Chapter 17

Erosion

Introduction

The four major locations in which boiler erosion occurs are at the fire side, the preboiler, the afterboiler, and the water side and steam side.

Fire-side mechanisms cause most erosion-related failures and can be further subdivided as erosion related to soot blowing, steam cutting, fly-ash attack, coal-particle impingement, and falling slag. Fluidized-bed and other special-purpose boilers sometimes suffer severe attack. Boilers burning wood chips and bagasse are often eroded by entrainment of tramp contaminants such as sand and other foreign material in furnace gases. Incinerators suffer similar fire-side problems. Because fire-side mechanisms cause most erosion-related failures, each mechanism will be discussed in detail.

Erosive metal loss on water-side surfaces is comparatively rare. Cases do occur, however. Internal-surface discontinuities or solid foreign objects lodged within tubes can disturb flow, increase turbulence, and cause wastage.

Preboiler attack is confined primarily to feedwater systems. Turbine erosion is common in afterboiler regions. Burner nozzles, blowdown piping, condensate return lines, and many other boiler components are also eroded.

Soot-Blower Erosion

Locations

As the term *soot-blower erosion* implies, damage occurs near or in the direct path of soot-blower discharge. Superheater tubing is usually attacked. Common damage locations include tubes along the path of retractable soot

Figure 17.1 Superheater section thinned by soot-blower erosion. Note the flattened surface. The tube bulged and ruptured on the thinned side. Also, note how the eroded surface color is not dissimilar to unattacked regions, indicating intermittent attack.

blowers, and particularly those tubes nearest wall entrances of retractable blowers. Other damage locations include furnace corners opposite wall blowers. Platens in the convection section are often targets, as are any tubes near malfunctioning soot blowers.

General description

Perhaps the most common cause of erosion in boilers is soot-blower attack. Usually a misdirected blower allows a high-velocity jet of steam or air carrying condensed water droplets to impinge directly upon tube surfaces, rather than to be directed between tubes. Physical abrasion and accelerated oxidation cause metal loss. Damage can be accelerated by fly ash entrained in the high-velocity jet stream directed against the tube surface. Erosive thinning often leads to tube rupture (Figs. 17.1 and 17.2).

Critical factors

Soot-blower erosion is caused by improper blower alignment. Entrainment of either condensed water or fly ash in the blower gas also accelerates attack. Raising blowing pressure increases gas velocity and thus promotes damage by entrained fly ash. Improper alignment and operation are the most common sources of damage.

Figure 17.2 Tube rupture caused by a misdirected soot blower. Rupture edges are thin and ragged because of tearing of the wasted steel in the eroded zone. The tube surface is light gray and shiny as a result of erosion of the normally present fire-side oxides and deposits.

Identification

Attacked surfaces are locally thinned, usually producing longitudinally aligned zones of flattened metal bordered on both sides by shoulders of unattacked metal. When viewed in transverse cross section, the tube appears to have been "planed" along its length (Figs. 17.1 and 17.2). Grooving and more irregular attack will be present if eddies and gas channeling are pronounced.

Metal surfaces will be smooth or have smoothly undulating contours. Only a thin, dark, oxide layer, or no oxide layer at all, will be present if attack is fresh. If attack is old or intermittent (as is often the case with soot-blower attack), oxide and deposits will cover thinned surfaces. However, the oxide and deposit layers will usually be thinner than on adjacent unattacked surfaces. Close visual observation of thinned surfaces will often show very shallow wavelike striations frozen into the metal surface (Figs. 17.3 and 17.4). The striations will be aligned perpendicularly to steam flow across the surface.

Attack usually is present at the opening of the soot-blower valve and continues along the blower path, decreasing in severity as the distance

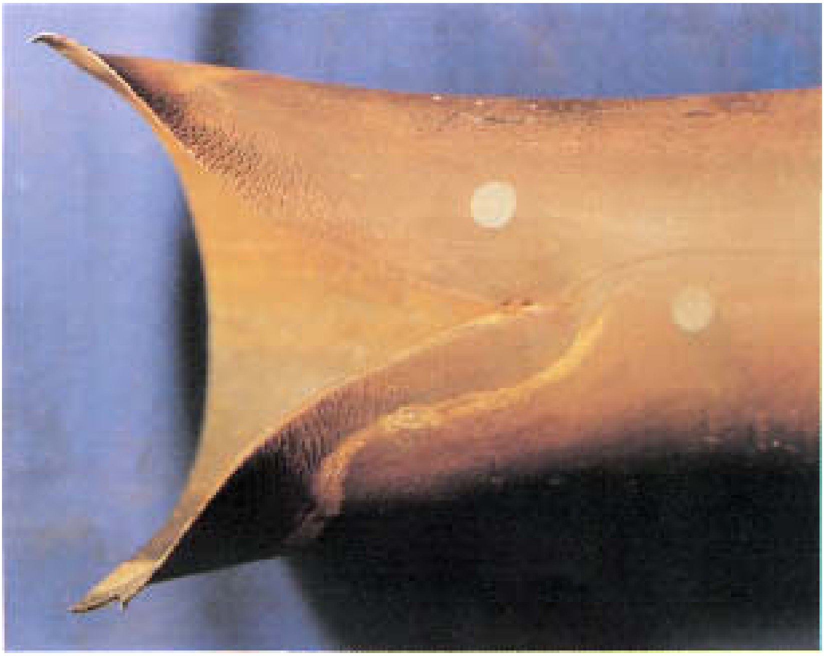

Figure 17.3 Numerous parallel surface ripples at the edges of an external-surface rupture in a superheater tube. The light circles are regions where acid drops removed the thin oxide layer during laboratory testing.

