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Technical Evaluation Report

Maintenance Practices to Manage Aging: A Review of Several Technologies

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MAINTENANCE PRACTICES TO MANAGE AGING: A REVIEW OF SEVERAL TECHNOLOGIES

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EXECUTIVE SUMMARY

The quality of a maintenance program directly affects the ability of a nuclear power plant to detect and mitigate the effects of age-related degradation. The Nuclear Plant Aging Research (NPAR) Program, which is sponsored by the NRC Office of Nuclear Regulatory Research, has contracted with Pacific Northwest Laboratory and its subcontractor, Battelle Human Affairs Research Center, to analyze effective maintenance activities used to manage the aging of systems and components.

The maintenance programs used by two commercial industries and two military organizations were selected for this study. The four programs are as follows:

- the United States commercial airline industry
- the United States Air Force B-52 bomber
- the United States Navy Ballistic submarine
- the Japanese nuclear power industry.

The maintenance programs of these four organizations offer valuable lessons for managing aging in the U.S. nuclear power industry. Specifically, they indicate the need for an effective maintenance program to manage the degradation of critical systems and components due to aging. An effective maintenance program includes three basic elements:

- a systematic approach to the conduct of maintenance tasks
- methods for monitoring and assessing maintenance activities
- mechanisms for feedback and corrective actions to improve maintenance effectiveness.

A systematic approach to maintenance includes a comprehensive maintenance policy, clear maintenance program objectives and goals, and the physical conduct of maintenance based on the overall policy, objectives, and goals.

The structure of the maintenance program is important to ensure that aging issues are addressed. This analysis identified four elements inherent in an effective maintenance program that are also important to an aging management program. The elements are as follows:

- the prioritized selection of critical systems and components
- understanding aging through the collection and analysis of equipment performance information
- mitigating aging with maintenance
- the use of feedback to improve the aging management program.

The first element is the prioritized selection of critical systems and selected components. Critical systems and components can be selected by several methods. For example, the aviation industry's reliability centered maintenance program uses a risk-based approach to identify safety-significant equipment.

The second element is an understanding of aging processes that affect critical plant systems and components. This is accomplished by collecting and analyzing equipment operating characteristics and performance data. The maintenance program should be designed to detect, identify, and correct problems caused by aging mechanisms, such as corrosion, wear, and fatigue, before the safety or reliability of the plant is impaired.

The third element involves the actual conduct of maintenance to mitigate aging degradation. Once the aging process of critical equipment is understood, maintenance tasks designed to detect and correct equipment degradation can be selected and scheduled. Activities to mitigate aging include inspection, surveillance, equipment monitoring, replacement, and overhaul.

The fourth element is the need for feedback mechanisms to allow for continual maintenance program refinement and improvement. These mechanisms may consist of specific maintenance activities that serve as a basis for establishing and scheduling future inspection and maintenance tasks. They may also consist of groups of personnel who evaluate and improve the maintenance programs. The feedback mechanisms are vital if the maintenance program is to address changing needs such as the degradation of plant equipment due to aging.

This report examines the approach taken by each of the four organizations to address these four elements. A summary of the maintenance-related activities to address system and component aging is presented in Table 1.

TABLE 1. MAINTENANCE ACTIVITIES THAT ADDRESS AGING

AGING ISSUES FOR COMPLEX EQUIPMENT	ORGANIZATION			
	Air Force B-52 Program	Commercial Aviation Industry	Japanese Nuclear Industry	Navy Ballistic Submarines
Initial Design Philosophy	• Initially designed for 5,000 flight hours - Air Force has repeatedly extended B-52 operating life	• Designed for indefinite operation over economic life of aircraft • Design criteria to ensure aircraft safety includes: - fail-safe - safe-life - damage tolerance	• Designed for indefinite operation based on successful completion of periodic inspections	• Designed for 30 year life - no life extension issues
Prioritized Selection of Critical Systems and Components	• RCM approach - B-52 systems and components receive either critical or non-critical classification	• RCM approach - maintenance steering group (MSG) process identifies critical equipment based on risk of potential failure	• Comprehensive industry-wide inspection requirements determined and specified by MITI • Phase I of PLEX Program identified critical plant equipment for life extension	• Navy PMS deterministic approach - continual monitoring of operating equipment combined with specific preventive maintenance tasks
Understanding Aging Through Collection and Analysis of Equipment Information	• Performance data includes: - usage rates of spare parts - changes in levels of corrective maintenance - equipment failure rates - operational readiness rating • Information analyzed by Senior Officer Steering Group	• Performance data includes: - failure rates - age-reliability characteristics - simple ranking process • FAA, airlines, manufacturers share data and information on an industry-wide scale	• Technical information exchange between MITI, utilities, etc. • Phase II of PLEX Program tests equipment to determine and provide understanding of the extent of aging degradation	• Performance data includes: - rate in change of material condition - results in useful life prediction • Information analyzed by the System Maintenance and Monitoring Support Operation (SMMSO)
Mitigating Aging with Maintenance	• Maintenance activities based on: - flight hours scheduled in: - phase checks every 200, 400, 600 fh's • Program depot maintenance - extensive maintenance every 4 years	• Maintenance activities based on: - flight hours, cycles and age scheduled in: - "alphabet" checks-a,b,c,d	• Periodic/voluntary inspections to detect and mitigate aging degradation • Phases III and IV of PLEX Program develops and implements maintenance activities for life extension	• Crew performs preventive maintenance during operation • 30-day refit follows 3-month deployments • 18-24 month refueling overhaul every 12 years • Trident - hard-time limits in some equipment
Feedback to Improve Effectiveness of Aging Management Program	• Aircraft Condition Inspection - every 4 years - basis for establishing inspection tasks and future schedules • Product Improvement Working Group convenes to: - review performance - determine needed improvements and design modifications	• Air Worthiness Assurance Task Force to: - evaluate condition of aging fleet - recommend corrective actions to maintenance programs • Supplemental Structural Inspection Program specifically addresses aging aircraft	• Working to reduce duration of periodic inspection through improved technology in maintenance and inspection techniques	• Daily communication between SMMSO and local repair group • Technical feedback reports are submitted by operating crew • High level system review meetings to evaluate maintenance effectiveness

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1.0 INTRODUCTION

The nuclear industry and the United States Nuclear Regulatory Commission (NRC) realize that as nuclear power plants age, maintenance program effectiveness plays an increasingly important role in safe and economic plant operation. Recent events at nuclear power plants have shown that improper or nonexistent maintenance can significantly contribute to plant incidents.

The Nuclear Plant Aging Research (NPAR) Program, which is sponsored by the NRC, is conducting a study to assess maintenance practices to manage nuclear power plant aging. The NRC Office of Nuclear Regulatory Research has contracted with the Pacific Northwest Laboratory,[a] operated by Battelle Memorial Institute for the Department of Energy, and its subcontractor, Battelle Human Affairs Research Center, to analyze maintenance activities in government and industrial organizations. Specifically examined were maintenance practices to manage system and component aging.

1.1 OBJECTIVE

The objective of this study is to identify effective maintenance practices that could be adapted by the U.S. nuclear power industry to manage nuclear power plant aging. This study will help the NRC to understand the role of maintenance practices in developing and implementing effective aging management programs.

To address this objective, two commercial industries and two major Department of Defense programs were analyzed. These organizations were selected because they possessed effective maintenance programs, and because they placed a high priority on properly addressing system and component aging issues. The four programs are:

- the United States commercial aviation industry
- the United States Air Force B-52 bomber program
- the United States Navy ballistic submarine program
- the Japanese nuclear power industry.

This study examined the current and planned maintenance programs and related the aging mitigation activities of these four organizations. Interviews were conducted with the Air Force Logistics Command personnel at the Tinker Air Force Base and with the Naval Sea Systems Command personnel responsible for submarine maintenance programs. Also examined were the constraints and policies under which the organizations have developed and implemented their maintenance programs. This was particularly important when assessing the applicability of the programs of the military organizations since they are not

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necessarily constrained by the same economic and policy considerations that affect the commercial industries.

1.2 ORGANIZATION OF THIS REPORT

For a maintenance program to effectively address the aging of systems and components, it must be developed and implemented in a manner that allows the plant to identify and respond to changing maintenance requirements (e.g., as plant age increases). Section 2.0 of this report focuses on characteristics that have been identified as important elements of effective maintenance programs.

The subsequent sections are devoted to reviewing the maintenance programs of the selected organizations. Section 3.0 describes the organizations' design philosophies and approaches to selecting systems and components critical to safe equipment operation.

Section 4.0 discusses the types of operating performance data that the organizations collect and analyze to understand aging and to assess maintenance program effectiveness. Section 5.0 describes the actual maintenance activities used by the organizations to mitigate aging, and Section 6.0 discusses feedback and corrective actions to improve maintenance practices.

Section 7.0 describes research and action areas from the selected organizations that are particularly applicable to the U.S. nuclear industry.

Section 8.0 presents key findings of the review to identify aging issues that are central to a safe and effective maintenance program.

2.0 ELEMENTS OF AN EFFECTIVE MAINTENANCE PROGRAM

For any maintenance program to be effective, it must be designed to detect and correct the effects of equipment aging before they impair plant safety or operation. Thus, the impacts of aging equipment and the maintenance tasks needed to mitigate them should be inherent to the design of an effective maintenance program. A systematic maintenance program is needed to identify and manage the effects of aging equipment in nuclear power plants.

This section describes the program elements that have been identified as necessary for an effective maintenance program. This is intended to build a foundation that can be used to discuss specific aspects of maintenance programs designed to address issues associated with aging equipment. The process elements needed for an effective maintenance program are shown in Figure 2.1. The rest of this section is devoted to a brief discussion of each these elements.

2.1 SYSTEMATIC APPROACH TO MAINTENANCE

The first important element of an effective maintenance program is that it be established and implemented in a systematic manner. A systematic maintenance program consists of three components. The first is the development of an overall maintenance policy defining the scope of the maintenance program. Next, the objectives and goals are defined within the context provided by the maintenance policy. Only when these policy objectives and goals have been established can the methods and procedures for the conduct of maintenance be logically developed. The three components of a systematic program are shown in the first pyramid of Figure 2.1.

2.1.1 Maintenance Policy

Sound maintenance policy is the starting point for the development of a coherent maintenance program. From this policy stems the objectives and goals, the strategies for the conduct of maintenance, the philosophy for monitoring and assessment of effectiveness, and the strategies for corrective action and feedback. Thus, the purpose of the maintenance policy is to define the scope, objectives, activities and general responsibilities for all plant maintenance operations.

A formal maintenance policy represents a statement by top management of the importance of the maintenance function in achieving safety and other plant goals. It emphasizes that maintenance activities be conducted systematically and in accordance with objectives and rules. Without such a policy, the maintenance program is at risk of having insufficient vision and resources to be successful. In such situations, the maintenance program is prone to becoming primarily reactive, and the program will not be structured to most efficiently respond to changing plant maintenance requirements, such as those presented by the degradation of plant equipment due to aging. Once the formal maintenance policy is established, the maintenance management must establish a set of performance goals and objectives by which the effectiveness of the maintenance program can be measured.

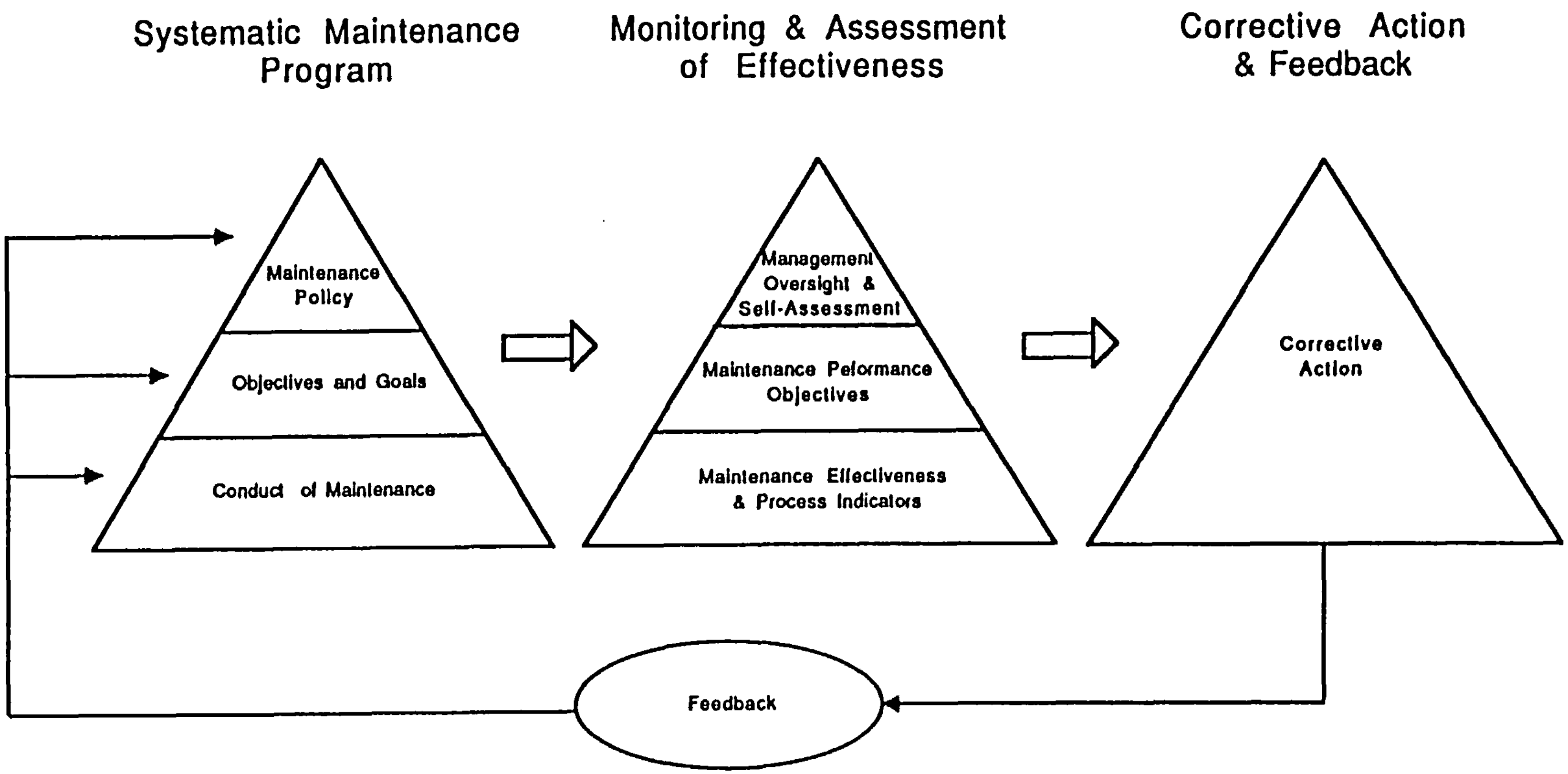

FIGURE 2.1. Elements of an Effective Maintenance Program

2.1.2 Maintenance Goals and Objectives

The maintenance department management is responsible for translating the conditions and requirements set down in the maintenance policy into effective maintenance actions. This is accomplished through the development of clear program goals and objectives. The program objectives provide a means to focus the maintenance activities on the relevant policy requirements. Quantified performance goals assist in determining the degree to which these objectives are being achieved.

