ASME RESEARCH

Risk-Based Inspection Guidelines

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In-service inspections can play a significant role in minimizing equipment and structural failures. However, for many components that are required to maintain pressure boundary integrity or that are subjected to severe service conditions in the nuclear power, fossil-fired power, and the petroleum and chemical processing industries as well as other applications, in-service inspection requirements are either established based upon prior experience and engineering judgment or are nonexistent. Most in-service inspection requirements or guidelines, if they exist, are usually established with only an implicit consideration of risk-based processes and information, such as the likelihood of failure for the plant-specific material, operation, and loading conditions, and of the consequences of component failure. All aspects of inspections, that is, objectives, method, timing, and acceptance criteria, can significantly affect the likelihood of component failure.

Catastrophic structural failures over the past decade such as pipe ruptures in fossil-fired generating stations, tank failures in the processing industry, collapsing bridges, and the breakup of major aircraft components while in flight highlight the need to more explicitly relate risk to inspection programs.

Given this situation, the ASME Codes and Standards Research Planning Committee suggested that a research program be initiated to determine how risk-based methods could be used to establish inspection requirements and guidelines for systems and components of interest to mechanical engineers. This article outlines the research program that was approved by the ASME Board on Research and Technology Development and the ASME Council on Codes and Standards.

The fundamental objective of this research program is to use risk-based methods for developing inspection guidelines that maintain safety, while being cost-effective, for new or revised ASME codes and standards. These methods include developing processes such as probabilistic risk assessment and probabilistic structural mechanics. (For further discussion of these methods, see the November 1984 and July 1986 issues of *Mechanical Engineering.)* This research work is being performed for areas ranging from systems and components in nuclear and fossil-fired power stations to those in aircraft.

In order to meet the short- and long-term objectives of the ASME research project, a two-phase program is being applied. Phase 1 is primarily providing the general document that recommends and describes appropriate methods for establishing risk-based inspection guidelines for any facility or structural system in conjunction with an appendix document. The appendix document will recommend and describe specific methods for supporting ASME Section XI of the Boiler and Pressure Vessel Code in utilizing risk-based inspection methods for the review of inspection requirements at nuclear power facilities. In addition, other areas of interest to ASME where structural failures have the potential to result in a large human or economic loss, are being prioritized for consideration in Phase 2.

Phase 2 will involve the preparation of additional appendix documents that recommend and describe

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specific risk-based methods for use in preparing new or revised codes and standards to establish inspection guidelines for non-nuclear facilities or other structural systems.

A paper entitled, "Probabilistically-based Inspection Guidelines," which was presented at the Risk Analysis Forum as part of the 1986 ASME Winter Annual Meeting, served as a starting point for the project. The paper provided a review of current inspection requirements for systems and components in several industries and identified some of the risk-based methods that are currently available for the development of guidelines for cost-effective inspections.

In accordance with the research plan, a simplified, but comprehensive, risk-based process has been developed for outlining the scope of inspections for components in any given system. An enhanced failure modes, effects, and criticality analysis methodology has been developed to obtain information for prioritizing what should be inspected and determining where to look. This tool integrates information on prior operating experience and inspection results, if any exist, with the identification of potential degradation mechanisms, failure modes, and effects. It ranks each component based on risk by combining the likelihood and consequences of component failure. Simplified methods for defining the timing and approach that should be used to perform the inspection of an important component are currently being developed. Extension of these methods to nuclear power plant vessels and piping systems is also currently being researched.

Examples from the applications that are being drawn upon for the research program are discussed below. Use of risk-based inspection methods for examining nuclear power plants through marine ship hull structures typifies some of the technology that is being explored in the research program.

