Introduction and Overview

Need for Remaining-Life-Assessment Technology

A large percentage of power, petroleum, and chemical plants the world over have been in operation for such long durations that the critical components of these plants have been used beyond the design life of 30 to 40 years. This percentage is likely to become even more significant during the next decade because of the hiatus in new plant construction over the last several years. There is a strong desire on the part of many plant owners to continue to operate their plants for another 20 to 40 years. The factors that have led to this situation include:

1. The escalating costs of new construction and diminishing capital resources
2. Excess capacity, although precarious and derived from aging plants
3. Extended lead times in plant construction
4. Uncertainties in projected demand growth rates
5. Limited availability of suitable sites for new construction
6. Increasingly stringent environmental, safety, and other regulations
7. Increasing awareness of the technological feasibility of extending component life.

Several preliminary studies have shown that the cost of life extension of a typical fossil power plant may be only 20 to 30% of the cost of constructing a new plant and that the benefit-to-cost ratios are very high (Ref 1). Similar estimates for other types of plants are not available.

The term “life extension” has often been misunderstood. The purpose of life-extension activities is not to continue the operation of a plant beyond its useful life, but merely to ensure full utilization up to its useful life. The idea is to avoid premature retirement of plants and plant components, on the basis of the so-called design life, because actual useful lives could often be well in excess of the design life.

Extension of plant life may cease to be a desirable objective if it results in reduced availability or plant efficiency. Many improvements in material quality and design of critical components have been made over the last two decades. Selective replacement of components with more-modern designs should be part of the life-extension process. In this manner, the availability and efficiency of the life-extended plant may actu-
ally be improved in comparison with the initial conditions.

A key ingredient in plant life extension is the remaining-life-assessment technology. If such assessments indicate the need for extensive replacements and refurbishments, life extension may not prove to be a viable option. Above and beyond this objective, life-assessment technology serves many other purposes. It helps in setting up proper inspection schedules, maintenance procedures, and operating procedures. The data and methodologies needed for life extension are the same as those needed for optimizing these factors. It should therefore be recognized at the outset that development of techniques for life assessment is more enduring in value and broader in purpose than simply the extension of plant life. For instance, it has been possible to extend the inspection intervals from six to ten years for modern rotors on the basis of assessments based on fracture mechanics, resulting in considerable savings (Ref 2). Many fossil power plants originally designed 30 years ago for base-load operation are now being pressed into cyclic duty for economic reasons. Life-assessment techniques can quantify the penalty in terms of reduced plant life resulting from the changed operating mode. The start-up and shutdown procedures for plant components can be optimized, resulting in increased efficiency, reliability, and life. In view of the manifold benefits from life-assessment technology, considerable research has been carried out in this area during the last five to ten years. The remainder of this chapter will present a broad overview of the materials problems in fossil power, petroleum, and chemical plants, the failure criteria employed, and their relevance in the context of remaining-life assessment.

**Fossil Power Plants**

The availability of electrical power and the development of the millions of devices that use it have made electricity the energy of choice in contemporary industrial societies. This convenient energy form, which is available to us at the flip of a switch, is used in countless ways. Practically every economic sector—industrial, commercial, residential, and transportation—depends on the availability of electricity.

**Types of Electric Power Plants**

The principal route for producing electricity is the conversion of mechanical energy of rotation into electrical energy using a generator. The large generators used by electric utilities employ a shaft comprising the magnetic field (rotor) which rotates inside a stationary electric field containing conducting wires (stator), as shown schematically in Fig. 1.1 (Ref 3). Rotation of the shaft is achieved by coupling it to a turbine in which the kinetic energy of a moving fluid is converted into mechanical energy of rotation. The working fluid can be wind, water, steam, or combustion gases—leading to the resulting classification of turbines as wind turbines, hydroelectric turbines, steam turbines, and combustion turbines. Of these, the most common is the steam turbine, which employs steam produced from burning fossil fuels in a boiler or from the heat produced by atomic reactions inside a nuclear reactor. It is estimated that in the United States approximately 70% of the electricity is produced in fossil power plants, 15% in nuclear power plants, 12% in hydroelectric power plants, and the remainder from other types of sources (Ref 3). This mix may be somewhat different in other countries. In any event, the fossil-fuel power plant is and will continue to be the mainstay of electric power production. The fossil fuel can be employed to make steam to drive a steam turbine, or, alternatively, the combustion gases under high pressure can be used to drive a combustion turbine. Combined-cycle plants in which both combustion and steam turbines are employed in tandem result in greater efficiency and are becoming increasingly common. In these plants, the exhaust gases from a combustion turbine are used to make steam to drive a steam turbine.

