LIFE EXTENSION

INTRODUCTION

This material examines techniques for determining equipment expected remaining life and, when necessary, extending that life. The goal is to assist management in determining when increased catastrophic failure probability, caused by aging of major structural parts, requires attention.

A life extension program provides technical rationale for allowing aging equipment, particularly equipment beyond its nominal life expectancy, to continue to operate. Such a program is distinctly different from routine maintenance. Routine maintenance prevents losses by detecting and correcting problems with “wear parts” such as bearings.

POSITION

Management should establish programs to determine and monitor the expected remaining life for major equipment. Proper maintenance will provide much of the data needed to calculate expected remaining life; however, the analysis required to control remaining life must begin before 75% of the nominal life expectancy is over.

Accurately calculating expected remaining life requires knowing the operating history. To accurately calculate expected remaining life, all operating parameters must stay within the design limits, and local conditions in critical areas must be continuously monitored. Document any abnormal operation. Table 1 lists examples of parameters that must be controlled and monitored.

Life extension programs should be based on risk. Risk is the product of the failure probability and consequence cost, and is the basis for selecting areas or components for improvement or further inspection.

Unless otherwise clearly specified and justified by the manufacturer, nominal life expectancy should not exceed the limits shown in Table 2.

TABLE 1

Example Of Critical Control Parameters

Object	Parameter	Control(s)	Measure(s)	Potential problem(s)
Boilers	Pressure	Pressure control, pressure limiting control, safety valve	Pressure gauge	Plastic deformation
	Metal temperature	Firing rate, fireside condition, water chemistry	Local thermocouples	Creep, local plastic deformation, metallurgical damage
	Temperature rate-of-rise	Firing rate	Calculated	Plastic deformation, thermal fatigue
	Chemistry	Operating practice	Regular analysis	Corrosion and erosion; has system-wide affects
Steam Turbines	Pressure	Boiler controls, blading conditions	Pressure gauges	Plastic deformation
	Temperature	Boiler controls	Local thermocouples	Creep, local plastic deformation, metallurgical damage
	Temperature rate-of-rise or -fall	Operating procedures	Calculated	Thermal fatigue
	Speed	Governor, overspeed trip	RPM (Hz) meter	Plastic deformation, crack initiation
Combustion turbines	Temperature	Various	Local thermocouples, calculated	Creep, local plastic deformation, metallurgical damage
	Temperature rate-of-rise	Operating procedures	Calculated	Thermal fatigue
	Speed	Governor, overspeed trip	RPM (Hz) meter	Plastic deformation, crack initiation
Generators	Temperature	Load, cooling system	Local thermocouples	Insulation system degradation
	Speed	Governor, overspeed trip	RPM (Hz) meter	Plastic deformation, crack initiation
Transformers	Temperature	Load, cooling system	Thermometer(s)	Insulation system degradation
	Insulating fluid condition	Various	Periodic analysis	Insulation system degradation

TABLE 2

Nominal Life Expectancy For Selected Equipment

EQUIPMENT TYPE	NOMINAL LIFE EXPECTANCY
Power and rectifier transformers	30 yr
Arc Furnace Transformers	12 yr
Combustion turbines 0.2 or more starts/fired h	10 yr
Combustion turbinesless than 0.2 starts/fired h	20 yr
Steam turbines	30 yr
Water turbines	35 yr
Internal combustion engines	30 yr
Generators, mechanical parts only	Same as driver
Generators, windings	30 yr
Electric motors	30 yr
Boilers and pressure vessels greater than 900°F (480°C) 30 yr	20 yr
Piping greater than 900°F (480°C)	20 yr

Include the following components in life extension programs for equipment listed in Table 2:

- Rewind transformers, motors and generators at the end of their nominal life expectancy.
- Sample or replicate any metal component, including superheater components, high pressure turbines, etc., that operate above 900°F (482°C) to establish the present state of creep-related damage. Stress and fracture mechanics analysis should be used to predict probable remaining life based upon crack initiation and propagation.
- Sufficiently inspect any component subject to mechanical or thermal fatigue to establish the present state of damage. Stress and fracture mechanics analysis should be used to predict probable remaining life based upon crack initiation and propagation.
- Inspect thoroughly any component subject to environmentally assisted corrosion, such as austenitic stain less steel tubes or 18Mn-5Cr generator retaining rings for onset of cracking. Spot check pressure components and completely inspect rotating components.
- Evaluate forged or welded turbine rotors. Perform complete nondestructive testing of rotor surfaces, rotor bores and blade attachment points. Stress and fracture mechanics analysis should be used to predict probable future performance based upon crack initiation and propagation. Contour adjustments should be provided as needed.
- Unstack and inspect built-up turbine rotors for disk bore and keyway cracking and fretting.
- Deblade all turbines and perform complete nondestructive testing, and stress analysis. Redesign nozzles, diaphragms and blades or buckets for any turbine with adverse experience. Completely inspect and perform a stress analysis for casings, throttle valves and other steam or hot gas path components.

DISCUSSION

Background

Most plant equipment was normally expected to have a 20 yr – 30 yr life for at least three reasons.

- Most equipment failure rates follow the “bathtub curve.” (See Figure 1.) After an initial high failure rate, there is a long period of low failure rate, followed by an increasing failure rate signaling “wear out” or end of life.
- Technological developments have made new units available that are significantly more efficient.
- Until recently, analytical tools available to designers have not allowed for life expectancy predictions beyond 20 yr – 30 yr.

Upgrading equipment rather than replacing it has become an increasingly favored option. Improved inspection techniques and analytical tools have opened the door to more accurately determine local stresses and predict long term performance.

Aging

Equipment deteriorates during operation. Bearings degrade, boiler tubes thin and electrical insulation becomes brittle. Maintenance personnel manage deterioration by inspecting and repairing components that are expected to deteriorate. Local deterioration that is expected, based upon previous experience, is called wear.

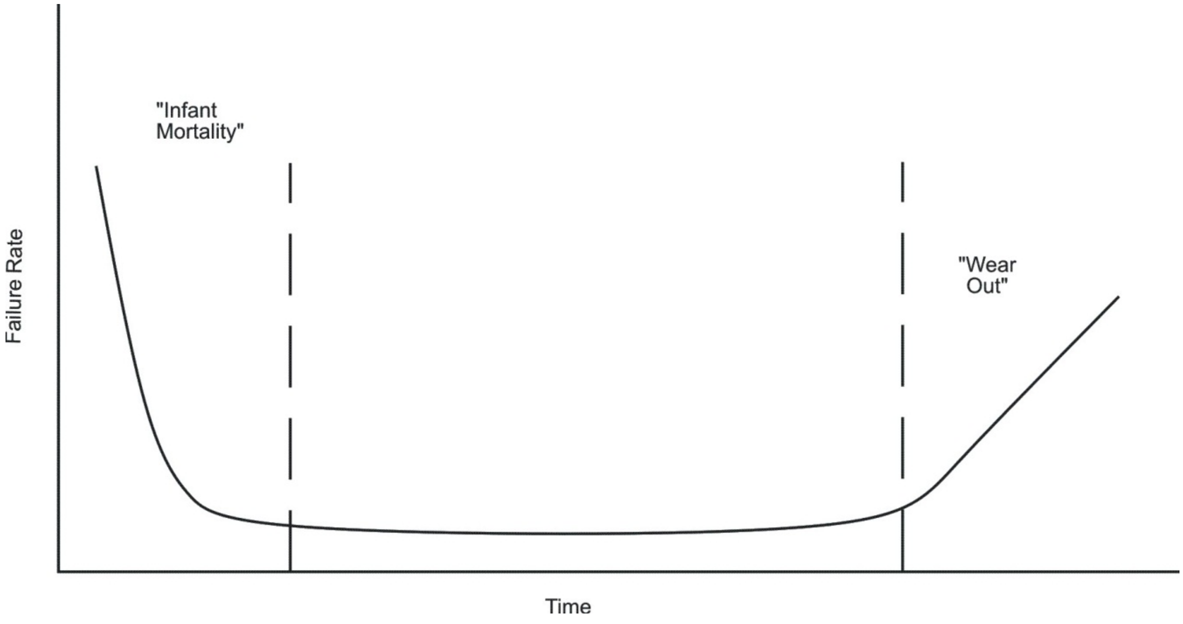


Figure 1. Typical Equipment Failure Rate Curve.