The primary objective of the maintenance department is to ensure that all plant systems and components are available to perform their intended functions throughout their service lives. This is accomplished by developing effective maintenance practices according to the established goals and objectives of the program. The maintenance activities should be commensurate with the safety and reliability significance of the plant systems and components. By developing performance goals and monitoring the effectiveness of the maintenance program with respect to these goals, the maintenance management can assess how well the objectives are being met. The development of maintenance goals and objectives provides the link between the overall maintenance policy and the actual conduct of maintenance.

2.1.3 Conduct of Maintenance

The detailed design and physical conduct of maintenance activities is the third major component of a systematic maintenance program. The conduct of maintenance consists of activities that prevent, predict, and restore failures or performance degradation of systems and components. These activities include:

- analysis of performance data
- analysis of operational data
- predictive maintenance based on operational data
- preventive maintenance based on manufacturer's recommendations, operating experience, good engineering practice (including aging concerns), and preventive maintenance feedback
- corrective maintenance as necessary.

The balance and nature of these types of maintenance should be consistent with meeting the established maintenance program goals and objectives. For example, corrective maintenance may be appropriate for equipment for which degradation failure will have no impact on plant safety or operation. On the other hand, a predictive maintenance task may be desirable for safety significant components with fast-acting failure mechanisms, while surveillance or in-service testing may be best suited for equipment demonstrating slow-acting failure mechanisms.

2.2 MONITORING AND ASSESSMENT OF EFFECTIVENESS

Monitoring and assessment are essential activities in implementing and sustaining an effective maintenance program. Monitoring and assessment involve collecting and evaluating the performance data from all levels of a maintenance organization. This information provides the basis for management to identify maintenance problems, analyze possible causes, and implement effective corrective actions.

The specific monitoring points of a maintenance program are determined by the requirements of both the regulatory agencies and by the policies, objectives, and goals of the organization's maintenance program. The monitoring and assessment efforts should provide plant management with the information needed to identify, diagnose, and correct maintenance problems. This is particularly important when considering the special problems that apply to aging equipment.

2.3 FEEDBACK AND CORRECTIVE ACTIONS

The third major element of an effective maintenance program is the feedback and corrective actions needed to continually improve the maintenance program. This includes the analysis of equipment performance data and the development of organizational mechanisms for taking corrective actions in response to maintenance-related problems. With effective feedback, the maintenance program learns from its own experience and lowers the incidence of repeated mistakes or errors. Corrective actions may originate in any part of the maintenance process and may be fed back to which ever portion of the program will eliminate the cause of the maintenance program's ineffectiveness. Appropriate corrective actions can be identified by comparing actual maintenance performance to the plant and maintenance goals and objectives.

Corrective actions result from monitoring and assessing the effectiveness of the maintenance program, and the feedback process provides information to all levels of the systematic maintenance program. The corrective actions resulting from the monitoring and assessment of maintenance performance can affect the overall maintenance policy, the goals and objectives of a maintenance program, and the physical conduct of maintenance.

Information from the monitoring and assessment process should be gathered in a structured and systematic manner. A careful analysis of this information is necessary to determine the root cause of a problem and to be able to formulate appropriate corrective actions to feed back into the maintenance program.

The development of a systematic maintenance program ensures that sufficient attention is directed toward all plant systems and components to ensure safe operation throughout the life of the plant. The collection and use of equipment performance data ensures that the maintenance program focuses attention and resources as necessary to detect and correct equipment aging problems.

The following sections describe the manner in which various organizations have incorporated these three principal requirements into their maintenance programs to assist them in addressing the aging degradation of their systems and components. In general, the findings from this review are that the programs successfully incorporate these elements into their programs. Also discussed are the opportunities for the U.S. nuclear power industry to adopt various aspects of these programs to assist them in managing the aging of nuclear power plant systems and equipment.

3.0 DESIGN PHILOSOPHIES AND THE SELECTION OF CRITICAL EQUIPMENT

The philosophies that govern the operation and maintenance of a system significantly influence the approach an organization takes to managing the aging of the components and systems. Policies, goals, and objectives for the maintenance program are all developed based on the underlying design and operating philosophy. Identifying those components and systems critical for continued and safe operation is also a related factor that influences the maintenance approaches to address equipment aging.

This section reviews the design and operating philosophies of the four organizations. Also examined in this section are the methods that the four organizations use to identify and prioritize those components and systems that are critical for continued safe operation.

3.1 DESIGN AND OPERATING PHILOSOPHIES

When comparing the different maintenance programs, one must understand the differences in context and driving forces that are inherent in these industries. The design and operating philosophies of several of the analyzed organizations are quite different--especially between the commercial and military organizations. The Japanese nuclear industry and the U.S. commercial aviation industry though are similar in their design and operating goals. Both use equipment that has been designed to operate as long as is economically feasible, and both have limited resources available to conduct maintenance activities.

The maintenance of the Air Force B-52 aircraft does not have such resource constraints as those of the commercial organizations. Continued operation is not based so much on economics as on the strategic requirements that are imposed on the Air Force by the Strategic Air Command. A specified number of aircraft are required to be mission-ready at all times, and cost is of virtually no consideration in maintaining the required number of aircraft.

The U.S. Air Force has developed a systematic maintenance program to support the operation of its fleet of B-52 bombers. The fleet consists of approximately 270 aircraft that are deployed at 24 Air Force bases. The maintenance plan is designed to retain the operational readiness of the B-52 bomber fleet while continuing to extend the operational life of the aircraft. The maintenance program for the B-52 is mission-driven, and a specified number of the aircraft are required to be operational at any given time.

Though the B-52 bomber was originally designed for 5,000 total flight-hours, they were redesigned early in their operational life for 12,000 flight-hours, and have subsequently received additional modifications to further extend their service lives. The average flight age of the aircraft in the active inventory is currently 13,000 flight-hours, and it is anticipated that the flight-age of these aircraft will approach 22,000 flight-hours by the year 2000.

Like that of the B-52 bomber, the maintenance program for ballistic submarines is driven by the requirement to meet an assigned deployment date. The objective of the maintenance plan is to support the operating schedule and ensure safe, reliable operations for extended periods between refueling overhauls. The maintenance program also seeks to maintain 100 percent operational capability during the submarine deployment period, and to minimize maintenance cost throughout the submarine's useful economic life, which is nominally 30 years.

3.1.1 Aging Criteria in the Aircraft Design Stage

The commercial aviation industry has established a record of safety and reliability by designing maintenance programs that not only keep aircraft operational, but ensure a minimal impact on safety in the event of failure. This achievement is the result of close cooperation between regulatory agencies, aircraft manufacturers, and the airlines in designing the aircraft and the initial aircraft maintenance programs.

In order to ensure aircraft safety, several concepts are introduced in the design stage that address aging effects. These are as follows:

- fail-safe
- safe-life
- damage tolerance.

The fail-safe concept is based on the assumption that the failure of any single component on an aircraft will not cause the catastrophic failure of the aircraft. Beginning with the Boeing 707, the fail-safe approach was applied to the design of all U.S. commercial jets. This approach ensures that if a principal structural component were to fail, a secondary, or fail-safe load path would have sufficient residual strength to carry the load. The implications of the fail-safe concept on design requirements, is that parts must be constructed with a built-in redundancy to allow aircraft to operate safely with an undetected flaw until the next scheduled maintenance inspection and correction. For example, if a fatigue crack develops at a fastener hole, the rate of crack propagation must not reach a critical stage before the next scheduled inspection.

The safe-life concept was incorporated into aircraft design in the 1950s and requires the replacement of a part in accordance with the expected life of that part (e.g., the landing gear of an airplane is replaced after a specified number of flight cycles). Under this concept, the manufacturer designs aircraft for a specific life based on economic considerations, and the plane is retired from service when it becomes economically impractical to replace structural components such as the fuselage or wings.

Damage tolerance, a third design concept was adopted by the Federal Aviation Administration (FAA) in 1978. Damage tolerance is the ability of an airframe to resist failure due to fatigue, corrosion, accidental damage or poor maintenance practices for a specified period of unrepaired usage. A damaged structure will continue to carry operational loads until the damage is detected either by the problem becoming evident, such as a crack, or during a scheduled inspection. This approach assumes that damage will occur to a component from any number of possible conditions, including poor maintenance practices or equipment aging. These components must be designed to safely accommodate that damage until it is corrected.

The development of aircraft maintenance programs and the design of the aircraft are closely related efforts. Maintenance requirements are structured so that failures are prevented or detected before they become critical. Inspections are scheduled to detect damage from fatigue or corrosion before the damage reaches a critical stage and affects aircraft safety. The manufacturer, airlines and FAA work together to determine the maintenance requirements for an aircraft; however, these efforts are not effective unless they are incorporated into a maintenance program that ensures that the inspections are performed.

3.2 SELECTION OF CRITICAL SYSTEMS AND COMPONENTS

In reviewing the maintenance activities of the four organizations, three approaches were identified for the selection of critical systems and components, and maintenance tasks. Using these approaches, the organizations have developed programs for detecting and mitigating equipment aging problems based primarily on the safety-significance of the selected critical systems and components. The three approaches are as follows:

- Reliability Centered Maintenance (RCM), which is used by both the commercial aviation industry and the U.S. Air Force B-52 bomber fleet.

- The combination of equipment monitoring techniques and a detailed annual inspection of critical plant systems and components used by the Japanese nuclear industry.

- The combination of continuous monitoring of operating equipment with periodic maintenance layovers used by the U.S. Navy ballistic submarine program.

3.2.1 Reliability Centered Maintenance

Both the U.S. commercial aviation industry and the U.S. Air Force B-52 maintenance programs are based on reliability centered maintenance (RCM). RCM involves the systematic evaluation of system and component failure modes for the development of scheduled preventive maintenance tasks. An RCM analysis identifies the maintenance requirements of systems and components according to the safety and operational consequences of equipment failure.

During the development stage of a maintenance program, the systems and structures of the aircraft are evaluated to determine their failure modes and safety significance. Actuarial analysis is performed to determine the effects of age on equipment, and maintenance tasks are chosen that will detect equipment and structural degradation before the safety of the aircraft is impacted. In order to ensure that the maintenance programs are adequate, they are developed long before the aircraft actually goes into service.

In developing maintenance requirements for the B-52, the Air Force classifies all aircraft systems and components as either critical or non-critical. The severity of the component failure consequence determines the classification. Critical components and systems are limited to a certain number of flight hours or duty cycles, or until a specified expiration date. Then a critical item is removed, inspected, repaired if necessary, and tested. It may then be reinstalled or placed in spares. Non-critical items remain in service until failure. Normally, when there is a redundancy, the system or component will be classified as non-critical.

During the commercial aircraft design process, representatives from the airlines and manufacturer work together in a Maintenance Steering committee. This committee develops an initial set of aircraft maintenance requirements, using a logic decision process outlined in the Maintenance Steering Group handbook. Matteson, McDonald, and Smith (1984) outline four steps used by the Maintenance Steering Committee in developing an initial maintenance program. These steps are as follows:

- identification of active and passive items that require preventive maintenance
- identification of the functional failure associated with each component
- creation of a logic tree to determine applicable maintenance tasks
- review of the aircraft structure to establish an inspection program.

The identification of active and passive maintenance items requires a careful physical and functional description of each component detailing all of the functions which it performs. This step also identifies any redundancies that ensure continuation of function in the event of failure.

The identification of component functional failure addresses the consequences of degradation failure for each component. Functionally significant systems and components are identified as part of this activity. These functionally significant items are analyzed for failure modes and effects to identify the dominant causes and consequences of failure.

The creation of a logic tree incorporates information from the previous steps to identify applicable and effective maintenance tasks for the component. Applicable means that the task works and effective means that it is worth doing. This process addresses potential multiple failures that affect safety. If an operator uses a component infrequently, or if its function is unclear, then the logic tree requires the operator to perform a failure finding task to prevent multiple failures.

Finally, an aircraft structure review is performed. This review covers the critical elements of the primary structure that would have a major impact on structural integrity in the event of a failure. Each element is reviewed to determine its expected fatigue life, crack propagation rate, and corrosion susceptibility. These factors are considered in the development of the inspection program.

The Maintenance Steering Committee presents a proposed maintenance program for approval to the FAA Maintenance Review Board (MRB). The MRB issues a Maintenance Review Board Report outlining the minimum maintenance requirements for a new aircraft. This report contains an extensive listing of all maintenance significant items for both the aircraft's structure and its systems, and includes the following information for each item:

- item location
- failure effect category
- specific maintenance task assigned to the item
- frequency of the maintenance task.

This list of critical components and systems is modified over time based on the analysis of operational performance information. These monitoring and analysis activities are reviewed in Section 7 of this report.

