Chapter 2

Long-Term Overheating

Locations

Failures resulting from long-term overheating occur in water- and steam-cooled tubes such as waterwalls, downcomers, screen tubes, superheaters, reheaters, and roof tubes. Almost 90% of failures caused by long-term overheating occur in superheaters, reheaters, and wall tubes. Long-term overheating rarely occurs in economizers and floor tubes. Tubes that are especially subject to overheating often contain significant deposits, have reduced coolant flow, experience excessive fire-side heat input, or are near or opposite burners.

Tubes near chain-grate stokers, and adjacent to restricted or channeled furnace gases, commonly suffer long-term overheating. Other tubes subject to overheating include sections in which refractory has been spalled. In the case of recovery boilers, waterwall tubes near the smelt bed that are not covered with solidified smelt and carbonaceous material are subject to overheating. Slanted tubes, such as nose arches, are particularly susceptible to long-term overheating due to steam channeling. Fire tubes are rarely affected.

Failures usually occur in relatively broad areas and involve many tubes — for example, a number of tubes in the middle of a waterwall at about the same elevation. Usually many tubes are either ruptured or bulged.

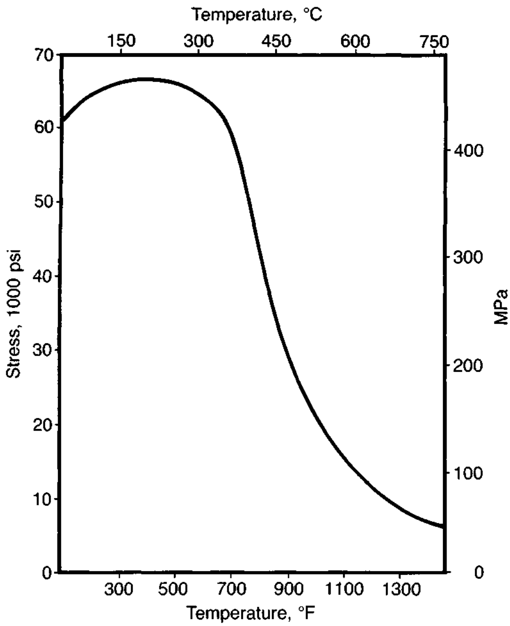

Figure 2.1 Yield stress of plain carbon steel as a function of temperature. Note the rapid strength decrease above 800°F (430°C).

General Description

Long-term overheating is a condition in which metal temperatures exceed design limits for days, weeks, months, or longer. This type of overheating is the cause of more boiler failures than any other mechanism. Because steel loses much strength at elevated temperatures (Fig. 2.1), rupture caused by normal internal pressure becomes more likely as temperatures rise.

The maximum allowable design temperature is primarily a function of tube metallurgy. As the amount of alloying element, particularly chromium and molybdenum, is increased, higher temperatures can be tolerated. Alloy tubes are therefore frequently used in superheaters and reheaters (Table 2.1). Long-term overheating depends on temperature, length of time at temperature, and tube metallurgy.

A mild steel tube subject to temperatures above 850°F (454°C) for more than a few days may experience long-term overheating. If temperatures remain elevated for a prolonged period, overheating will certainly occur. As temperatures rise, the severity of the overheating during a fixed period increases. No gross deformation or thermal deterioration may be evident.

Furnace-gas temperature often exceeds 2000°F (1093°C). Heat transfer into a boiler tube is controlled partly by the insulating characteristics of material near internal and external surfaces (Refer to Chap. 1, "Water-Formed and Steam-Formed Deposits"). Heat transfer is markedly in-

TABLE 2.1 Temperatures at Which Thermal Oxidation Becomes Excessive

Steel alloy	Approximate scaling temperature* °F	°C
Carbon	1025	550
½Mo	1050	570
½Cr-½Mo	1070	580
1Cr-½Mo	1100	600
2Cr-½Mo	1100	600
2¼Cr-1Mo	1100	600
3Cr-½Mo-1¼Si	1400	760
5Cr-½Mo	1150	650
5Cr-½Mo-1½Si	1550	850
5Cr-½Mo-Ti	1150	650
7Cr-½Mo	1250	680
9Cr-1Mo	1420	770
12Cr	1420	770
17Cr	1550	850
18Cr-8Ni	1600	870
18Cr-8Ni, Ti	1700	930
18Cr-8Ni, Cb	1650	900
18Cr-8Ni, Mo	1650	900
25Cr-12Ni	2000	1100
25Cr-20Ni	2000	1100
27Cr	2000	1100

*Temperature at which oxidation equals 10 mg/cm^2 in 1000 h.

fluenced by a thin gas film that normally exists on external surfaces. A temperature drop of over 1000°F (537°C) commonly occurs across this film. Deposits, corrosion products, refractories, and other materials on external surfaces also slightly reduce metal temperatures. The thermal resistance of the tube wall may cause a very slight drop in temperature across the wall.

