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Thermal Considerations in Boiler Tube Failures

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Abstract

During normal operations of a steam generator, the internal surfaces of all tubes form an iron oxide scale by reactions with steam. Under some abnormal conditions, deposits form on waterwall surfaces by reaction with boiler feed-water chemicals. The effect of these internal scales and deposits is to impede heat transfer and raise the tube metal temperatures.

A thermal analysis is presented that permits calculation of the tube metal temperature as a function of Q/A_O and internal scale thickness for both water and steam cooled tubes. Curves are presented that allow an estimate of the thermal damage that may occur and give a prediction when a boiler should be chemically cleaned. The thermal analysis is compared with previous studies on the cleanliness of boilers. Several examples of boiler tube failures are given and explained using the thermal analysis.

INTRODUCTION

In the normal operation of a steam generator, regardless of the temperature or pressure, steam or water will react with steel to form iron oxide. In superheaters and reheaters, the rate of scale formation is a function of the temperature and particular alloy. With very few exceptions, the steam is quite pure, and for all practical purposes, no attention need be paid to impurities. However, within waterwalls, both iron oxide and deposits of boiler feedwater chemicals may precipitate on the inside surfaces of the furnace tubes.

The effect of internal scale or deposits is to act as a thermal insulating barrier that impedes heat transfer from the hot flue gas to the steam/water emulsion. An insulating layer between the fluid on the inside of the tube and the hot flue gas on the outside raises the metal temperature. For the most part, the initial design allows some margin for tube metal temperature increase as a result of internal scale but excessive deposits must be removed in order to assure continued trouble-free operation. An increase in metal temperature above that established at the time of design will adversely affect the tube metal in the following ways:

1. Increase the oxidation or corrosion rate on both the outside and inside of the tube.
2. Increase the rate of microstructural degradation within the steel. As the microstructure changes from normal pearlite and ferrite to spheroidized carbides or graphite and ferrite, the high temperature strength of the material decreases.
3. Decrease the creep life; or, put another way, increase the creep rate.
4. Decreases the strength of the metal relative to the safe or code design limit.

The following paper is divided into three parts: 1) A thermal analysis is presented which correlates the design parameters for heat transfer with internal scale or deposit formation and gives the expected tube metal temperature increase. The analysis may be used for either steam or water cooled tubes. 2) Suggestions are made for the frequency of chemical cleaning which relate to the expected temperature increase within the steel tubing. The lower the temperature and pressure of operation, the longer may be the interval between chemical cleaning cycles. 3) The third portion will present several examples of boiler tube failures that are explained in light of the thermal analysis.

THERMAL ANALYSIS

Reaction of steam and steel forms a magnetite scale on the internal surfaces of all steam generator surfaces that will increase the tube metal temperature.

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$$

Similarly, corrosion products or boiler feedwater impurities may deposit on the internal surfaces of furnace tubes that will also raise the tube metal temperature. A calculation may be done to estimate the increase in tube metal temperature as a result of the internal scale. The scheme follows the heat flow analysis of Kreith[1] for the steady state.

NOMENCLATURE:

Q = heat flow, W (Btu/hr).
U_0 = overall heat transfer coefficient, W/M^2-C (Btu/hr-ft^2-F).
A_0 = area of the outside of the tube, M^2 (ft^2).
T_0 = flue gas temperature, C (F).
T_3 = tube metal temperature on the OD surface, C (F).
T_2 = temperature at the metal/scale interface, C (F).
T_1 = temperature of the ID of the tube, C (F).
T_S = bulk steam temperature, C (F).
r_3 = radius of the OD of the tube, M (ft).
r_2 = radius of the tube metal ID, M (ft).
r_1 = radius of the tube ID, M (ft).
h_S = steam side heat transfer coefficient, W/M^2-C (Btu/hr-ft^2-F).
h_0 = gas side heat transfer coefficient, W/M^2-C (Btu/hr-ft^2-F).
k_1 = thermal conductivity of scale, W/M-C (Btu/hr-ft-F).
k_2 = thermal conductivity of metal, W/M-C (Btu/hr-ft-F).