Through this method, the systems and components that are critical to the continued safe operation of the aircraft are selected. Based upon the safety significance of these systems and components, maintenance tasks that are both applicable and effective in mitigating aging are selected.

3.2.2 Monitoring and Inspection

The Japanese nuclear industry combines a required annual inspection program with voluntary programs developed by individual utilities. Annual inspection requirements include minimum guidelines for the systems and components to be inspected, and procedures to be followed. Voluntary inspections, which are not regulated, are left to the discretion of each utility. Figure 3.1 presents a diagram of how the RCM approach is used to refine the maintenance program to address aging issues.

One reason for this approach is that, unlike the U.S. nuclear industry, the Japanese regulatory strategy does not specify a fixed term for licensing a nuclear power plant. Rather than granting an operating license for forty years, plant re-certification depends upon successful completion of a periodic inspection. If significant degradation of plant components due to aging is observed during an inspection, the plant will not be certified for continued operation until the degradation is repaired. This consequence encourages Japanese plants to use voluntary inspections to enhance the effectiveness of their maintenance program and to ensure that their plant is operating safely.

Periodic inspections are conducted according to standard instructions that designate the systems and components subject to inspection, the procedures to be followed, and the assessment criteria used to evaluate the condition of the equipment. The following critical systems and components are subject to inspection:

- reactor and reactor coolant systems
- nuclear instrumentation system
- fuel assembly/handling system
- radiation control system
- waste disposal system

- reactor containment vessel
- auxiliary boilers
- emergency diesel generator
- steam turbines.

In addition to the periodic inspections, utilities perform voluntary overhauls and functional tests of equipment not included in the periodic inspections. This practice confirms that the equipment, and the plant as a whole, will continue to operate with a high level of safety, reliability and functional performance.

Each electric utility decides which items are to be inspected and the inspection frequency, taking into account the safety significance of the equipment, the availability of equipment spares, the equipment operating history, and the occurrence and nature of equipment failures. The voluntary maintenance activities are performed in accordance with standardized work plans, procedures, and test and inspection instructions. If abnormalities or evidence of aging degradation are discovered as a result of these inspections or functional tests, the equipment is repaired, and efforts are made to prevent recurrence of the problem.

3.2.2.1 Japan's Plant Life Extension Program

In 1985, the Japanese Government and the Japanese Nuclear Industry began working together to develop the Plant Life Extension (PLEX) Program. This eight-year program is managed by the Japan Power Engineering and Inspection Corporation (JAPEIC), and is directed at researching methods to improve the level of reliability, economy, and the lifetime of nuclear power plants in Japan. The program addresses the following issues (Mishima, 1988):

- a more precise prediction of nuclear plant life
- a diagnosis of the extent of plant degradation that can be attributed to aging
- development of methods for monitoring the aging process
- development of new techniques for repairing and replacing components with short service lives.

The Japanese PLEX program is divided into four separate phases. The approximate schedule for each phase is outlined in Figure 3.2.

The first phase, PLEX I, was recently been completed. Phase I consisted of a two-year feasibility study to identify the critical plant systems and components that need to be considered for plant life extension. This phase included three parts:

- a survey of current nuclear plant conditions
- plant evaluations to determine the feasibility of life extension

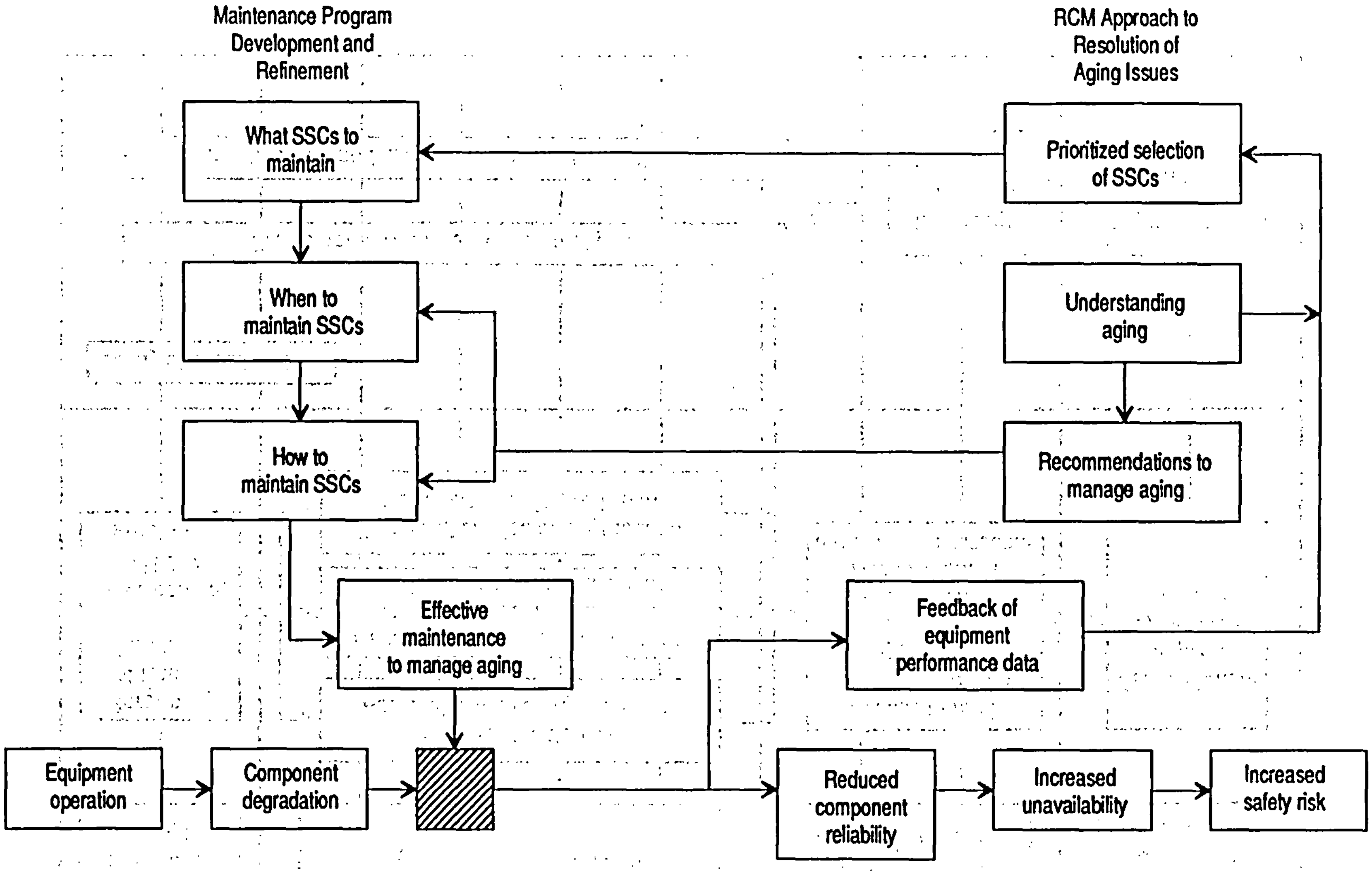

FIGURE 3.1. RCM Approach to Manage Aging

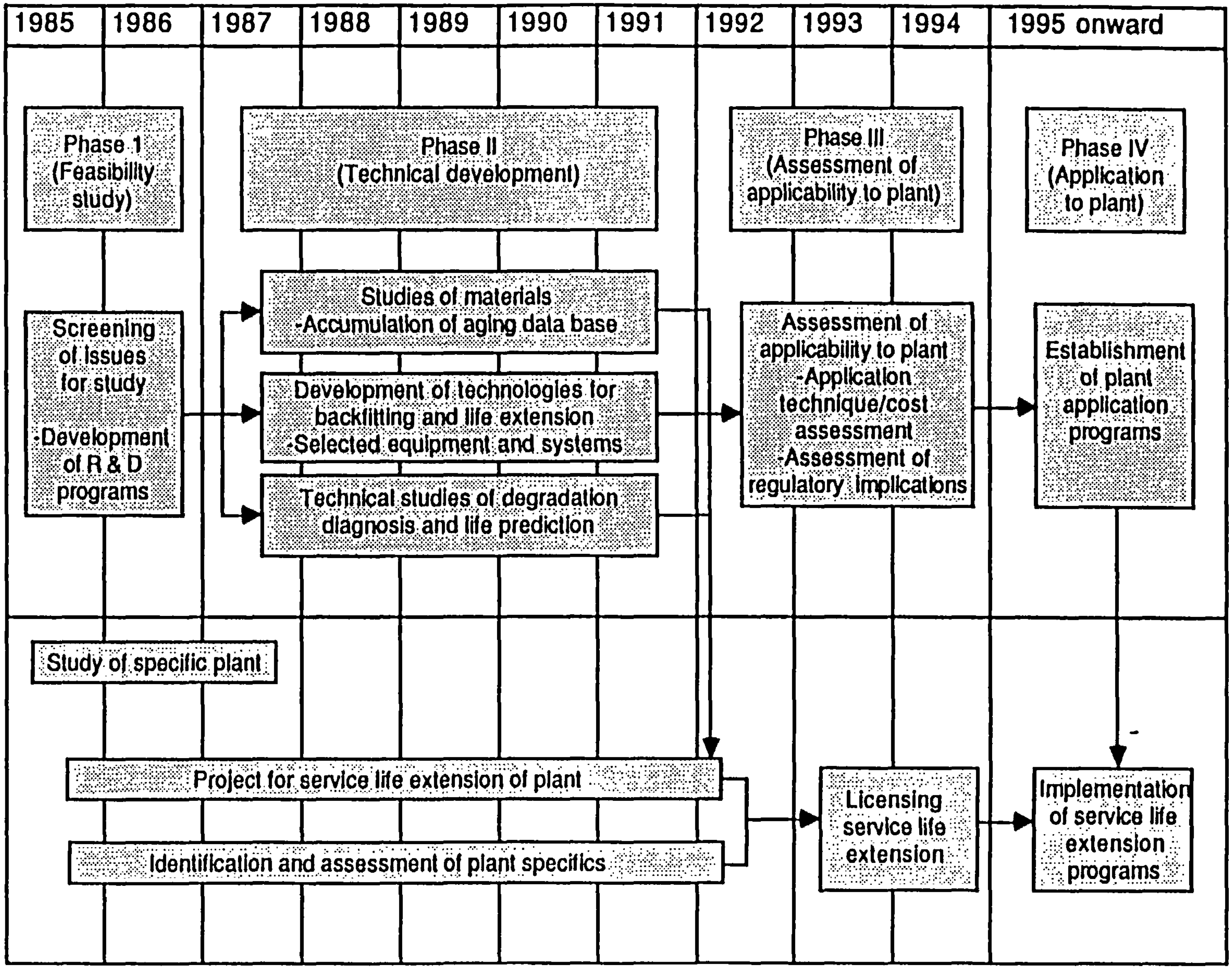

FIGURE 3.2. Schedule for Plant Life Extension Program (PLEX) - Japan

- the development of a schedule to determine future technical research requirements.

A diagram of the study areas included in Phase I is displayed in Figure 3.3.

Phase II of the PLEX program is aimed at providing an understanding of the various aging processes that affect critical plant equipment. Several variables are involved in the aging process, including manufacturing materials, equipment operating environment, aging mechanisms and degradation sites. The Japanese nuclear industry is currently addressing these variables in the second phase of the PLEX program, which is expected to continue through 1991.

The final two phases of the PLEX program will evaluate the finding of the Phases I and II, and develop methods for mitigating the effects of aging. These methods include the use of maintenance and monitoring techniques to detect and correct degradation, and record keeping and trending to predict equipment service life and improve the program. The development of these two phases, which are still in the planning stage, are expected to continue through the mid-1990s.

The Plant Life Extension Program is an effort by the Japanese utilities, vendors, and regulatory agencies to improve technology and extend the service life of existing light water reactors. This will be accomplished by focusing necessary resources on selected and prioritized systems and components to ensure the continue safe operation of Japanese nuclear power plants.

A discussion of the current and future activities of the PLEX program is provided in Section 4 of this report. A diagram of the key elements of the Japanese PLEX program is presented in Figure 3.4.

3.2.3 Continuous Monitoring and Inspections

The U.S. Navy has established a maintenance program for its ballistic submarines that uses scheduled maintenance tasks and extensive monitoring of the operating condition of plant systems and components. The Preventive Maintenance System (PMS) approach combines continual monitoring of all operating systems and components with specified preventive maintenance tasks designed to detect equipment degradation. The Navy establishes a detailed maintenance program for each class of submarine. Experience gained from maintenance on earlier classes of submarines is used in the development of maintenance programs for newer classes.