When considering heat transfer through the water-side surface, the effect of deposits is reversed. Steam layers and deposits insulate the metal from the cooling effects of the water, resulting in reduced heat transfer into the water and increased metal temperatures.

Bulging usually precedes rupture. Many times bulging results because hot-face (hot-side) temperatures are not uniform and local regions develop hot spots. Bulges can take many forms; some are shallow and sloping, while others are abrupt (Fig. 2.2). A single bulge or many bulges may occur. When many bulges occur along the hot faces, internal deposition is sometimes great.

Figure 2.2 Multiple, abrupt bulges on the hot face of a waterwall tube of a recovery boiler.

Bulging usually causes spalling of deposits at the bulge site, which reduces metal temperature locally. However, due to water flow the bulge geometry produces a flow disturbance that makes steam blanketing (in water-cooled tubes) more likely, thus raising temperature. Also, bulging increases surface area, allowing a greater fire-side heat input locally. In

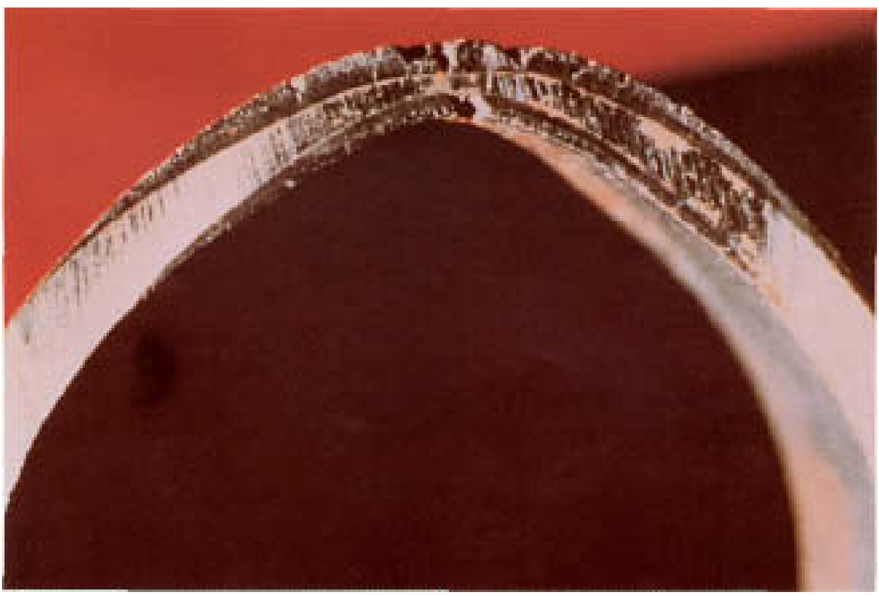

Figure 2.3 Thick, thermally formed oxide on internal and external surfaces of a bulged wall tube. Thinning of intact metal at bulge is due to both plastic deformation and thermal oxidation.

Figure 2.4 Thick, blistered magnetite layer on internal surface of 150-psi (1.0-MPa) tube. Oxide was formed during dry firing of boiler. Metal temperatures approached 2000°F (1100°C), causing slow, "viscous" flow of magnetite.

general, metal temperature is higher at bulges than in the surrounding metal. In many cases, continued existence of bulges is sufficient to cause overheating, even if associated deposits are removed.

Thermal oxidation (metal burning)

One sign of long-term overheating can be a thick, brittle, dark oxide layer on both internal and external surfaces (Figs. 2.3 and 2.4). If metal temperatures exceed a certain value for each alloy, thermal oxidation will become excessive. The temperatures at which alloys appreciably oxidize (scaling temperatures) are given in Table 2.1. Often, the thermally formed oxide layer contains longitudinal fissures and cracks. In other areas, patches of oxide may have exfoliated (Fig. 2.5). Cracks and exfoliated patches result from tube expansion and contraction caused by deformation during overheating and/or thermal stressing. Tube-wall thinning can result from cyclic thermal oxidation and spalling. This process can continue until the entire wall is converted to oxide, creating a hole (Fig. 2.6).