Inspection Program

A program is currently being implemented, by the U.S. Nuclear Regulatory Commission, for inspections dealing with operational safety verification, maintenance, and surveillance observation requirements for nuclear power plants. Although this program can enhance the inspections that are performed to find flaws and evaluate degradation mechanisms for insuring the pressure boundary integrity of components, these inspections are generally outside the scope of the Phase 1 research effort. The objective of this program, as stated in the current NRC Five Year Plan, is "to assess licensees' operation of nuclear power plants to ensure safe operation of the facilities in accordance with NRC regulations." An underlying objective supporting this overall objective is, "to ensure that the finite resources available for inspections are efficiently and effectively allocated to enhance reactor safety." A key element in this program is the use of insights from probabilistic risk assessments (PRAs) to focus inspection activities on the most risk-significant areas and issues.

Risk insights obtained from PRAs are incorporated into this program in two major ways. First, plant-specific "Risk-based Inspection Guides" are being prepared which identify the most risk-important systems and components at each plant. This information is provided to NRC resident inspectors for use in planning their routine plant inspection activities. Second, risk information from PRAs is being used directly in the planning and performance of team inspections by NRC regional and headquarters inspectors. Additional analysis of PRA information is required for both of these uses. In support of these activities, the NRC is providing additional training to inspection personnel in understanding and applying the information which is provided in PRAs.

To support the NRC risk-based inspection program, a five-day course has been developed that introduces NRC resident inspectors to event trees, fault trees, and the calculation and interpretation of risk importance measures such as the Fussel-Vesely and Birnbaum importance measures. It also introduces them to the extensive qualitative information on safety systems which is presented in PRAs, including the systems descriptions, dependency diagrams, success criteria, common cause-failure relationships and dominant event sequences. Major insights obtained from PRA analyses performed to date are also presented.

This course provides the inspectors with the ability to understand and selectively extract information from PRAs, without being overwhelmed by multivolume reports or intimidated by the terminology. It also introduces the inspectors to the Risk-based Inspection Guides, and to the method of analyzing PRA information used to develop inspection

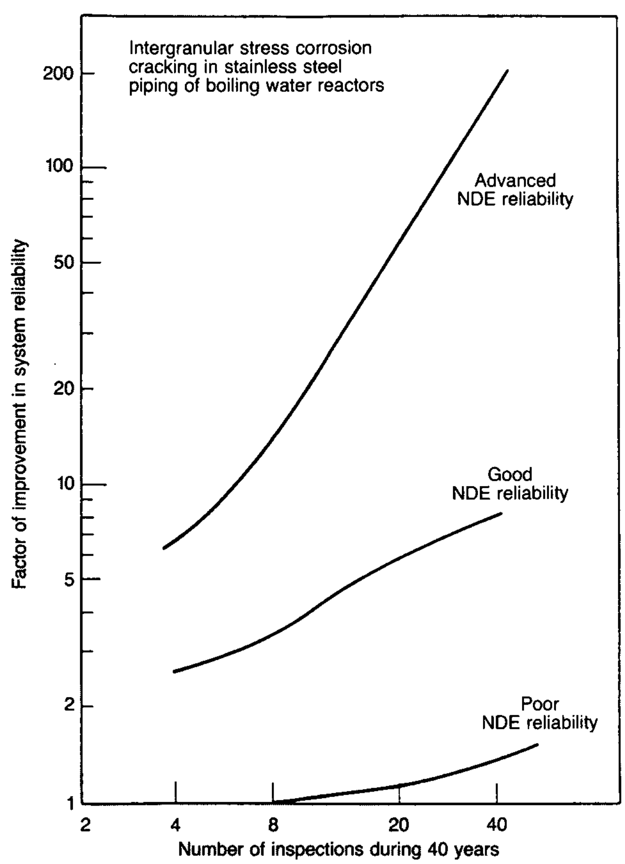

Figure 1. Piping reliability is enhanced by improvements in nondestructive examination (NDE).