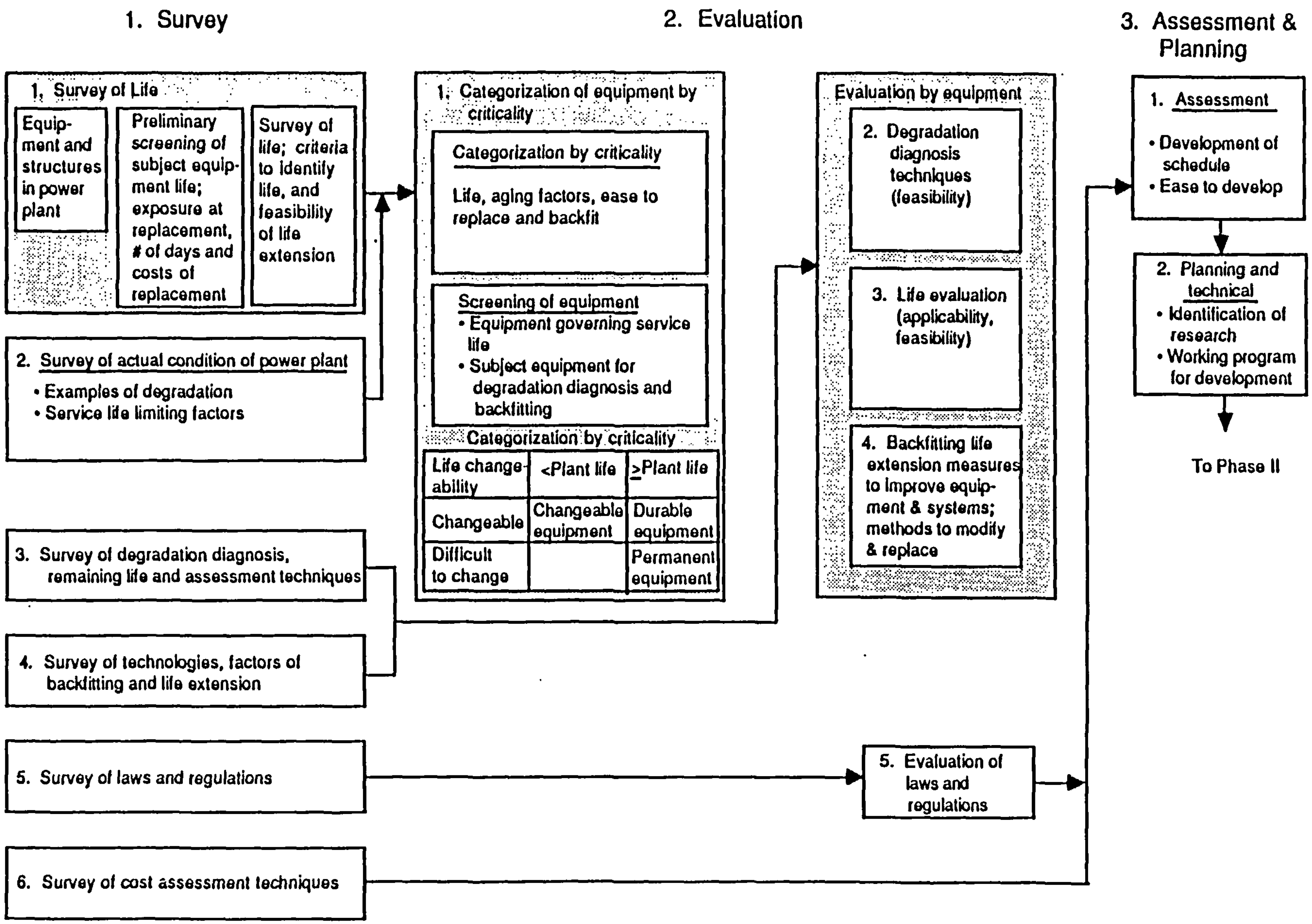

FIGURE 3.3. Study Areas of Phase One of the PLEX Program

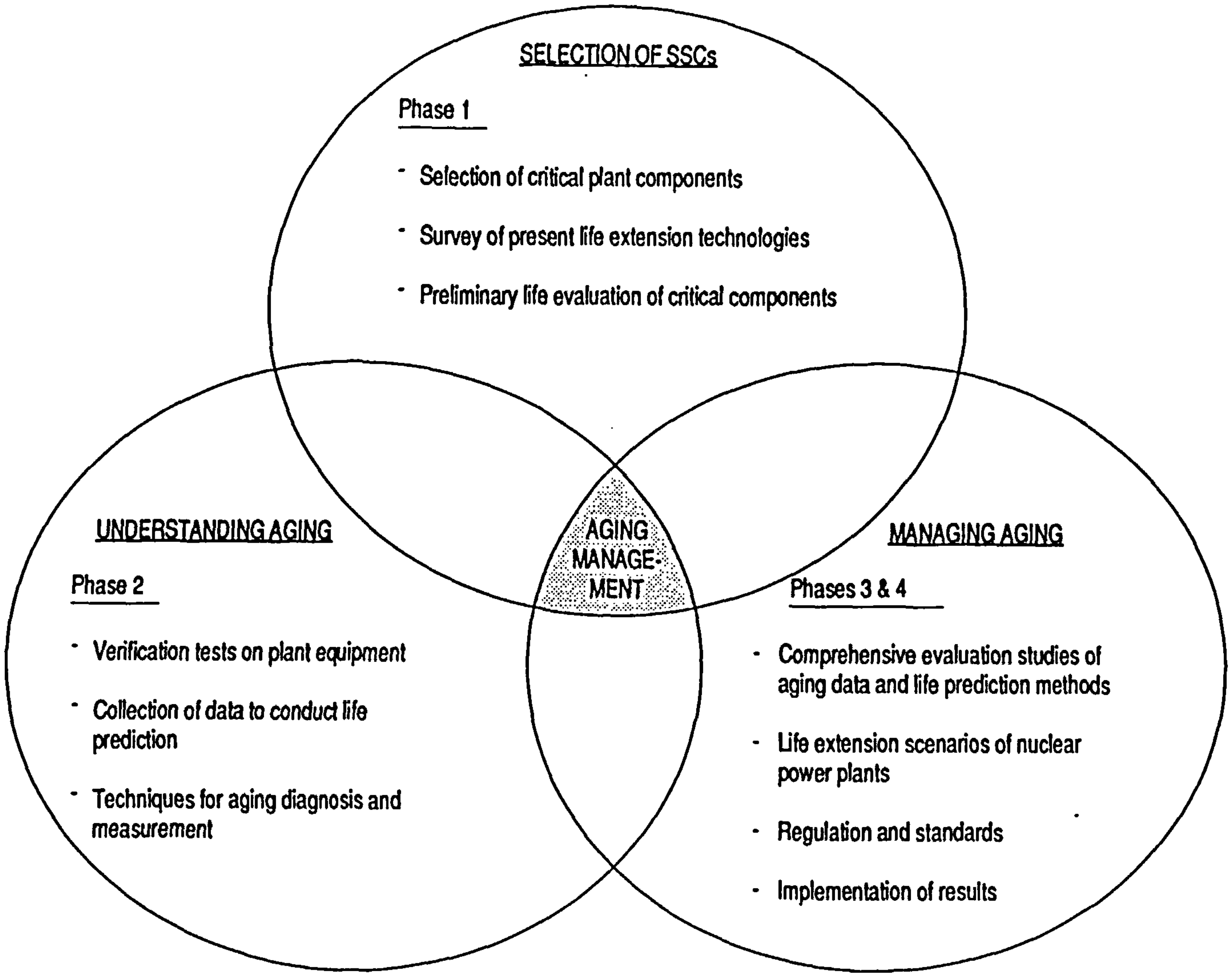

FIGURE 3.4. Key Interactive Elements of Japan's PLEX Program

4.0 UNDERSTANDING AGING THROUGH THE COLLECTION AND USE OF PERFORMANCE DATA

The second element of an aging management program is the set of activities that monitor and assess the effectiveness of the maintenance program. An important aspect of efforts to improve the management of aging equipment is the availability, completeness, and accuracy of equipment operational performance data. Performance data and information collected during monitoring activities provides a basis to identify maintenance problems, analyze possible causes, and implement effective corrective actions. It also provides the organization with the information needed to understand the effects of aging on critical systems and components. The four organizations were found to use different methods and performance indicators to evaluate their maintenance programs.

4.1 COMMERCIAL AVIATION INDUSTRY

The U.S. commercial aviation industry has an extensive system for assessing the effectiveness of its maintenance program and has responded to increased knowledge concerning aging with new programs designed to incorporate such knowledge. During the life of an aircraft, the airline, manufacturer, and FAA continually learn more about the failure modes and aging mechanisms associated with aircraft systems and components. This information is used to modify the aircraft maintenance program to properly address aging issues.

After the initial approval of the maintenance program, the frequency of performing preventive maintenance is controlled by the airline operating the aircraft, subject to continual surveillance by the FAA. To modify its maintenance program from the initial maintenance requirements described in the Maintenance Review Board report, the airline must show, based on operational performance records, that a change is warranted.

Performance records typically include the following information:

- engine shutdown and removal data
- component removals and verified failures
- system level delays and cancellations
- engine performance data.

Monitoring techniques focus on failure rates, age-reliability characteristics, and the use of simple ranking processes to identify areas needing special maintenance attention. The specific methods used to monitor reliability are generally left to the individual airline's choice. But regardless of the method employed, the information is made available for airline management and, as appropriate, FAA analysis (Matteson, McDonald, and Smith, 1984).

The airline provides the manufacturer with reliability and maintenance findings on its aircraft. When a problem that has fleet-wide safety implications arises (i.e., structural damage is detected that requires changes in maintenance procedures), the manufacturer issues a fleet-wide

Service Bulletin. Although not legally required, airlines usually respond to Service Bulletins.

The Boeing Commercial Airplane Company, for example, began issuing service bulletins calling for supplemental inspections of aging aircraft structures in the early 1980s. The service bulletins concern aircraft structures which were discovered to experience fatigue and corrosion damage not addressed in the initial maintenance program. These service bulletins have since evolved into a formal mandated structural inspection program which is one of the aviation industry's main programs to address the issues of aging aircraft. This program, entitled the Supplemental Structural Inspection Program, is discussed in Section 6.1.2.

When a condition has been verified as a safety significant problem, the FAA develops an Airworthiness Directive (AD) to correct unsafe conditions revealed by service experience. The AD is the primary vehicle by which the FAA mandates fleet wide inspection and repairs changes. In general, discussions among the manufacturer, airline, and the FAA precede the issuance of an airworthiness directive. Airlines are required to maintain current records of compliance with ADs for each aircraft in service. In addition, compliance information is a specific requirement when aircraft custody or ownership is changed. Most ADs and other design changes are intended to improve the safety, reliability, maintainability or operating costs of aircraft.

For example, in 1984 the FAA issued an AD requiring operators with aging aircraft to modify their examinations of structurally significant items by adjusting their method and frequency of structural fatigue and corrosion inspection. This AD requires aircraft with over 37,500 flight hours to be included within the Supplemental Structural Inspection Program.

Though the original aircraft maintenance programs were developed to be adequate for the full service life of aircraft, the collection and assessment of equipment performance data has caused the aviation industry to recognize that special programs are necessary in order to incorporate the results of recent aging-related research.

4.2 JAPANESE NUCLEAR INDUSTRY

Within the Japanese nuclear industry, extensive technical information is exchanged among the regulatory agencies, electric utilities, and other nuclear industry organizations. The power plants use this information to devise and implement preventive and corrective maintenance procedures, and enhance the effectiveness of their maintenance programs.

The periodic inspection programs used by the Japanese nuclear industry will remain in effect as they conduct new research to evaluate current program effectiveness. In initiating new maintenance programs or supplementing current ones, the industry considers background information on factors that affect the service life of nuclear plants. These factors include the following:

- Major components have individual service lives, and the safety and reliability of each component must be individually demonstrated. It is necessary to understand the factors that determine component service life, such as fatigue, corrosion, and erosion.

- Preventive and corrective maintenance must take into account aging factors. Attention should be given to procuring and replacing parts to ensure continued equipment reliability.

- Reduced performance may result from degradation due to aging factors that may not affect overall plant reliability.

- Even with adequate maintenance, there may be a point when it is not economically feasible to repair aged equipment.

Table 4.1 provides examples of data analysis activities that have been established by the Japanese nuclear power plants to address aging-related issues for major systems and components.

In 1987, the Japanese nuclear industry implemented the second phase, or technical development stage, of the Plant Life Extension (PLEX) Program. The focus of Phase II is to test critical plant equipment to better understand the equipment aging process. This information will be used to more accurately predict service life and will aid in the development of procedures for the repair and replacement of aging equipment.

Results from the first year of Phase II include complete verification tests in the following areas:

- degradation tests of low-alloy and stainless steels

- thermal aging in dual-phase stainless steel

- fracture toughness of stainless steel

- re-use of surveillance test coupons

- development of inspection or repair equipment for reactor pressure vessels.

Figure 4.1 outlines in detail the activities being conducted during the technical development stage. Completion of this phase is expected in 1991.

The final two phases of the Plant Life Extension (PLEX) program focus on developing methods for applying the findings of Phases I and II to Japanese nuclear power plants. Phase three evaluates the extent these findings were applied to plants that will compile life prediction data and plant extension proposals. A plan for plant extension will then be developed, taking into consideration economic and regulatory requirements. Phase four will implement the resulting programs.