Creep rupture (stress rupture)

Creep rupture (stress rupture) is a form of long-term overheating damage that usually produces a thick-lipped rupture at the apex of a bulge. Creep produces slow plastic deformation and eventual coalescence of microvoids

Figure 2.5 Thermally deteriorated metal on failed wall tube of a utility boiler. Note the spalled and cracked oxide resembling tree bark caused by expansion of tube during bulging and thermally induced stresses.

Figure 2.6 Through-wall oxidation of a tube from a low-pressure boiler. Brittle black magnetite patches still adhere to the rupture mouth. Elsewhere the oxide has spalled. Such through-wall oxidation is most common in low-pressure boilers, where internal pressures are not sufficient to cause premature failure.

Figure 2.7 A small, ragged creep rupture at the apex of a bulge. Note the small secondary fissures and the relatively thick rupture edges.

in metal during overheating. Often a small longitudinal fissure will be present at the apex of a heavily oxidized bulge (Fig. 2.7). In other cases, the rupture will be larger and have a fish-mouth shape (Fig. 2.8). The rupture will usually have blunt and slightly ragged edges. Similar, but smaller, longitudinally oriented ruptures and fissures may exist nearby.

Chain graphitization

A somewhat uncommon form of damage, *chain graphitization,* can also occur after long-term overheating. The damage begins when iron carbide

Figure 2.8 Two superheater tubes from a utility boiler [1400 psi (9.7 MPa)], failed by creep. Note the fish-mouth ruptures. Compare with Fig. 2.7.

particles (normally present in plain carbon or low-alloy steels) decompose into graphite nodules after prolonged overheating above 800°F (427°C). The graphite nodules, if distributed uniformly in the steel, rarely cause failure. However, nodules sometimes chain together, forming planes of cavities filled with graphite. The nodules usually form at microstructure defects, in places where there are chemical impurities, and along stress lines. Stresses generated by internal pressures cause tearing of the metal along chains of nodules, much as a postage stamp is torn from a sheet along the perforated edges.

Chain graphitization is usually found at welds (Fig. 2.9). Less commonly, damage occurs away from welds and forms helical cracks spiraling around tube surfaces (Fig. 2.10). Such failures are sometimes confused with creep damage, but careful microscopic observation will reveal the presence of graphite nodules at or near fracture edges.

Critical Factors

Long-term overheating is a chronic, rather than transient, problem. It is the result of long-term deposition and/or long-term system operating problems. Heavy internal deposition on both hot and cold sides of water-

Figure 2.9 Rupture at longitudinal weld due to chain graphitization. Note the blunt, rough rupture edge. Such failures occur after long-term mild overheating.

Figure 2.10 Spiral through-fissures due to chain graphitization. These fissures formed along lines of maximum shear stress.

wall tubes often indicates that deposits have insulated the tube wall from cooling effects of the water, contributing to overheating.

Experience has shown that when the ratio of deposits on hot to cold faces of water-cooled tubes exceeds 3, fire-side heat input is substantially higher on the hot face. When this ratio approaches 10, heat input on the hot face relative to the cold face can be quite excessive. In many cases, the ratio will be below 3 if the heat input is not excessive on the hot face; when chemical water treatment is deficient; or when water chemistry is overwhelmed by contaminants.

Deposits on superheater tubes caused by carryover and/or contaminated attemperation waters can produce overheating. In most steam-cooled tubes, heat-flux differences between the hot and cold sides are not pronounced. Resulting deposit patterns are characteristic of contamination rather than excessive heat input. Other sources of overheating include overfiring, incorrect flame pattern, restricted coolant flow, inadequate attemperation, and improper alloy composition.

Identification

A thick, brittle magnetite layer near the failure indicates long-term overheating. At greatly elevated temperatures (short-term overheating) reduction in metal strength is such that failure occurs before significant amounts of oxides can develop.

Bulging and plastic deformation are almost always present if the tube is pressurized. Tubes ruptured as a result of long-term overheating usually show bulging and plastic deformation at the failure site. The rupture is almost always longitudinal, with a fish-mouth shape. Rupture edges may be knifelike or thick depending on the time, temperature, and stress levels involved. Multiple bulges may occur.

Water-side deposits will usually be present and will often be hard and stratified. Deposits will usually be "baked" onto the wall and will become hard and brittle. Deposits tend to show multiple layers of different colors and textures, the innermost layers being hardest and most tenacious.