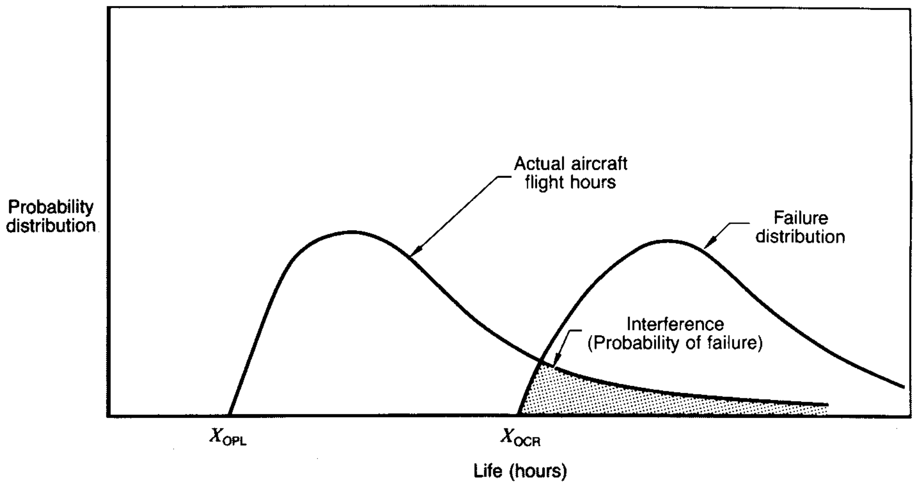

Figure 2. In predicting risk of structural failure, the probability of failure is determined from two Weibull distributions. The shaded area indicates a finite probability of failure whose magnitude is a function of the degree of overlap of the two distributions.

plans for risk-based team inspections.

The Risk-based Inspection Guides present risk information derived from plant PRAs in a format which does not require PRA knowledge to understand or apply. The format has been developed to be immediately useful to NRC resident inspectors in planning and performing their routine inspection activities, and in evaluating the risk significance of inspection findings and operational events. Guides have been, or are being, produced for all plants for which PRAs are available to the NRC.

Each guide presents a discussion of the most risk-important accident initiators for the plant, followed by descriptions of the dominant accident sequences that lead to core melt. When possible, plant design features that cause unusual vulnerabilities to specific accident initiators are identified.

This discussion is followed by a listing of plant systems associated with 98 percent of the inspectable risk of core melt. This list is ordered two ways according to two different risk importance measures. These are the fraction of the total core melt frequency to which failures of components in each system contribute (the Fussel-Vesely Importance Measure), and the probability of core melt assuming that the system has failed (the Birnbaum Importance Measure). These prioritization schemes are based on the failure probabilities used in the PRA analysis, and inspections are performed to prevent degradation of these probabilities.

For each of these risk-important systems, a brief system description is provided, along with other important information provided in, or developed from, the PRA. For each system, risk-important components are tabulated and inherent major failure modes are described. Single failures and unusual system vulnerabilities identified from the PRA are also noted.

In addition, an abbreviated system walkdown checklist is provided addressing only the risk important components. This table allows the resident to perform relatively rapid system inspections which address most of the risk associated with the system.

Cross-reference tables are also provided which list the component failure modes relevant to specific types of inspection efforts such as maintenance, surveillance, and operator actions.

Since not all plants have PRAs available for analysis, a technique has been developed to produce inspection guides for those plants. It uses insights from published PRAs regarding the risk importance of safety and support functions to infer the risk-important systems and components at other plants. Test comparisons between guides produced this way, and guides produced by analyzing the PRAs directly, indicate that this procedure produces meaningful and useful risk-based inspection guidance when PRA information is not available.

The NRC's Risk-based Operational Safety and Performance Assessment inspection procedure utilizes risk information presented in a power plant PRA to structure and prioritize the inspection activities of a team of technical experts engaged in an extended inspection of one to several weeks. A methodology is provided for the identification (from the PRA) of risk-important components and important accident mitigation and recovery actions to use in assessing the operational readiness of the power plant.

This inspection procedure focuses on determining whether or not the plant is operated and maintained in such a way that: plant challenges are minimized; safety systems, equipment and components will be available, reliable, and operable; plant operators are capable of recognizing and responding appropriately to plant challenges, and capable of conducting timely and effective accident mitigation and recovery actions; and the licensee has appropriately factored available risk information into the plant's programs, procedures and design.

