter alternative, seeking ways to operate existing plants longer. Currently, utilities do not know what are the technical requirements for maintaining proper operation of an aged plant, how to satisfy regulatory requirements and how to deal with other institutional problems that might arise. Utility managers will most probably have to make decisions on life-extension programs with considerable uncertainty as to the outcome of their efforts. In addition to the uncertainty associated with regulatory decision-making, there is no experience to indicate that plant improvements will necessarily result in profitable operation for an extended lifetime. With these uncertainties, utility managers will have difficulty in assuring their executives a profitable return on investments for life-extension efforts.

If money were no object, any plant could be repaired to run indefinitely, using as many replacement components and as much labor and downtime as required. Consequently, utilities must study the financial impact of any life-extension program before taking any action. Economic feasibility studies of life extension of nuclear plants have been conducted by the Electric Power Research Institute (Negin, 1982). The results of these studies revealed that life extension of nuclear power plants is a realistic objective provided the assumptions used in their analysis are valid.

Even if life extension of nuclear plants is economically feasible, the potential safety concerns of operating an aged plant must be considered as well. The public and plant personnel will certainly be concerned about having on old nuclear plant continue to operate. The burden of proof will be on the utility to assure the regulatory authorities that the plant will operate safely when called upon to do so given that the plant and all its equipment have continually grown older. At this point, it is not clear what new regulations, guidelines and procedures will be required for a utility to obtain approval of an application for extended operation.

Some of the regulatory agencies concerns may be reflected in additional technical requirements to assure the capability of safety-related systems and components to perform their intended safety functions. Utility managers need to know the history and the status of the plant in order to assess the functional capability of safety-related systems, as well as non-safety systems. In particular, it is important to know the effects of age on equipment and whether age is a design limit. Given the technical problem of plant aging and the safety concerns of operating an aged plant, the problem which utilities face for extending the life of their nuclear facility is to determine all the technical and institutional requirements which would assure the safe and efficient operation of the plant for an extended life and to increase the probability of obtaining an extended operating license.

1.2 Purpose

The purpose of this report is to state clearly the barriers to life extension and to describe what a utility must do and think about in order to extend plant life. Furthermore, the report will draw attention to the unanswered questions regarding the functional requirements of plant systems and components, the uncertainty associated with assessing the impact of age-related degradation on the operability of equipment and the difficulty of defining precisely the status of the "health" of the plant at any time.

One of the important tasks is to determine the environmental and operating conditions under which systems and components were originally designed to function. In particular, utility managers must know how age was a consideration in the design of equipment. Design information would be essential for the utility in order to judge the remaining useful service life of equipment and to determine effective maintenance and surveillance practices to assure continued proper operation of this equipment. In the absence of such information, utility managers must initiate efforts to formulate age-related design limits for each of the plants systems and components; the work would involve collection of operating data (e.g., mechanical and thermal cycles, radiation levels) and thorough monitoring of equipment to observe degradation processes. The lack of understanding of age-related degradation would make it difficult for plant managers to rely solely on aging assessments in determining the functional capability of equipment. For this reason, uncertainty will play an important role in utility decision-making regarding life extension of nuclear plants.

Also, utilities must be concerned about the adequacy of existing maintenance and surveillance practices at their plants. Maintenance that has not been properly conducted because of improper procedures or installation of substandard components will result in a significant decrease in equipment operability. This report reviews several maintenance and surveillance procedures developed to detect degradation in equipment and to maintain proper operation of equipment. Many components can be identified which should be monitored for degradation. Turbines, pumps, valves, and condensers might have deep-seated flaws, nondestructive evaluation using x-radiation may be used to detect these flaws. Main steam piping and valve bodies should be monitored for the effects of erosion. The steel and head flanges of the reactor pressure vessel should be monitored for cracks. The upper and lower casing of the turbine should be monitored for flange cracking, vibration effects at support points, erosion and corrosion.

Another important objective of this report is to help the reader understand th complexity of age-related degradation phenomena thoughout the nuclear power plant. A large number of phenomena can cause failures such as wear, creep, corrosion and mechanical and thermal fatigue. For utilities, the task of increasing the equipment's operability requires the process of understanding the age-related degradation effects on equipment, obtaining accurate knowledge of failures or of degraded components, carefully analyzing the problem and developing sound corrective measures to lengthen component life.

1.3 Method of Attack

Investigation of the subject matter of this report was carried out in the following manner:

(1) Available literature on life-extension and aging of nuclear power plants was reviewed by conducting a computerized literature search. A major part of this literature dealt with age-related degradation of safety-related equipment and its impact on the qualification procedures for this equipment.

(2) Interviews and meetings were held with utility engineers to discuss the technical and institutional barriers to life-extension. After the first meeting, it was concluded that the best approach for investigating these issues was to conduct interviews with engineers expert in the following areas: electrical equipment and instrumentation, mechanical equipment, licensing and safety, and system chemistry and corrosion. The interviews were aimed at determining the plant equipment most susceptible to age-related degradation, the functional requirements of plant systems and components and whether age is a design basis, and the steps utilities should take for successful life extension of their nuclear plants.

(3) Finally, literature on the plant in consideration was reviewed to understand the different components and systems and the technical requirements for the safe and proper operation of the

plant. Literature reviewed included the Final Safety Analysis Report and the Technical Specifications for systems at the plant. An effort was made to identify age-related design limits for systems and components. In addition, the operating history of the plant and the maintenance and surveillance practices in use were studied; the aim was to determine improved operating practices and better maintenance and surveillance procedures that could be implemented to help extend the life of the plant.

1.4 General View of Major Findings

One of the important technical barriers to extension of the life of a nuclear power plant is ignorance of the age-related design limits of critical components and systems. This information would allow the utility to define the status of the plant relative to the plant's design lifetime. A review of the literature on nuclear-power-plant design did not indicate the age-related design limits of systems and components. Furthermore, it is not clear how a basis for defining these limits would be determined. Efforts must be undertaken by the utility to discover what equipment should be tested and monitored and what data should be taken. Also, practical technical studies are required to estimate the condition of plant systems and components relative to their design limits. The utility must be able to determine the time when it can expect a gradual loss in useful service life of critical components of the reactor system.

Knowledge of design limits is essential for assessing the end of the useful life of components and systems and for anticipating failure. However, it is also important to detect and mitigate aging effects. There are several plans that may be implemented to detect aging effects, including reliability assessment, operation monitoring, trending analysis and accelerated aging. Existing maintenance and surveillance practices must be reviewed and if necessary improved procedures that identify aging effects should be instituted. In addition, research into the basic mechanisms of aging would be beneficial to the utility. To mitigate age-related problems, the utility must determine which components should be replaced or upgraded and what improved operating procedures would slow the aging process.

Finally, it must be emphasized that a decision to implement a life-extension program will have to be made with considerable uncertainty as to its success. The uncertainties regarding the effects of plant aging would make decision-making difficult. Utilities cannot ignore the negative aspects associated with plant aging, namely, higher operation costs, reduced productivity, the potential for unanticipated catastrophic failure, and the presence of undetected deterioratng parts. The absence of design information makes it difficult to make any judgement about the remaining useful service life of plant equipment. Furthermore, even with extensive efforts by utilities (including replacement and upgrading of major equipment) to prepare a nuclear plant for extended operation, there is uncertainty in gaining the confidence of regulatory agencies and obtaining an extended operating license. Utilities will probably not know what to expect in terms of additional technical requirements to assure the capability of safety-related equipment to perform their intended safety function.

CHAPTER 2

NECESSARY ACTIONS TO EXTEND PLANT LIFE

Utilities must carefully determine the technical difficulties that must be addressed in order to successfully extend the life of an aged nuclear power plant. For a utility, extending plant life means doing what is necessary to assure that equipment will operate safely and efficiently in order to meet plant capacity factor goals for an extended time. From an economic viewpoint, the utility must have confidence in the functional capability of equipment (that unexpected failures will not occur at an unacceptably high rate) and believe that the plant will perform profitably. Also, to assure public safety, the utility must be able to demonstrate to regulatory agencies that aged safety systems will operate to prevent release of radioactivity to the environment. There are many steps a utility can take to achieve the goals of operability and safety. But it must be emphasized that economic constraints and technical limitations might make it difficult and even impossible to take certain necessary actions.

From the research conducted to date, including interviews with utility staff and reviews of relevant literature, the following is a list of necessary actions to be taken by a utility to help extend the life of a nuclear power plant:

(1) Identify operational modifications which could be made for life extension.

(2) Identify plant modifications potentially needed for life extension.

(3) Document the operational life of the plant and determine documentation needs for life extension.

(4) Document cases of premature component failure. Note the identified cause. Compare major equipment reliability records with the records of similar equipment in similar plants to trend the performance of the plant's own equipment. Analyzing why equipment at the plant fares better or worse than the industry average could prove to be a very effective method for anticipating problems.

(5) Conduct a survey of the plant's physical condition needs. Review maintenance records and conduct interviews with the operation crew to identify potential trouble areas. Assess the condition of accessible equipment.

(6) Make a list of equipment in the plant requiring additional inspection, tests, or analyses.

(7) Determine whether similar major equipment (turbine generators, feedwater pumps, feedwater heaters, moisture separators, reheaters, condensers, structural supports, etc.) in nuclear and fossil plants have similar failure rates. If not, determine causes for the different experience.

(8) Manage the aging of nuclear power plant systems, components and structures. Identify aging effects, ways to mitigate the degradation, and identify means to prevent premature aging of specific components (discussed in Chapter 4).

(9) Make sure that spare parts are available when needed.

(10) Decide which equipment have to be monitored, determine the types and number of instruments to be used and what data should be taken and how it should be processed.

(11) Consideration must be given to all significant types of degradation that can have an effect on the functional capability of equipment. It should be noted that there are considerable uncertainties regarding the aging process and the environmental factors that could result in such degradation.

(12) Determine the age-related considerations that were taken into account when manufacturers designed components. This information was not available in the literature received from the utility and does not appear to be easily available from equipment vendors in most cases.

(13) Determine the documentation requirements for preparing a new safety analysis report to support an application for operating license extension.

(14) Determine which equipment needs replacement, upgrading or overhauling.

(15) Determine the feasibility of replacement or repair of major equipment such as the steam generators.

(16) Determine the number of thermal and mechanical cycles (fatigue limits) equipment could sustain without failing.

(17) Maintain qualification of all safety-related equipment taking into account the effects of aging. Note the uncertainties in accelerated aging testing and the lack of understanding of the full effects of age-related degradation mechanisms

(17) (discussed in Chapter 4).

(18) Understand the true expected life of various electric cable insulations under a variety of service conditions to support extended plant life. Utility engineers believe cable insulation will be significantly susceptible to age-related degradation.

(19) Verify that biological shield concrete and/or primary shield tanks are suitable for extended life and determine verification data requirments, if any, through plant life. This should include heating and cooling effects as well as neutron irradiation effects.

(20) Conduct accelerated mechanical and thermal cycle tests with operating steady-state stresses superimposed to understand the actual lifetime and potential vulnerabilities in the following equipment: control-rod-drive components, thermal sleeves, main turbo-generator shafts and rotors, and reactor coolant pump shafts.

(21) Determine whether major rotating equipment failure rates are age-dependent.

(22) Document mechanical and thermal cycles at the plant and compare with original design in order to assure extended life feasibility.

(23) Review plant maintenace programs to determine whether more comprehensive efforts would be advisable if plants are to be operated for 60 to 80 years versus 40 years.

(24) If possible, extend steam generator service-life by improving

maintenance practices. Investigate steam generator failures and discover effective remedies.

(25) Determine whether neutron radiation damage in reactor vessel material (embrittlement) will reduce the availability of the nuclear steam supply system during the extended-life operation of the plant.

(26) Investigate the effects of vibration and neutron irradiation on reactor core structure and internals.

(27) Study practices which have lead to successful operation of fossil plants for an extended lifetime. Use this knowledge to establish a basis for extending the operating life of nuclear plants.

CHAPTER 3

OVERVIEW OF AGE-RELATED DEGRADATION

3.1 Introduction

A nuclear plant, like any thermal-electric system, can supply power only as long as its component parts operate in a proper manner. In other words, a plant must function in accordance with actual design criteria. Since every plant is designed with some limitations depending on the capability of a specific component in the system, any degradation of plant equipment may limit generation output as well as affect overall efficiency of operations. Therefore, it is necessary to identify degradation possibilities of all equipment and understand the phenomena of age-related degradation before critical equipment in the plant may fail.