However, major components can accumulate damage that normal maintenance inspections do not detect. Or, grouped components, such as boiler tubes, can deteriorate and, as a result, large numbers of components can be found deficient during a single inspection. Large-scale deterioration over time, caused by service and the environment is called aging.

Wear and aging are related. Economic factors often determine whether a particular form of deterioration is considered wear or aging. For example, a few boiler tubes thinned by erosion and requiring replacement would clearly be wearing. All the tubes in the boiler thinned by erosion and requiring replacement would clearly be aging. If 50% of the tubes in the boiler are thinned by erosion and require replacement, two choices are possible: eliminate wear by replacing the eroded tubes, or eliminate the aging due to boiler tube erosion by replacing all the tubes.

End Of Useful Life

Uncontrolled wear and aging will eventually produce equipment conditions that will no longer allow the equipment to operate safely. Even if wear is controlled by proper maintenance, aging may render equipment unsafe.

Every piece of equipment ages differently and can reach its end of useful life in three ways:

- Accumulated damage can produce conditions in a major component that prevent the equipment from being safely operated.
- Grouped components can deteriorate to the point where the effort needed to inspect and replace individual components becomes intolerable, or the components begin to fail in service between inspections.
- A catastrophic failure can damage the equipment beyond repair.

Nominal Life Expectancy

Equipment has a nominal life expectancy determined by accepted industry practice and experience, based on design specifications. The design life may or may not equal the nominal life expectancy.

Nominal life expectancy and design life are point values.

Expected Remaining Life

Each piece of equipment also has an expected remaining life. Expected remaining life is a range of values or a probability distribution. It is the period of time after which the probability of failure becomes unacceptably high. The expected remaining life of new equipment is a relatively wide band, generally centered on the design life. (See Figure 2.)

As equipment ages, damage accumulates. The accumulated damage can be measured, the equipment operating history analyzed, and a more refined estimate of remaining life calculated, using techniques described in this section. The sum of operating time and the most probable expected remaining life may or may not equal the original design life. And the expected remaining life, while still a range or probability distribution, will probably be more precise. (See Figure 3.)

Calculating expected remaining life generally involves identifying four areas:

- Part(s) of the equipment that will limit its continued service.
- Damage mechanism(s) that will cause the limiting part(s) to fail.
- Inspection techniques that will locate damage and characterize the extent of damage.
- Mathematical model(s) of the equipment or its structure that can use the equipment history and existing condition to calculate its expected remaining life.

The basis for calculating expected remaining life may not be clear. An original equipment design life may not have been specified, or the basis for the original design life may never have been defined in easily measurable terms. The life status may be further complicated by equipment operating and maintenance history.

Life Extension

Although some 100 yr old equipment is still in service, other equipment cannot be safely operated beyond ten years. If the calculated expected remaining life is not acceptable, repair techniques can stabilize or eliminate the damage. It is possible to replace components, or to perform heat treatment, isostatic pressing, reshaping and weld overlaying and other damage reversing or damage limiting operations.

The calculated expected remaining life shown in Figure 3 indicates that the equipment will probably not reach its design life. The cause of the unexpectedly rapid aging may be found and corrected and the damage may be repaired, increasing the expected remaining life. (See Figure 4.) This is called “life extension.” Note the expected remaining life, while longer than before, is less certain.

If the life extension program continues, with further inspections, repairs, and expected remaining life recalculations, the situation may resemble Figure 5. The expected remaining life is well beyond the original design life.