The procedure describes how PRA information should be used to rank the risk importance of component and operator failures (basic events), based on the core melt frequencies associated with the dominant cut sets. Initiating events, component and instrumentation failures, and operator errors and recovery actions are all addressed. Based on this information, the lines of inquiry of the inspection *and* the composition of the inspection team are to be driven by the PRA information. An impor-

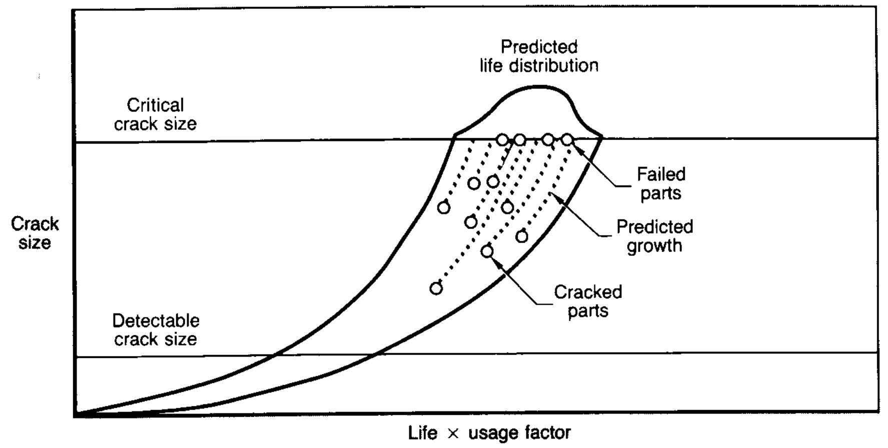

Figure 3. Based on a field inspection of aircraft, a crack growth curve is used to help build the aircraft failure distribution.

tant aspect of this inspection procedure is that it addresses operator performance in recognizing and responding to off-normal situations, and in mitigating the effects of accidents. Risk-important accident sequences from the PRA are used to develop simulator scenarios, which are then used to test the responses of plant operators and the adequacy of the plant procedures for coping with the accidents.

Inspection in the U.K.

One of the most active areas in the United Kingdom with regard to in-service inspection and safety assessment is the extended life justification of the Magnox generation of nuclear installations. The basis for extended life of these installations is the long-term safety review. As part of this review, an extensive amount of ultrasonic inspection has been carried out mainly on gas ducting but also on a limited amount of thicker boiler shells. The philosophy of this inspection, however, has not been based on any probabilistic analysis. Instead, the philosophy has been first to carry out a sample inspection of all the different features, concentrating particularly on welds. Following this, if type defects are detected, all such features are inspected; otherwise it may be judged that no further inspection is required, at least in the short term. While it has been said that no probabilistic method has been applied to this inspection, it does not take a very skilled eye to see that there are inherent probabilistic assumptions in the procedure.

In the U.K. nuclear submarine program, a probabilistic-based approach has been employed to both optimize and measure the gain in confidence from in-service inspection. The model uses an expert system together with mathematical modeling to form an initial best estimate of the start-of-life defect distribution for welds. The through-life history is then applied to arrive at an end-of-life failure probability. A series of inspection programs can now be applied through life and their effect on the failed probability measured. Clearly, the results and conclusions about the optimum inspection depend on the initial assumptions and judgments in the original program. In order to overcome this, once an inspection program is set out and results become available, a Bayesian logic is applied to gain confidence in the initial defect distribution and through-life prediction.

Outside of the nuclear field, there appears to be little if any significant movement toward a risk-based inspection logic. The exception to this is the inspection of the North Sea oil rigs. Here, a method very similar in principle to that discussed for the nuclear submarine program has been used. Crack initiation followed by crack growth is the assumed failure mechanism, meaning that no initial defect distribution for the joints is required. Having built the probabilistic model, a series of inspection programs can be simulated to arrive at an optimum program. As with the previous case, the optimum program is a function of the basic assumptions and so, again, Bayesian logic is used in a feedback loop to gain confidence in these assumptions.