There has been evidence of age-related degradation at nuclear power plants in operation due to a wide variety of mechanisms. Of the more than 35,000 abnormal operating events reported in 1969 through 1982, about 5,900 events had age-related causes (ORNL, 1983). Age-related degradation is expected to be a major factor in the performance of mature nuclear plants and an important barrier to successful life extension. Among other such factors are safety-related plant backfits, and premature replacement of major components such as steam generators.

Literature reviewed to date on nuclear power plant aging have addressed the problem of age-related degradation in the context of the qualification of safety-related equipment. A substantial amount of research into the basic mechansims of material degradation has been conducted at Sandia Laboratories (Bader, 1982). This has included research on the influence of oxygen diffusion in materials in conjunction with radiation, radiation dose-rate effects, and the synergistic effects of heat, radiation, and humidity. However, it should be recognized, on the basis of the rate of progress from past research on aging and synergistic effects, that results are obtained slowly.

Age-related degradation is a significant problem which utilities must deal with throughout the plant. All plant systems and components must be evaluated to determine their susceptibility to age-related degradation. The influence of environmental and operating conditions on material degradation should be completely understood. This can be difficult because aging cannot be usefully investigated in real time; accelerated aging testing (Bader, 1982) must be performed, and it is uncertain that the acceleration produces real-time aging. The uncertainties about the effects of aging is one of the major fators which will affect utility decision-making regarding life-extension. It would be in the interest of utilities to investigate the mechanisms of age-related degradation and the effects of aging on plant equipment.

3.2 Mechanisms of Age-Related Degradation

What we mean by age-related degradation (also referred to as aging) is the effect of operational, environmental, and system conditions on equipment which lead to a degradation of performance of equipment over time (IEEE, 1974). Nuclear power plants in operation have shown evidence of aging due to the following (Marriott, 1984):

(1) subtle, unanticipated material-environmental interctions (for example, stress corrosion cracking of stainless steel piping welds and steam genertor failures)

(2) the effects of neutron radiation on the fracture toughness of reactor vessel steels - a degradation mechanism anticipated in design but whose rate was under predicted (Marriott, 1984)

(3) overuse in normal service or too-frequent testing (for example, valve-seat wear)

(4) mechanical and thermal cycling resulting in fatigue

(5) wear

(6) creep

(7) environmental effects (synergistic effects of heat, radiation and humidity, and for example, loss of insulator resistance).

Backfits and design changes may introduce new aging mechanisms or special aging concerns. For example, installation of added electronic equipment in a controlled air-conditioned environment may add to the heat load sufficiently to make local temperature control inadequate, thereby, contributing to thermal degradation of the electronics. Similarly, replacement of a pump with one of larger capacity in an auxilliary system may lead to degradation of interrelated piping components due to water hammer or erosion (Marriott, 1984).

Utilities should undertake efforts to fully understand the subtle mechanisms of aging and their effects on equipment. It is not known how fast equipment age and how heat, radiation and humidity affect the aging process. Answers to these questions may suggest steps to improve the environmental conditions surrounding equipment and to slow the effects of aging.

3.3 Factors Affecting Aging

The environment within a reactor system is characterized by high temperatures, radiation fields (especially high-energy neutrons) and high stresses. Age-related degradation of equipment during normal service operation may be the result of a variety of environmental stress mechanisms acting either independently or synergistically. Table 3.1 lists components and the stresses they may be susceptible to in a nuclear plant. The environmental stresses may be constant, periodic, or intermittent. Equipment stress resulting from normal operation may be grouped in two general categories; external environmental stresses and internal functional load stresses (Ratio, 1983).

External environmental stresses are typically incurred from such influences as atmospheric conditions (pressure, temperature, humidity, and chemical composition), radiation, vibration, and maintenance operation. Internal functional load stresses result from such sources as power supply fluctuations (electrical stresses), mechanical operation (mechanical stresses, self-induced vibration) and process fluid variations (Ratio, 1983).

This brief description of factors influencing aging should not be considered complete. There may be other environmental and mechanical forces which can contribute to the aging process. The extreme environmental conditions (high temperatures and pressures and neutron radiation) in a reactor system, which haven't been encountered in other technological systems, means that plant managers must continue to be

TABLE 3.1
Stresses on Components in a Nuclear Power Plant

Source: (Drago, 1982)

Component Types	Stresses*
Accumulators, tanks	T,M,C,H
Air dryers	T,M
Annunciator modules	E,H
Batteries	E,C,H
Blowers, fans, compressors	M,E,V
Battery changers	E,M
Circuit breakers, motor starters, fuses	E,H
Control Fods	M,R,V
Control rod drive mechanisms	M,R,W,V
Demineralizers	C
Electric connectors (cable, bus, wires)	E,R,C
Internal combustion engines	M,T
Filters, strainers, screens	W
Fuel elements	R,V,T,M,C
Generators, inverters	E,M,V
Electric heaters	T,E
Lifting devices (cranes, hoists, jacks)	M,T,R
Heat exchangers (coolers, heaters, steam generators, evaporators)	T,M,C,R,H
Instruments, controls, sensors	E,H,M
Mechanical function units (gear boxes)	M
Motors (electric, hydraulic, pneumatic)	E,M
Penetrations, air locks, hatches	M
Pipes, fittings	C,M,V
Pumps	M,V
Recombiners	C
Relays	E,H
Shock suppressors and supports	M
Switches	E,H
Switchgear, load control centers, motor control centers, panel boards	E
Transformers	E
Turbines (gas, steam)	M,C
Valves	M,W
Valve operators	
Pressure vessels (reactor vessels, pressurizers)	R,T,M,C

*Stress codes - thermal (T), mechanical (M), radiation (R), humidity (H), wear (W), electrical (E), vibration (V), chemical reactions (C).

vigilant for signs of trouble.

3.4 Evidence of Aging from Operating Plants (ORNL, 1983)

As mentioned in section 3.1, about 17% of the abnormal operating events reported to the NRC had age-related causes. About 8% of the events resulted from instrument "drift" - the set point, or calibration of a safety-related instrument was found to be outside acceptance criteria contained in the plants technical specifications. The remaining 9% of the events were attributed to other age-related causes such as wear, corrosion, oxidation, crud deposition and fatigue. Those age-related effects caused degradation or failure in a variety of components. Of the components that failed due to age-related causes, 20% were valves; 14% pumps; 5% diesel generators; 3% steam generator tubes; 3% heat exchangers; and less than 1% each for about 120 other components.

Although the data base is small now, industry-wide experience with nuclear plant operation can provide utilities with valuable information in the future about equipment which has degraded due to age-related effects. Continued support of industry-wide data collection should be encouraged by utility managers. Also, individual utilities should take steps to collect aging effects data from their nuclear plants.

3.5 Concept of Aging in Equipment Qualification

The nuclear power industry has made a concentrated effort to include the effects of aging in the qualification of safety-related equipment. In order for equipment to be qualified, it is necessary that the effects of age-related degradation on the safety-related function be considered. The intent of qualification is to demonstrate that safety-related equipment will perform its safety-related function during a design-basis event while it is in its worst state of deterioration. Design-basis events are postulated events (specified by the safety analysis of the plant) used in the design to establish the acceptable performance requirements of the structures and systems (IEEE, 1980).

The assessment of equipment aging effects includes an analysis of the equipment to determine any significant aging mechanisms. The equipment is reviewed in terms of design, function, materials, and environment for its specified application. A significant aging effect adversely affects the ability of the equipment to perform its safety function under design basis events.

After identifying the significant aging effects of the equipment, accelerated aging techniques are used to simulate the aging mechanism in the real environment. This simulation is accomplished by applying in-service stresses (for example, thermal, radiation, wear and vibration) at magnitudes or rates that are greater than expected in-service levels but less than the material property limitations. Next, the artificially aged equipment is installed in its service location and exposed to simulated environmental conditions of design-basis events. The equipment is considered to have passed the qualification test when it meets the values of performance parameters which demonstrate the ability of the equipment to perform its safety function for applicable service conditions.

3.6 Chapter Summary

The effects of aging must be known completely by plant managers in order for them to have assurance that the plant's aged equipment will continue to function properly for an extended lifetime. Thorough detailed aging analyses of equipment can indicate which materials are most sensitive to age-related degradation caused by thermal, radiation, humidity, or wear stress mechanisms (this will be discussed in the next chapter). Once these stress mechanisms are known, the maintenance and surveillance crew can focus attention on those particular parts of the equipment to determine if the age-related degradation rates are greater than what had been originally anticipated. Although some of the mechanisms of age-related degradation and the factors which influence this degradation are known, still much remains to be discovered about the rate of aging, synergistic effects of heat, radiation and humidity, and methods to account for aging in the qualification of equipment for nuclear power generating stations.

CHAPTER 4

MANAGING NUCLEAR POWER PLANT AGING

4.1 Introduction

Experience with most technical systems shows that component aging failures are to be expected with increasing service. These may prove to be troublesome to manage in a nuclear power plant since parameters necessary to predict useful life in the plant environment are often not available. But, to establish a safety basis for operating nuclear plants beyond their design lifetimes, utilities must initiate efforts to determine what the aging effects are, and how to detect and mitigate them.

4.2 Identification of Aging Effects and Anticipation of Failure

Utilities must perform a thorough analysis to systematically identify the components, systems and structures that are likely to cause availability and safety problems if not maintained, restored or replaced. Several plans may be used to detect aging effects and to anticipate failure. These are: reliability assessment, operation monitoring, trending analysis, non-destructive evaluation and accelerated aging testing.

4.2.1 Reliability Assessment (Kahl, 1984)

With the aging of the U.S. nuclear plant population, it will eventually be possible to develop an understanding of the aging of systems and components from the historical operating records of these plants. To assure safe extended generating life of old nuclear plants will require an understanding of the changes in reliability of safety systems caused by aging. Predominant modes of failure may change in latter years of operation, and the ability to identify and monitor these modes will be essential to safe operation.

A primary in-plant information source for documenting component aging and its effects is the maintenance work logs kept by plant maintenance supervisors to track component failures and repairs. The In-Plant Reliability Data System (Kahl, 1984) is being developed by the Oak Ridge National Laboratory to collect, organize and study this component information from a sampling of U.S. nuclear power plants. The previous focus of the IPRDS program had been the corrective maintenance histories of safety related equipment, including pumps, valves, diesel generators, batteries, battery chargers, and inverters. Current efforts of the IPRDS program include broadening the information base to involve other in-plant records that contribute information needed to reconstruct the operating and failure histories of components.

The important in-plant documents and their appropriate contributions to the component aging history include:

(1) Operator's log - Gives the day-to-day operating regimes and the cycling of systems and components through various phases of plant operation and documents unusual developments or occurrences that may upset the internal component environment (e.g., system parameters), or the external environment (e.g., high radiation, fire).

(2) Surveillance and testing procedures and results - Provides the

regimes of periodic testing operations that the component is required to undergo. Documents methods and monitoring techniques currently used to detect symptoms of aging or other degradation.

(3) Preventive maintenance (PM) procedures - Describes the component parts replaced, adjusted, or repaired, thereby identifying steps used in mitigating aging consequences and identifying any potential for human factor effects.

(4) Systems description and drawings - Gives plant location of components, flow paths within a system, and interconnections between systems, which help in defining internal and external environments affecting the components.

Assembling the operating history of failed components from these sources and using information from post mortem evaluations can lead to an understanding of the complex mechanisms of aging and means for its early detection by proper monitoring and prevention techniques. Documented in Table 4.1 is the failure history of a feedwater pump. Degrees of failure severity are represented by the following three distinct levels:

- Incipient failure - no effect on pumping function was noted, but evidence of impending problems did exist (e.g. noisy bearing)
- Degraded failure - the pump function was impaired; and
- Catastrophic failure - pump could not function.

A decreased number of catastrophic failures and overall failures per year is evident from this table after implementation of the PM policy. As one might expect from improved surveillance as part of the improved PM program, the reported incipient failures of the pump increased

TABLE 4.1
Frequency of Failure (by degree of severity) For a Feedwater Pump From 1976-1980

Source: (Kahl, 1984)

Year	1976	1977*	1978	1979	1980
Number of incipient failures	8	16	3	2	3
Number of degraded failures	1	0	4	1	0
Number of catastrophic failures	1	2	0	0	0
Total number of failures	10	18	7	3	3

*Plant managers initiated an improved preventive maintenance policy.

notably within the first year after initiation of the PM program. As seen in the failure history, incipient failures can provide evidence of degradation mechanisms and may yield forewarning of more severe problems.

Only with a comprehensive history of the component operating regimes and system parameters, coupled with effective PM, and accurate information of the operating environment conditions can one develop an aging history of a component.