Figure 17.4 Finely spaced, wavelike, parallel undulations on eroded fire-side external surface of superheater tube. The striations resemble waves viewed from the air and are aligned perpendicularly to the direction of steam impingement. (Compare with Fig. 17.3.)

from the blower increases. Frequently, the blower is misaligned, is frozen in position, or is blowing wet steam because of water entrainment.

Bulging will usually be absent in internally pressurized tubes suffering erosion. Rupture is usually longitudinal but can follow grooves whatever their orientation. Rupture edges will be thin and ragged.

Elimination

Proper soot-blower operation, alignment, and function are required to reduce attack. Periodic inspection of nozzle position and alignment is recommended. Elimination of moisture in blowing steam can be accomplished by allowing adequate steam warm-up and providing for adequate drainage of steam supply lines. Metallizing, welding, and plasma spray techniques can increase wall thickness in affected areas and thereby prolong tube life. Coating processes, however, can slightly reduce heat transfer locally and do not remove the root problem.

Cautions

Soot-blower damage can resemble oil-ash or coal-ash corrosion, as well as fly-ash erosion. If heavy deposit accumulations are present atop thinned tube walls, damage may be due to oil-ash or coal-ash corrosion, even though these tubes exhibit other characteristics of erosion. Boilers burning wood, bagasse, and other waste materials are particularly likely to suffer erosion since sand, dirt, and cement dust may be entrained in combustion gases. Attack by entrained particulate resembles soot-blower attack. Location of damage in the direct path of the soot-blower stream is necessary for diagnosis of failure.

Related problems

See also Chap. 9, "Oil-Ash Corrosion"; Chap. 10, "Coal-Ash Corrosion"; and the sections titled Steam Cutting from Adjacent Tube Failures, Fly-Ash Erosion, Coal-Particle Erosion, and Falling-Slag Erosion in this chapter.

Steam Cutting from Adjacent Tube Failures

Locations

Affected tubes can occur in any part of the boiler. Cutting is most severe when internal steam pressures, and consequently temperatures, are high. Thus, superheaters and reheaters are often severely attacked. A nearby failed tube is always present. Usually damage is highly localized and is worst in line of sight with the nearby failed tubes. Occasionally, if the original failure is not detected promptly, a single failure leads to chain reactions involving multiple tube breaches.

General description

Damage produced by escaping high-velocity fluids eventually causes other nearby tubes to be steam-cut. The wastage mechanism is essentially the same as soot-blower attack. However, attack is usually more localized. Wastage occurs rapidly.

Critical factors

Pressure of escaping fluids and proximity of affected tubes dictate the damage potential. Wastage rates increase as pressures (and consequently temperatures) increase, and distance decreases.

Identification

Wasted surfaces sometimes resemble those produced by soot-blower attack (see the section titled Soot-Blower Erosion). Surfaces close to nearby leaking tubes are likely to be smoothly undulating and grooved (Figs. 17.5 and 17.6). The irregularity of wastage increases as distance to the erosion source decreases. Freshly attacked surfaces contain almost no oxide or deposition. Surfaces are usually shallowly pebbled or striated and have an undulating contour. Often, the damage can be directly correlated with the nearby failure by line-of-sight extrapolation.

Elimination

Since steam cutting is caused by other unpredictable tube failures, and such failures can occur anywhere in the boiler, it is not practical to design or plan for the damage. The only reasonable way to reduce the incidence of failure is to reduce the likelihood of other failures.

Cautions

Steam cutting is usually obvious because of associated failure or failures. However, such damage can sometimes be confused with damage from other forms of fire-side erosion including fly-ash, coal-particle and falling-slag erosion. Also, once the steam-cut tube begins leaking, escaping fluids from

Figure 17.5 Utility superheater tube cut by steam leaking from an adjacent tube that failed at a manufacturing defect. Note the smoothly undulating surface and removal of red and black oxides and deposits in the wasted area.

Figure 17.6 Grooving on pendant U-bend superheater leg caused by steam leaking through a corrosion-fatigue crack at the U-bend. Grooves were rusted after removal from boiler.

subsequently damaged tubes can modify the nearby failure that was the primary cause of attack (see Case History 17.10).

Related problems

See also the sections titled Soot-Blower Erosion, Fly-Ash Erosion, Coal-Particle Erosion, and Falling-Slag Erosion in this chapter.