Visual inspection is adequate for oxidation, spalling, and bulging. Thermocouple measurement during service frequently supplies good information. The best way to ascertain that long-term overheating has occurred is by metallographic inspection of a failed tube.

Elimination

Eliminating long-term overheating requires removal of a chronic system defect. Headers, U-bends, long horizontal runs, and the hottest areas should be inspected for evidence of obstruction, scales, deposits, and other foreign material. Excess deposits should be removed by chemical or mechanical cleaning and prevented from recurring. Firing procedures, Btu value of fuels, and in-service furnace temperatures near overheated areas should be checked. Attemperation procedures should also be reviewed. If needed, changes in metallurgy, tube shielding, and the judicious use of refractories should be considered.

The source of significant deposits must be identified and eliminated. Common causes of deposits include improper water treatment, system contamination, improper boiler operation, and/or excessive heat input. Each potential cause must be addressed methodically.

Cautions

It is incorrect to assume that long-term overheating automatically produces significant tube damage. While small microstructural changes may occur in the tube wall, these changes often do little to reduce service life or significantly weaken the tube. However, if overheating continues for a long time, failures will eventually result.

Long-term and short-term overheating failures may appear similar. Frequently, evidence of both long-term and short-term overheating will be present at the same failure. Failures due to long-term overheating are sometimes associated with chemical attack and other significant metal wastage, while chemical attack in short-term overheating is rare. The presence of corrosion does not exclude consideration of long-term overheating. Because a brief episode of short-term overheating may follow long-term overheating, the sequence of thermal events can be difficult to diagnose without microscopic examinations.

Related Problems

See also Chap. 1, "Water-Formed and Steam-Formed Deposits"; Chap. 3, "Short-Term Overheating"; Chap. 4, "Caustic Corrosion"; and Chap. 14, "Hydrogen Damage."

CASE HISTORY 2.1

Industry:	Gas products
Specimen Location:	Superheater, 3 ft (1 m) above firebox floor near the center of the boiler
Specimen Orientation:	Horizontal, immediately adjacent to a firebrick wall
Years in Service:	12
Water-Treatment Program:	Phosphate
Drum Pressure:	Design is 700-psi (4.8-MPa) package boiler, but operated at 600 psi (4.1 MPa)
Tube Specifications:	2 in. (5.1 cm) outer diameter, SA-213-T22
Fuel:	Natural gas

A brittle black magnetite layer covered both external and internal surfaces of this superheater tube. The thermally formed oxide fractured and spalled, substantially reducing wall thickness (Fig. 2.11). Thinning was more severe along the side of the section abutting a firebrick wall.

Most metal was lost from external surfaces and was caused by thermal oxidation at temperatures between 1100 and 1350°F (600 and 727°C). Gas channeling and higher temperatures were present along the tube side abutting the firebrick. These factors accelerated oxidation and spalling processes.

In the past, nearby tubes had ruptured as a result of thinning associated with thermal oxidation. No deposits were present on internal surfaces, and attemperation was not used. Fire-side slagging was not present in this intermittently run boiler.

Failures were a chronic problem associated with design and operation. The proximity of failures to the firebrick wall strongly linked the overheating to boiler design.

Figure 2.11 Severe thermal oxidation and spalling of magnetite on external surface. The laminated nature of the scale indicates multiple episodes of spalling and oxide reformation.

CASE HISTORY 2.2

Industry:	Steel
Specimen Location:	Center of waterwall
Specimen Orientation:	Vertical
Years in Service:	8
Water-Treatment Program:	Phosphate
Drum Pressure:	1200 psi (8.3 MPa)
Tube Specifications:	3 in. (7.6 cm) outer diameter
Fuel:	Blast-furnace gas

Longitudinal fissures and thick-walled, ruptured bulges were present along the hot side of this section (Fig. 2.12). Surfaces are covered with an irregular tan slag layer, and the external surface near the through-fissure is checkered.

The rupture and fissuring were caused by very long-term exposure of the metal to temperatures between 850 and 1050°F (454 and 566°C). Evidence suggests that exposure to these temperatures may have been occurring for several years. Overheating was caused by excessive heat input relative to coolant flow rate.

Figure 2.12 Longitudinal fissures along hot side. Note the through-fissure at the bulge apex.

Nearby tubes showed similar, although less severe, attack. Deposits on hot-side internal surfaces were less than 20 g/ft^2 (22 mg/cm^2). The boiler had been cleaned 3 years prior to failure.