4.2.2 Operation Monitoring

Plant operation data attainable from the output of already existing instrumentation, such as detectors and sensors, can be analyzed either on-line or off-line for early identification of system degradation. Use of advanced monitoring techniques for maintenance and testing can also allow for on-line detection of degradation (Keyvan, 1984).

A special class of surveillance techniques called "condition monitoring" (CM) uses quantitative indicators to monitor the "health" of equipment. CM relies on measuring a number of relevant parameters and plotting the results to observe a trend in the degradation of critical components in the equipment. This can be done continuously or intermittently on a schedule that is consistent with the existing preventive maintenance schedule. The assessment of existing damage versus the undamaged and failed conditions allows for extrapolation of remaining life (Sugarman, 1984).

CM is based on measuring degradation of the components with the most limiting lifetimes. The limiting components can be identified through testing and/or analysis. Usually, equipment located in the worst case environment considering all stresses (radiation, temperature, humidity) is selected for monitoring. The method is applicable for mechanical as well as electrical equipment (Sugarman, 1983).

Condition monitoring techniques are related to preventive maintenance and accelerated qualification testing. Examples of such techniques are vibration monitoring to detect rotating machinery bearing wear and partial discharge testing of large motors. These techniques detect wear and forecast incipient failure of components. Condition monitoring is merely an enhancement of existing techniques which can be incorporated into present nuclear plant surveillance and preventive maintenance procedures (Sugarman, 1984).

4.2.3 Trending Analysis

Trending the performance of the plant's own equipment and analyzing why it fares better or worse than the industry average can be a very effective method for anticipating age-related problems. A detailed surveillance program may be employed, initially involving visual inspection of equipment, environmental survey and a review of plant maintenance records and procedures to identify potential trouble areas. The program can be supplemented by interviews with the operation crew to identify various problem areas where visual and record inspection fails (Keyvan, 1984).

The results of these efforts may be compiled in a computer inventory management system. This program would use also other data extracted from plant specific records and information systems. Examples of data sources are operation and outage logs, maintenance orders, the IPRDS and licensee evaluation reports. In addition, other sources of data from plants of the same manufacturer and vintage as the plant under consideration can be included in the program (Keyvan, 1984).

The inventory management program can be designed to give detailed information about components. For example, detailed analysis of historical data related to plant outages can be performed, identifying equipment which has exhibited an increasing failure rate and/or long outage duration, which may possibly be attributed to age or outdated design. The program would be most useful if it were capable of segregating components which were reaching their endpoints at the end of the plant's life (Keyvan, 1984).

4.2.4 Non-Destructive Evaluation (Fagenbaum, 1984)

In order to detect the slightest material degradation in critical equipment, emergency core cooling systems, piping and other plant components, it is necessary to have available the most advanced testing methods. Non-destructive evaluation techniques allow plant operators to carry out inspection routines quickly and easily to avoid system failures that would threaten the safety of the entire plant. The non-destructive evaluation techniques used today include: x-ray radiography, xerography, fluoroscopy, neutron radiography, visual aids, focused ultrasound and multiple-frequency eddy currents.

Because of the nature of deep-seated flaws that may be located in nuclear power systems in or near the reactor containment building such as in pressure vessels, steam generators, turbines, pumps, valves, condensers, and cooling water pumps, NDE inspection requires instruments capable of penetrating and diagnosing the innermost part of an object. This type of testing generally involves an energy exchange in the form of absorption and emission of radiation. X-radiation is among the best-known ways of doing this within the nuclear power industry. Radiographic observation involves the recording of x-radiation transmitted onto a film to produce a shadow picture. Using radiography, it is possible to locate shrinkage, the position of cracks, discontinuities, foreign materials, and gas cavities.

Tools that are being increasingly applied to the non-destructive evaluation of nuclear fuel materials are pulsed neutron sources and high resolution two-dimensional neutron detectors. A notable characteristic of thermal neutron radiography, as opposed to x-ray evaluation, is the high penetration ability of the neutron when it is used with metals. Another attribute is the ability of neutron radiography to pick out the material containing hydrogen in a test element. This is due to the large neutron cross sections for hydrogen at thermal energies.

Visual aids such as periscopes, telescopes, microscopes, photographic recordings, fiber-optic devices and borescopes are among the simplest of instruments used to monitor the integrity of components like pipes and tubes. For example, the borescope is used to inspect the interior surfaces of vessels and tubes and consists of an eyepiece and an optical train. An instrument that is smaller, more flexible and microprocessor-based is the fiberscope. This device uses smooth fibers of transparent material that transmit light very efficiently. Each fiber carries light independently of the others. One bundle of fibers transmits light from an external source to illuminate an object; the second bundle carries the image formed by the objective lens at the tip of the instrument back to the eyepiece.

Liquid penetrant tests are often a useful method of checking for surface defects, and for subsurface defects with surface openings. This type of test typically uncovers flaws like surface cracks, lack of bond between edges of joined material, porosity, laminations, and leaks in tanks and tubing. Materials that have been inspected with liquid penetrants include ceramics, glass, ferrous and non ferrous metals, powdered metal products, plastics, and synthetic products.

Although non-destructive evaluation techniques are effective tests to characterize and qualify flaws in plant equipment, there are limitations to its usefulness. In many cases there are differences in the engineer's and technician's interpretation of NDE equipment data from inspection routines. For example, coolant piping and pressure vessel systems in nuclear power plants are made of materials that are nonhomogeneous in composition, and which during non-destructive testing will sometimes generate signals that mimic flaws. Also, there are factors that make testing difficult. These include heat, humidity, radiation, and inconvenient equipment and system locations. Finally, it is not known what equipment cannot be tested for by NDE techniques.

4.2.5 Accelerated Aging (Bader, 1982)

A technique that is of limited success for determining the remaining life of plant components is accelerated aging. It is sometimes necessary to use accelerated aging tests to predict the life of long-life components. The objective of accelerated aging is to increase the rate of aging of a component subject to the constraint that the dominant physical mechanisms responsible for aging do not change from those associated with operation at normal stress. This testing procedure has been applied at nuclear power generating stations to satisfy the aging requirement for qualification of safety-related equipment (this equipment is listed in Table 4.2).

The requirement to account for degradation of the functional capability in the qualification of safety-related electrical equipment for nuclear power applications became generalized by the publication of IEEE (Institute of Electronics and Electrical Engineers) Std 323-1974 and its endorsement by Regulatory Guide 1.89. In 1980, the aging requirement was extended through IEEE Std 627-1980 to the qualification of mechanical equipment. The existing aging qualification procedure can be summarized as follows: identify significant aging mechanisms, establish accelerated aging procedures based on existing technology, and establish a qualified life. In practice, this frequently is translated into deriving a qualified life primarily on the basis of thermal aging.

After a large amount of equipment qualification testing and analysis, there is a widespread recognition of the limitations of accelerated aging techniques in establishing equipment qualification lifetimes. The NRC regulation requiring qualification of safety-related equipment has posed the problem for utilities of establishing a qualified life for this equipment, which is the period of normal service represented by the accelerated aging part of the qualification. To extend the life of a nuclear plant, utilities might have to establish

TABLE 4.2
Safety-Related Equipment Required To Be Qualified

Source: (NRC Regulatory Guide 1.89, 1974)

Engineered Safeguards Actuation
Reactor Protection
Containment Isolation
Steamline Isolation
Main Feedwater Shutdown and Isolation
Emergency Power

Emergency Core Cooling
Containment Heat Removal
Containment Fission Product Removal
Containment Combustible Gas Control
Auxiliary Feedwater
Containment Ventilation
Containment Radiation Monitoring

Control Room Habitability Systems
Ventilation for Areas Containing Safety Equipment
Component Cooling
Service Water
Emergency Shutdown
Post-Accident Sampling and Monitoring
Radiation Monitoring
Safety-Related Display Instrumentation

qualified lives for most, if not all, equipment in the plant. It is important to understand that this task would be difficult in view of the limitations of accelerated aging techniques. Whatever accelerated aging procedure is used, it is very likely to produce significantly more or significantly less degradation of functional capability than will take place in the application. The reason for this is that existing accelerated aging techniques cannot recreate the exact environmental and operating conditions under which equipment normally functions. Usually the effect of a single stress (thermal) has been accounted for; however, the real environment consists of many other stresses, some of which act synergistically. There are no practical models for these aging stresses. Furthermore, the non-linear reaction rates present in the real service environment are very difficult to simulate accurately by accelerated aging techniques which fail to account for the slow interactions between the environmental stresses and the equipment.

Installed equipment is subject to all of the aging stresses and synergistic effects and all of the interface influences of the real service environment. The effects of aging of interfaces and junctions between materials and components and the synergistic effects of combined stresses and/or chemical reactions are not known. In view of the uncertainties associated with existing procedures for taking equipment degradation into account, it is essential to monitor equipment degradation in service as a supplement to existing qualification procedures. Since existing surveillance, inspection, testing, repair, and maintenance procedures do not adequately fulfill the needs of degradation monitoring, there is a need to study this topic. Utilities should undertake an investigation to determine what existing surveillance procedures can be applied directly to degradation monitoring and what monitoring procedures require development.

4.2.6 Thermal and Radiation Aging Degradation of Selected Materials

(CYAPC, Docket 50-213)

A partial list of materials which may be found in a nuclear power plant along with an indication of the material susceptibility to significant degradation due to radiation or thermal aging is given in Table 4.3.

Susceptibility to significant thermal aging in a 45°C environment and normal atmosphere for 10 to 40 years is indicated by an (*) in the appropriate column. Significant aging degradation is defined as that amount of degradation that would place in substantial doubt the ability of typical equipment using these materials to function in a hostile environment.

Susceptibility to radiation damage is indicated by the dose level and the observed effect identified in the column headed BASIS. The meaning of the terms used to characterize the dose effect is as follows:

- Threshold - Refers to damage threshold, which is the radiation exposure required to change at least one physical property of the material
- Allowable - Refers to the radiation which can be absorbed before serious degradation occurs.

The materials list can be used by a utility to make judgements as

TABLE 4.3
Thermal and Radiation Aging Degradation of Selected Materials

Source: (CYAPC, Docket 50-213)

MATERIAL[1]	POTENTIAL FOR SIGNIFICANT AGING		RADIATION SUSCEPTIBILITY	
	10 years	40 years	Rads Gamma	Basis
Integrated Circuits N-Mos			10^3	Threshold
Transistors			10^4	Threshold
Vulcanized Fiber	*	*	10^5	Threshold
Capacitors-Tantalum			10^6	Allowable
Polyethylene	*	*	10^7	Allowable
Tetzel			10^6	Threshold
Silicon Rubber			10^6	Threshold
Diodes			10^4	Threshold
Polyester (unfilled)	*	*	10^5	Threshold
Nylon	*	*	10^5	Threshold
Polycarbonate		*	10^6	Threshold

[1] These materials may be found in cables, connectors, motors, sensors, instrument panels, valve operators and other electrical equipment.

to the possibility of a particular material in a particular application being susceptible to significant degradation due to radiation or thermal aging. This list can be expanded as additional information becomes available. Also, it would be useful to know the effect of other aging stresses on the materials listed, particularly the synergistic effects of combined stresses. Further study on the aging degradation of materials to establish a safety basis for extended life operation of a nuclear plant is needed.

4.3 Solving Age-Related Problems (Marriott, 1984)

After identifying age-related problem areas in the plant, the next step is definition of alternative remedies for each of the plant's physical problems. Remedies include replacement, overhaul, use of spares, early warning instrumentation, actions to eliminate the failure mode, specialized preventive maintenance, improved training, and contingency analysis for permitting operation with equipment out of service. For each problem, all remedies must be economically compared to select the best solution.

4.3.1 Equipment Replacement or Upgrading (Marriott, 1983)

Replacing or upgrading certain aging equipment will be necessary for extending the operating lives of nuclear power plants. The costs of replacing aging equipment appear to represent a small portion of the total plant costs provided that down time isn't excessive. Critical components that may need to be replaced are steam generators, turbine-generators, major pumps and valves, condensers and electric cables and insulation. It is not known whether the reactor pressure vessel must be replaced. Failure of the reactor pressure vessel from embrittlement is a worry because of the reactor safety problems which it might pose and because of the high cost of replacing a reactor vessel. The utility must determine which equipment will likely pose reliability problems as the plant ages. Those equipment which have shown chronic patterns of failure in the past must be upgraded or replaced. Equipment in this category are the steam generators, the reactor core, the turbine generator and the reactor coolant pumps.