Fly-Ash Erosion

Locations

Damage frequently occurs in economizer, superheater, reheater, and roof tubing, although other tubes may be affected. Since fly ash is usually more erosive when particle temperatures are lower, economizers are frequently attacked. Inlet areas of reheaters are common wastage sites because of higher gas velocities and eddying present there. Areas in the superheater where slagging is pronounced are common problem regions, as gas flow in the narrow slag channels increases. Any location where channeling or eddying of gases occurs is susceptible to wastage. Erosion is usually localized and frequently is restricted to regions such as gaps between tube rows, banks, and duct walls.

General description

Fly-ash erosion is caused by particulate matter entrained in high-speed flue gases striking metal surfaces. Major accelerating factors are high gas velocity and large amounts of abrasive components in the fly ash. These factors accelerate loss by increasing the amount of kinetic energy per impact and by increasing the number of impacts per unit time in a given area. Table 17.1 shows maximum design gas velocities for various types of firing or fuel.

Fly-ash erosion is common in boilers fired with overfeed stokers, which allow considerable amounts of ash to enter the gas stream more readily. Those boilers using an overfire air system may reduce particulate. Partial-suspension burning causes greater amounts of particulate matter to enter the gas stream. Thus, collectors are generally used. When collectors malfunction, damage increases.

TABLE 17.1 Design Gas Velocity (fps) through Net Free-Flow Area in Tube Banks to Prevent Flue-Dust Erosion

	Baffle arrangement	
Type of firing or fuel	Multipass	Single pass
Pulverized coal	75	75*
Spreader stoker	50	60
Chain-grate stoker, anthracite	60	75
Chain-grate stoker, coke breeze	60	75
Chain-grate stoker, bituminous	100	100
Underfeed stoker	75	100
Blast-furnace gas	75	100
Cyclone furnace	—	100
Wood or other waste fuels containing:		
Sand	50	60
Cement dust	—	45
Bagasse	60	75

* For PC units burning fuels having more than 30% ash on a dry basis, limit the maximum velocity through the free-flow area to 65 fps. For PC units burning coals producing fly ash with known high-abrasive tendencies, such as Korean or central Indian coals, limit the maximum velocity through free-flow area to 45 fps.

NOTE 1 fps = 1 ft/s = 0.3048 m/s

SOURCE: Courtesy Babcock & Wilcox, *Steam/Its Generation and Use*, Babcock & Wilcox, New York, 1972.

Boilers using fuel contaminated with sand and dirt—such as wood chips—suffer damage almost identical to fly-ash erosion.

Critical factors

Erosive metal loss increases as particle hardness, flow velocity, and ash concentration increase. Of these factors, flow velocity and ash concentration are most important (Fig. 17.7). Erosive loss increases as the angle of impingement between gas flow and the metal surface increases. The direct incidence of fly ash is more damaging than glancing blows. As temperature increases, erosive metal loss decreases because particles become softer.

Size, hardness, and composition of particulate matter also influence attack. Particles larger than about 0.001 in. (0.0025 cm) and those containing high concentrations of aluminum and silicon compounds are more erosive because of high particle hardness and large particle kinetic energy.

Identification

Fly-ash erosion frequently causes smoothly polished surfaces. In other cases, irregular flow marks and grooving are produced by eddies around slag encrustations, hangers, brackets, etc. (Fig. 17.8). In extreme cases, thinning can cause rupture. Attack may be localized or general.

Discrimination between fly-ash erosion and other forms of fire-side erosion requires more information.

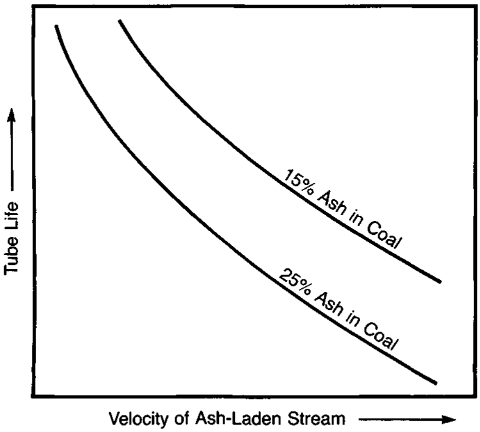

Figure 17.7 Effects of velocity and ash content on the life of a tube. Increases in the number and velocity of the impacting ash particles can result in reduced service life. (*Courtesy of Electric Power Research Institute,* EPRI Manual for Investigation and Correction of Boiler Tube Failures, *EPRI, 1985. Originally in E. Raask, "Tube Erosion by Ash Impaction,"* WEAR, ***13****:(1969), pp. 301–315.*)

Figure 17.8 Deep grooves cut into the hot side of a waterwall tube. Grooving was caused by channeling of furnace gases containing entrained fly ash.

Locations in the boiler in which attack occurs, positions of deflecting baffles, amount of entrained fly ash, and local gas velocity are important clues to attack. Fire-side oxide and deposit layers are usually much thinner on wasted regions, allowing discrimination from coal-ash or oil-ash corrosion, in which deposits and corrosion-product accumulations are extensive. No chemical attack is present as might be expected in cold-end corrosion. When ruptures occur, they are usually thin-edged. Close inspection of the rupture site often reveals thinning of the external surface and no overheating or corrosion. Metallographic examination may reveal microscopic plastic deformation on thinned surfaces caused by impingement of high-velocity particles.