TABLE 4.1. Approaches to Life Extension for Permanently Installed Equipment

System/Component	Degradation Factor	Life Extension Approaches Issues
1. Reactor pressure vessel	Fatigue, brittle fracture	• Comparison of operating history with thermal cycle drawing for design • Review of surveillance program
2. Reactor internal structures (Shroud, shroud support, top guide, core support, jet pump, ICM guide tube, CRD and ICM housing)	Embrittlement, corrosion, IASCC	• Study of measures against IASCC • Study of replaceability of equipment • Study of repairing technology
3. Concrete structures, RPV pedestal	Cracking, degradation of materials	• Study of degradation diagnosis technology and repairing technology • Installation of degradation monitoring samples
4. Heat exchanger (chamber rubber lining, shell, tube)	Corrosion, deformation	• Review of data of corrosion allowance • Installation of degradation monitoring samples • Study of replaceability (making easier to replace)
5. Cable	Insulation degradation	• Study of replaceability (making easier to replace)
6. Turbine low pressure casing	Degradation of materials	• Study of repairing technology
7. Piping (those that cannot be replaced such as buried pipings)	Corrosion	• Review of data of corrosion allowance • Study of replaceability (making easier to replace) • Study of materials

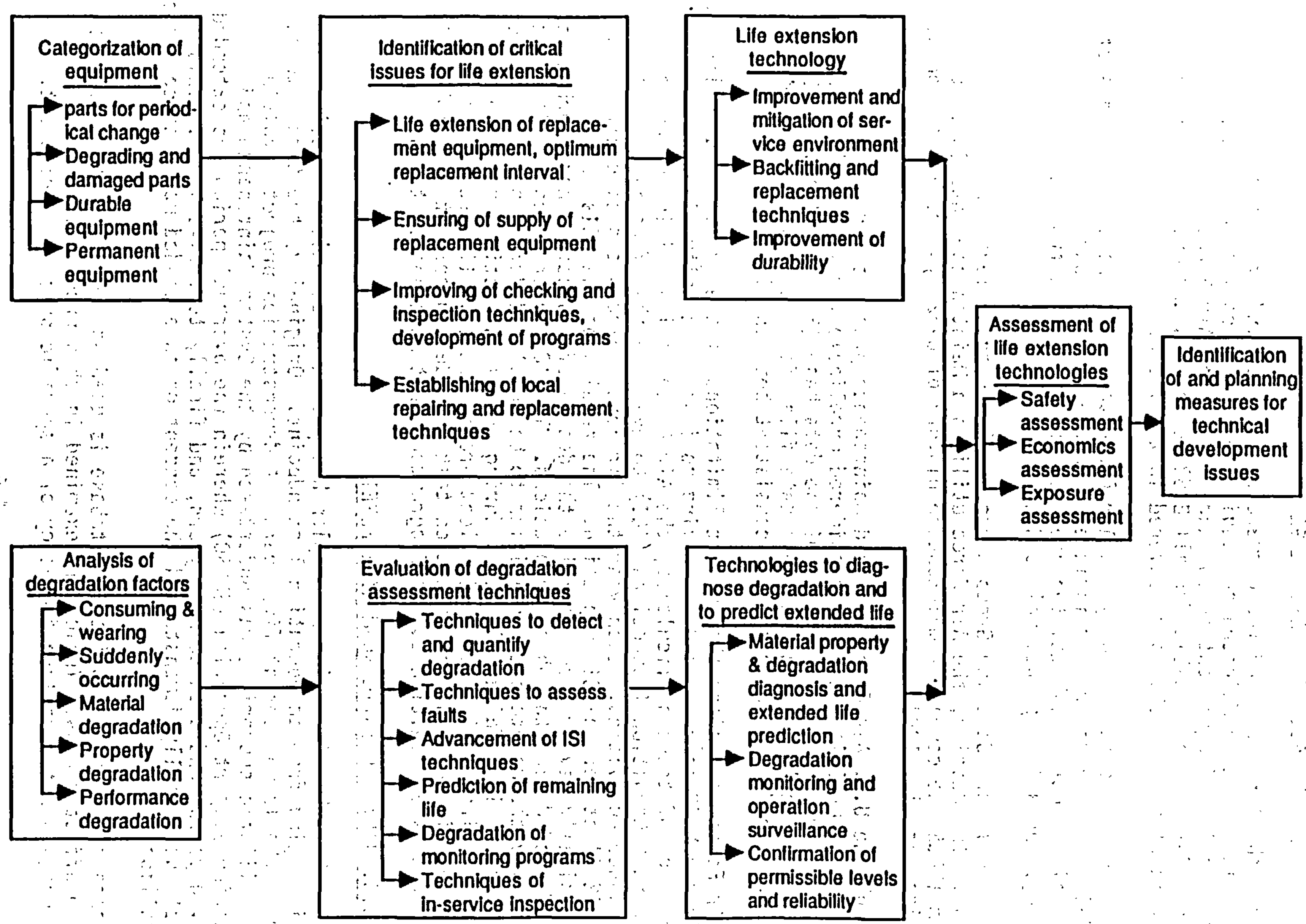

FIGURE 4.1. Technical Development Stage of the PLEX Program

4.3 U.S. AIR FORCE B-52 BOMBER FLEET

For both the Air Force and the commercial aviation industry, the use of Reliability Centered Maintenance requires extensive collection, organization, and evaluation of equipment performance data. The Air Force Strategic Air Command (SAC) is responsible for all B-52 operations and must document and report maintenance problems discovered in the field.

Performance indicators used by the Air Force to assess the effectiveness of its B-52 maintenance program include the usage rate of spare parts, changes in the levels of corrective maintenance, failures resulting from inadequate training, and a low operational readiness rating.

A Senior Officers Steering Group meets regularly to evaluate the maintenance program. In addition, the Air Force utilizes a Maintenance Data Collection System (MDCS) to compile a maintenance history of B-52 systems and components (Summitt, et al., 1983).

Although the U.S. Air Force has good maintenance programs for the B-52 bombers, the MDCS is presently considered unreliable for identifying equipment aging problems due to limitations of the data base (Summitt et al., 1983). There is currently no method to test data files for accuracy and completeness, and data recording practices are inconsistent between air bases.

The Air Force recognizes the current limitations of the quality and ability to verify the MDCS accuracy and is working to improve the situation. As a consequence of these difficulties, the Air Force relies mainly on the results of Aircraft Condition Inspections (ACI) to evaluate the effectiveness of its maintenance activities. Each year the Air Force selects ten aircraft out of the B-52 fleet for an ACI inspection. The results of the ACIs are systematically reviewed to determine the degree of inspection and overhaul to be performed during the phase inspections. The ACI information is also used to identify the maintenance activities to be completed during programmed depot maintenance. If a failure is found during an ACI inspection, thirteen additional aircraft from the B-52 fleet are inspected. If a repeat is found during that inspection, an inspection task intended to correct the problem is considered as an addition to the Programmed Depot Maintenance tasks.

4.4 U.S. NAVY BALLISTIC SUBMARINE FLEET

To date the submarine maintenance plan has proven to be quite effective in managing aging from an operational standpoint. Originally, the time between major overhauls was set at five years. A demonstration project involving three ballistic submarines was undertaken by the System Maintenance and Monitoring Support Operation (SMMSO) wherein the overhaul period was extended to seven years, and then to nine years, and finally to twelve years. This project successfully demonstrated the concept of an extended maintenance cycle for ballistic submarines.

Data obtained from the logistics database is used as a measure of maintenance program effectiveness. Indicators examined in this process include spare parts usage and the failure frequency of a specific system or component.

Significant failures of systems or components are also evaluated to determine if improvements to the maintenance program are required.

The Navy presently identifies aging problems by observing a change in condition over an extended period of time. At each major overhaul, for example, measurements of equipment operating characteristics are made and data are recorded on inspection survey sheets, photographs are taken, and the rate of change in equipment condition over the past performance period is assessed.

Data from the inspection survey sheets is entered into the SMMSO computer database and subsequently used to analyze the rate of change in condition due to aging, as well as other factors. This data is used in analysis to determine the present condition and to project the useful life of the equipment being surveyed. For the most part, insight on the aging process has been a learn-as-you-go process. Some accelerated life studies and some fatigue/cycle to failure studies are also performed; however, this is not common practice.

5.0 MITIGATING AGING WITH MAINTENANCE

The identification of appropriate and effective maintenance processes to detect and mitigate aging degradation is an essential part of a maintenance program of each of the four organizations examined.

The extent to which a maintenance program relies on any particular process depends on many factors. These include system and component criticality, operating schedule, maintenance budget, and equipment redundancy. The success of the four maintenance programs discussed below in managing the aging of systems and components is generally credited to their systematic, scheduled preventive maintenance activities.

5.1 COMMERCIAL AVIATION INDUSTRY

The maintenance programs used by the aviation industry are intended to be adequate for the life of the aircraft. This is based on the philosophy that maintenance programs are "living," meaning that they are constantly revised and improved to take into account the most recent information about aging and the failure modes of aircraft systems and components.

There are some types of failure that cannot be prevented no matter how intensive the maintenance activities are designed (Nowlan, 1978). For this reason, the equipment designers do not try to prevent failures altogether, but design the aircraft so that such failures will not affect safety. Likewise, the maintenance programs are designed to detect failures before they become critical and affect the safety of the airplane.

5.1.1 Types of Maintenance Performed

The maintenance program used in the aviation industry includes specific maintenance processes for each piece of equipment. The maintenance processes are selected based on the safety significance of the equipment and on its exhibited relationship between age and reliability. The aviation industry uses:

- on-condition equipment monitoring
- hard-time restoration or replacement of equipment
- condition monitoring.

On-condition monitoring is a scheduled inspection or test used to determine the functional condition of a system or component. This process is restricted to those components on which a determination of continued functionality can be made by visual inspection, measurements, tests, or other means without a tear-down inspection or overhaul. On-condition monitoring activities are designed to detect potential failures caused by equipment degradation and call for removal or repair of an item "on the condition" that it does not meet a required standard.

The hard-time processes places an age limit on a part, requiring it to be removed for restoration or replacement after a specified operating age. For many, items exhibit wear, and the probability of failure becomes significantly greater after a certain operating age. If no potential failure condition can be defined for a piece of equipment, on-condition tasks are not feasible.

Condition monitoring is characterized by the absence of preventive maintenance. An item is said to be maintained by condition monitoring if it is permitted to remain in service without preventive maintenance until a functional failure occurs. This process is oriented to after-the-fact detection of degradation or failure. Condition monitoring is also used to detect possible failure of equipment that has hidden functions or are not readily apparent to the operating crew or maintenance technicians. Condition monitoring applied to those systems and components where the use of design redundancies permit failures to occur without affecting operating safety.

Once the appropriate maintenance tasks for the systems and components on an aircraft have been identified, a schedule for the frequency of preventive maintenance tasks is established. The initial preventative maintenance schedule for critical systems and components is specified in the Maintenance Review Board Report.

5.1.2 Maintenance Scheduling

The most carefully constructed maintenance program would be of little value without an organized maintenance schedule to keep the program in operation. An aircraft maintenance schedule requires a series of progressive checks, and is based on the following factors:

- the number of flight-hours the aircraft has logged
- the number of flight-cycles experienced by the aircraft
- the chronological age of the aircraft.

A typical maintenance schedule for a commercial aircraft is made up of a series of "alphabet" checks that comply with federal rules. Each check is progressive, that is a B-check includes everything done in an A-check, plus more. The five predominant scheduled checks that are performed are:

- Daily: A visual check of the overall condition of the airplane.

- A-Checks: A general inspection performed at least every 125 flight-hours.

- B-Checks: An in-depth inspection of control functions at a maximum interval of 900 flight-hours.

- C-Checks: An in-depth inspection of systems and the structure performed over four successive B-checks, with a maximum of 3600 flight hours between checks.

- D-Checks: A complete structural inspection to determine continued airworthiness after approximately 20,000 flight hours, or about every four years.

Table 5.1 presents examples of the types of maintenance performed during each scheduled maintenance check.

A systematic schedule of maintenance checks is vital to the aviation industry in managing the effects of aging aircraft. Frequent inspections allow the industry to identify and correct problems while they are small, as well as providing opportunities to gain a better understanding of component failure modes and the aging of aircraft systems.

The overall objective of the maintenance program developed and used by the commercial aviation industry is to ensure the continued airworthiness of an aircraft over its economic life. The initial maintenance programs developed by the FAA, manufacturer's and airlines are thus designed to detect and correct aging degradation of aircraft equipment.

5.2 JAPANESE NUCLEAR INDUSTRY

The Japanese nuclear industry has regularly scheduled maintenance and inspection outages in conjunction with plant refueling. The work scheduled for these outages is part of a 10-year inspection plan, which is submitted to the Ministry of International Trade and Industry (MITI). MITI, the Japanese regulatory authority for nuclear power plants, also receives annual updates of the 10-year plans from the nuclear utilities.

The periodic inspections consist of nondestructive tests, overhaul inspections and functional tests designed to determine and alleviate the effects of aging in nuclear plant systems. The tests and inspections involve a large number of preventive maintenance tasks. For example, all safety valves and selected pumps and other components are disassembled, overhauled and subjected to functional tests.

A list of systems evaluated during the periodic inspections for both pressurized and boiling water reactors is shown on Table 5.2 (NUREG-1333, 1990). Specific components within the systems are also listed, as are the types of inspections performed. Many of the inspections are witnessed by MITI or its designated representative. Extensive post-maintenance tests are performed before restarting the plant.

5.3 U.S. AIR FORCE B-52 BOMBER FLEET

The maintenance activities for the B-52 aircraft are scheduled in a series of maintenance inspections that are conducted in phases every 200, 400, and 600 flight-hours. These phase inspections are normally performed at the aircraft's home base and consist of a combination of preventive maintenance and corrective maintenance.

The Material Management Directorate within the Air Force Logistics Command is responsible for major inspections of the B-52; these inspections are conducted at Air Force maintenance depots. Depot facilities consist of a set of maintenance specialty units where work is performed by a civilian labor force of skilled specialists.

TABLE 5.1. Types of Maintenance Performed During Aircraft Inspections

Inspection	Equipment Category	Type of Maintenance
Daily	Landing gear	Check of tire and brake wear; inspection of landing gear struts
	Structure	General inspection of wings
A	Landing gear	Visual inspection and lubrication, apply brakes and visually inspect brakes for wear and condition
	Structure	General visual inspection of external skin condition with special emphasis on cutouts such as door frames and windows
	Engines	Test of standby engine
B	Structure	Inspection of pressure bulkheads for signs of corrosion
	Engines	Inspection of compressor blades for wear
C	Landing gear	Treatment of wheel wells and main landing gear for corrosion protection
	Structure	Inspections of engine pylons and cabin interior for corrosion
D	Cabin	Interior removed, seats overhauled and reinstalled. Modifications made as required including emergency lighting, installation of fire resistant fabric, and new equipment
	Engines	Engines removed, serviced, and remounted. Overhauls performed as required.
	Structure	Landing gear inspected, new seals installed and reassembled. Complete internal inspection of wings. Modifications to prevent fatigue and fix corrosion.
	System	Navigation equipment repaired, autopilot in tail system rewired. Worn pivot bushings and metal sleeves for moving parts replaced. All hydraulic systems inspected for wear.