4.3.2 Condition Monitoring

A condition monitoring program can be implemented at a nuclear power plant to extend equipment life where it is technically and economically feasible. This program can be integrated with the plant maintenance and surveillance programs and makes few additional demands on the plant maintenance resources (Bader, 1982).

Condition monitoring (or degradation monitoring) of environmentally qualified equipment is performed using the maintenance data recorded on the maintenance histories. Equipment that reaches the end of its qualified life but is not showing any degradation in the parameters being monitored may be subjected to an engineering evaluation for continued use so long as proper maintenance is performed and condition monitoring continues (Sugarman, 1984).

The condition monitoring program is an on-line, interactive, information system designed for processing maintenance and surveillance data for the environmentally qualified equipment. The input data consist of the following: the equipment identification number and type of surveillance tests, procedure number, brief description of the equipment including manufacturer and model number, equipment location and elevation, and two setpoints. The first setpoint is used as an early warning indication of possible degradation in the equipment. The second setpoint is where corrective action must be taken to either repair or replace the equipment (Sugarman, 1984).

Not all equipment is equally suited to being monitored for age-related degradation. Heavy rotating equipment such as turbine generators is particularly appropriate for condition monitoring because of the severe economic consequences of an unscheduled outage to an electrical generating station if they go down unexpectedly. Condition monitoring is currently being performed for this equipment by using techniques such as acoustic and vibration monitoring for bearing wear and dielectric-loss measurements on stator insulation (Sugarman, 1983).

The utility must select safety-related equipment items for which condition monitoring procedures are most likely to produce a significant benefit to public safety. Condition monitoring of lighter equipment such as motor operators, solenoids, cables, and transmitters may be technically feasible and may be a desirable option for meeting safety and regulatory requirements. Some equipment such as electronic equipment, tends to fail catastrophically and without warning and therefore is not an appropriate subject for condition monitoring. In Table 4.4, representative equipment items are categorized into three groups of equipment according to the perceived applicability to condition monitoring (Sugarman, 1983).

TABLE 4.4
Categorization of Equipment for Condition Monitoring

Source: (Sugarman, 1983)

Equipment For Which Condition Monitoring May Not Be Feasible

Terninal Blocks
Manual Switches
Amplifiers
Signal Converters
Recorders
Meters

Equipment For Which Some Condition Monitoring May Be Feasible

Penetrations
Power Supplies
Temperature Sensors
Radiation Monitors

Equipment For Which Condition Monitoring Is Feasible

Batteries
Battery Chargers
Generators
Transformers
Cables
Motors (for pumps, compressors, etc.)
Solenoids
Relays
Limit Switches
Circuit Breakers
Transmitters

Condition monitoring techniques can be classified as either destructive examination (e.g. elongation of samples of insulation material) or non-destructive examination (e.g. dielectric loss measurements on stator windings in motors). It is important that the test parameters be correlated with degradation that occurs with the age of the equipment. Some parameters such as temperature and instrument drift are indicative of more than one effect and cannot be used alone to determine the condition of the equipment (Sugarman, 1983).

A well-structured condition monitoring program enhances utility knowledge of equipment operational status. Utilities must identify existing surveillance procedures that can be applied directly to condition monitoring and identify monitoring procedures that require development. The most important aspect of condition monitoring is definition of the material or component property to be measured. This property should degrade over time and be related to performance, although not necessarily a direct performance property. For equipment subject to condition monitoring programs, the component property to be measured must be determined. An effective condition monitoring program can provide continuing assurance of equipment operability over long time periods.

4.3.3 Improved Operating Procedures (Tally, 1984)

An integral part of ensuring continued plant safety and longevity of components is to operate the plant within the design envelope provided by the designer. Each nuclear steam supply system design has basic functional requirements that define what the system must be capable of experiencing without failure. These functional requirements include transient and steady-state descriptions bounding anticipated and many design-basis conditions and events. The transient descriptions define the various fluid conditions throughout the system as a function of time and are based on how the designer expects the plant to be operated.

To methodically maintain and monitor records on plant transients, a transient logging program may be employed. The first step in this program is to provide guidelines for logging all significant transients that the NSSS might experience. Next the actual operating plant experience is compared with the functional design requirements to see if the actual fluid conditions and number of cycles in the original design documentation bounded the conditions which the plant experienced for each transient. This program allows operators to note important trends in plant operating characteristics and to take corrective action before key components are significantly degraded. Paying close attention to the operating history has another advantage. After a component failure has occurred, the operational history of the component can help in attempts to pinpoint the cause of failure.

4.3.4 Spare Parts Inventory Management (Suomi, 1983)

To assure timely replacement of failed parts, utilities may implement a spare parts management program. This program must include a thorough evaluation of equipment and a consistent application of sound engineering judgement so that an optimized inventory may be maintained.

Availability of spare replacement parts can be a potential source of problems for an aged nuclear power plant being considered for life extension. Certain components may be obsolete or the original manufacturers may no longer be in business; the utility may have to go to considerable expense and trouble to get replacements.

Perhaps the most significant factor in determining whether or not a part should be stocked will be the effect of the part's failure on the availability, safety, and reliability of the plant. If a spare parts management program is to remain effective, it must take into account the effects of facility age, new maintenance techniques, changes in delivery lead time, changes in part costs, and state-of-the-art equipment changes. Considerations such as these require that the inventory be periodically re-evaluated so that stocking levels can be adjusted, poorly designed parts replaced, and unnecessary items eliminated.

4.4 Chapter Summary

A comprehensive assessment of nuclear power plant component operating histories, maintenance histories, and design and fabrication details is essential to understanding aging phenomena. Programs can be implemented to detect aging effects and to mitigate them. Component maintenance or replacement schedules should include considerations of the specific aging characteristics of the component materials. Ongoing programs should exist at the plant to review surveillance and maintenance records to assure that equipment which is exhibiting age-related degradation will be identified and replaced as necessary. In conclusion, utilities could make it feasible to extend the life of operating nuclear plants by upgrading plant equipment, implementing good maintenance, surveillance, and spare parts inventory control programs and necessary reliability assurance programs involving repair and replacement of equipment.

CHAPTER 5

AGE-RELATED DESIGN LIMITS OF COMPONENTS AND SYSTEMS

When considering operation of a nuclear power plant beyond the 40 year design lifetime, it is important for the utility manager to know the status of the plant in relation to the design life of the plant. In most cases, the design life of various components and systems are not available to the utility. When the lifetime-design limits are given, a question arises as to how these limits were determined. A review of the literature available from the utility studied on plant systems and components failed to reveal design lives and the reason the age of equipment and systems would limit their proper functioning in the plant. Also, from discussions with the utility staff, this information does not appear to be easily available from the equipment vendor. In the face of such ignorance, utility managers must necessarily initiate research efforts to formulate age-related design limits for each of the plants systems and components and to investigate methods to estimate the plant status in relation to the design limits.

Design information regarding the useful life of plant systems and components would help utilities identify components likely to fail if not replaced or restored. This information could be in the forms of a design lifetime and age-related design limits. The design life of equipment is the time during which satisfactory performance can be expected for a specific set of service conditions. The life may be specified in calendar time. However, operating time, number of operating cycles or other performance intervals, as appropriate, may be used to determine this time. Age-related design limits can be given in terms of the following stress level mechanisms: fatigue (number of cycles), wear (amount of erosion of material), radiation (extent of deterioration of molecular structures) and temperature (threshold limits create material deterioration).

The only design information found in this study was a list of component cycles or transient limits in the Standard Technical Specifications for Westinghouse PWR's (NUREG-0452, Fall 1981). This list is given in Table 5.1. It is not known how Westinghouse arrived at these cyclic limits. Discussions with the utility revealed that information regarding the number and types of cycles or transients experienced at the plant are not gathered routinely, although some of this information could be obtained by studying the operating log of the plant. Also, discussions revealed that it is highly probable that these limits have not been reached as the number of transients expected over the lifetime of the plant (based on past experience) falls below these limits. However, the importance of these limits for extending the life of the power plant must be assessed and if necessary a transient logging program (Tally, 1984) should be implemented.

The transient logging program would be the first step in the process of demonstrating the adequacy of the reactor coolant system components for the 40 year design life. This objective may be achieved in four progressive stages, examining operating plant data, comparing with design requirements, revising design requirements, and revising stress analyses (Tally, 1984).

TABLE 5.1
Component Cyclic or Transient Limits

Source: (Standard Technical Specifications for Westinghouse PWR's, NUREG-0452, 1981).

COMPONENT	CYCLIC OR TRANSIENT LIMIT	DESIGN CYCLE OR TRANSIENT
Reactor Coolant System	(250) heatup cycles at < 100°F/hr and (250) cooldown cycles at < 100°F/hr	Heatup cycle- Tavg from <200°F to >550°F Cooldown cycle-Tavg From >550°F to <200°F
	(100) cycles of loss of offsite A.C. electrical power	Loss offsite A.C. electrical ESF Electrical System
	(500) reactor trip cycles	100% to 0% of RATED THERMAL POWER
Secondary System	(1) steam line break	Break in a > 6 inch steam line
	(5) hydrostatic pressure tests	Pressurized to >(1350) psig.

The second step in the evaluation process would be to compare the actual operating plant experience with the functional design requirements to see if the actual fluid conditions and number of cycles in the original design documentation bounded the conditions the plant experienced for each transient. If there were significant differences, their impact on the reactor system must be evaluated.

Finally, any differences between the design transient descriptions and the actual operating plant data must be resolved by refining the design transient description. Since these descriptions constitute functional requirements and are the bases for the reactor coolant system stress report, the stress report must be reviewed and supplemented with engineering evaluations and analyses (Tally, 1984).

A major problem with assessments of the functional requirements of equipment in operating plants is lack of age-related testing or data to support the ability of old equipment to operate for its design life. Equipment qualification methods may be used, in the absence of age-related design limits and bases for these limits, to determine the bases for aging assessments and to forecast the ability of equipment to perform at dates in the future through evaluation of present degradation as compared to past history. Qualification methods generally consist of:

(1) tests which subject equipment to the most severe adverse environments expected to occur at the installed equipment location and/or

(2) analyses which considers hazardous environments and their potential for causing unacceptable failures of equipment.

Typical adverse environmental parameters specified in testing or analysis include: temperature, pressure, humidity and radiation. The method used to evaluate the functional capability of the equipment is to test the ability of the materials making up the equipment to function in a given environment over a period of time. Resistance to ionizing radiation, thermal rating, and corrosion resistance of materials are often evaluated to determine the material status after exposure to normal and adverse environments. The evaluation may be difficult since exact materials of construction are often unknown to both the utility performing the assessments and the manufacturers of the equipment (Bader, 1982).

As discussed above, equipment design qualification may be used to estimate plant status with respect to functional capability and to forecast the ability of equipment to perform in the future (being aware of the limitations of accelerated age testing). In addition, equipment qualification may be used to formulate a qualified life for each piece of equipment (amenable to qualification procedures) susceptible to age-related degradation. A representative sample of the equipment is placed in an aged condition, naturally or artifically, to simulate all significant aging effects. Proper operation within its specified service conditions results in qualification of the equipment for a period of time. This time period is defined as the qualified life of the equipment. For equipment with no significant aging mechanisms, its qualified life is equal to its design life. The determination of qualified life should be based on conservative engineering analysis (IEEE, 1980).

The results of equipment qualification testing can partically make up for our ignorance of the age-related design limits of equipment by giving bases for aging assessments and yielding a qualified life for which equipment was demonstrated to be functional for specified service conditions. This and other testing methodologies should be investigated by the utility for their usefulness in estimating the status of the plant's equipment operability and for formulating age-related design limits for various equipment.

CHAPTER 6

IDENTIFYING AGING PROBLEMS AT THE PLANT STUDIED

6.1 Areas of Investigation

In previous chapters, technical issues regarding nuclear power plant aging and life extension have been addressed with particular emphasis on means of identifying components in the plant which may not function properly because of age-related degradation. A question which should be asked is what areas in the nuclear power plant are most susceptible to age-related degradation. A representative nuclear power plant was studied to answer this question. Four major areas were considered for investigation: structural components of equipment, mechanical equipment, electrical equipment (including instrumentation and controls), and environmental aging effects.

6.2 Structural Components of Equipment

The first consideration must be given to the supporting structure for all the systems and components in the plant. This includes the building structure, auxiliary steel, supports for piping, air conditioning ducts, cable pans, conduits, and other components and equipment foundations. All safety-related items were designed for accident (extreme loading) conditions, which provides a considerably high margin of safety for normal operating conditions. The non-safety items were also designed conservatively across the board. This high margin of safety and the fact that they are seldom used caused these items to be least susceptible to aging due to fatigue, creep or rupture. There are a few exceptions such as snubbers, heavy rotating-equipment foundations, and foundations of heavy equipment connected to hot piping systems such as heaters, heat exchangers, and condensers, which may be subjected to fluctuating thermal loads. It is not known how many thermal cycles these structures are capable of sustaining without failing. The utility must establish an inspection and surveillance program to monitor these items (NUSCO, 1984).