Elimination

Decreasing fly-ash erosion requires a system operations approach. This includes making sure all baffles, collectors, refractories, and the like are working properly. In extreme cases, redesign of boiler components may be required. Of course, reducing the amount and velocity of fly ash will also limit damage. In extreme cases, fuels less prone to produce erosive ash may have to be used. High load and excess air increase flue-gas velocity, and thus, increase attack.

Slagging promotes fly-ash erosion by channeling gases and increasing eddying. Appropriate fuel additives and soot blowing can reduce slagging. Baffles have been used to distribute flue gases, and consequently, fly ash, more evenly. However, where gas flow is horizontal through tube banks, baffling is generally absent. Slag fences have been used to prevent larger slag pieces from entering horizontal tube banks. Shielding and metal spray coatings are beneficially used in certain erosion-prone locations.

Cautions

Fly-ash erosion resembles other forms of erosive attack, including soot-blower erosion, impingement from nearby leaking tubes, coal-particle erosion, falling-slag erosion, and coal-ash and oil-ash attack. Cold-end corrosion also can be confused with erosion by fly ash. Location of failures and knowledge of boiler operation are important in making a correct diagnosis.

Related problems

See Cautions above.

Coal-Particle Erosion

Locations

Water-cooled tubes that line the cylindrical combustion chamber of cyclone-type coal burners are common attack sites. Incompletely burned coal particles can also accelerate fly-ash erosion in superheaters and wall tubing. Attack is common in utility boilers.

General description

In general, attack occurs in tubes lining the cyclone burner. Erosion becomes pronounced when the refractory covering the tubes or the wear liners is damaged or worn out, exposing unprotected tubes. The high-velocity coal particles, moving at speeds up to 300 ft/s (9.0 m/s) (in utility service), impinge on tube walls and cause rapid wear. Attack is similar in appearance to fly-ash erosion.

Critical factors

The degradation of the refractory and wear liners contributes to attack. Low-silicate coals produce less damage.

Identification

In most cases, diagnosis of coal-particle erosion is simple. Damage closely resembles fly-ash erosion but occurs at or near a cyclone burner and damages the refractory or wear liners. Inspection usually reveals damaged areas and the associated spalled refractory.

Elimination

Frequent inspection and periodic maintenance of the refractory and wear liners will eliminate most damage.

Cautions

Not all attacked tubes need to be replaced. However, tubes should always be inspected to determine wall thickness after they are found to be damaged.

Related problems

See the discussion under Fly-Ash Erosion in this chapter.

Falling-Slag Erosion

Locations

This damage is rare and usually is confined to slanted tube walls near the bottom of large boilers, which direct ash into the ash hopper. Most damage occurs near side walls, where greater amounts of slag tend to accumulate since slag from side walls is more likely to strike these areas.

General description

Erosion is caused by slag particles that fall from above. The particles strike the slanted walls and cause wastage. If large slag particles fall, they can dent and bend tubes.

Critical factors

The amount of slag per unit area, and the tendency of this slag to fall, control the damage rate. Slag formation is favored in a furnace containing a large wall area; having a low or high flue-gas velocity; burning a high-slagging coal containing high sodium and chlorine concentrations; having low flue-gas temperature; or cycling thermally and/or running high tube temperatures. Such slag can be easily shed.

Identification

Falling-slag erosion produces flat spots on slanted tubes. If large slag chunks falling from great heights strike surfaces, tubes can be dented and deformed. Microscopic examination often reveals the plastic deformation associated with this damage.

Elimination

Reduction of slagging decreases damage. This may necessitate a change of coal type. The higher the fusion temperature of the coke ash, the lower the slagging rate. Use of fuel-additive chemicals may also reduce slagging potential. Structural alterations such as increasing tube-wall thickness, and use of weld overlays or wear bars have been used to extend tube life.

Cautions

Falling-slag erosion can resemble erosion caused by fly ash, coal dust, soot blowers, and steam cutting. However, the widespread attack on slanted tubes near ash hoppers is usually definitive.

Related problems

See the discussion under Fly-Ash Erosion in this chapter.

Preboiler and Afterboiler Erosion

Locations

Feedwater-pump components, including impellers, fittings, valves, and housings are often eroded. Less commonly, transfer lines, pipe elbows, and blowdown components are attacked.

Afterboiler erosion is confined primarily to turbines. Because of high velocities inherent in turbine operation, turbine components frequently suffer erosion. Turbine blades are wasted both by hard particles and by water-droplet impingement. Latter-stage buckets are most frequently affected by water-droplet impingement. Carbon steel piping may be attacked in the presence of wet, high-velocity steam, causing damage that falls more into the category of erosion-corrosion. Valve stems, nozzle blocks, diaphragms, and early-stage buckets commonly suffer hard-particle erosion due to exfoliated oxide particles from superheaters, reheaters, main steam leads, and hot reheat piping.