TABLE 5.2. Systems Evaluated During Inspections of Pressurized (PWR) and Boiling (BWR) Water Reactors

	BWR		PWR	
Electric Facility	Name of Facility	Contents of Inspection	Name of Facility	Contents of Inspection
Reactor	Reactor pressure vessel	Inservice inspection (non-destructive inspection and leak test)	Pressure vessel	Inservice inspection (non-destructive inspection and leak test)
	Fuel assembly	Sippy inspection, visual inspection, fuel shuffling inspection and reactor shutdown margin inspection	Fuel assembly	Sipping inspection, visual inspection, fuel shuffling inspection and reactor shutdown margin inspection
Reactor coolant systems	Main steam lines Safety valve	Disassembling and inspection, functional test	Steam generator heat exchanger tubes	Eddy current test
	Relief valve	Ditto (inclusive of function of automatic pressure reducing system)	Pressurizer Safety valve	Disassembling and inspection, leak test functional test
	Isolating valve	Leak rate test, functional test,		Ditto
	Turbine bypass valve	Functional test	Main relief valve	Functional test
	High pressure core injection system Low pressure core injection system Core spray system	Functional test, disassembling inspection (inclusive of auxiliary steam turbine), main valve disassembling and inspection	Main steam lines Safety valve	Leak test, functional test
			Relief valve	Ditto
			Isolating valve	Functional test
			Turbine bypass valve	Ditto
	Reactor isolation coolant system Reactor auxiliary coolant system Feed water pump	Functional test	High pressure core injection system Low pressure core injection system	Functional test, pump disassembling and inspection, main valve disassembling and inspection
	Vessels, pipings, pumps and valves	Inservice inspection	Accumulator High pressure, injection system Reactor upper head injection system	Functional test, main valve disassembling and inspection
			Auxiliary feedwater system	Functional test, pump disassembling and inspection
			Vessel, piping, pumps, valves	Inservice inspection

TABLE 5.2 (continued)

	BWR		PWR	
Electric Facility	Name of Facility	Contents of Inspection	Name of Facility	Contents of Inspection
Instrumentation system	Instrument air system Boric acid injection system	Functional inspection	Control rod driving system Instrument air system	Functional test
	Control rod driving system	Functional test, overhauling inspection of the drive mechanism, disassembling and inspection of the scrum valve	Safety protection system	Calibration test
	Safety protection system	Inspection of safety protection element (functional), calibration test		
	Nuclear reactor protection system	Functional test of plant interlock		
Fuel assembly and fuel handling system	Fuel handling system	Functional test	Fuel handling system	Functional test
Radiation control system	Field monitoring Area-monitoring Process monitoring	Functional test	Field monitoring Area and process monitoring Annulus recirculation exhaust system Recirculation system for main control room	Functional test
	Emergency gas treatment system Recirculation system for main control	Functional test, filter performance test		
Waste disposal system	Gaseous waste treatment system Liquid waste treatment system Leakage detector for liquid radioactive waste and warning device	Functional test	Gaseous waste treatment system Liquid waste treatment system Solid waste treatment system Leakage detector for liquid radioactive waste and warning device	Functional test
	Solid waste storage	Inspection of control condition	Solid waste storage	Inspection of control condition
Containment vessel	Containment vessel Isolation valve Vacuum breaker	Leak rate test Functional test, Disassembling and inspection Functional test	Containment vessel Isolation valve Vacuum relief valve	Leak rate test Functional test, Disassembling and inspection Functional test
	Containment vessel Spray system	Functional test, pump disassembling and inspection, main valve disassembling and inspection	Containment vessel Spray system	Functional test, pump disassembling and inspection, main valve disassembling and inspection
	Combustible gas concentration control system	Functional test, main valve disassembling and inspection	Containment vessel hydrogen recombiner	Functional test
	Reactor building	Leak test	Ice condenser	Functional test

TABLE 5.2 (continued)

BWR			PWR	
Electric Facility	Name of Facility	Contents of Inspection	Name of Facility	Contents of Inspection
Steam turbine system	Turbine and accessories (valves, etc.)	Overhauling inspection Functional test (valves, etc.)	Turbine and accessories	Overhauling inspection Functional test (valves, etc.)
Auxiliary boiler	Auxiliary boiler and accessories (valves, etc.)	Overhauling inspection	Auxiliary boiler	Functional test
Emergency power generating system	Emergency power generating set	Functional test	Emergency power generating set	Functional test
Others	Others	Overall plant performance test	Others	Overall plant performance test

Programmed Depot Maintenance (PDM) is performed every four years, necessitating that the aircraft be out of service for about four months. Maintenance of critical items is performed at this time. The PDM provides the aircraft with four months of extensive maintenance, refurbishment, upgrade and overhaul which restores it to new condition. All repaired systems and components are bench checked before installing them on the aircraft. After installation, and before returning the aircraft to operational status, ground checks of the installed systems and components are performed, and a test flight of the aircraft is conducted.

Aircraft Condition Inspections (ACIs) are performed concurrently with the PDM. An ACI is a special inspection over and above the normal inspection requirements and is performed to provide a basis for establishing inspection tasks and developing future inspection schedules.

5.4 U.S. NAVY BALLISTIC SUBMARINE FLEET

The Navy's ballistic submarine maintenance program identifies the frequency of maintenance, type of maintenance, and organization responsible for the maintenance for each system and component on the submarine. The program also identifies which items receive condition monitoring or are allowed to run to failure, and which items require on-condition monitoring or preventive maintenance. The maintenance program relies on the submarine crew members to monitor system and component operating conditions as well as perform selected preventive and corrective maintenance tasks. More extensive maintenance is conducted at shipyards or submarine tenders.

The maintenance program relies on preventive maintenance much more than on condition maintenance. Preventive maintenance, based on the performance of other submarines of the same class, is employed to mitigate the effects of equipment aging. A maintenance record card (MRC) is prepared and maintained for each component and system that is designated for monitoring in the maintenance plan. Separate records are maintained for reactor and propulsion plant equipment, and extensive preventive maintenance is performed on both.

The surveillance philosophy for equipment performance monitoring is to use Non-Destructive Inspection (NDI) where possible. This is to avoid breaking into systems that have been certified for operational integrity, such as those exposed to sea-pressure. As a result, commercially available NDI techniques are relied on extensively to indicate a change in condition.

Monitoring techniques include the use of pyrometers, flow meters, vibration monitors, ultrasonic measuring devices, and spectroanalysis of oil. These techniques are used quite effectively to monitor changes in equipment condition or performance over extended periods of time. Performance data pertaining to equipment aging on older submarines is used to identify systems and components on newer submarines where aging could be identified by using NDI.

Ballistic submarines operate on a three-month deployment schedule followed by a 30-day refit period at a shipyard or submarine tender. During the refit, preventive and corrective maintenance that is beyond the capabilities of the boat's crew is performed, and the submarine is readied for the next deployment. Approximately once every four years, a 60-day restricted availability is performed. This is an extended maintenance period intended to upgrade systems and components.

Over the 30-year life of the submarine, it is scheduled for refueling approximately every twelve years. During the refueling period, extensive preventive and corrective maintenance is performed on many of the submarine's systems, structures, and components (SSCs). The refueling overhaul requires 18 to 24 months. Following a refueling overhaul, each system undergoes extensive testing while the submarine is still in the shipyard. Subsequently, the submarine undergoes sea-trials with ship-yard personnel on board. All items found deficient during sea trials are corrected, a new baseline is established on the MRC cards, and the boat is returned to the fleet for active duty.

More recently, the Trident submarine maintenance program has introduced a new approach into the ballistic submarine maintenance programs. Hard-time limitations are placed on many components, requiring their removal from the submarine. A new or refurbished component replaces the original, which is sent to a maintenance facility for overhaul. The Tridents are designed to facilitate these activities, and extensive standardization of equipment is used throughout the Trident submarine class. This approach ensures that when needed, each submarine is fully operational, and that maintenance activities have a minimal impact on the submarine's operating schedule.

6.0 FEEDBACK AND CORRECTIVE ACTIONS TO IMPROVE MAINTENANCE

The performance data gathered during equipment monitoring provides important information to address the increased maintenance requirements of aging equipment. An organization's ability to collect and evaluate equipment performance data is a critical practice that enables feedback and corrective actions to improve the maintenance program. The four organizations take different approaches to analyze performance data in order to identify and initiate corrective actions to their existing maintenance programs.

6.1 COMMERCIAL AVIATION INDUSTRY

Time lines for overhauls and inspections of aircraft systems and components are established as part of commercial aviation maintenance programs. These time lines are continually modified and refined as technology advances in airframe, engine, and equipment design, and as knowledge expands on preventive maintenance. Airlines can initiate changes in their maintenance inspection schedule through negotiations with the FAA based on specific operating experience data or engineering studies. The manufacturer recommends changes by issuing Service Bulletins to the airlines, and the FAA issues Airworthiness Directives when mandatory changes to maintenance programs are required.

On April 28, 1988, the top half of a Boeing 737 fuselage section tore loose on a flight from Hilo to Honolulu, Hawaii. The National Transportation Safety Board (NTSB) determined the probable cause of the accident to be the failure of Aloha Airline's maintenance program to detect the presence of significant fatigue damage, which ultimately led to the separation of the fuselage upper lobe. This incident has caused new concerns for the industry on how to better ensure the safety and reliability of aging aircraft. As a result, the aviation industry has formed an Airworthiness Assurance Task Force to foster a consistent approach to aging concerns for each major airplane manufacturer. This task force has made several recommendations for industry-wide corrective actions to airline maintenance programs.

This section discusses the dangers of fatigue and corrosion in aging aircraft. Special maintenance programs for aging aircraft are also addressed.

6.1.1 Fatigue and Corrosion: Predominant Dangers to Aging Aircraft

A number of factors other than chronological age affect the operational and economic life of a commercial jet aircraft. Perhaps the best indicator is the number of flight cycles, especially the number of compressions and decompressions during flight which keep the air pressure in the cabin at a comfortable level. Most planes are designed for a nominal economic lifetime of 20 years, but for widely varying numbers of cycles and flight hours. For example, the Boeing 747 was intended for long flights and designed for 20,000 flights and 60,000 hours. The Boeing 737 was intended for relatively short flights and so designed for 75,000 flights and 51,000 hours.

Under cyclic loads, imperfections in the aircraft structure can form the nucleus of tiny cracks that may eventually grow and degrade structural capability. This is known as fatigue, and is directly related to the number of flight cycles an aircraft is subjected to. Any metal part that moves or is subject to stress experiences fatigue. Damage may develop from loads imposed by repeated cycles of takeoff, flight, pressurization and landings of an aircraft.

Corrosion occurs when the aircraft structure is exposed to atmospheric salts, water, or runway contamination. Corrosion is more unpredictable than fatigue, and is hard to prepare for in the design process. Corrosion will occur at different rates depending on the surrounding environment, making it especially difficult to design an aircraft to withstand this type of damage.

The combined effects of fatigue and corrosion can be disastrous. A crack due to fatigue will normally grow at a predictable and detectable rate. If corrosion is present, however, the rate of growth may be accelerated by a factor of ten. Inspection and maintenance programs are the key to managing the effects of fatigue and corrosion (Murphy, 1989).

Due to the effects of corrosion and fatigue, maintenance programs must change as aircraft age and accumulate more flight hours. Figure 6.1 illustrates some of the well known areas of fatigue and corrosion damage. Fatigue usually starts around the skin rivets and other details such as bolts and fittings. Corrosion is most often found in the belly of the plane, where water collects. Maintenance programs are being modified to detect and mitigate these effects as they are discovered.

Special maintenance activities designed specifically to determine and mitigate the effects of aging have been implemented by the manufacturers, airlines, and the FAA. Supplemental Structural Inspection Documents were issued by the manufacturers as service bulletins, and, with the issuance of airworthiness directives by the FAA, became mandatory parts of the maintenance programs in 1984. Following the Aloha Airline 737 accident, the Airworthiness Assurance Task Force on aging aircraft was formed. This task force included members from the manufacturers, the FAA, and the airline industry's Air Transport Association (ATA). Several new programs to address the issues of aging aircraft have been initiated as a result of recommendations from this group.

6.1.2 Supplemental Structural Inspection Program

The Supplemental Structure Inspection Program (SSIP) was developed in the early 1980s by the FAA and aircraft manufacturers to extend the operational life of older aircraft and to ensure their safe operation (Fotos, 1988). The SSIP provides for continuous structural inspection to identify fatigue cracks and other damage resulting from aging.

This program covers areas of the aircraft structure that were not necessarily of concern during the original structural analysis and maintenance program development.