6.3 Mechanical Equipment

The second consideration was given to mechanical equipment and components. The actual operating temperatures, pressures, loads and mechanical and thermal stress levels were compared to the associated values which were used as a design basis and found to be much lower. The main costly problem which only affects a small, but important, portion of piping and major equipment is material degradation due to corrosion which may result in stress-corrosion cracking (NUSCO, 1984).

Experience in operating the plant studied has shown a number of material degradation processes to have occurred in the steam generators. In the design and licensing of the reactor, minor steam generator tube inleakage was anticipated and was not considered a major safety concern. However, widespread degradation that could lead to major leakage developing from failure of a number of tubes during a design-basis accident and result in significant release of radioactivity to the environment is a potential safety concern (Bader, 1982).

The degradation processes that have occurred at the plant are wastage and tubing support plate corrosion. Wastage, or general corrosion of the primary side tubing in creviced areas by acid phosphates, has largely been eliminated by the abondonment of phosphate water chemistry. Tube-support-plate corrosion or denting due to the non protective magnetite growth on the carbon-steel support plate has been triggered by the presence of chlorides, an acid environment and oxidizing ions such as copper or nickel. In addition to producing dents and deformation in the inconel tubes, leading to primary-side stress-corrosion cracking, denting processes result in considerable distortion and cracking of the tube-support plate as well. Proper oxygen control or deaeration in the condenser and feedwater lines, as well as in the steam generator, together with careful monitoring of condenser leakage have appeared to be the best defense against denting reactions (Bader, 1982).

Although the older problems, such as denting and wastage have been controlled, others that are slower to develop could become more evident in the future. Two of the most important of these are intergranular corrosion and stress-corrosion cracking in the alloy 600 tubes. In intergranular corrosion, the boundaries between the tiny grains of metal near the outer surface of a tube are slowly attacked by a process still not fully understood. Stress corrosion cracking is a related phenomenon that occurs when a surface exposed to a corrosive environment is also subjected to tensile stress. Again, the process is not fully understood, but cracking could begin on either the inside or the outside of a tube (Douglas, 1984).

Opportunities for controlling steam generator corrosion and subsequent mechanical damage involve equipment modifications and improved procedures in the secondary loop and especially in the condenser cooling loop. The following plant modifications could be made to minimize the potential for tube degradation in the future (Nutwell, 1983):

- Retubing and replacement of existing feedwater heaters and moisture-separator/reheaters to eliminate sources of copper-bearing materials in heat exchangers, which have contributed to tube denting.
- Replacement of copper/nickel and aluminum alloy tubes in the existing condensers with titanium tubes.
- Installation of a demineralized-water storage system to provide high quality water to the steam generators for use during scheduled shutdown, startup, and hot-standby operations.

With all treatments of corrosion in steam generators there are uncertainties and utilities need to know the answers to many questions to ensure the safe continued operation of the plant. Some unanswered questions are:

(1) How is degradation progressing following remedial action?

(2) Have remedial actions taken to correct one type of degradation introduced possibly a second one?

(3) What water chemistry controls really are satisfactory to ensure reliability and safety?

Utilities should continue investigation of steam generator corrosion problems to answer these questions.

6.4 Electrical Equipment and Instrumentation (NUSCO, 1984)

The structural parts of safety-related electrical equipment such as panels, boards, cable pans, and conduits have been designed for extreme loading conditions and degradation or potential failures are not expected to be a concern for extended life operation. The utility engineers think that electric insulation, cables, devices and instrumentation may present a problem. Preventive measures and/or replacement will be required by the utility for insulation and cables. However, replacement in the same manner that is routinely done will be required for devices and instrumentation.

6.5 Environmental Aging Effects (CYAPC, Docket 50-213)

Based on the present licensing requirement, all nuclear plants have to have some level of environmental qualification for all safety-related equipment. This results in establishing the qualified life of each piece of safety-related equipment. At the plant the qualified life for each electrical equipment item which is required to function in a harsh environment must be determined. Harsh environments are the result of loss of cooling accident or high energy line break inside containment. All harsh environment equipment is included in the surveillance and maintenance programs to detect unexpected age-related degradation.

Some of the generic electrical equipment items which are included in the qualification program and the schedule for preventive maintenance for each item are listed in Table 6.1. The majority of the surveillance and preventive maintenance which is done on this equipment is currently performed on a periodic basis. The surveillance and preventive

TABLE 6.1
Surveillance and Preventive Maintenance of Equipment Located in a Harsh Environment.

Source: (CYAPC, Docket 50-213)

Generic Equipment	Period
4 KV Motors	Each Refueling
480 Volt Motors	Each Refueling
Motor Operators	5 Years
Solenoid Valves	3 Years
Limit Switches	2 Years
Instrumentation	Each Refueling
Transmitters	
Radiation Detectors	
Pressure Switches	
Acellerometer	

maintenance procedures include visual inspections, where applicable, to observe any indications of postulated aging degradations. In those equipment where accelerated aging was included in the harsh environment testing program, such as with cables, visual inspection may be the only surveillance performed on a regular basis.

CHAPTER 7
OTHER TECHNICAL ISSUES IN NUCLEAR PLANT LONGEVITY EXTENSION

7.1 Maintenance of Pressure Boundary Integrity

Changes in reactor vessel material properties may occur during plant life due to environemntal effects. In particular, the embrittling effects of fast neutron irradiation on reactor vessel steels could pose a serious problem for utilities in any life extension program. Neutron bombardments can generate imperfections or defects in the regular array of atoms in crystalline solids. The accumulation of radiation damage over time results in the loss of ductility of the metal.

Annealing may be used partially to restore the ductility of a metal. Annealing is a process of heating a metal to a sufficiently high temperature (usually higher than one-third the absolute melting point) for long enough time to produce the desired mechanical, physical or other properties. A well-annealed metal is stable against any further metallurgical changes which might be thermally induced during service. The recovery of ductility by this process is an important phenomenon from the practical standpoint that it may be possible to repair reactor pressure vessels by periodic annealing. There seems to be a clear incentive for utilities to begin practical consideration of how large reactor vessels might be annealed (Smallman, 1970).

However, there are drawbacks of in-place annealing of the reactor pressure vessel. The effectiveness of annealing has not been demonstrated yet. Furthermore, even if annealing proves to be effective in removing radiation damage, it is not known how the vessel would be repaired with the primary shield concrete in the way. Another drawback is the lack of space in the containment to perform the repair. Finally, the thermally-induced residual stresses which might be created in the metal sections within the thermal gradient zone of the annealing boundary could become serious new concerns.

In addition to embrittlement of reactor vessel steels, another threat to the integrity of the pressure boundary is fatigue. Fatigue may be characterized as a progressive failure phenomenon that proceeds by the initiation and propagation of cracks to an unstable size as a result of application of fluctuating loads over a period of time. The pressurizer, pressure vessel and primary piping are subject to large, cyclic thermal stresses which together with the stresses from fluid-structural interactions and vibration could result in thermal fatigue of these components. Since practically all fatigue failures start at surfaces, there is a constant need to guard against creation of imperfections in the surfaces of pressure-boundary components by using the most advanced testing methods to detect the slightest material degradation in these components. Liquid penetrant tests are often useful non-destructive evaluation methods to check for surface defects, and for subsurface defects with surface openings.

7.2. Experience with Component Replacements (Nutwell, 1983)

To extend the service life of nuclear power plants it will be important to be able to demonstrate the feasibility of replacements and to ensure that radiation exposures to personnel would be kept low. An important component that could need to be replaced in order to extend the life of the plant is the steam generator. The reason for this is that steam generator tube leaks cannot be preventively plugged indefinitely; for every tube that is preventively plugged, the number of remaining tubes allowed to be plugged (a design margin provided by the NSSS vendor) decreases. The experience of utilities with replacing and repairing degraded steam generators is useful for other utilities which may face the same problem. In particular, changes in past repair schedules and construction techniques may help utilities reduce total downtime.

Several years of detailed planning of construction activities usually preceded actual replacement of steam generators. Initially, design studies were performed to identify modifications needed inside the containment for replacement of the steam generators. These studies included identification of equipment, piping and cable to be removed, location of cut lines for removal of concrete floor slabs and shield walls, and evaluation of existing structural steel for new loads imposed by temporary equipment. To assist in the studies a scale model of the containment was built. The model helped to determine the feasibility of various rigging schemes and was used to identify the structure and equipment that had to be removed from the containment to provide sufficient laydown areas and work space.

An important concern in the replacement effort was reducing the radiation exposure to workers. Studies were made of tasks associated with the repair to assess the radiation exposures anticipated (Nutwell, 1983). These tasks were then reviewed for possible changes that would reduce the associated doses. Low-level radiation areas were identified and posted inside the containment to provide workers with low-exposure rest areas. In addition, decontamination or shielding techniques were considered for application in areas of frequent use.

Before work could begin on replacing the steam generators, a number of changes had to be made inside the containment. Insulation was removed from steam generators and connected piping. Portions of piping attached to each steam generator were removed. An equipment hatch trolley was installed in the hatch to ferry equipment and materials. After the changes were made, the steam generators were cut apart and new components were installed.

A review of the replacement experience suggested a number of changes in the construction techniques for future repairs. Installing pedestal cranes earlier in the outage can eliminate conflicting needs for the use of the polar crane. In addition, upgrading the auxiliary hook on the polar crane could simplify the rigging scheme for inverting the steam generator upper assemblies. These changes and other adjustments are expected to reduce total downtime required for future repairs (Nutwell, 1983).

7.3 Plant Improvements

Successful life extension of aged nuclear power plants will probably require changes in existing plant equipment and the addition of new equipment to maintain the operability of aged equipment. Some of the major improvements to be considered include:

(1) secondary-system improvement to forestall future steam-generator degradation

(2) plant changes to prepare for effective management of outages of major repairs

(3) improved maintenance and surveillance of critical plant components, particularly the pressure boundary, and

(4) additional instrumentation, such as detectors and sensors, for early identification of system degradation

Top-priority remedies for controlling steam generator corrosion are likely to be condenser retubing, a maintenance program to minimize subsequent leakage there, and feedwater heater retubing with ferrous alloys. One of the key findings of research on steam generator corrosion is that much lower levels of ions and dissolved oxygen in the steam generator water are required to prevent corrosion than was previously thought. The condenser is one of the principal sources of ionic impurities in the secondary water loop when steam is cooled after passing through a turbine. The condenser system, as well as parts of the turbine system and feedwater system develop leaks which draw in oxygen, a corrosive element when combined with other contaminants. By retubing the condenser and prevention of air leaks through proper maintenance, the purity of the water can be improved and corrosion reduced. Also, to further minimize the potential for degradation of steam generator tubes in the future, existing feedwater heaters and moisture separators may be replaced to eliminate sources of copper-bearing materials in heat-exchangers. Copper salts are soluble in water and accelerate corrosion even in low concentrations. (Douglas, 1984)

Plant changes can be made to prepare a utility for effective management of outages for major component replacments and repairs. A maintenance building can be erected to give construction personnel access to the radiation-control area and a clothing-change facility. A new computer system may be installed to improve health-physics control over radiation exposure of all personnel entering and leaving the radiation-control area. To store the large amount of repair materials involved in repairs and for associated plant changes, a large warehouse may be built and a computerized inventory-control system may be installed. (Nutwell, 1983).

As plants age, the use of improved maintenance and surveillance of equipment become more important due to several factors including reduced equipment reliability, parts availability and increased unscheduled outage frequency. Condition monitoring of electrical equipment such as batteries, generators, cables, motors, circuit breakers and transmitters is important in order to maintain the safety of the plant. Heavy rotating equipment should be monitored to detect bearing wear; vibration monitoring could be used for this equipment. More frequent calibration checks should be made on instruments to detect instrument drift. To improve nondestructive examination of steam generator tubes, the use of multifrequency eddy current techniques should be encouraged. This allows assessment of tube integrity and the presence of denting. The thermal sleeves of the pressurizer should be monitored to detect surface cracks before fatigue failure occurs due to theraml cycling.