General description

Erosion is metal loss caused by impact of solids or liquids. Attack is promoted by turbulent, high-velocity fluid flow. Rapid pressure changes promote water jetting and turbulence. Abrupt changes in flow direction and the entrainment of hard particulate matter in fluids also contribute to wastage. Although appearing simple, the erosion process is complex. Metal loss is often considered to occur by physical deformation of the surface. Shearing or fracture may occur subsequently as deformed areas are impacted by the erodent.

Factors controlling the rate of metal loss are related to the quantity, impact angle, speed, and density of the erodent. Metal loss is a strong function of erodent kinetic energy. Erosion damage may be roughly considered inversely proportional to alloy hardness. Usually, in the absence of significant corrosion, the harder the alloy, the more resistant it will be to attack. Erodent velocity has a very important effect on metal loss. Doubling velocity may increase metal loss by a factor of 4 or more. If particulate matter is entrained, mass, size, and particle-size distribution all affect attack.

Critical factors

Feedwater system. Impingement of high-speed, turbulent water causes most attack. Entrained particulate matter may accelerate metal loss. If gases become mixed with fluids, cavitation (see Chap. 18, "Cavitation") is more likely than "simple" erosion.

Turbine. Turbines are subject to erosion caused by impingement of solid particles and condensed water droplets. Solid-particle erosion is caused by exfoliated oxides, primarily from superheaters, reheaters, and main steam piping, impacting turbine components. Oxides are often dislodged by stresses associated with thermal transients. Impingement of condensed steam droplets produces wastage on latter-stage buckets, drain lines, and piping. If condensed fluids have low pH, erosion-corrosion becomes more significant.

Identification

Preboiler. Erosion caused by turbulent water flow in pumps usually produces smooth grooves, craters, and general thinning (Fig. 17.9). The oxide layer in eroded regions is thinner or absent, usually is a different color, and has a smoother surface texture than in unattacked adjacent regions. A drop of acid placed on freshly eroded carbon steel will reveal

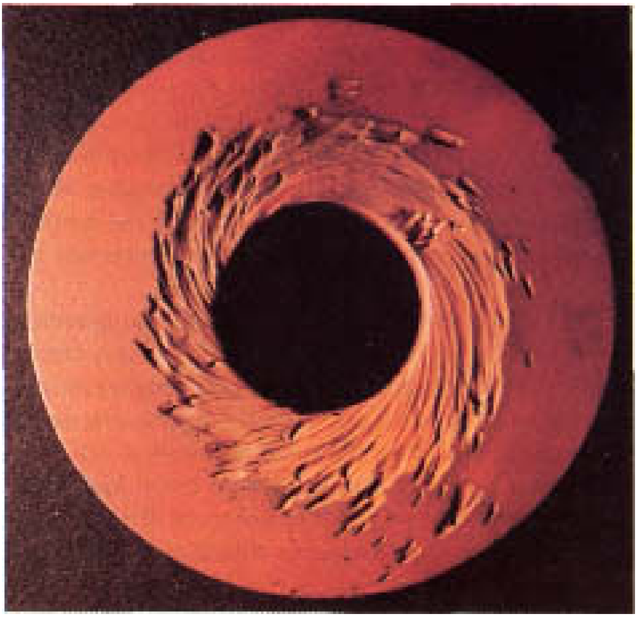

Figure 17.9 Feedwater-pump spacer eroded by turbulent high-speed water. Flow patterns are obvious.

bright metal in a matter of seconds. Unattacked surfaces usually require considerable exposure to reveal bare metal. Flow patterns are often obvious.

Unless particulate matter is entrained, close visual inspection will reveal no evidence of individual scratches, sleeks, or dents. Usually, such damage is apparent only when a larger amount of hard particulate matter is entrained within the carrying liquid.

Afterboiler. Erosion caused by impingement of water droplets in latter turbine stages produces general wastage, which is most noticeable on leading edges of buckets (Fig. 17.10). Blade edges are marked by fine, transverse serrations and grooves (Fig. 7.11). Cone-shaped projections may rise from surfaces (Fig. 17.12). Often these cones will be tilted so that conical axes parallel impingement direction. Hence, cones are usually present on leading bucket faces and are less numerous or absent on back blade faces. Similar impingement cones can occur on mild steel surfaces such as turbine drain lines (Fig. 17.13).

Damage caused by hard-particle erosion causes tearing and microdenting of leading bucket edges. Striations and tilted cones are usually absent. A ragged feather edge usually develops.

Figure 17.10 Ragged leading edges of final-stage turbine blades. Damage was caused by water-droplet impingement.