The fossil fuel employed in a steam turbine plant can be pulverized coal (PC), oil,
Introduction and Overview

Fig. 1.1. Schematic illustration of the principle of the turbine-generator combination (Ref 3).

or natural gas. Of these, coal is the most abundant and hence the most commonly used fuel for steam turbine plants, while gas turbine plants generally employ oil and natural gas. To cope with increasingly stringent environmental standards, particularly in terms of sulfur- and nitrogen-containing compounds, and to improve the efficiency of combustion, a variety of alternative processes in which coal is combusted in a fluidized bed containing lime or is converted into coal-derived gas or liquid and then combusted are being vigorously pursued worldwide. Jaffee has described ten different plant configurations for generating electricity from coal, as shown in Fig. 1.2 (Ref 4).

Historical Evolution of Fossil Plants

The historical evolution of fossil-fired steam power plants is shown in Fig. 1.3 (Ref 4). In this illustration, the shaft output, maximum steam pressure, steam temperature, and plant thermal efficiency are plotted using different scales. The discontinuous variation in each plot results from the data points being plant-specific; the over-all trends, however, are quite clear. During the period beginning in 1920, plant capacity has increased from less than 0.5 MW to almost 1300 MW; steam throttle pressures have increased from 690 to 1380 kPa (100 to 200 psi) to more than 24.8 MPa (3600 psi). Steam temperature has increased from 230 °C (450 °F) to temperatures in excess of 565 °C (1050 °F). To improve the efficiency of the steam turbines, additional reheat cycles in which the working fluid is reheated again and expanded once again through intermediate pressure turbines have been added. This phenomenal increase in plant capacity and operating conditions has been possible only through corresponding improvements in materials technology.

Typical PC Fossil Plant and Component Damage Mechanisms

Figure 1.4 shows the arrangement of the various elements of a PC fossil plant (Ref 4). Here, water is first preheated to a relatively low temperature in feedwater heaters and pumped into tubes contained in a boiler. The water is heated to steam by the heat of combustion of pulverized coal in the boiler and then superheated. Superheated and pressurized steam is then allowed to expand in a high-pressure (HP) steam turbine and cause rotation of the turbine shaft. The outlet steam from the HP turbine may once again be reheated and made to expand through an intermediate-pressure (IP) turbine and then through a low-pressure (LP) turbine. The turbine
shafts are all connected to one or more generator shafts which in turn rotate and convert the mechanical energy of rotation into electrical energy in the generator. The exit steam from the LP turbine is condensed in the condenser and is once again fed back to the boiler through the feedwater heaters and pumps. A closed loop of the water and steam is thus maintained. A second water loop through a cooling tower provides the cooling water needed to condense the steam exiting from the LP turbine. Combusted gases from the boiler are passed over more heat exchangers to preheat the incoming air to the boiler, are cleaned in scrubbers, and then are allowed to escape into the environment through the stacks. The pressure, temperature, and specific volume of the steam at various stages are illustrated in Fig. 1.5. It is thus clear that a variety of materials of construction are needed to withstand a wide range of these conditions in the plant,
depending upon the local conditions of pressure, temperature, and chemical environment. The capacity, reliability, efficiency, availability, and safety of plants depend critically on the integrity of the components and materials employed. A number of damage phenomena, such as embrittlement, creep, thermal fatigue, hot corrosion, oxidation, and erosion, can impair plant integrity at elevated temperatures. At lower temperatures, corrosion, erosion, pitting, corrosion fatigue, stress corrosion, hydrogen embrittlement, and fatigue can play major roles. A list of key components, property requirements, and materials of construction for steam power plants is presented in Table 1.1 (Ref 5). As can be seen from the table, low-alloy ferritic steels containing carbon, molybdenum, and/or vanadium constitute the bulk of the materials used in steam power plants. For highly stressed components operating at high temperatures
Damage Mechanisms and Life Assessment of High-Temperature Components

Fig. 1.4. Schematic diagram of a coal-fired steam power plant (Ref 4).