Finally, additional instrumentation may be installed to detect age-related degradation and for obtaining plant operating data important in defining age-related design limits. Instrumentation will be needed to indicate the stresses imposed on pressure boundary components including mechanical, thermal and radiation stesses. Improved instrumentation may be installed for monitoring water purity and oxygen content in the secondary-system water. Equipment will be needed to detect the effects of flow-induced vibration and neutron irradiation on reactor internals.

CHAPTER 8

INSTITUTIONAL ISSUES IN PLANT LIFE-EXTENSION

8.1 Important Instiutions Affecting Life Extension

Nuclear power stations are regulated by several federal and state agencies. The most important, and their respective spheres of action are the following:

U.S. Nuclear Regulatory Commission (NRC): Public safety and environmental impacts.

State Public Utilities Commission (PUC): Electricity pricing.

State Energy Facilities Siting Council: Land use and environmental effects.

Most of the following discussion is focused upon the role of the NRC as its influence in the various areas of station operation is pervasive. Further, its approval of extended life operation is essential.

No nuclear power station has yet reached the expiration date of its operating license (OL), although some stations have been shut down prior to that point (e.g., Indian Point 1, Humbolt Bay, Dresden 1, Shippingport). All but the most recently built plants have recieved OL's of 40 years duration, beginning from the date of Construction Permit (CP) issuance. Thus, the effective operating life allowed under such licenses has been approximately 30 years, reflecting the fact that approximately ten years has typically been required for plant construction.

The current NRC practice is to issue new OL's for 40 years from the time of commercial operation. This has been done under a re-interpretation of existing regulations, and does not recognize newly information regarding the practical operating life of a power station. For that matter, the 40 year OL duration is not based upon any clearly stated physical plant design limitation.

For plants having OL's with durations which commenced at the date of CP issuance, an application for an extension of the OL duration instead of a date 40 years after fuel loading would be equivalent to a request to be treated on the same basis as the most recently licensed plants. The likelihood that such a request would be treated favorably would be strengthened by the existence of a set of plants already being treated as would be requested. Alternatively, a utility could request extension of the OL for a different duration.

At this point, it is impossible to know how such a request would be treated. This is because no power station license extension has yet been requested from the NRC, and because the NRC has not yet established a policy regarding the decision criteria governing such requests. Such requirements as exist are summarized in Table 8.1. In the work of this project, discussions were held with NRC staff members dealing with either the licensing or research aspects of plant aging. This was done in order to be able to characterize current positions and policy trends of the NRC in this area. Briefly stated, very little has or is about to happen in the definition of an NRC position regarding nuclear power plant longevity extension. The current NRC schedule envisions formulation of a policy on OL extension by about 1990, providing that resources for such a formulation becomes available.

Consequently, in the near term, it will remain necessary to speculate upon how requests for OL extensions would be treated by the NRC.

The focus of relevant NRC activities to-date have been in the areas of plant aging effects, research reactor OL extensions, and special treatment of the oldest power stations. The concern with plant aging has been focused upon anticipation of age related plant safety degradation on a time scale which could be shorter than a plant's OL. Primary concern with safety related organic materials degradation, electrical and electronic system degradation, embrittlement and fatigue. Activity in this area is likely to become stronger and to become a long term program. It will likely be most useful in the context of longevity extension in identifying important age related safety problems and in improving the body of knowledge concerning age related component degradation.

The NRC experience in extending the OL's of research reactors is summarized in Table 8.2. A license extension may be granted upon receipt of a request for extension at least 30 days prior to the OL expiration date. Examination of the technical case for such an extension and holding of public hearings may occur after the OL expiration date, while the reactor continues to operate. Such extensions have routinely been granted with research reactors in the past. In such extensions public hearings have been the exception, and have only been held to deal with actions by public intervenors. Notably, power reactor CP extensions have been granted in a similar fashion.

An important question for power reactors is that of how revised safety requirements would be treated for older reactors. The research reactor precedent is not useful for this question as safety requirements have not changed significantly over the lives of these units. In the areas of quality assurance, record keeping and security, increased requirements have been imposed on all such reactors. It appears that the intensity of re-examination of old safety related questions in research reactor license extensions depend strongly upon the prior operating record of the reactor. Reactors which appear to be well staffed and managed and with few licensee event reports also appear to be granted greater trust for future operation. This trend probably constitutes an important lesson for power reactor operators, in that a history of competent, event-free operation should provide safety regulators with a stronger basis for use of discretion in the judgement of safety requirements than otherwise.

Experience to-date with the NRC's Systematic Evaluation Program may provide some guidance regarding how evolving safety requirements would be applied to older nuclear power stations. That program has focused upon the oldest dozen of the large LWR plants, to determine where equipment modifications should be made in order to maintain safety levels consistent with those of the newer plants. Tools used in performing this assessment have been benefit-cost analysis and probabilistic risk analysis (PRA). The former assessment has involved a comparison of expected safety improvement benefits to the costs of implementation. This is important because of the NRC's recognition of the high costs of implementation of design changes in an existing plant as a factor in the decision of whether such changes should be required. The use of PRA has been important in trying to focus the resources to be used for safety improvements upon the largest contributors to public risk. The same tools are available to utilities in assessing where plant improvements are worthwhile, and for justifying the decisions reached to the NRC.

The most difficult area of safety regulation to be dealt with concerns problems where benefit-cost analysis indicates that a plant modification is not justified, but where PRA indicates that a potentially important, previously unrecognized, contributor to risk exists. Important examples of such problems arise in the various external events which may imitate accidents and/or disable systems important to safety. In the areas of seismic events, floods, tornadoes and explosions, safety standards have become much more stringent over the past 25 years. It may be economically prohibitive for existing plants to meet current criteria, yet public safety protection may require such satisfaction. If the utility suspects the existence of such a situation it may be prudent to undertake early discussions with the NRC in order to obtain an early resolution in order to have a sound basis upon which to plan longevity extension programs.

The implication of this discussion is that if a utility wishes to extend the life of a plant it is possible to enhance the probability of success by early establishment of a program for continual plant improvement. This program should have the goals of reliable operation, improvement of public safety and protection of the owner's investment. These three goals are mutually supportive. Their pursuit requires examination throughout the plant of potentially important systems and components. The important point, however, is the need for starting such a program as soon as possible. Successful life extension is far more likely to be achieved under a program to maximize the plants operational longevity than one which is focused upon getting the plant into a minimal condition sufficient to obtain an extended OL.

It should be expected that preparation of a new Safety Analysis Report (SAR) would be required for an OL extension. The policy is currently undefined, but it is also prudent to prepare a new Environmental Report (ER). Preparation of the former would likely be more difficult than the latter. With the SAR, a focus upon age related safety problems would be expected. Often such problems are badly defined, and the technical basis for their resolution is not always available. In preparation of a new ER the utility would have the benefit of knowledge of environmental effects in the plant neighborhood which would have been observed over the plant's prior operating life. Capturing this benefit requires that adequate records be kept in order to document such environmental effects. However, establishment of the required records should be consistent with the type of environmental monitoring routinely required of an operating nuclear plant.

8.2 The First Decade of Extended Plant Life

For most operating nuclear power stations the operating license has been issued for a duration of 40 years, measured from the date of issuance of the construction period. Because the plant construction duration is typically in the neighborhood of a decade, the practical lifetime of the OL is actually approximately 30 years.

During the past two years, however, the NRC has been issuing 40 year OL's with durations which commence with commercial operation. Effectively the OL duration of these more recently licensed plants is approximately ten years greater than that for the previously licensed units. This recent precedent then raises the likelihood that the plants with the older style OL's will easily be able to have their termination dates extended to a point 40 years beyond the debut of commercial operation. As no plant has yet applied for such an extension it is currently unknown whether this conjecture is correct. However, if it is correct, one of the major uncertainties, that of regulatory instability associated with longevity extension for the current generation of plants will be effectively eliminated. This is because the regulatory action involved for an older plant would be that of re-interpretation of existing regulations rather than that of creation and implementation of a new set of regulations, as would be required for extension of the duration of an expiring OL. The prospects for utility success in requesting the former type of action would be expected to be much greater than with the latter.

If such an action were successful, most of the expected future economic benefits of longevity extension would be within reach. This is because the net present worth of future benefits which cannot be captured until after ten years is likely to be less than that of the benefits available during the first ten years of extended operation.

With continuous compounding at a rate, λ, the net present worth of benefits, b, which cannot be captured until time, t, in the future is equal to $be^{-\lambda t}$. Similarly, the net present worth, $B(t_1,t_2)$ of benefits accrued between future times t_1 and t_2 is given as,

$$B(t_1,t_2) = \int_{t_1}^{t_2} b(t') \, e^{-\lambda t'} dt' \tag{8.1}$$

For $b(t')$ being constant, as would be the case with a base-loaded nuclear power station, the net present worth of accumulated discounted benefits is given as,

$$B(t_1,t_2) = \frac{b}{\lambda} (e^{-\lambda t_1} - e^{-\lambda t_2}) \tag{8.2}$$

A quantity of interest is the ratio of the net present worth of benefits accumulated from the present to time, t, to the worth of benefits accumulated from time, t, until a time of infinity. This ratio is given as,

$$R(t) = e^{\lambda t}-1. \tag{8.3}$$

For $\lambda = 0.069$ this ratio is equal to unity. Stated differently, for a discount rate greater than 7% annually, all net benefits accrued after ten years of extended operating life are smaller than those accrued during the first 10 years of extended life. The current real discount rate is approximately 8% (12% for the opportunity cost of money, less 4% for general inflation). At this rate of discounting, the value of R (10 years) is 1.23 (i.e., 55% of all future benefits would be captured during the first decade of extended life). Consequently, it may be judged that the likelihood is low that safety regulatory impediments would create a significant barrier to economically attractive nuclear power station longevity extension. This is because any justified investment in plant life extension would be able to be recovered in only a few years as long as interest rates typical of recent years continue to obtain.

8.3 Extended Life After the First Decade

The natural limits which would determine the lifetime of a nuclear power plant are not obvious. Conceivably, plant life could be much greater than forty years. Thus, the questions which must be faced by the regulatory authorities in permitting continued operation for an indefinite term are of interest.

Under existing regulations, operation of a nuclear power station for more than 40 years does not require issuance of a new OL upon termination of the initial license. Rather, exercising existing authority, the NRC may extend a current OL indefinitely. It is required that application for such an extension be recieved at least 30 days prior to expiration of the current license. Upon such an application, the NRC is allowed to permit continued operation beyond expiration of an OL, while the examination of whether a license extension should be granted is conducted.

What is currently unknown is what requirements and procedures would govern NRC decision making in granting such an extension. No such OL extension has ever been asked, or granted. No programs exist currently within the NRC to define the detailed requirements for granting of an OL extension. Consequently, the current uncertainty regarding future such NRC requirements can be expected to persist for many years more.

Existing NRC programs relating to plant aging:

The NRC has established a program in the Division of Research focused upon problems of plant aging. This is the activity most relevant to the technical requirements which would govern granting of future OL extensions. This effort has been concerned with age related deterioriation of the plant in ways which could affect safety, with an emphasis upon problems likely to become important before expiration of the initial operating license.

Items recieving most attention are summarized in Table 8.4. It is seen that degradation of systems involving hydrocarbon based materials and of materials exposed to nuclear radiation are of special concern. These problems have been reflected strongly in utility programs on plant aging to-date. This may indicate that such programs may not yet have been formulated systematically in anticipation of future problems, but rather in reaction to previous NRC concerns.

It is likely that the NRC plant aging program will grow, as the current plant population ages. As this occurs, the role of this program in influencing plant aging strategies by utilities is likely to remain large. At the time of this writing, the important directions of future concerns have been identified by the NRC staff as concerning reactor vessel embrittlement, electrical insulation degradation, organic seal deterioriation and electronic instrumentation unreliability.

It is important to recognize that the full range of age related plant problems of potential interest to a utility is greater than that identified by the NRC. However, the ability of the NRC to insist upon high priority attention to its concerns often has the effect of distorting the emphasis placed by an organization upon different issues.

8.4 Uncertainties of License Extension

In requesting a license extension, major areas of uncertainty include the following:

- The degree to which "grandfathering" would be permitted in exempting an old plant from certain current regulations,
- Whether public hearings would be required for extension of a license, and the degree to which the procedures for such an extension would approach those for issuance of a new license,
- Whether preparation of a revised Safety Analysis Report (SAR) and Environmental Statement (ES) would be required.

It is impossible to predict the resolution of any of these questions. Regarding "grandfathering", the NRC has an inconsistent record. However, the arguments for exemption of a plant from a particular requirement become weaker as the future duration during which the plant is expected to operate increases. Consequently, it appears prudent to maintain the plant in a state as closely in compliance with current regulations as is economically feasible if it is desired to obtain indefinite future operation.