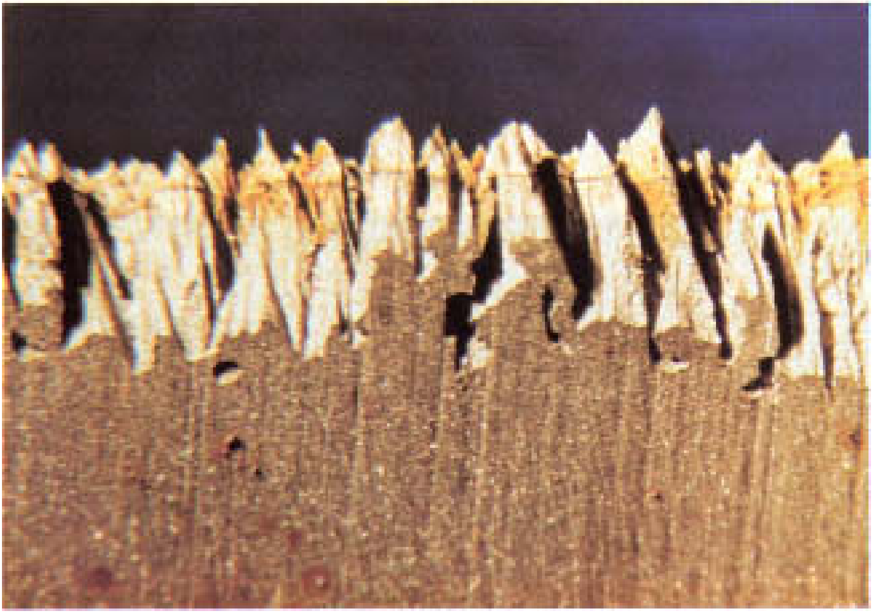

Figure 17.11 Fine, striated grooves on front face of final-stage turbine blade caused by water-droplet impingement. (Magnification: 7.5X.)

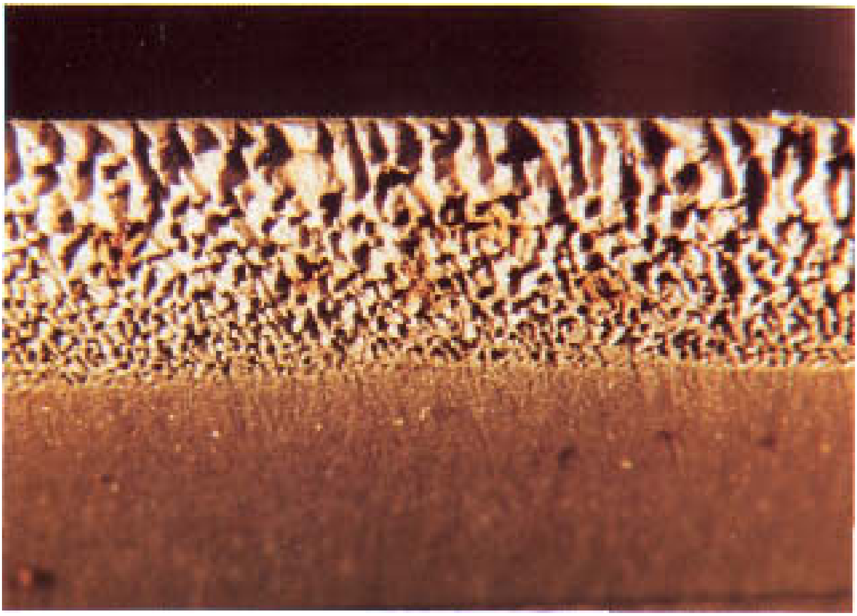

Figure 17.12 Dimpling of back edge of bucket surface shown in Fig. 17.11.

Elimination

Lessening attack requires eliminating the erodent, decreasing erodent kinetic energy, shielding surfaces, or substituting alloys that are more erosion-resistant. If pumps, valves, and piping are sized, designed, and operated properly, attack is rare. Turbine erosion problems can be more troublesome.

Figure 17.13 Erosion on mild steel turbine drain line. Surface is festooned with small, conical projections pointing toward the direction of impingement.

Magnetite exfoliation in superheaters, reheaters, and steam-transfer lines (see Chap. 1, "Water-Formed and Steam-Formed Deposits") is the major cause of solid-particle erosion in turbines. The exfoliation process is lessened when thermal stresses and tube temperatures are reduced. If superheater and reheater tubing is old, it is likely that tubes will contain considerable thermally formed oxide. Tube replacement or chemical cleaning may be necessary to remove thick oxide layers. Turbine screens and shielding devices should be maintained in good repair.

Alloys used in fabricating turbine buckets are quite similar worldwide, consisting of chromium stainless steels. However, cobalt-based alloys, titanium, and proprietary metals are gaining wider usage. Cobalt-based erosion-shield alloys have been used in latter stages.

Corrosion accelerates erosive metal loss. Almost all metals contacting steam or water experience some corrosion. Thus all erosion in boiler systems containing water or steam is an erosion-corrosion process. It is only when corrosion has a relatively small effect on metal loss that the process can be called "erosion." If erosion predominates, chemical inhibition can usually do little to reduce attack. But if corrosion is significant, the judicious use of inhibitors and/or pH modification may be beneficial.

Cautions

Cavitation is closely related to erosion. Damage occurs where high-velocity turbulent fluids are present. Cavitation damage may superficially resemble hard-particle erosion. However, cavitation does not occur in steam and is not likely to produce smooth, undulating, or grooved surfaces.

Attack by concentrated chelant increases substantially with flow velocity. Grooving and general thinning from chelant corrosion strongly resemble erosion alone. Chelant attack in feedwater lines, steam drums, and generating tubes is frequently confused with erosion.