Fig. 1.5. Relationships among steam pressure, temperature, and specific volume in the various components of a large steam power plant (Ref 4).
Table 1.1. Property requirements and materials of construction for fossil steam plant components (Ref 5)

<table>
<thead>
<tr>
<th>Component</th>
<th>Major property requirements</th>
<th>Typical materials</th>
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</thead>
<tbody>
<tr>
<td>Boiler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterwall tubes</td>
<td>Tensile strength, corrosion resistance, weldability</td>
<td>C and C-Mo steels</td>
</tr>
<tr>
<td>Drum</td>
<td>Tensile strength, corrosion resistance, weldability, corrosion-fatigue strength</td>
<td>C, C-Mo, and C-Mn steels</td>
</tr>
<tr>
<td>Headers</td>
<td>Tensile strength, weldability, creep strength</td>
<td>C, C-Mo, C-Mn, and Cr-Mo steels</td>
</tr>
<tr>
<td>Superheater/reheater tubes</td>
<td>Weldability, creep strength, oxidation resistance, low coefficient of thermal expansion</td>
<td>Cr-Mo steels; austenitic stainless steels</td>
</tr>
<tr>
<td>Steam pipe</td>
<td>Same as above</td>
<td>Same as above</td>
</tr>
<tr>
<td>Turbine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HP-IP rotors/disks</td>
<td>Creep strength, corrosion resistance, thermal-fatigue strength, toughness</td>
<td>Cr-Mo-V steels</td>
</tr>
<tr>
<td>LP rotors/disks</td>
<td>Toughness, stress-corrosion resistance, fatigue strength</td>
<td>Ni-Cr-Mo-V steels</td>
</tr>
<tr>
<td>HP-IP blading</td>
<td>Creep strength, fatigue strength, corrosion and oxidation resistance</td>
<td>12% Cr steels</td>
</tr>
<tr>
<td>LP blading</td>
<td>Fatigue strength, corrosion-fatigue pitting resistance</td>
<td>12% Cr steels; 17-4 PH stainless steel; Ti-6Al-4V Cr-Mo steels</td>
</tr>
<tr>
<td>Inner casings, steam chests, valves</td>
<td>Creep strength, thermal-fatigue strength, toughness, yield strength</td>
<td>Cr-Mo-V and 12Cr-Mo-V steels</td>
</tr>
<tr>
<td>Bolts</td>
<td>Proof stress, creep strength, stress-relaxation resistance, toughness, notch ductility</td>
<td></td>
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<tr>
<td>Generators</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>Yield strength, toughness, fatigue strength, magnetic permeability</td>
<td>Ni-Cr-Mo-V steels</td>
</tr>
<tr>
<td>Retaining rings</td>
<td>High yield strength, hydrogen- and stress-corrosion resistance, nonmagnetic</td>
<td>18Mn-5Cr and 18Mn-18Cr steels</td>
</tr>
<tr>
<td>Condensers</td>
<td>Corrosion and erosion resistance</td>
<td>Cupronickels; titanium; brass; stainless steels</td>
</tr>
</tbody>
</table>

(for example, turbine blades and bolts), higher-alloy tempered martensitic steels generally containing 12% Cr are used. In combustion turbines, metal temperatures often exceed 760 °C (1400 °F) in the combustor sections and in the early stages of blades and vanes.