CASE HISTORY 2.3

Industry:	Utility
Specimen Location:	Rear wall, 30 ft (9.1 m) from front wall
Specimen Orientation:	Vertical
Years in Service:	1½
Water-Treatment Program:	Polymer
Drum Pressure:	620 psi (4.3 MPa)
Tube Specifications:	3 in. (7.6 cm) outer diameter
Fuel:	Pulverized coal

The tube has a series of several prominent bulges longitudinally aligned along the hot-side crown (Fig. 2.2). Thick layers of hard, tenacious iron oxide cover each bulge, except where spalling has dislodged the oxide. Internal surfaces on the hot side are covered with spongy, porous deposits, which cover a hard, black magnetite layer. The back wall at the same elevation saw many failures. The boiler had frequent load swings and was operated intermittently.

The tube was overheated in a temperature range between 950 and 1150°F (510 and 620°C) at the bulges for a long time. Formation of deposits was due to an imbalance between coolant flow and fire-side heat input. Deposit weights were about 5 g/ft^2 (5 mg/cm^2) on the cold side and 26 g/ft^2 (28 mg/ cm^2) on the hot side. Deposits were caused by exceeding the solubility of inversely soluble species, by evaporative concentration, and by mechanical entrainment of particulate matter.

Because of the frequent load swings and intermittent operation, closer operational monitoring was suggested.

CASE HISTORY 2.4

Industry:	Steel
Specimen Location:	Primary-superheater bank
Specimen Orientation:	Vertical pendant
Years in Service:	16
Water-Treatment Program:	Polymer
Drum Pressure:	1200 psi (8.3 MPa)
Tube Specifications:	2¼ in. (5.7 cm) outer diameter
Fuel:	Coke gas

Three large bulges are present on the pendant legs of this U-bend section. Each bulge is ruptured at its apex. The legs expanded to about a 2½-in.

Figure 2.13 Bulged and ruptured superheater U-bend. The legs are slightly expanded.

Figure 2.14 As in Fig. 2.13. Fragmented thermally formed oxide surrounds the rupture.

(6.4-cm) outer diameter from their 2¼-in. (5.7-cm) original value. Bulges are shown in Figs. 2.13 and 2.14. Internal surfaces are free of significant deposits, while external surfaces are covered with a tenacious, fragmented oxide layer. Eighteen tubes were similarly affected. This boiler operates on waste heat from a slab furnace.

The tube was overheated for a period of several days or longer at temperatures above 1000°F (540°C), but below 1350°F (730°C). The wall strength was decreased at elevated temperatures, and tubes were thinned and weakened by thermal oxidation. As a result of these two forms of weakening, the legs bulged and then ruptured.

Operating records showed an increase of almost 100°F (56°C) in steam temperature approximately 2 months prior to failure. This increase was correlated with changes in firing associated with alteration of the slab mill's operation.

CASE HISTORY 2.5

Industry:	Utility
Specimen Location:	Primary-superheater inlet; section with hottest flue gas
Specimen Orientation:	Horizontal
Years in Service:	20
Water-Treatment Program:	Phosphate
Drum Pressure:	1200 psi (8.3 MPa)
Tube Specifications:	Circumferentially welded tubes, 2¼ in. (5.7 cm) outer diameter
Fuel:	Currently coal (1% S, less than 10% ash); until 6 months before failure, oil (2% S, 200–400 ppm V) was used as fuel

The section contains a massive, thick-walled, longitudinal rupture just above a circumferential weld. The rupture occurred immediately downstream of the weld. The tube was bent into an "L" by the burst. The rupture terminates at one end in a pair of thick-walled transverse tears (Fig. 2.15). A thick, tenacious magnetite layer covers external surfaces, except those near the

Figure 2.15 Massive thick-walled fracture caused by creep. Note the circumferential weld just below the failure. The tube is torn and bent to a 90° elbow by the violence of the rupture.

rupture, where the oxide has cracked and spalled. Elemental copper and spotty deposits are present on internal surfaces.

Failure was caused by prolonged overheating at temperatures above 1050°F (570°C). The direct rupture was a stress (creep) rupture. Coolant flow irregularities immediately downstream of a partially intrusive circumferential weld, along with internal deposition, which reduced heat transfer, were contributing factors. Additionally, a switch from oil to coal firing likely changed fire-side heat input.

The superheater had a history of boiler-water carryover, and load swings were common. Previous failure had occurred in this region at least 2 years before the current rupture.