Related problems

See also Chap. 5, "Chelant Corrosion"; Chap. 18, "Cavitation"; and the section titled Falling-Slag Erosion in this chapter.

Water-Side and Steam-Side Erosion

Erosion is very rare in water- and steam-cooled tubes. However, wastage will occur where flow is restricted by foreign objects, collections of scale, and the like. Usually, however, other associated problems such as overheating will cause failure before erosion can cause severe damage (see Case History 17.4).

CASE HISTORY 17.1

Industry:	Utility
Specimen Location:	Superheater
Specimen Orientation:	Vertical
Years in Service:	5
Water-Treatment Program:	Coordinated phosphate
Drum Pressure:	2400 psi (16.5 MPa)
Tube Specifications:	2½ in. (6.4 cm) outer diameter, SA-213
Fuel:	Pulverized coal

A series of failures of superheater tubes occurred almost 2 years after extensive retubing. Nearby tubes contained forming defects present as deep fissures. These fissures opened in service, causing steam cutting of adjacent tubes (Fig. 17.5).

It is remarkable that failures similar to this one occurred almost 2 years earlier, and for essentially the same reason. In spite of the extensive retubing, some defective tubes were missed. Tubes containing deep fissures remained in service for at least 2 years before failure occurred. When these defective tubes finally failed, extensive steam cutting of nearby tubes resulted.

CASE HISTORY 17.2

Industry:	Utility
Specimen Location:	Primary-superheater pendant
Specimen Orientation:	Vertical pendant
Years in Service:	25
Water-Treatment Program:	Coordinated phosphate
Drum Pressure:	1800 psi (12.4 MPa)
Tube Specifications:	2⅜ in. (6.0 cm) outer diameter
Fuel:	Coal

A superheater tube failed at a pendant U-bend. Failure was caused by corrosion-fatigue cracking. Leakage was relatively slight before opposite legs were steam-cut (Fig. 17.6). More tubes had to be replaced because of chain-reaction failures associated with steam cutting than because of the precipitating corrosion fatigue.

CASE HISTORY 17.3

Industry:	Refining
Specimen Location:	Flue-gas cooler used to preheat boiler feedwater
Specimen Orientation:	Vertical
Years in Service:	4
Water-Treatment Program:	Polymer
Drum Pressure:	150 psi (1.0 MPa) in cooler tubes
Tube Specifications:	2 in. (5.1 cm) outer diameter

A longitudinally split section of flue-gas cooler used to preheat boiler feedwater contained helical grooves on internal surfaces (Fig. 17.14). Some grooves penetrated the tube wall, producing helical cracks, while other grooves went only one-third of the way through the wall. Grooves were undercut in the direction of gas flow.

Erosion occurred along a helical coil inside the tube. The helix was used to increase turbulence and eliminate deposits. High-velocity flue-gas flow became sufficiently turbulent at the helix to cause erosion failures.

Figure 17.14 Spiral grooves cut into internal surface of flue-gas cooler by erosive gas flow. A spiral, stainless coil present inside the tube caused increased localized turbulence.

CASE HISTORY 17.4

Industry:	Pulp and paper
Specimen Location:	Superheater U-bend
Specimen Orientation:	Vertical
Years in Service:	10 months
Water-Treatment Program:	Phosphate
Drum Pressure:	570 psi (3.9 MPa)
Tube Specifications:	1½ in. (3.8 cm) outer diameter
Fuel:	Black liquor

Severe localized metal loss from internal surfaces caused a perforation in a U-bend 10 months after tube installation. This was the only tube that was affected in this manner. An elliptical pattern of metal loss was present in the immediate vicinity of the perforation (Fig. 17.15). Islands of intact tube wall were present in the wasted region.

Failure was caused by impingement of high-velocity fluid on tube surfaces. It is likely that an object lodged in the tube on the upstream side of the bend constrained the water flow into a narrow channel. Erosion was induced locally by increased water speed and greater turbulence near the foreign object.

Figure 17.15 Elliptical metal-loss pattern and intact island of tube metal at perforated superheater U-bend. Erosion was caused by an object left in the tube 10 months earlier.

CASE HISTORY 17.5

Industry:	Utility
Specimen Location:	Corner tube in a waterwall
Specimen Orientation:	Vertical
Years in Service:	19
Water-Treatment Program:	Coordinated phosphate
Drum Pressure:	2250 psi (15.5 MPa)
Tube Specifications:	3 in. (7.6 cm) outer diameter
Fuel:	Pulverized coal

A rupture occurred at a repair weld. Welding was used to increase lost wall thickness to about 50% of the specified wall thickness. These welds built up metal loss from fire-side surfaces.

External-surface metal loss was caused by erosion due to the impingement of fly ash entrained in flue gas. Deep grooves were cut in the tube wall at membrane gaps (Fig. 17.8).

This boiler had a history of slagging problems. High solids and silica concentration in the fuel accelerated attack.