Nickel- and cobalt-base alloys known as superalloys are the preferred candidates for the higher-temperature end of the spectrum, whereas components operating near 540 °C (1000 °F), such as the turbine shafts and disks, are made of low-alloy ferritic steels.

**Reactor Pressure Vessels for Petroleum Refining**

The refining or manufacturing of petroleum products and of chemicals in a refinery involves both physical changes, or separation operations, and chemical changes, or conversion processes. An illustration of an over-all refinery including both types of operations is shown in Fig. 1.6. Physical separation primarily involves distillation of the crude oil into various fractions according to their volatility. The system involves heating the crude by pumping it through
Damage Mechanisms and Life Assessment of High-Temperature Components

Crude ad mole operations of crude oil are dependent on the kind of crude oil being run. Fig. 1.6, Generalized over-all refinery from crude oil to salable products (American Petroleum Institute, cited in Ref 6).

Crude oil—

- Atmosphere or Vacuum Distillation
- Refining
- Solvent Refining
- Sediment Decolorizing
- Wax Refining Plant
- Fuel Distillation
- Coking
- Reforming
- Hydrogenation
- Isomerization
- Blending
- Gaseous Fractions
- Petroleum Products
- Lubricating Residue
- Heavy Gas Oil
- Heavy Fuel Oil
- Diesel Oil
- Gas

Modern petroleum refining and petrochemical processing may involve operating conditions for the ferritic steel pressure vessels extending to metal temperatures up to 565 °C (1050 °F) and pressures up to 28 MPa (4 ksi). The operating conditions in the pressure vessels of some typical refining processes are listed in Table 1.2 (Ref 7 and 8). For a given application, material selection must consider not only operating conditions but also conditions during start-stop transients. The mechanical behavior considered includes such properties as fracture toughness, creep rupture, and thermal fatigue. In addition, the corrosion and environmental behavior of the materials for normal operation, process upset, and shut-down conditions have to be taken into account. Since fabrication involves extensive welding, the properties of the weldments are of great importance. It is common practice to design, fabricate, and inspect pressure vessels according to the ASME Boiler and Pressure Vessel Code. The code calls
for the following material properties: (1) strength necessary for the guarantee of the allowable stress, including room- and design-temperature tensile, creep, and fatigue properties; (2) notch toughness at the lowest operating temperature; and (3) weldability. In addition to the minimum code requirements for the fabricated condition, steels for high-temperature, high-pressure hydrogenation service are required to withstand such environmental degradation processes as temper embrittlement, hydrogen embrittlement, hydrogen attack, and creep embrittlement.

The selection of materials of construction has always been a major concern in the petroleum industry. In the past, the concern has been based largely on safety and economic incentives, which dictate against unexpected equipment failures that could result in hazardous exposures or extended plant shutdowns. Forced shutdown for extensive repair or replacement of reactor pressure vessels would require months or years. It is estimated that unscheduled downtime of a petroleum refinery pressure vessel can cost in excess of $50,000 per hour (Ref 9). More recently, however, the need for extending the lives of current plants well beyond their originally anticipated lives has gained considerable attention. The factors driving this need are essentially the same as those for fossil power plants, as described earlier.

Most steels for refinery and petrochemical applications fall within the following categories: (1) carbon steels; (2) carbon-molybdenum steels; (3) low- and intermediate-alloy chromium-molybdenum steels; and (4) martensitic and ferritic stainless steels. The applicable ASTM specifications covering tubular products, plates, castings, and forgings are listed in Table 1.3 (Ref 10). Allowable stresses used in the manufacture of pressure vessels are designed in accordance with Divisions 1 and 2 of Section VIII of the ASME Boiler and Pressure Vessel Code. The code defines allowable stresses for carbon and carbon-molybdenum steels up to 540 °C (1000 °F). Chromium-molybdenum and ferritic stainless steels are rated up to 650 °C (1200 °F). The only steels for which allowable stresses are given above 650 °C are the austenitic steels.