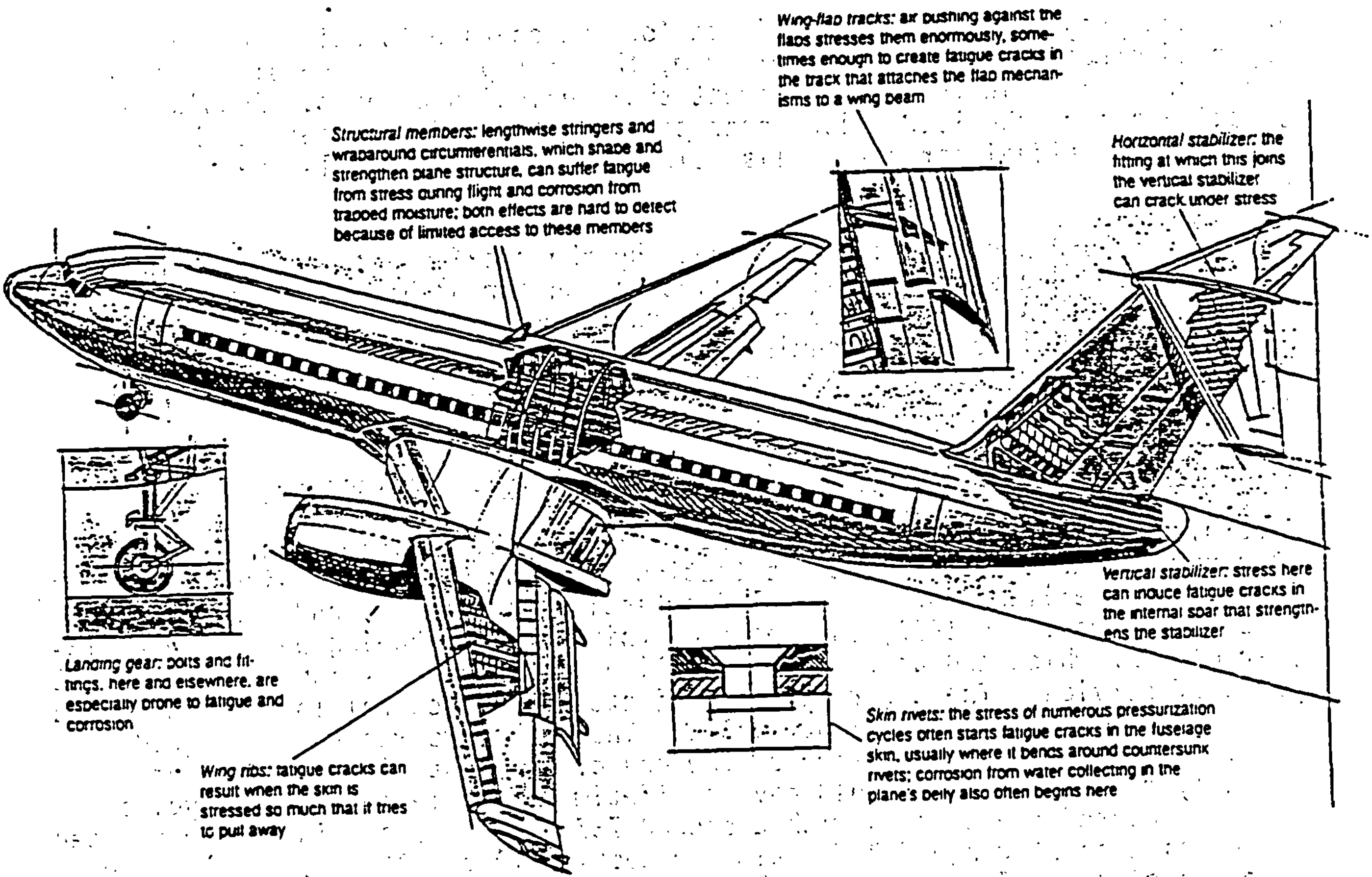

FIGURE 6.1. Areas of Fatigue and Corrosion Damage on Aging Aircraft (Murphy, 1989)

Manufacturers identify and issue a Special Structure Inspection Document for all structural components of an aircraft that have damage or fatigue characteristics that could affect the aircraft's structural integrity (Broderick, 1986). This document establishes a special inspection procedure for each of those components. Based on the data provided by the manufacturer, the airlines adjust the frequency and method of structural inspections to ensure continued airworthiness as aircraft age.

While the program is not a substitute for the operator's existing FAA-approved structural inspection program, the SSIP provides the airlines with procedures to evaluate and supplement their existing program. Should fatigue cracking occur, the SSIP allows operators to detect damage before the aircraft's residual strength falls below the regulatory fail-safe requirements.

Though the SSIP was initially developed by the manufacturer and distributed to the airlines as a set of service bulletins, an airworthiness directive was issued by the FAA in 1984 requiring operators with aging aircraft to incorporate the inspection requirements of the SSIP into their existing maintenance programs. The AD requires aircraft that have exceeded 37,500 flight cycles to be included in the SSIP.

6.1.3 Structural Analysis of Aging Aircraft by the Manufacturer

Aircraft manufacturers monitor the structures of high cycle aircraft through structural tear-downs and fatigue testing. Boeing Commercial Aircraft's aging aircraft surveillance program includes testing, tear-down, and inspection of older airframes. In 1987, as a part of this program, Boeing purchased an 18-year old 737 which had accrued 60,000 flights and 42,000 flight-hours over 18 years of service. The aircraft was subjected to structural load tests to add another 70,000 simulated flight cycles. The structure was still in good condition with little corrosion at the end of the test, indicating that a properly maintained 737 should have a lifetime of at least 130,000 cycles. Boeing repeated the process with a second 737 airframe, and in 1988 purchased a high-time short range 747 for similar testing (Ott & O'Lone, 1988). The fuselage of the 747 is currently being subjected to pressure cycling to explore extended fleet usage beyond the original economic design life objectives of 20,000 flights and 60,000 flight hours.

Douglas Aircraft has purchased one of the oldest operating DC-9s and performed extended service life testing of the equivalent of nearly 70 years of service. This included 66,500 cycles of original service and 141,500 simulated flight cycles. After testing, a tear down inspection of 14,000 fastener holes indicated that their useful life had not been exceeded (AW&ST, 1988).

6.1.4 Structural Modifications for High Cycle Aircraft

A new emphasis on structural requirements has resulted from the Aloha Airline 737 accident. Based on recommendations of the industry's Airworthiness Assurance Task Force, the FAA has ordered structural modifications to older aircraft, signaling a change maintenance policy. Previously, the FAA had required only periodic inspections to detect structural fatigue and corrosion damage, and called for replacement only when such conditions were found. In March 1990, the FAA issued a series of airworthiness directives calling for more than $800 million in modifications to older Boeing 747, 737, and 727 aircraft. Some of the required modifications for the aircraft models are illustrated in Figure 6.2.

In September 1989, the task force made recommendations calling for similar modifications to older McDonnell Douglas aircraft. The FAA is expected to issue airworthiness directives in the summer of 1990 that will require mandatory structural modifications ranging from minor bolt replacements to landing gear overhauls.

6.2 JAPANESE NUCLEAR INDUSTRY

In addition to the Plant Life Extension Program currently underway, the Japanese utilities are devoting considerable resources to reduce the duration of the periodic inspections, and to improve the quality of maintenance activities performed during these inspections. The duration of periodic inspections has been reduced over the last few years. Several factors contribute to this trend:

- the reduction in corrective maintenance as initial equipment problems have been solved
- aggressive evaluations and the use of equipment performance information
- increased efficiency in the organization and administration of periodic inspections
- long-standing cooperation between utilities, regulatory agencies, and equipment manufacturers
- overall technical improvements in the performance of maintenance and repair
- extensive education and training programs.

A periodic inspection currently takes approximately 100 days. Because of this, and the fact that the maximum interval between inspections is 13 months, the maximum operating capacity within current regulations is 80%. The Japanese nuclear industry is trying to find methods to reduce the time required to perform an inspection and to extend the time period between inspections. The utilities have proposed several methods by which to reduce inspection time:

- improve detection techniques to provide more accurate and reliable inspection results to minimize inspection and evaluation time
- develop automated inspection tools to minimize radiation exposure and inspection time

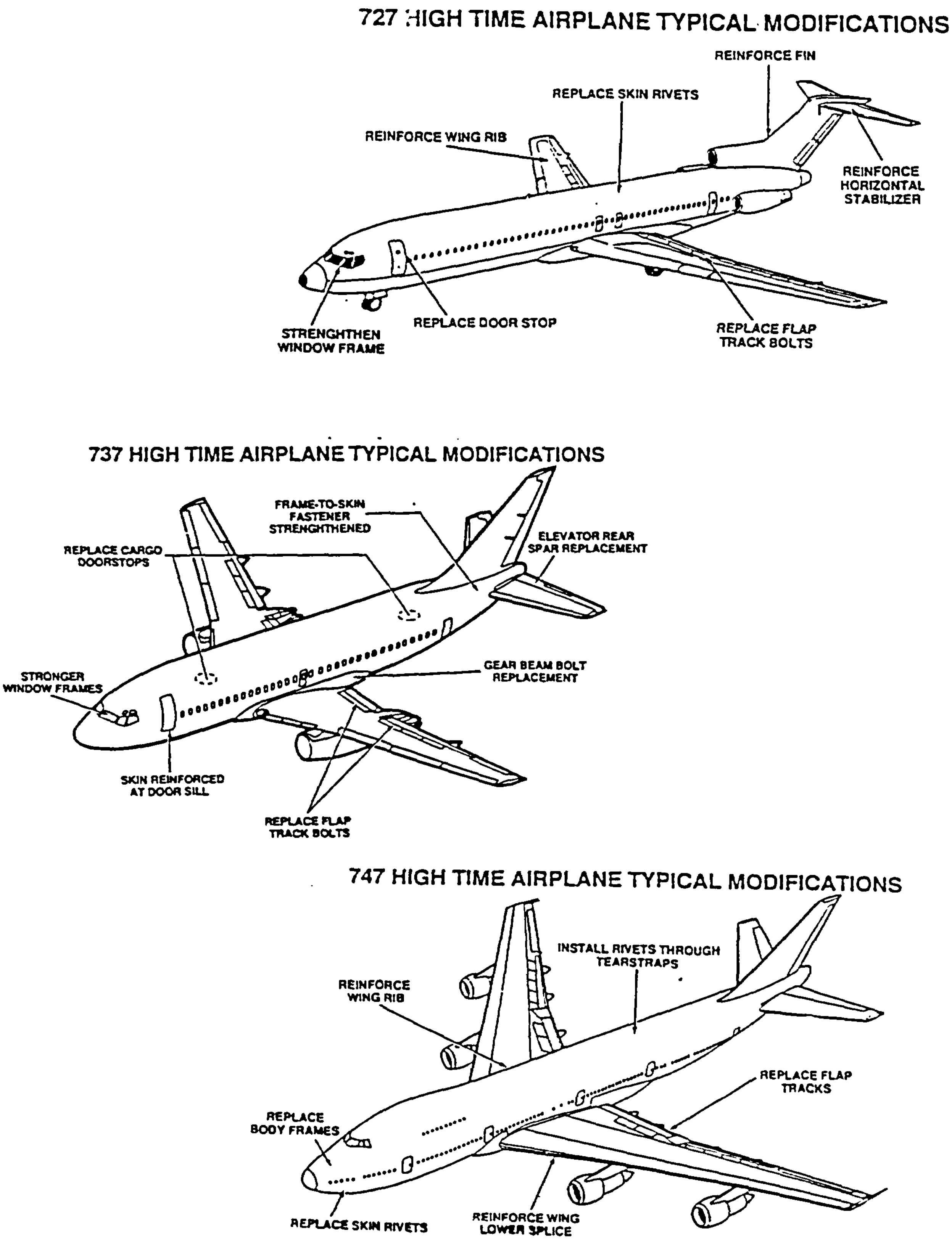

FIGURE 6.2. Typical High Cycle Aircraft Modifications (Fotos, 1989b)

- alleviate "critical paths" in the work performance

- continually evaluate data collected on equipment performance to identify inspections that can be reasonable be performed less frequently

- develop computer management systems for processing and evaluating equipment performance data.

One utility has submitted a request to MITI to extend the amount of time their facility is allowed to operate between scheduled outages from 13 to 15 months. MITI is currently investigating the effects of extended inspection intervals in plants that are performing well and have a 13-month operation and 10-week inspection cycle. Utilities will also be required to demonstrate that major components can operate reliably for more than a year to extend their operating schedule (NUREG-1333, 1990).

6.3 U.S. AIR FORCE B-52 BOMBER FLEET

The Material Management Directorate communicates daily with the Strategic Air Command (SAC) maintenance organization at each of the air bases where B-52 aircraft are assigned, and with the maintenance organization at SAC Headquarters. Each SAC maintenance organization equipped with B-52s has an extensive maintenance program that ensures the aircraft are mission-ready on a 24-hour basis. Maintenance at this level is conducted using many of the concepts and techniques of the commercial aviation industry.

The Air Force convenes a Product Improvement Working Group (PIWG) every three months to review performance, needed improvements, and design modifications on the B-52. These reviews are based on flight performance data, repair records, and pilot and crew feedback. The purpose of the PIWG is to resolve major maintenance problems, such as directing procedural changes and initiating development programs or authorizing aircraft engineering changes and modifications. This working group is multi-disciplinary, representing all parties involved with the aircraft. The Air Force has empowered this group to make recommendations and generally funds and implements their proposals. Inspection tasks and schedules can be modified by direction of the SAC air base Deputy Commander for Maintenance, who is responsible for maintenance at individual Air Force bases.

6.4 U.S. NAVY BALLISTIC SUBMARINE FLEET

There is daily telephone/computer communication between the repair site team leader and the System Maintenance Monitoring and Support Operation (SMMSO) program manager wherein specific highlights are discussed by hull number. This communication can also include a request for engineering support from SMMSO. The SMMSO is responsible for determining the need for equipment condition monitoring, including monitoring for aging and reporting to a maintenance planning and procurement organization. This organization, in turn, is responsible for maintenance planning and work procedure development.

In addition to daily communication, a system of Technical Feedback Reports are initiated at the crew member level and passed up through the chain of command to management. Within the SMMSO performance monitoring program, high level system review meetings are conducted at periods ranging from once per year to once every three years. Participants at these meetings evaluate the effectiveness of the maintenance program, identify areas of change, assign new action items, and evaluate the progress of on-going action items.

7.0 RESEARCH AND ACTION AREAS

Each of the four organizations examined have established research programs to help them understand and mitigate the effects of aging. This section discusses some of the aging-related research areas which are being considered by the four organizations in their aging management programs.

7.1 THE LOGISTICS OF SPARE PARTS FOR AGING COMPONENTS

A factor that will eventually impact the ability of nuclear power plants to effectively manage aging involves the logistics of maintaining an adequate supply of replacement items for the aging equipment (NRC, 1986). As equipment manufacturers discontinue production of older items or abandon nuclear product lines, it will become increasingly difficult to procure the spare and replacement parts needed to safely and efficiently operate the plant. The logistics of maintaining an adequate supply of replacement items for aging equipment has become a major problem in maintaining the operational readiness of both the B-52 aircraft and older Navy ballistic submarines.

Experience has shown that the cost of supporting the B-52 bomber has increased dramatically as a result of extending its useful life. This is due in large part to the increase in cost caused by unavailable spare parts for many aircraft components and subsystems (Capotosti and Curran, 1981). This situation, called Diminishing Manufacturing Sources (DMS), has forced the Air Force to authorize a "make-in-lieu-of-buy" policy for a number of components. These components are fabricated at a repair depot by the Air Force Logistic Command. This approach may be adopted by the nuclear industry as maintenance resources and economics allow.

DMS is also recognized by the Navy as a serious problem, especially in the procurement of spare parts for older submarines. In cases where no acceptable replacement component can be purchased, the shipyard manufactures the required component.