Concerning whether public hearings would be required for a license extension, much would depend upon whether such an extension were defined as a license amendment. Under the terms of the "Sholly" amendment, a public hearing may be required upon public intervention in connection with any amendment of a plant's OL. It appears likely that at least the first few future OL extensions would be contested. Consequently, it would probably be prudent to expect a request for an OL extension to be contested and to require public hearings.

A final area of uncertainty concerns the documentation which would be required for an OL extension. The documentation of new safety issues to be resolved would likely be addressed in a revision to the FSAR, much as the FSAR represents an extension of the Preliminary Safety Analysis Report (PSAR). In this mode, it would not be necessary for the Ammended FSAR to address again issues which would have been treated previously in the original FSAR. Concerning the ES, things are less clear. This is because the National Environmental Policy Act (NEPA), which requires that an Environmental Statement be prepared, has never been interpreted with respect to an OL extension. Among the most important questions yet to be answered are whether a new or revised ES would be required in connection with an OL extension, and what the scope of such an ES would be. Such questions are usually answered through formulation of a proposed policy by the NRC and refinement of that policy through judicial review. This process is likely to be contentious and can require several years for completion, during which uncertainty can be expected to reign.

8.5 Possible Actions by the NRC

The greatest contribution which could be made to facilitate the OL extension process would be for the NRC to formulate policy in the following two areas:

- Concerning requirements for conversion of an OL which has commenced from the start of plant construction into an OL commencing from the start of fuel loading, and
- Concerning requirements, including the points addressed previously, for OL extension.

Until this is done, the process of judicial review of these policies cannot be initiated. Such a review could be started after formulation of a policy by an individual utility requesting a license extension, since such a request presumably would trigger any challenges by public intervenors to the extension process. It is important that this process be started early in order that it may become stabilized before it becomes urgently needed.

8.6 The Roles of Agencies Other Than The NRC

As is mentioned previously, many governmental organizations other than the NRC may play important roles in nuclear plant life extension. Any organization which issues a permit needed for operation of a plant may potentially block plant life extension through failure to extend the life of an existing permit. Typically, 50 such organizations might be involved with a single plant. The roles of several potentially important agencies are discussed subsequently.

The Public Utility Commission (PUC) is potentially important because of its role in deciding which investments connected with a plant may be allowed into the rate base. It will be necessary to convince the PUC that any investments for plant life extension are prudent in that they will confer net benefits upon electricity consumers. A major obstacle to such a demonstration is likely to be the uncertainty currently associated with obtaining extension of a plant's OL.

Many states have agencies which oversee siting of energy facilities. Typically, they will issue a limited duration permit for use of a site by a nuclear power station with terms consistent with those of the NRC's OL. The agreement of such an agency to extend the life of operation would usually be necessary. In order to obtain such cooperation it would be necessary to show that such operation would be to the net benefit of the inhabitants of the state.

Table 8.1

Requirements for Extension of Operating License

Requirement:	License amendment for extended operation.
Public Hearings:	Not required.
Public Notice:	Required.
Filing for Extension:	Required > 30 days prior to license expiration.
Safety Review by NRC:	May proceed in parallel with extended operation.
Relevant Experience:	Research reactor OL extensions. Power reactor CP extensions.

Table 8.2

Research Reactor OL Extensions

Public Hearings:

Usually not required (only upon intervention).

Cases with Hearings:

UCLA (safety, sabotage)

GE Test Reactor (seismic)

AFFRE

Safety Review:

De Novo review required.

Revised Safety Requirements:

Imposed during plant life, not at time of license extension.

Detail of Safety Review:

Depends upon prior operational, equipment experience.

Relicensing Ratchets:

Operation and maintenance QA.

Emergency planning.

Power Reactor CP Extensions:

- None have required hearings.
- Most have been routinely granted.
- All have required safety reviews.

TABLE 8.3

Net Present Worth of Future Benefits

Compound Interest Rate, λ (yr^{-1})	Net Discounted Value R(t=10 yrs.) Ratio of Benefits Captured Before t=10 yrs. to Benefits Captured after t=10 yrs.	Time at Which R(t) = 0.5 (yr)	Time at Which R(t) = 1.0 (yr)
.04	0.49	10.13	17.33
.05	0.65	8.10	13.86
.06	0.82	6.75	11.55
.07	1.01	5.79	9.90
.08	1.23	5.06	8.66
.09	1.46	4.50	7.70
.10	1.72	4.05	6.93
.11	2.0	3.68	6.30
.12	2.32	3.38	5.78
.13	2.67	3.12	5.34
.14	3.06	2.89	4.96
.15	3.48	2.70	4.63
.16	3.95	2.53	4.34
.17	4.47	2.38	4.08
.18	5.05	2.25	3.85
.19	5.69	2.13	3.65
.20	6.39	2.03	3.47

Table 8.4

Age Related Technical Issues of Interest in Current NRC Program

- Reactor pressure vessel embrittlement
- Intergranular stress corrosion in primary system piping
- Degradation of electrical insulation
- Degradation of electronic systems
- Degradation of organic seals
- Steam generator tube wear and fatigue
- Thermal fatigue within primary system

CHAPTER 9

COSTS AND BENEFITS OF PLANT LIFE EXTENSION

In deciding whether to pursue plant life extension, it is necessary to perform a cost-benefit analysis. This must be done in order to determine the point at which marginal investments in plant improvements would become unjustified.

Such an analysis is needed for each of the following intervals of life extension:

- Until expiration of the original plant OL.
- Until expiration of a revised OL at 40 years after issuance of the initial plant OL.
- After extension of the OL duration beyond 40 years.

9.1 Time Horizon Effects

As the time horizon for analysis is extended outward, the level of detail possible and necessary in the analysis decreases. The objective of each analysis is to identify the priority of actions which should be undertaken in the near future in order to avoid a loss of capacity at a date further into the future. As the analytical time horizon increases the magnitude of a future capacity loss necessary to justify a given level of current expenditure grows monotonically. Thus, the number of potential causes of lost future capacity which are important enough to be of concern will decrease as the time increases into the future at which the capacity would be lost.

Consequently, the inteval of greatest interest for life extension planning is that from the present until expiration of the plants initial OL.

9.2 Scope of Planning

To this point, the major focus of nuclear industry efforts for plant life extension has been on complying with NRC requirements which anticipate age-related degradation of safety during the current OL of a plant, and with repairing unanticipated age-related component failures (e.g., removal of the thermal sleeve, which failed from fatigue, within the reactor vessel of the Milestone 2 power station). Future efforts will have to anticipate the full range of possible age-related failures, and work to prevent them. The vast majority of such failures would lead to impairment of the economic performance of a plant, but would be unimportant with respect to public safety. Consequently, the criteria for allocation of resources for achieving longevity increases must be reexamined. To-date, such critera have been primarily those of public safety protection, and have been prescribed by the NRC. In the future , the set of important criteria must be much larger, should encompass those of the NRC; but must be oriented toward maximizing economic performance. For an existing plant such maximization corresponds to maximizing reliability. Consequently, the task of longevity extension becomes that of compiling a list of components and systems in the plant which are important from the perspective both of reliability and safety, the performance of which would be expected to become impaired or interrupted over time. Such a list is likely to encompass most of the systems of the plant, and the most important entries on it are discussed previously. Then, for each such component a strategy which mixes means of preventing such degradation and of monitoring for incipient component or system impairment must be devised and implemented. Doing this is laborious, but straightforward.

Inevitably, because of resource limitations it will be necessary to rank in priority the alternative problems to be pursued. The proper tool for such a ranking is a probabalistic reliability assessment. In such an assessment, the event paths leading to altered reliability must be identified, including paths where incremental component performance degradation, rather than complete failure occurs. Then, the probabilities, the different paths, and their age-dependencies, must be quantified. From this process, it should be possible to identify the leading contributors to unavailability, and those which would be expected to become important over time. From such an identification, the high-priority components and systems which deserve special emphasis in a longevity increase program will become apparent.

This analytical process is conceptually straightforward, and much of the foundation for it has been created in the form of probabilistic risk assessment. The major future development efforts which are needed are the following:

- Definition of the methodology to be employed to the point that implementation is justified (this task consists of an extension of current probabilistic risk analysis methods), and
- Formulation of a database useful in probabalistic reliability assessment (this task is large and more difficult than has been the case with probabilistic risk assessment).

With such a tool it should be possible to estimate the economic benefit of investment in plant improvement. Such an investment would appear as the equivalent capital value of plant capacity, which would be increased through increased availability. From knowledge of such benefits, the breakeven level of present investment can be estimated, and the priority ranking of alternative investments can be achieved. It would be valuable to have such estimates available today, since it appears to be indicated strongly that current levels of investment in plant longevity extension are substantially suboptimal. From this discussion, it is apparent that maximization of plant life extension is equivalent to maximization of temporally-averaged plant availability into the indefinite future.

A secondary benefit of plant life extension, in addition to those of continued electricity production, is avoidance of the need to decommission the plant. The associated costs of decommissioning can be substantial, having been estimated previously to be in the range of \$200 to \$700 per MWe (stated in 1985 dollars). In addition to deferring such economic costs, plant longevity extension also permits deferral of the tasks of decommissioning, such as physical demolation, decontamination and of the associated permitting processes.

Further, just as extending the lives of a given set of plants obviates the need to build new plants, such life extension ultimately reduces the number of old plants which must be decommissioned.

9.3 Costs of Life Extension

In addition to the direct costs of hardware investments for life extension it is necessary to invest in development of analyses of life extension strategies and in development of tools for performance of such analyses. These investments are in the class of research investments, where their benefits are potentially available to many other parties without regard to whether they might have participated in the costs of development. The development of the needed analytical tools may be aided by arrangements either to spread their costs over many potential users of the tools or to restrict the use of the tools to those who would have funded the development. These considerations are important as it appears that the costs of development of the needed database may exceed several tens of millions of dollars.

In addition to the costs of analyses upon which life extension decisions would be based, another major element of life extension cost is that of obtaining an OL extension. As is discussed previously, such extensions may be obtained initially to a new expiration date which is 40 years after the start of operation, and later for an indefinite duration. Especially for the first few plants to seek an OL extension the costs of preparing the required documentation and of the public hearings, which are likely to be part of any OL extension approval process, are also likely to be large.

9.4 Benefits of Plant Longevity Extension

The ultimate question in plant life extension is that of whether the most economical way of providing electricity during a future interval is by means of the plant in question. The major alternatives for such a generation include use of a different plant, building a new plant, and conservation. The value of life extension and the factor which motivates its use is not that of the electricity generated during extended life. Rather, it is the difference in cost of generating such energy between use of the extended life plant and the next most attractive alternative for such generation.

Consequently, evaluation of the attractiveness of plant life extension requires knowledge of the economics of generation of the most attractive alternative technologies.

As an example, if the net cost of electricity derived from plant life extension were equal to that of building a new plant, then, there would exist no explicit economic incentive to provide such generation through life extension. Rather, the decision regarding which route to follow would depend upon such subjective factors as the expected ease of licensing, the local political climate, attitudes among members of the State Public Utilities Commission and expectations regarding the future behavior of plant cost variables.

The major cost factors favoring plant life extension are that the plant in question would already be in operation, with all of the prior problems of siting, licensing, and construction having been resolved, and the costs of construction having been incurred. Thus, the principal attraction of plant life extension is the ability to avoid such costs and their associated uncertainties.

A secondary benefit of plant life extension is the ability to avoid decommissioning of the plant. The direct economic costs of decommissioning can be large and highly uncertain. Decommissioning can also involve significant occupational radiological exposures. Currently the regulatory policies regarding the schedule and constraints of decommissioning and regarding how decommissioning shall be financed, are undetermined. They are also, likely to remain undetermined into the forseeable future. Consequently, the incentives are strong to avoid undertaking such a decommissioning until the relevant policies have been established by the precedent of prior decommissioning of at least a single plant. Even after the relevant policy has been established, the incentives will remain strong to defer the expenses of decommissioning as long as possible.

CHAPTER 10

SUMMARY: STRATEGY FOR NUCLEAR POWER PLANT LIFE EXTENSION

10.1 Overview

From the preceeding discussion it is apparent that nuclear power station life extension encompasses the entire plant and that it has no clearly visible termination date. For the typical plant much less investment plant monitoring and planning for life extension is being done than appears to be optimal. The strategy for life extension which emerges from the preceeding discussion would emphasize the following elements:

- Planning as if the plant would operate into the indefinite future
- Formulating a full plant program of system upgrading, monitoring, maintenance, and performance forecasting
- Development of a plant specific probabilistic reliability analysis, and use of this analysis as the basis of management planning for longevity increases
- Bringing the plant into compliance, to the degree feasible, with current NRC safety requirements
- Building a record of reliable trouble free plant performance as a basis for justifying permission from the NRC and from society for continued operation.