In both the above applications of probabilistic-based inspection, the driving force for optimization is the need to minimize risk to human operators, be it from the obvious dangers of the North Sea or the less tangible dangers of irradiation. However, since the objective is to obtain the best return for a given effort, it would seem perfectly logical to extend optimization considerations to include financial factors.

NDE Reliability

The detection of defects by nondestructive examination (NDE) is often a difficult task, particularly if safety requirements dictate a high level for the probability of detection for crack-like defects. To quantify the reliability of current and improved NDE methods, the NRC has supported a long-term research program at Pacific Northwest Laboratory. Research results have revealed a number of serious shortcomings in industry practices for field inspections. More importantly, the nuclear power industry has benefited from resulting upgrades to the *Rules for Inservice Inspection of Nuclear Power Plant Components* as spelled out in Section XI.

Figure 1 shows how enhanced NDE reliability can improve the safety and reliability of reactor piping systems. Fracture mechanics calculations have predicted rapidly growing stress corrosion cracks in the stainless steel pipes of boiling wa-

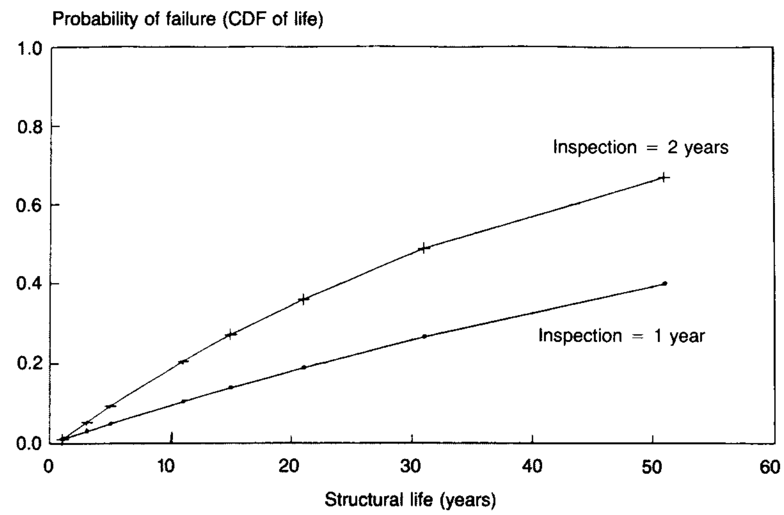

Figure 4. To estimate the life expectancy of structures, a cumulative probability distribution function (CDF) is used. This figure shows the CDFs of structural life for an example marine vessel under two strategies: inspection every year and inspection every two years.

ter reactors. Timely detection and repair of these cracks can lead to marked enhancements in system reliability. The performance of field inspection teams was first carefully measured in a controlled testing environment. Performance data for the top teams (good NDE reliability) were statistically quantified and proven to be clearly superior to the corresponding performance of the least qualified teams (poor NDE reliability). As indicated in Figure 1, the good NDE performance can dramatically improve the piping reliability by nearly a factor of 10.

Furthermore, the expected gain in performance from new and improved technology (advanced NDE reliability) can provide yet another factor of 10 improvement in piping reliability. Since the advanced inspections can also be performed less frequently, improved technology is a winning proposition for cost-benefit reasons, mainly because costly reactor downtime is significantly reduced.

Quantitative risk techniques are also currently being developed in other countries, such as Sweden and West Germany, taking into account NDE requirements for reactor system components.

For secondary piping systems, personnel at Point Beach Nuclear Plant, near Two Rivers, Wis., have developed an in-service inspection program to detect and quantify significant service-related degradation and pre-existing conditions that could jeopardize the integrity of those systems in the future. A Badness Factor Program has been developed to rank components on their susceptibility to erosion-corrosion and stress-induced fatigue. It uses hydrodynamic variables to assign a factor to each component and pipe fitting so that a comparison of the relative magnitudes of this factor can be made for a given system or piping section. Although a qualitative decision is then made to identify locations for degradation, the approach provides useful insights for development of a quantitative risk-based approach to optimizing the inspection of the thousands of locations within these systems.