Figure 2

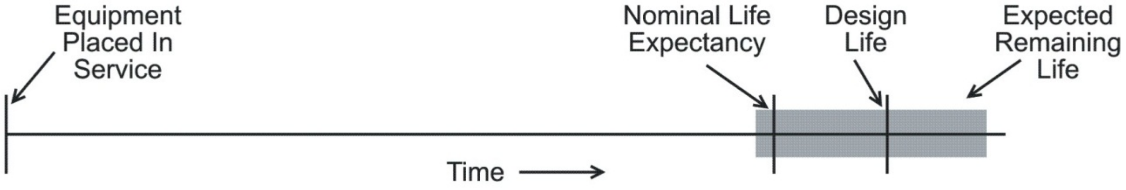


Figure 3

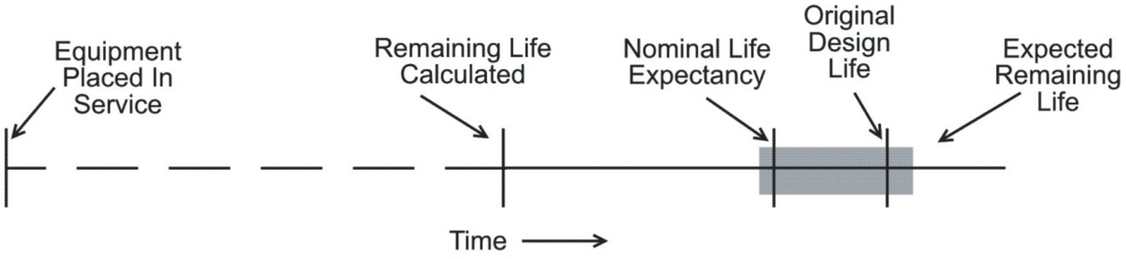


Figure 4

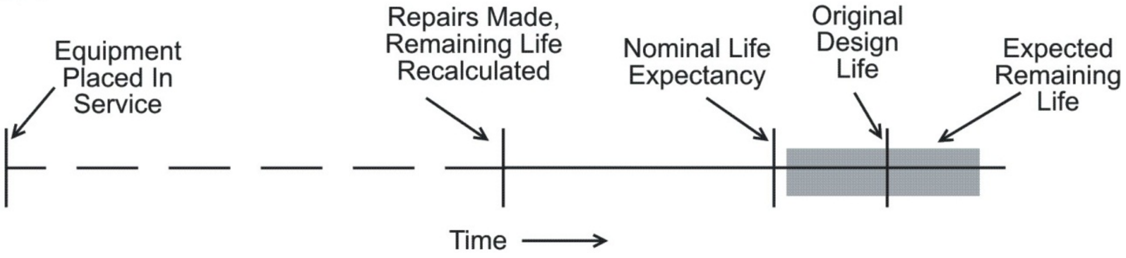
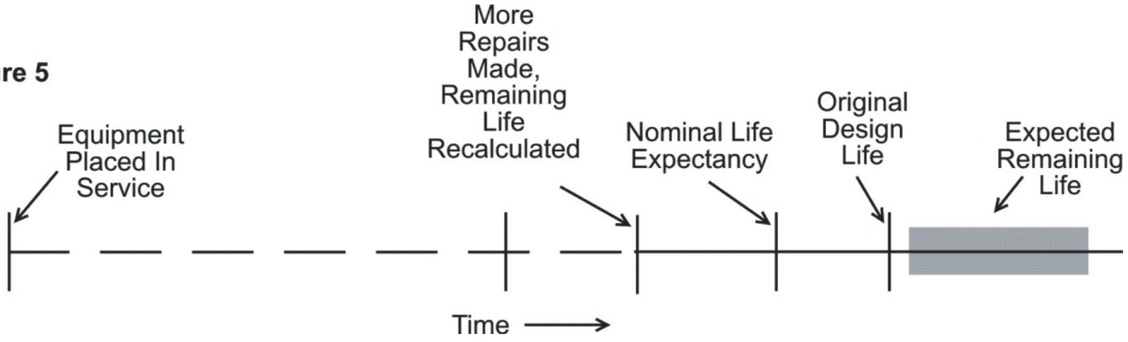


Figure 5



Figures 2-5. Expected Remaining Life (With And Without Life Extension).

A life extension program can increase expected remaining life by:

1. Demonstrating that component integrity allows continued operation, or
2. Repairing or replacing components with unacceptable failure probabilities.