CASE HISTORY 17.6

Industry:	Pulp and paper
Specimen Location:	High-pressure section of condensing turbine, last row, condensing section
Specimen Orientation:	Horizontal turbine shaft
Years in Service:	6
Water-Treatment Program:	Chelant
Drum Pressure:	45-MW turbine, 3600 rpm, 830°F (450°C) superheated steam

Turbine buckets were damaged severely on leading edges. Edges were striated and grooved (Fig. 17.11). Erosion was caused by high-velocity fluids in which water droplets were entrained. Erosion damage due to water-droplet impingement is not uncommon in late stages of condensing turbines.

A 65-psi (0.45-MPa) steam-extraction, nonreturn valve failed to seat properly during an electrical turbine trip. The 65-psi (0.45-MPa) header emptied through the turbine (vacuum condition). The turbine speed increased to 5000 rpm (design 3600 rpm) before manual shutdown.

CASE HISTORY 17.7

Industry:	Utility
Specimen Location:	Division wall in a circulating fluidized-bed boiler
Specimen Orientation:	Vertical
Years in Service:	18 months, but only operating about 6 months because of numerous maintenance shutdowns
Water-Treatment Program:	Chelant
Drum Pressure:	1275 psi (8.8 MPa), ~1700°F (930°C) external-surface temperature
Tube Specifications:	3 in. (7.6 cm) outer diameter, mild steel
Fuel:	Furnace bed of sand, lime, and wood chips

The section has a massive longitudinal rupture in a zone of severe metal loss from external surfaces (Fig. 17.16). Failure was caused by external-surface erosion. Microstructural examination revealed that hard particulate matter (sand) was entrained in bed gases. Impingement of sand against the tube reduced wall thickness, resulting in severe thinning. Rupture occurred when internal pressure exceeded the yield strength of the thinned tube.

The forced-draft fan maintained a 60- to 70-in. (15- to 17.5-cm) pressure head of water to fluidize the bed. No refractory or other surface protective devices such as studs or wear bars were present at the failure site.

Figure 17.16 Ruptured division-wall tube from fluidized-bed boiler. Attack was caused by sand abrasion in the bed.

CASE HISTORY 17.8

Industry:	Refining
Specimen Location:	Condensate return header
Specimen Orientation:	Elbow (horizontal to vertical)
Years in Service:	Unknown (more than 5)
Tube Specifications:	6½ in. (16.5 cm) outer diameter, mild steel

Internal surfaces were covered in some areas with a smooth, black magnetite layer. Severe metal loss was present in large, distinct patches (Fig. 17.17). The metal loss produced smooth, mildly rolling contours free of deposits or corrosion products. Flow-oriented striations were present at the perimeter of the affected area (Fig. 17.18).

Condensate lines frequently suffer corrosion by carbonic acid. However, this tube shows evidence of erosion only. Metal loss is localized and distinctly flow-oriented. Such patterns are characteristic of erosion. Evidence suggests that magnetite particles entrained in the condensate contributed to metal loss.

Figure 17.17 Localized metal loss in a bend of a condensate return header.

Figure 17.18 Erosion patterns at edge of wasted area. As in Fig. 17.17. Note flow patterns. (Magnification: 7.5X.)

CASE HISTORY 17.9

Industry:	Pulp and paper
Specimen Location:	Economizer
Specimen Orientation:	Curved, predominantly vertical
Years in Service:	8
Water-Treatment Program:	Phosphate
Drum Pressure:	1200 psi (8.3 MPa)
Tube Specifications:	2 in. (5.1 cm) outer diameter, mild steel
Fuel:	Black liquor

Substantial thinning of the external surface of the tube wall is present at the inner curvature of a bend in an economizer tube. A ragged rupture perforates the wall in a zone of severe thinning (Fig. 17.19). Away from the rupture, surfaces are relatively unattacked.

The rupture was caused by erosive wall thinning. Normal internal pressures could no longer be contained at the eroded site and the tube ruptured.

Erosion was caused by impingement of hard particulate matter entrained in flue gases. There was evidence of mild cold-end corrosion on all external surfaces.

Figure 17.19 Rupture in an economizer tube caused by severe localized external-surface erosion associated with particulate matter entrained in flue gas.

CASE HISTORY 17.10

Industry:	Utility
Specimen Location:	Front convection wall
Specimen Orientation:	Vertical
Years in Service:	8
Drum Pressure:	2500 psi (17.2 MPa)
Tube Specification:	2¾ in. (7.0 cm) outer diameter, SA201 A1
Fuel:	Coal

A tube failed at a weld support. Escaping water cut away the support and perforated the adjacent tube (Fig. 17.20).

The question that naturally arises in multiple failures is which failure occurred first. If erosion is severe, the original failure can be entirely eradicated. Luckily, other nearby supports were included with the received section. Careful visual inspection revealed small corrosion-fatigue cracks at poorly fused support welds. Upon sectioning and microscopic examination, small fissures were located near the original failure; these fissures were almost identical to (but deeper than) those found at adjacent braces. Hence, the original failure was likely caused by corrosion fatigue at a weld support.

Figure 17.20 Steam cutting of utility convection tubes. The original failure occurred at a welded support bracket and was due to corrosion fatigue. The adjacent tube was breached by escaping steam from the original failure.