A plant life extension plan embodying these elements would be far more comprehensive and far looking than any in existence currently. It would also be more costly initially, but ultimately more rewarding.

It is expected that the life extension program would focus initially upon the most vulnerable parts of the plant such as organic components and the reactor pressure vessel. Later, as resources would permit, the scope of interest would become broadened until the entire plant would be included.

10.2 Major Conclusions Regarding Age-Related Plant Degradation

Concerning the age-related degradation of a plant the major conclusions of this study are the following:

- Age-related design limits for various components are not indicated in the literature received from the utility and do not appear to be easily available from the equipment vendor.
- Organic materials such as those in electrical insulation, cables and instrumentation are most susceptible to aging effects.
- Material degradation due to corrosion is the main costly age-related problem affecting a small but important portion of mechanical equipment (eg. steam generators, piping).
- Changing fuel loading designs can mitigate the age-related degradation of the reactor pressure vessel due to neutron irradiation.
- Practices which have lead to successful operation of fossil plants for an extended lifetime may be used to establish a basis for extending the operating life of nuclear plants.
- The effects of neutron irradiation and flow-induced vibration on reactor core structure and internals is not accurately known and should be investigated in more depth.

- Age-related design limits can be given in terms of the following stress level mechanisms:
  - fatigue - due to cycling
  - wear -erosion of material
  - radiation - deterioration of molecular structures
  - temperature - threshold limits create material deterioration
- Trending of equipment failures and individual part degradation assists the maintenance control activity in performing both failure and extended-life analyses.
- Effective spare parts management is essential for plant life extension as it assures the availability of spare parts when needed.
- Condition monitoring is an effective way of meeting regulatory requirements, maintaining qualification status, and improving the reliability of equipment.
- In most electrical equipment, the limiting components are made of plymeric materials and they age because of thermal degradation.
- The transient logging program allows important trends in plant operating history to be observed and corrective action taken before key components are significantly degraded.
- A comprehensive assessment of nuclear power plant component operating histories, maintenance histories, and design and fabrication details is essential to understanding aging phenomena.
- To assure high plant availability during extended life

operation, the following steps may be taken:

  - Introducing redundant back-up systems to chronic-problem systems in order to avoid outage time.
  - Modification of plant arrangements to allow a system to be maintained with a plant at power.
  - Optimizing space allowances for maintenance efforts.
  - Upgrading equipment which has shown chronic patterns of failure in the past.

- The following plant modifications may be made to minimize the potential for tube degradation in steam generators due to corrosion in the future (Nutwell, 1983):
  - Retubing and replacement of existing feedwater heaters and moisture-separator/reheaters to eliminate sources of copper-bearing materials in heat exchangers, which have contributed to tube denting.
  - Replacement of copper/nickel and aluminum alloy tubes in the existing condensers with titanium tubes.
  - Installation of wet-layup systems to provide mixing and to maintain water quality in steam generators and in the condensate and feedwater systems during extended plant shutdowns.
  - Addition of a full-flow condensate polisher to ensure supply of high-purity water to steam generators.
  - Installation of a recirculation system to provide a closed loop between the feedwater system and the condenser for wet layup and flushing of the secondary system.

  - Installation of a demineralized water storage system to provide high quality water to the steam generators for use during scheduled shutdown, startup, and hot-stand by operations.

- The performance of the majority of safety-related equipment is not significantly degraded by aging. There are some materials utilized in safety-related equipment that deteriorate over time, whichcauses performance changes (Bader, 1982).
- Only organic materials in instrumentation and control equipment are analyzed individually for aging effects.
- Aging encompasses chemical and physical changes that are influenced by:
  - temperature
  - electrical stresses
  - mechanical stresses
  - composition of environment (including oxygen, moisture, and corrosion components)
  - nuclear radiation
- To manage nuclear power plant aging a systems approach is suggested that looks at the problem by addressing the following topics (Bader, 1982):
  - process control
  - reliability analysis
  - acceptance tests and control of spares
  - in-service inspection and maintenance
  - failed equipment
  - data collection
  - material behavior
- During qualification testing limitations of materials due to aging are commonly noted. These limitations necessitate maintainence and surveillance activities in the plant to

provide assurance that aging effects do not become significant. Additional important conclusions are the following:

- All structural components have been designed conservatively and are least susceptible to age-related degradation.
- Operating mechanical and thermal stress levels for mechanical equipment are lower than those used as a design basis.
- It must be determined if there is a need for documentation of actual mechanical and thermal cycles at nuclear power plants to compare with original desing in order to assure extended life feasibility.
- The qualified life of an equipment may be extended if it can be shown that the service or environmental conditions originally assumed were overly conservative with respect to those that apply at the equipment's location in its installed configuration.
- Of the abnormal operating events reported in 1969 through 1982 that had age-related causes, almost half of the events resulted from instrument drift. The remaining events were attributed to other age-related causes such as wear, corrosion, crud deposition and fatigue.

10.3 Unanswered Questions

The development of a methodology for planning for plant aging and life extensions requires identification of the answers to the following important unanswered questions.

- What are the basic mechanisms of material degradation due to aging? What factors influence the aging process?
- How can the actual aging phenomena be simulated in a

qualification program to produce the same amount of degradation in the equipment as it would actually experience?

- Which safety-related equipment should be monitored for degradation? Can existing surveillance procedures for degradation monitoring be used? What monitoring procedures require further development?
- What must be done to establish qualified life when no practical acceleration model exists for aging stresses other than thermal stresses?
- Which areas in the plant cannot be tested by non-destructive evaluation techniques?
- What modifications in operating practices are required for life extension?
- What design modifications can be made to extend plant life?
- What components and structures would require repair or replacement for plant life extension?
- Are all components and structures that are subject to age-related degradation capable of being repaired or replaced?
- In the absence of explicit age-related design limits, what can the utility do to respect such limits? What tests should be conducted and what data should be gathered? How can the utility estimate the status of the plant relative to its design limits?
- What are the information requirements for a systematic approach to identify age-related problem areas in the plant?
- What additional technical requirements would be necessary to assure the capability of safety-related systems/components to perform their intended safety functions?

- What are the fatigue limits of control rod drives, thermal sleeves, turbo-generator shafts and rotors, and reactor coolant pump shafts?
- What is the source of the component cycle and transient limits in the Westinghouse Standard Technical Specifications (Table 5.1)?
- Are there any areas in the plant where corrosion has not occurred yet, but is anticipated?
- Is it possible to correlate corrosion rates with water chemistry or operating history for the plant?
- How quickly is the life of a component being used up? What techniques and tools are needed for determining the remaining life of plant components?
- What improved analysis and evaluation techniques are needed to diagnose and correct problems in critical plant components?

10.4 Recommendations

A utility interested in nuclear plant life-extension should consider taking the actions listed in Table 10.1.

Discussion

Some items requiring further discussion are listed below:

Item 1. Design information, especially design limits and basis, from equipment vendors would help utilities understand how age was considered in the design of equipment. This information is important for assessing the status of the plant. Even though in most cases this information appears not to be readily available, utilities would benefit from obtaining all the information that they can get from the vendors of equipment.

Item 2. Reactor vessel damage, from the effects of neutron irradiation, may be reduced by changing fuel loading designs. This is very important in view of the doubts regarding the effectiveness of in-place annealing of the vessel to restore the ductility of the vessel material.

Item 4. To detect age-related degradation, condition monitoring techniques may be used along with existing maintenance and surveillance practices. These techniques may be applied to heavy rotating equipment such as turbine generators to detect bearing wear. Condition monitoring relies on measuring a number of relevant parameters and plotting the results in order to observe a trend in the degradation of critical components in the equipment.

Item 5. Often, the operating history of equipment can be useful in identifying age-related degradation and when a component must be replaced. The utility can establish programs to review surveillance and maintenance records to critical plant equipment, including those of pressure boundary components and safety-related equipment. The aim is to discover when critical equipment will pose a problem for the continued safe and efficient operation of the plant.

Item 8. A review of the description of components, such as piping and instrumentation, may indicate outdated parts and materials of composition which are susceptible to age-related degradation. New and improved equipment may be installed to replace these aged equipment.

Item 12. Additional instrumentation may be installed near critical plant components such as the steam generators, pressurizer, turbines, pumps and valves to give information about the operating conditions and the environmental stresses afecting these equipment. This information is important for the utility in order to determine age-related design limits, as well as for early identification of system degradation.

The remaining items in the Table indicate the importance of monitoring critical equipment in the plant in order to prevent early failures, of early planning of plant changes to prepare for major component replacements and repairs and of steps to minimize steam generator corrosion and to restore the ductility of the pressure vessel. These action items are essential for extending the longevity of the plant.

Finally, it is important to note that these steps might not be enough to assure successful life-extension. With the uncertainties involved in predicting and preventing component failures due to the aging of the plant, utilities will have to do more than they have done in the past to maintain operability of all equipment. In particular, safety-related equipment must be subject to closer scrutiny because of the likely concern of regulatory agencies with the safety of the plant. But, with concentrated efforts to determine the effects of aging on the functional capability of all systems and to identify means to mitigate the aging process, utilities can eventually commit themselves to the life extension of their nuclear plants.

TABLE 10.1

Utility Actions to Extend Plant Life

Utility Action	Objective
Obtain all available design information from equipment vendors, especially design limits and basis.	To determine how age was a consideration in the design of equipment.
Change fuel loading designs for the reactor vessel.	To minimize reactor vessel damage from neutron irradiation.
Reduce the number of thermal and mechanical cycles at the plant.	To prevent thermal and mechanical fatigue of the pressure boundary.
Improve maintenance and surveillance practices for all equipment, particularly for cables, insulation, instrumentation and pressure boundary components.	To help detect and mitigate age-related degradation.
Establish continual programs to review surveillance and maintenance records of pressure boundary components and safety-related equipment.	To assure that critical equipment exhibiting age-related degradation will be identified and replace as necessary.
Require considerations of specific aging characteristics of component material in component maintenance and replacement schedules.	To use components with materials that have long-life characteristics.
Evaluate the effects of flow-induced vibration on reactor internals.	For early detection of damage to reactor internals.
Review the description and drawings of plant control wiring, piping, and instrumentation.	To identify aging or out-dated parts for possible charge or replacement.

Utility Action	**Objective**
Monitor the effects of vibration on heavy rotating equipment such as turbine generators.	To detect bearing wear.
Review the operator's log, surveillance procedures, testing procedures and preventive maintenance practices.	To collect aging effects data from the plant.
Identify alternative suppliers for spare parts for equipment which might not be available from the vendor when the equipment must be replaced.	To assure availability of spare parts when needed.
Install additional instrumentation near pressure boundary components (i.e., instruments to measure stresses on these components).	To provide early identification of system degradation.
Collect focused plant operational data, such as number of thermal and mechanical cycles, from existing instrumentation.	To help identify age-related design limits of critical equipment.
Replace copper/nickel and aluminum alloy tubes in existing condensers with titanium tubes.	To minimize the potential for PWR steam-generator tube degradation in the future.
Analyze the load-carrying capabilities of the equipment-hatch barrel, identify equipment to be removed and evaluate the existing structural steel for new loads imposed by temporary equipment.	To prepare the plant for major component replacements and repairs.
Carefully plan construction activities for repairs or replacements in high radiation fields.	To ensure that radiation exposures to personnel would be kept low.

Utility Action	**Objective**
Inspect the thermal sleeves of the pressurizer regularly by nondestructive evaluation techniques (e.g., using x-radiation to detect surface cracks).	To prevent fatigue failure due to thermal cycling.
Monitor for flange cracking and vibration effects at support points of turbine upper and lower casings.	To prevent turbine failure.
Monitor nuclear safety class main steam piping and valve bodies for erosion.	To maintain pressure boundary integrity.
Investigate the feasibility of in-place annealing of the reactor pressure vessel.	To ensure the success of repairing the damage caused by neutron irradiation on pressure vessel steels.
Monitor the generator rotor shaft for the effects of load cycles and vibrations.	To prevent generator failure.
Inspect cables and insulations made of polymeric materials.	To detect thermal degradation.
Monitor the foundations of heavy equipment connected to hot piping systems (e.g., heaters, heat exchangers, and condensers).	To detect the effects of fluctuating thermal loads.

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