Not all equipment can be analyzed for remaining life. For example, motors, generators and transformers have electrical winding insulation systems that cannot be economically and reliably modeled.

Life Extension vs. Maintenance

Inspections are key activities in both life extension and maintenance. The program framework determines whether an inspection extends life or merely manages wear.

Maintenance inspections are generally designed to determine whether the equipment being inspected will operate safely until the next scheduled inspection. Particularly in new equipment, maintenance inspections are life extension inspections, because they focus on the components that are likely to fail at that time of equipment life.

In the context of a life extension program, inspections have added significance. Each inspection is designed to add confidence to a calculated estimated remaining life. Before equipment reaches the end of its nominal life expectancy, inspections that are more complete than normal maintenance inspections will be needed to determine the state of aging.

A sound life extension program will establish the state of equipment aging and demonstrate that equipment failure probability will remain at an acceptable level during one or more routine inspection intervals. Even if no conditions are found that require correction, a life extension program requires a commitment to reinspect at least selected areas to confirm the aging assumptions made in the initial expected remaining life analysis.

Determining the expected remaining life for plant equipment is a complex process, and life extension programs have limitations. Furthermore, increasing the expected remaining life may not be feasible for some equipment. Options to repair or replace components may be needed.

Risk

Life extension programs should be based on risk. Risk is the product of the failure probability and consequence cost and is the basis for selecting areas or components for improvement or further inspection.

Failure consequence cost is not necessarily more easily determined than probability of failure. The events following a failure, such as a turbine blade break, are not predictable. The blade may or may not penetrate the casing. Or, the blade may break 100 other blades, half of which penetrate the casing. The uncertainty of the scope of damage impacts several calculations including estimated consequence cost, repair cost, length of outage, and cost of replacement power, all of which have uncertainties of their own. Probable risk, therefore, is most valuable for comparison purposes.

Risk-based analysis can be easily updated and refined. Refinement reduces uncertainty by starting with areas of highest risk having the greatest uncertainty.

The American Society of Mechanical Engineers (ASME) has published two useful guides, CRTD Vol. 20-1, Risk-Based Inspection—Development of Guideline, Volume 1, *General Document*, and CRTD Vol. 20-1, Risk-Based Inspection—Development of Guideline, Volume 3, *Fossil Fuel-Fired Electric Power Generating Station Applications* for developing risk-based programs. These guides provide information that may help develop risk-based inspection and maintenance programs for many types of structures, including plant equipment.

Calculating Estimated Remaining Life

Equipment is not designed to fail, nor is it expected to last forever. Unfortunately, the life of most items cannot be predicted accurately while they are being designed or constructed. But some analysis is possible. Designs for components vulnerable to fatigue can be based on laboratory tests that provide an “S-n” curve. The S-n curve relates the maximum stress level to the number of cycles of stress reversal the material can withstand. Designs for components vulnerable to creep can be based on laboratory tests that relate the creep rate to stress and temperature levels. Designs for components vulnerable to erosion or corrosion can be based on predicted erosion and corrosion rates.

Unfortunately, tests can be expensive and can take a long time to run. For example, a test to establish a 30 yr life typically requires at least three years of equivalent wear.

Even if a design life estimate basis is rational, the estimate is still likely to be extremely conservative, because large safety factors are needed to cover uncertainty. And, unless at least two sets of equivalent data are available, an inherently inaccurate single-point extrapolation is needed. Even with multiple data points, extrapolation may provide questionable results.

Design, construction, operation, maintenance and repair can change the component aging rate. For example, the following conditions may create a positive or negative change:

- Off-specification materials may have been used.
- Materials from different heats or lots may perform differently.
- Unexpected environmental reactions may occur.
- Poor workmanship, poor quality welds, or faulty machining, improper heat treatment, dropping during handling and sloppy installation can introduce unintended stresses.
- Operating problems can be involved which are not intended by the designer.
- Materials may be contaminated with chlorides or other potentially harmful materials. Contamination leading to failure has been caused by improper marking and paints, lack of control of materials in process, fire protection water or flood water.
- Equipment may be rerated with or without the designer’s concurrence.