Selection of materials and upper limits of operating temperature are governed both by the ASME Boiler and Pressure Vessel Code (Section VIII) from a creep point of view and by the Nelson diagrams (described in Chapter 7) from a hydrogen-attack point of view. For reactors used in high-pressure hydrogenation service, where hydrogen pressure can be as high as 28 MPa (4 ksi), the upper limit of temperature set by the Nelson diagrams is below the limits set by the creep considerations. These vessels (e.g., hydrocrackers, hydrodesulfurizers) are usually made of 2½Cr-1Mo steels and are permitted to operate only up to about 455 °C (850 °F). Creep per se is not a major concern in these vessels. Potential failure mechanisms for these vessels involve brittle fracture at low temperatures under transient conditions aided by embrittlement and environmentally assisted phenomena. In the other extreme, in reactor vessels where refining is carried out purely by thermal processing (e.g., catalytic crackers), hydrogen attack is not an issue; these vessels are made of carbon and carbon-molybde-
num steels and operate at temperatures up to about 510 °C (950 °F) in the case of carbon steels and 540 °C (1000 °F) in the case of carbon-molybdenum steels. The potential failure mechanism for these vessels involves primarily creep rupture. In between the above two cases fall reactor vessels which operate under moderate hydrogen pressures and in the creep regime (e.g., catalytic reformers). These vessels are generally made of 1Cr-½Mo and 1¼Cr-½Mo type steels and operate at temperatures up to 540 °C (1000 °F). Failure scenarios here involve creep at high temperatures as well as brittle fracture at low temperatures aided by embrittlement phenomena.

**Design Life of Components**

Components which operate at low temperatures below the creep regime are generally designed on the basis of yield strength, tensile strength, and fatigue strength by applying suitable safety factors to these values. Because deformation and fracture are not time-dependent under these circumstances,
there is no specific value of “design life” associated with them. In principle, as long as the applied stresses do not exceed the design stresses, these components should last indefinitely, although in practice various factors cause reductions in life. In the case of high-temperature components operating in the creep regime, both deformation and fracture are time-dependent. They are therefore designed with respect to a target life usually based on a specified amount of allowable strain or rupture in 100,000 h. A further factor of safety is applied in selecting the stress, which translates into an expected life of 30 to 40 years, leading to the notion of a 30-to-40-year design life for the component. Many metallurgical and operational factors can extend the actual component life beyond the design life. Alternatively, if these factors are adverse, actual life can be reduced. Some of the many favorable and unfavorable factors that hold the balance between design life and actual life are illustrated schematically in Fig. 1.7 (Ref 11).

Built-in safety factors in design with respect to stress and temperature are intended to ensure that the minimum design life is met. Material-property data are invariably subject to scatter, resulting in a broad band or spectrum of behavior. Designs are generally based on minimum or mean values of mechanical properties, after further corrections for safety have been applied. If the actual materials of construction exceed these expectations, the actual life can then far exceed the design life. This uncertainty in material behavior is illustrated in Fig. 1.8 for a Cr-Mo-V steam turbine rotor steel, with respect to its creep-rupture life. At a stress of 83 MPa (12 ksi) and a temperature of 540 °C (1000 °F), the design curve yields an expected life of 11.4 years. Use of the minimum curve or the mean curve can yield an expected life of 55 or 266 years, respectively. Similar scatter is also encountered with respect to other material properties, leading to major uncertainties in expected life. Units operated conservatively can be operated beyond their design lives. For instance, if a combustion turbine is operated more sparingly than originally intended, it can operate for many years beyond its design life. In the early days, design of components was often based on linear extrapolation of short-time creep and fatigue data to approximate the long-term behavior. Long-term data are now available for many standard materials as a result of international efforts to gather and analyze long-term test data. In some instances it has been found that the original linear extrapolations may have been overly conservative and that the actual expected lives may exceed the design lives. Most of the creep and stress-rupture data used in designing high-temperature components are based on small samples tested in air in the laboratory. For heavy-section components, the oxidation effects may be less pronounced than for small specimens, resulting in an added margin of safety. All of the above factors contribute to extended component life.

In contrast to the above factors, a number of other factors can lead to premature failure of components. Stresses in compo-