DMS is not a major factor in the airline industry primarily due to its growth. Currently, most airlines have adopted an approach where the equipment manufacturer guarantees the availability of spare parts for the useful life of the aircraft. This approach includes maintenance support for most major components such as generators, hydraulic pumps, avionic systems, and navigation systems. Increasing support from the aircraft and engine manufacturers has been provided in the form of longer product quality warranties, reliability and maintenance cost guarantees, and free logistic support and design changes when inservice performance is less than specified (EPRI, 1984).

7.2 CORROSION CONTROL PROGRAMS

The Supplemental Structural Inspection Program, which handles the inspection of aging aircraft structures, assumes that the operators have kept their aircraft generally free from corrosion. Boeing started an aging fleet evaluation program in early 1987. By mid-1988, about 60 aircraft had been surveyed for the effects of corrosion as part of this program. These aircraft have shown a wide range of conditions from excellent to "significantly below expectation," with the primary problem being corrosion. The program also showed that aircraft without lifelong aggressive corrosion control programs usually had corrosion problems (Dornheim, 1988).

Airlines must now inspect for corrosion, but the FAA permits the inspections to be conducted in different ways. The Airworthiness Assurance Task Force was established to learn whether the airlines should be permitted less discretion in the way corrosion control is conducted. An important consideration of the Task Force is the fact that different operational environments argue against identical procedures. In March 1990, the FAA proposed extensive regulatory standards for corrosion control of U.S. commercial aircraft as one response to the midair breakup of the Aloha Airlines 737 in 1988.

The current industry standard states that if corrosion causes a ten percent loss in fuselage skin thickness, replacement of that portion is required. The FAA has proposed to further restrict the allowable corrosion loss to five percent. Measuring equipment calibration errors make it difficult to accurately measure small amounts of corrosion; therefore, the FAA will require more frequent and thorough inspections. In addition, the FAA will mandate "fixes" to problems, referred to as terminating actions by maintenance personnel. This includes actions such as replacing one metal when dissimilar metals interact to alleviate the need for further inspections to detect corrosion (Ott, 1988a).

The commercial aviation industry is also looking to the military for methods of corrosion control. The Navy has done much research in developing corrosion control techniques. One of the Navy's several developments is Unicoat paint, a single coat that serves as primer and topcoat. The single layer improves protection and saves weight. Several new F-14s treated with the paint are undergoing operational evaluation. Another development is a water-displacing compound for internal corrosion coating. One product, called Amlguard, is a transparent coating that keeps the underlying structure visible and allows for inspections (DeMeis, 1989).

The Air Force has been conducting research over the last 12 years in the development of a system to detect corrosion by automatically monitoring increases in the electrical resistivity between small, metallic sensors mounted on aircraft components (Battelle, 1989). Output signals from the individual sensors are transmitted to a centralized computer system mounted on the aircraft. The computer calculates rates of corrosion occurring on the surfaces of the airframe structures. The system provides continuous information, thus enhancing safety and possibly reducing the need to perform visual inspections. The system is currently being designed for use on Air Force F-15 fighter aircraft, C-130 transport aircraft, and the MH-60 helicopter. Though still in the development stage, it is envisioned that the system and the information it generates will be an important tool for use by maintenance personnel responsible for ensuring the structural integrity of an aircraft's airframe components.

7.3 TECHNOLOGICAL DEVELOPMENTS BY THE AIRLINES

After a commercial airplane enters service, ongoing inspections and maintenance of its structure are necessary to ensure a continued high level of safety. Experience has shown that the inherent structural integrity of commercial aircraft has been maintained by operator inspection and maintenance programs. However, after many years of service, these aircraft will reach an age where an increase in fatigue cracking may be expected. Non-destructive inspection (NDI) techniques are being developed and verified for use by operators to ensure the structural integrity of aircraft (Hagemaier, Bates and Steinberg, 1988).

Damage tolerance and NDI reliability programs consistently show that eddy current inspection is superior to other existing non-destructive testing (NDT) methods for detection of fatigue cracks. Existing eddy current instruments enable the inspector establish the existence and relative severity of fatigue cracks and corrosion. CAT Scan techniques from medicine, already used on engine disks and blades, may improve inspection of material cross sections and multiple bonds. Infrared thermography can be used to check for composite debonds and repair integrity. Automation and computer enhanced imagery would help in detection and record keeping. For example, automated ultrasonic scanning of a rivet row would contribute an image record forming a comparative history of the structure over time.

Part of the research conducted by the FAA into developing and evaluating NDI equipment will address the development of training material on the use of such equipment for aircraft mechanics, in recognition of the need to ensure their familiarity with and understanding of new techniques and equipment (Blake, 1988).

Analytical procedures for airframe life prediction have been developed by NASA and are currently used in the design and assessment of new airframe structures. In future efforts, NASA is expected to assist the FAA in developing methodology to determine the structural integrity of aging airframes (Rosen, 1988). They will also help to develop methods of assessing the effects of multiple crack site behavior in airframe structures, and determining crack size and distribution parameters that could affect the safe life of aging aircraft. This information would provide the basis for determining required inspection techniques and intervals for old airframes and to provide a rational basis for safe life extension.

NASA has also developed NDI and evaluation methods that can be used for structural inspections and validation of analytical life prediction methods. Future NASA efforts will support the FAA in developing improved methods to assess the integrity of bonded structures, areas of corrosion damage, and possibly development of automated inspection and evaluation methods. This would increase the reliability of airframe inspections and enhance the safety of aging aircraft.

7.4 JAPANESE NUCLEAR AGING RESEARCH EFFORTS

The Japanese have established a number of research and development programs to address nuclear plant aging. These research and development projects, conducted as joint cooperation efforts between government and private organizations, are intended to improve the maintenance program currently used by the Japanese nuclear industry. A list of these research and development projects is provided in Figure 7.1. Included is information on the scope of the research and the organization responsible for the project.

Category	No.	Subject of Research and Development	Contents	Example of Subject Equipment	Working Organizations: Governmental	Utilities	Suppliers	Joint Work	Others	Remarks
1. Material	1.	Establishment of basic data bank for materials	To collect from literature and experiments and put in order basic data of materials (such degradation phenomena as cracking, fatigue, corrosion and strength reduction) as required for the evaluation of the feasibility of a long-term continuous operation of nuclear power plant, which will be used as a neutral data bank for a long time. Obtained data (data of degradation factors such as corrosion and fatigue) will be used for prediction of life.	RPV, SG, RIN, pipings, valves, etc.	(O)	O	O	(O)		-RPV: reactor pressure vessel SG: steam generator RIN: reactor internals -To establish private sector data base and public data base.
2. Degradation Diagnosis and Life Prediction	1.	Establishment of methods of predicting life of equipment and criteria for appropriate maintenance	To establish methods to reasonably predict and decide the remaining life of major equipment which can hardly be replaced, on the basis of checking, degradation diagnosis and basic materials data and maintenance criteria. To improve existing maintenance criteria based on the results of fracture mechanics, etc.	RPV, RIN, pipings, etc.	(O)	O	O	(O)		-To officialize evaluation methods and criteria developed on the results of studies of the private sector.

CODE: (O): Main responsibility on
O: Supported by

FIGURE 7.1. Research and Development Areas for Life Extension

Category	No.	Subject of Research and Development	Contents	Example of Subject Equipment	Working Organizations					Remarks
					Governmental	Utilities	Suppliers	Joint Work	Others	
2. Degradation Diagnosis and Life Prediction (continued)	2.	Establishment of technologies for monitoring critical equipment	To establish technologies for detecting and quantifying degradations of equipment critical to life extension, taking into account such characteristics as irradiation and operating conditions of a nuclear power plant. If necessary, to make experiments for demonstration.	PPV, PCV,	(0)	0	0	(0)		
	3.	Establishment of method of evaluating the soundness of concrete structure	To identify degradation mechanism and degradation diagnosis methods (destruction) of concrete structure and to establish degradation diagnosis methods, verification methods of soundness and life prediction methods.	Building, RPV pedestal, turbine frame, etc.		0	0	(0)	0	(construction)
	4.	Establishment of plant information retrieval system	To establish system capable of conveniently and readily approaching plant information to be accumulated as the life of plant is extended and to rationalize jobs for checking, maintenance and management.	General	(*) 0	0	0	(0)		(*)Related to improvement of nuclear power information

FIGURE 7.1 (continued)

Category	No.	Subject of Research and Development	Contents	Example of Subject Equipment	Working Organizations					Remarks
					Governmental	Utilities	Suppliers	Joint Work	Others	
2. Degradation Diagnosis and Life Prediction (continued)	5.	Evaluation by actual operating history of design thermal cycle	To give fatigue evaluation to design thermal cycle (low cycle) currently set with some allowance using actual operating history, to predict remaining life, and to improve a method of monitoring actual operating history.	PRV, RIN, primary pressure boundary, pipings, etc.		(0)	0			
	6.	Study of method to take surveillance test specimen	To establish a method to take test specimen at the time of service life extension according to Notice 501 and JEAC 4201 and an alternate method.	RPV, etc.	0	(0)	0			Method and time of taking: Utilities. Alternate method: Suppliers. Notice: Government
3. Replacement and Repairing	1.	Development of basic technologies for backfitting and repairment	To develop common basic technologies necessary for replacing and repairing rationally (when a process is shortened) equipment at the time of life extension in the future. As such basic technologies, the following are considered: • underwater welding • prearcing • underwater inspection • remote operability	General	(0)	0	0			Method to repair reactor internals in water is to be studied jointly by BWR utilities (1986 thru 1988)

FIGURE 7.1 (continued)

Category	No.	Subject of Research and Development	Contents	Example of Subject Equipment	Working Organizations					Remarks
					Governmental	Utilities	Suppliers	Joint Work	Others	
3. Replacement and Repairing (continued)	2.	Exposure reduction	To reduce exposure at the time of operation and maintenance against the increase of dose associated with long term operation of plant, by, for instance, improvement of water quality decontamination, shielding, remote automation, etc.			(O)	O			
	3.	Application of technologies for replacement and repairing high dosage major equipment	To establish, using mock-up equipment, technologies for checking, repairing and replacement of major equip- expected to require working under high dose.	SG, RIN, large diameter piping, etc.	(O)	O	O			
	4.	Application of technologies for replacing and repairing plant equipment	To shorten plant shutdown time at the time of life extension, by establishing technologies for rationally replacing and repairing (including handling, bring-in and removing-out technologies) major equipment within plant.	Buried pipings, turbine, etc.		O	O	(O)		

FIGURE 7.1 (continued)

Category	No.	Subject of Research and Development	Contents	Example of Subject Equipment	Working Organizations					Remarks
					Governmental	Utilities	Suppliers	Joint Work	Others	
4. Economics	1.	Study of necessity of life extension based on long-term power supply program	To study necessities of constructing, decommissioning and life extending nuclear power plants based on the projected economic growth, energy demands, etc.	General		(O)				
	2.	Development of long-term plant maintenance program	Plant life extension requires well-planned checking, maintenance and replacement, taking into account degradation of equipment and life cycle costs. To develop long-term program for the maintenance of plant for that purpose.	General		(O)	O			Maintenance of reliability up to life extension.

NOTE: Names of specific equipment and technologies will be reviewed by utilities in their joint research activities in the future.

FIGURE 7.1 (continued)

8.0 KEY FINDINGS

Safe and reliable power plant operation depends on a maintenance program that incorporates well-planned maintenance, assessment activities, and corrective action. The issue of age-related degradation spans every element of a maintenance program. A safety-related aging incident could be traced to poorly designed equipment, to an ill-planned maintenance schedule, or to antiquated maintenance techniques. As industries learn more about aging systems, structures, and components, their commitment to an effective maintenance program becomes increasingly important. Most important at this stage are methods for industry to apply aging issues to existing or developing maintenance programs. Based on our review of industrial and governmental organizations, four aging issues are central to a safe and effective maintenance program:

- the prioritized selection of critical systems and components
- understanding aging through the collection and analysis of equipment performance information
- mitigating aging with maintenance
- the use of feedback to improve the aging management program.

First, maintenance activities for systems and components must be prioritized. Section 3.0 discussed the importance of prioritizing systems and components according to safety significance. It also presented methods by which to determine safety significance. Several design concepts, when applied to systems and components, make such systems less safety-significant and thus reduce maintenance requirements. The fail-safe concept assumes that the failure of any single component will not cause a catastrophic failure of the equipment. Safe-life refers to the replacement of a part in accordance with its expected life, regardless of condition. Damage tolerance assumes that a damaged structure will continue to operate safely until the damage is detected.

Determining initial maintenance requirements is not enough to ensure proper maintenance. An effective maintenance program must conduct activities to collect and analyze equipment performance data. Such analyses allow one to better understand the effects of aging degradation on equipment. This information can be used to alter maintenance activities, upgrade schedules, or replace equipment. Section 4.0 discusses several examples of analysis activities. For example, the Japanese nuclear industry has implemented the Plant Life Extension Program to test critical equipment for age-related degradation.

Once maintenance requirements are determined, it is also important to select and perform the appropriate types of maintenance activities. Section 5.0 discusses three maintenance processes that are particularly applicable to aging. On-condition monitoring is a scheduled inspection to determine condition. This test is designed to detect potential failures caused by aging degradation. Hard-time restoration places an age limit on each part after which it is replaced, regardless of condition. Age limits are determined through equipment performance analysis programs such as those described in section 4.0. Condition monitoring is used only for redundant systems and components. In this case, the equipment is allowed to operate until a failure occurs, since this failure will not affect system safety.

Finally, an effective maintenance program must include a system of feedback and corrective actions. Such a system helps to ensure that maintenance programs incorporate the most current information on aging and other safety issues. These systems vary among industries. The aviation industry, for example, has recently created an Airworthiness Assurance Task Force which studies aging-related safety incidents and recommends corrective actions to airline maintenance programs. Section 6.0 provides initiatives from other industries that have also worked to improve maintenance programs.

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