Predictive and preventive maintenance techniques can identify minor deterioration before a serious condition develops. Good repairs can prolong life by arresting damage or replacing damaged components. Inappropriate or poorly performed repairs can shorten life.

State-of-the art technology for predicting equipment life can be both helpful and harmful. Improved analysis can reveal deficient design, and improved inspection methods can discover deterioration better than older methods. But reduced life or unnecessary repair damage can result if the ability to evaluate findings does not develop simultaneously with the ability to find suspected flaws.

Design and remaining life prediction is uncertain. Deterministic methods must be very conservative to cover the uncertainties, which can result in unnecessary repairs. Probabilistic rather than deterministic methods are recommended. Probabilistic methods use probability distributions as input rather than point estimates of values. The output of a probabilistic analysis is a probability distribution relating failure probability to time. Determining failure probabilities is a specialized task requiring considerable experience and computer support.

Service Limiting Components

Calculating expected remaining life goes hand-in-hand with continued safe and economic operation, but the distinction between the two is seldom clear. Consider a water tube power boiler. After annual inspections are performed, obvious deficiencies, such as tube blisters, eroded or corroded areas, cracked attachment welds and ligament cracks in drums and headers are corrected. Calculating the expected remaining life involves a more in-depth study, which might include making the following assessments:

- Analyzing the condition of tube groups as a whole, considering their long-term ability to perform. This analysis might include measuring oxide thickness, analyzing operating history, analyzing accumulated damage in dissimilar metal weld joints and doing metallurgical studies of tubes in high-temperature areas.

- Studying stress, operating history and metallurgical aspects of drums and headers. This might include performing a finite element analysis of transient-induced stresses in selected areas and testing samples or replicas from selected areas.
- Examining and evaluating the support structure.
- Studying accessories, such as attemperators and valves.
- Surveying associated piping, including verifying material specifications, analyzing stresses imposed under “as-found” conditions of hangers and supports, and condition testing.

Some equipment, such as turbines, may not have routinely serviceable parts. Failures of the casing, rotor, blading, throttle assembly — even accessories such as the steam strainer — all can be catastrophic. The difference between a remaining life determination and a “routine” overhaul may not exist.

Damage Mechanisms

Physical and chemical factors in the equipment operating environment limit equipment life if the equipment materials lack resistance to the aging those factors cause. Physical and chemical factors that cause equipment aging are called damage mechanisms. In remaining life assessments, potential as well as actual damage mechanisms must be considered. For example, adjusting turbine rotor contours may be needed to reduce calculated local stresses, even though no cracking may have occurred.

Most aging mechanisms progress exponentially. To ensure no aging mechanism can run unchecked, life extension analysis needs to begin well before equipment reaches the end of its design life. Although benchmark data should be collected when equipment is new or early in its life, effective life extension analysis can only take place later in life, after some aging has taken place.

Remaining life determination programs are effective only when equipment is operated in a controlled manner that produces predictable stresses on the equipment. These programs are limited to situations involving time-based or operating cycle-based deterioration. The following terms identify several types of failure or deterioration mechanisms.

Plastic deformation is a change in shape caused by stressing a part beyond its elastic limit. The elastic limit is affected by the temperature. Plastic deformation in local areas contributes to local stresses and distortion. Plastic deformation accumulates over time, particularly during transient peak stresses, such as heat-up stresses.

Creep is plastic deformation at stresses below the elastic limit. Creep begins on a microscopic level where damage accumulates over time until it creates microscopic voids. The voids slowly link up, eventually forming crack-like defects and causing failure. Creep voids can also be crack initiation sites for other failures. The creep rate is highly temperature and stress dependent. Creep is not likely to be a problem below 900°F (480°C). At higher temperatures, the problem depends upon the alloy and temperature. Creep damage can be estimated if the time/temperature history and local stress levels are known and if long-term creep testing data is available. Creep damage can be determined by cutting, etching and polishing samples, and examining them under a microscope for creep voids. Replicating a part is a more practical method for estimating the creep state of the part based upon its actual condition, however, replication can detect only surface damage.