Fossil-fired Components

The potential off-site consequences of component failures in fossil-fired power plants are much less severe than those for nuclear power plants or even some petrochemical plants. Consequently, a higher level of failures may be acceptable. This, along with the large population of fossil plants and the long time period over which such plants have operated, has led to a relatively large reliability experience base in fossil plant components. Consequently, in-service inspection of fossil plant components (where and when to inspect) is largely based on past experience, including experience with a given plant, or within a given utility, or among groups of utilities. Information on failures is shared among utilities, through channels such as the Edison Electric Institute or the Electric Power Research Institute. News of dramatic and unusual failures travels quickly through the utility industry and often leads to a rapid, concerted inspection and mitigation effort to avert similar failures at other plants. Turbine rotor failures and recent reheat steam line failures are examples of this.

Since modern day safety issues involved in fossil plant component failures have been relatively minor in terms of public risk, inspections are more focused towards minimizing costs. Forced outages of a plant are much more expensive than planned outages, which can occur at times of reduced power demands, such as during the spring and fall. Consequently, in-service inspections of fossil plant components are aimed to a large extent at averting failures that lead to forced outages.

Component repair or replacement occurs routinely during a scheduled outage and is usually less expensive during a scheduled outage than during a forced outage. Some components in fossil plants have useful lifetimes that are much less than the useful lifetime of the plant and are replaced routinely, preferably during a scheduled outage. Examples of this are waterwall tubes and superheater/reheater tubes. Failure of some tubes during service can be tolerated, with subsequent repair during the next scheduled outage. Inspections of tubes are often performed, with the frequency and location of inspections based on past experience. The results of such inspections assist in planning repairs during the current and future outages.

Some components are inspected during planned outages to detect potential problems that have been identified in other plants. Examples of this are thick-walled boiler components (headers) and seam-welded reheat lines. Such inspections are aimed at minimizing the likelihood of a forced outage as well as the potentially disastrous on-site consequences of a failure. The results of these inspections are intended to foresee a problem and to allow for timely acquisition of replacement parts.

Still other components are occasionally inspected during planned outages because of generic potential problems with that component. Prime examples are the rotor, disks, and blades of the steam turbine, and the rotor and retaining rings of the generator. Inspections of turbine components, especially the disks and rotors, are performed to identify potential problems of material degradation—especially cracking. Early detection of problems allows repair or replacement in a timely manner, thereby minimizing the costs of forced outages, as well as the potentially severe on-site consequences of a rotor failure. The lead time for acquisition of replacement parts can be years, so early warning of an impending necessary replacement is needed. Also, the cost of repair may be much greater if damage is allowed to progress. The results of inspections also provide valuable inputs to run/retire decisions. Such decisions are becoming more common in conjunction with life extension efforts for installed fossil generating capacity, and increased emphasis is being placed on periodic inspections as older plants are continued in service.

Aircraft Structures

Tactical fighter aircraft are designed for a finite lifetime using a baseline, or design, flight spectrum. This spectrum represents the typical mission profile for the aircraft. The actual lifetime of any particular aircraft, however, will depend not only on the number of flight hours, but also on the severity of the usage. An aircraft that is flown very hard (many high *g* maneuvers) will expend its design life much faster than an aircraft that undergoes a very benign flight spectrum. The rate of increase or decrease in life expenditure is directly proportional to the severity of usage and is referred to as the usage factor. The flight hours of each aircraft must be multiplied by the usage factor, prior to making any comparisons between aircraft historical data.