Metallurgical damage refers to any change in material microstructure that will result in degraded properties. For example, temper embrittlement reduces material toughness and raises its Fracture Appearance Transition Temperature (FATT), increasing the risk of brittle fracture.

Fatigue is failure of the material below its ultimate tensile strength, caused by progressive cracking. Cracking is caused by cyclic stress. Fatigue is classed high or low cycle fatigue. Generally, high cycle fatigue is related to machine rotational speed. Low cycle fatigue relates to startups and shutdowns or other operational cycles.

Crack initiation is the critical event in a fatigue failure. Once cracks have started, their propagation is relatively easy to model. When analyzing a model for fatigue, the analyst can assume an existing flaw, or better, assume a probability distribution for existing flaws or new cracks. Other failure mechanisms can initiate and propagate cracks.

Corrosion refers to a wide variety of electrochemical damage to metals. General corrosion attacks more or less uniformly whereas local corrosion produces pits or crack-like defects. General corrosion typically proceeds at a nearly constant rate and is therefore easily handled in remaining life determination studies. General corrosion often produces abrasive particles that can break away from the surface where they are produced and travel throughout the system. These particles will then contribute to erosion. Local corrosion presents a variety of difficult problems.

Corrosion fatigue is one of several hybrid mechanisms capable of producing failure under conditions where one mechanism alone would not be troublesome. Corrosion fatigue failures occur because stress levels are high enough to locally damage a passive anticorrosive material film, not the material itself. Damage to the film allows a local corrosive attack. Continued stress applications damage the passive layer, and failure eventually results. Other hybrid failure mechanisms include thermal fatigue and erosion corrosion.

Environmentally assisted corrosion is a form of local corrosion requiring a susceptible material and a specific environment. Almost any metal is vulnerable to some form of environmentally assisted corrosion. Most types of environmental corrosion produce crack-like defects. These defects are further exposed to either environmentally-assisted crack growth or fatigue-assisted crack growth. Stress corrosion cracking and chloride stress corrosion are among the types of corrosion that cause greatest concern to most equipment.

Erosion is caused by small-particle impact. Erosion in power plants is generally caused by water droplets or exfoliated corrosion products. Erosion in other facilities may be caused by materials in process or foreign materials.

Foreign object damage refers to damage caused by larger objects, and cannot be addressed in a remaining life study except as a probable result of an initiating failure.

Insulation system degradation refers to the total of mechanisms by which electrical insulation loses the ability over time to perform its function.

Inspection Techniques

Maintenance inspections generally use only nondestructive inspection techniques. Remaining life determination inspections routinely involve more in-depth procedures. For example, determining the creep rupture status of a high-temperature component may require cutting a sample to microscopically inspect the interior. Destructive testing may be needed to verify the mechanical properties. Not all remaining life determination testing is destructive. Considerable data is also acquired by hardness testing, replication and other on-site metallurgical techniques.

A remaining life determination program cannot be effective if there is no economical and reliable method of detecting any likely damage mechanism in any critical part.

Repair Techniques

When a local aging condition limits equipment remaining life, arresting or eliminating the local aging condition can extend the equipment remaining life. Accumulated damage caused by creep, fatigue, environmentally assisted corrosion and metallurgical changes generally cannot be corrected except by replacing the affected component or the affected part of the component. There are specific exceptions. For example, hot isostatic pressing has been used to reverse creep damage in combustion turbine blades. Contour adjustment by machining can remove cracks and reduce surface stresses enough to alleviate a life-limiting condition.

If part of a component is to be replaced by welding, carefully controlled procedures are needed. For example, a weld overlay applied to correct stress corrosion cracking can introduce surface stresses that make the structure more susceptible to fatigue cracking. Weld repairs to turbine rotors, turbine blades and other cyclically stressed parts require extremely careful design.

Rerating can be an alternative life extension method. Examples include pressure, temperature, capacity limits and heat up or load application rate restrictions.

Repair techniques include modifying controls and procedures as well as repairing, replacing, rerating and modifying components. For example, being assured a superheater header will last 20 yr is pointless if there are given limitations in temperature and in the number and severity of temperature transients. An exception exists if the temperature and its rate of rise can be measured on line and controlled.