When making predictions of risk of structural failure, the usage factor must be accounted for prior to determining the statistical distributions. Three-parameter Weibull distributions are used to model both the failure distribution and the aircraft flight hour distribution. The failure distribution must be determined from fleet inspection data, and is generated for each critical (or inspection) point in the aircraft. The probability of fail-

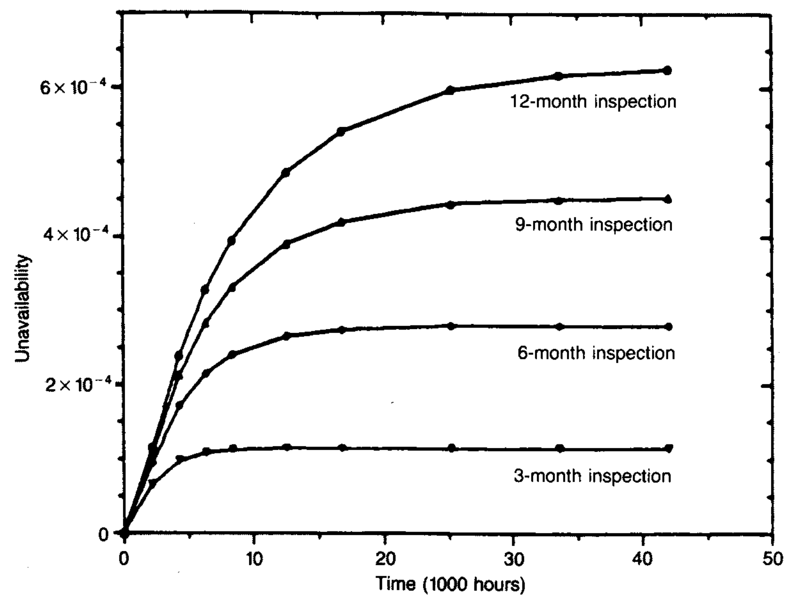

Figure 5. Low water level probability as a function of inspection interval for a water-tube boiler.

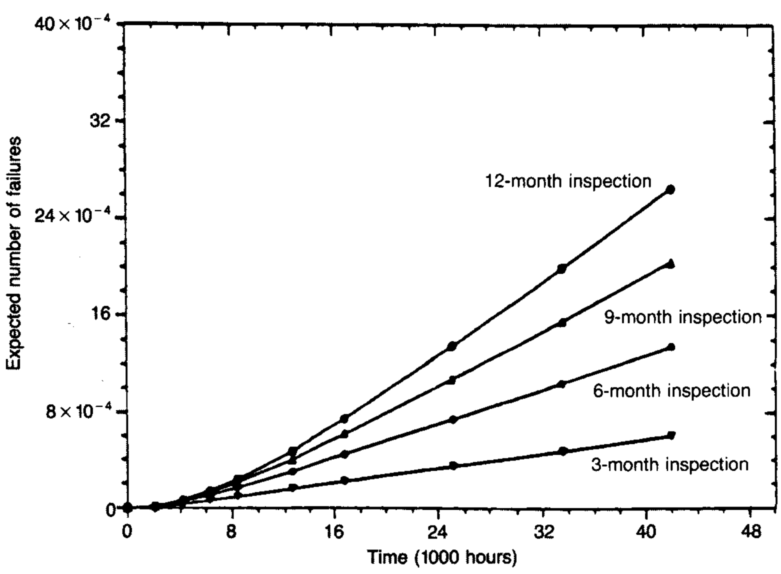

Figure 6. Expected number of failures as a function of inspection intervals for a water-tube boiler.

ure is determined from the two Weibull distributions, as shown in Figure 2. The shaded area indicates a finite probability of failure whose magnitude is a function of the degree of overlap of the two distributions.

Aircraft are inspected in the field at a number of critical points in the structure. The critical points are presently identified by the aircraft manufacturer based on the assessment of loads data from finite element models, structural details such as holes and cutouts, and past experience. Detailed analysis and testing are performed for each of these locations to produce a crack growth curve. The crack growth curve is used to help build the aircraft failure distribution for the specific critical point of interest.

A field inspection of a critical point will yield either no crack, a crack of noncritical size, or a crack of critical size. No-crack data points enter the analysis as suspended items, critical size cracks are treated as failures, and noncritical cracks are projected to critical size using the crack growth curve, as shown in Figure 3.

With the two distributions determined, the fleet commander can perform a number of different analyses to assist in the management of the aircraft fleet. Maintenance and inspections can be scheduled, the significance of inspection data can be assessed, and the risk of failure for additional flight hours and modified usage can be determined.

Marine Structures

Inspection and maintenance methods have large effects on structural life expectancy and extension. The estimation of structural life is not a simple task. Many factors affect the life expectancy of a structure. In the marine structures industry, these factors include design parameters, design safety factors, design methods, structural type, structural details, materials, construction methods and quality, loads including weight, water pressure, waves, engine and propeller vibrations, maintenance practices and levels, inspection methods, and other environmental factors. The estimation of structural life expectancy can be based on selected failure modes.

All possible failure modes of a structure need to be identified. Then the most critical failure modes should be selected and structural life based on these failure modes can be determined. A methodology of structural life assessment was suggested by Ayyub, White and Purcell [1]. The methodology is based on probabilistic analysis using reliability concepts [2], White and Ayyub [3,4], and the statistics of extremes. The methodology results in the probability of failure of the structural system according to the identified failure modes as function of time, that is, structural life. The results can be interpreted as the cumulative probability distribution function (CDF) of structural life. Due to the unknown level of statistical correlation between failure modes, limits or bounds on the CDF of the structural life were established. The limits correspond to the extreme cases of fully correlated and independent failure modes. For example, the CDFs of structural life of an example marine vessel were determined for two inspection strategies: namely, inspection every year and inspection every two years with a warranty inspection at the end of the first year. Example results are shown in Figure 4.

In the area of civil engineering, probabilistic fracture mechanics models were used to determine the risk of failure of steel highway bridges and to establish inspection and maintenance strategies. Other examples include reliability-based design and inspection of debris basins (for mudflows), public transportation systems, and pipeline networks.

Industrial Insurance

Probabilistic engineering risk analysis methods have been employed in progressive branches of industrial insurance to efficiently and economically assess the risks associated with loss prevention and property conservation. An example of the application of these methods is the occurrence rate of undetected low water level conditions in water-tube power boilers. Conventional control and safety systems have been compared with programmable electronic systems. The reduction in the expected number of undetected low water level conditions with increasing frequency of inspection and preventive maintenance was quantified, as shown in Figures 5 and 6. The applied methodology included failure modes and effect analysis, fault tree analysis and uncertainty analysis. Sources for component failure rates included Factory Mutual Research Corp. data, other published record data, and expert opinion. The results of the study indicated, among other things, that inspection frequency of the control system considerably affects the expected number of failures (ENF) within specified time frames. Quarterly versus annual maintenance provides more than a factor of six improvement for a low water fuel cutoff (LWFC) system that includes a sight-glass water level monitoring system. Further improvements in ENF are obtained by installing a second LWFC system or by substituting a conventional LWFC system (with a rate of 769 failures per million hours) with electronic systems demonstrating proven lower failure rates.

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The technology that was used to develop the NRC operational safety inspection program can be extended to establish the scope of inspections for finding flaws and evaluating degradation mechanisms in stressed components based on the estimated likelihood and consequences of failure. The Point Beach Badness Factor Program can also lend some insight into defining the scope of inspections for systems with multiple degradation mechanisms. The risk-based inspection work in the U.K. and the fossil-fired power plant component, aircraft structure, civil engineering structure, and industrial insurance applications can be drawn upon to assist in determining the frequency of and defining the methods for inspection. Finally, the NDE reliability studies provide a quantitative methodology for evaluating the effectiveness of inspection personnel, procedures and equipment on component failure rates. The primary research effort is to integrate all of this technology into a useful methodology for developing inspection guidance based on risk for any plant or structural system.

The benefits associated with the use of risk-based technology are not the little numbers that are generated. Rather, the benefits are the insights that are gained in working through these processes and the improvement in communications between the disciplines that are involved to maintain a high level of safety within the affected industries and for society in general. ■

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