In order to calculate the surface temperature, T_3, as a result of ID scale formation, h_0 is first calculated from equation 4 given the design parameters of U_0, r_3, r_1, h_S, and k_2 for the clean tube condition. The scale resistance is zero and $r_1 = r_2$, that is, there is no ID scale. Using this value of h_0, the design value of Q/A_0 and T_0, the value for T_3 is calculated. In practice, T_3 is set at the oxidation limit minus a small margin.

The addition of internal scale alters the heat flow; to calculate the effect of scale, the scale term is added to the denominator of equation 5. Final calculation of T_3 is a two step procedure. Using h_0, just calculated, and appropriate values for the other terms in equation 5 (note h_S is nearly unaffected by scale and is assumed to be constant in this exercise), T_0 and T_S are taken from design conditions, a new and smaller value of Q/A_0 is found. From equation 9, T_3 is calculated from this smaller Q/A_0.

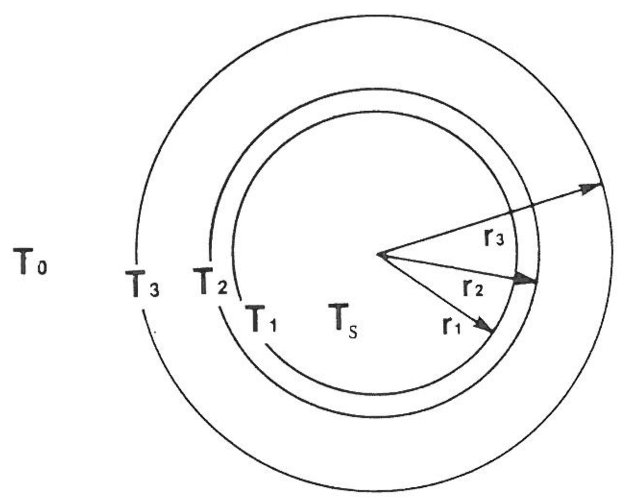
By using the thermal analysis, estimates may be made of tube wall temperatures as a function of internal scale/deposit thickness. The important variables are tube location as it affects Q/A_0 and U_0, and whether the tube is steam or water cooled, as h_S is affected. For furnace tubes, the unit's pressure will determine the saturation steam temperature and thus, the tube metal temperature under design conditions. Final superheat or reheat will determine the metal temperature for these portions of the steam generator. The ASME Boiler and Pressure Vessel Code gives an allowable stress for each temperature for all materials used in boiler construction. The design stress does not exceed the Code allowable stress. The actual wall thickness, tube diameter, and the unit operating pressure will determine the actual stress in a given tube. In practice, the actual stress is lower than the design stress as the operating pressure of the unit is lower than the design pressure and the actual tube wall thickness is greater than the specified minimum wall.

The amount of internal scale or deposit that may be tolerated by a particular tube before a high temperature metal problem occurs is a function of the unit pressure and tube location. For a high pressure central station steam generator furnace tube, where saturation steam temperature is about 360°C (680°F) and normal tube metal temperature is 385 - 399°C (725 - 750°F), a temperature rise of 28 - 42°C (50 - 75°F) is all that is possible before the oxidation limit for carbon steel is reached. This means that internal scale thickness of about .005 cm (2 mils) is the limit for the high heat release zones. As unit pressure decreases, so does the saturation temperture. For a 2068 KPa (300 psig) boiler, saturation steam temperature is 157°C (315°F) and normal metal temperature may be as low as 171°C (340°F). Under these conditions, deposit thickness may be more than 0.75 mm (30 mils) before metal temperature reaches 427°C (800°F).

What determines the frequency of chemical cleaning is the amount of scale and the rise in the tube metal temperature to the oxidation limit or design temperature. For the common boiler steels, the oxidation limits are:

Carbon Steel (SA 178A, SA 210 A1)	454C (850F)
Carbon + ½ Mo (SA 209 T1)	482C (900F)
1¼ Cr – ½ Mo (SA 213 T-11)	552C (1025F)
2¼Cr – 1 Mo (SA 213 - T-22)	579C (1075F)
Stainless Steel (SA 213 TP 304, 321, etc.)	704C (1300F)

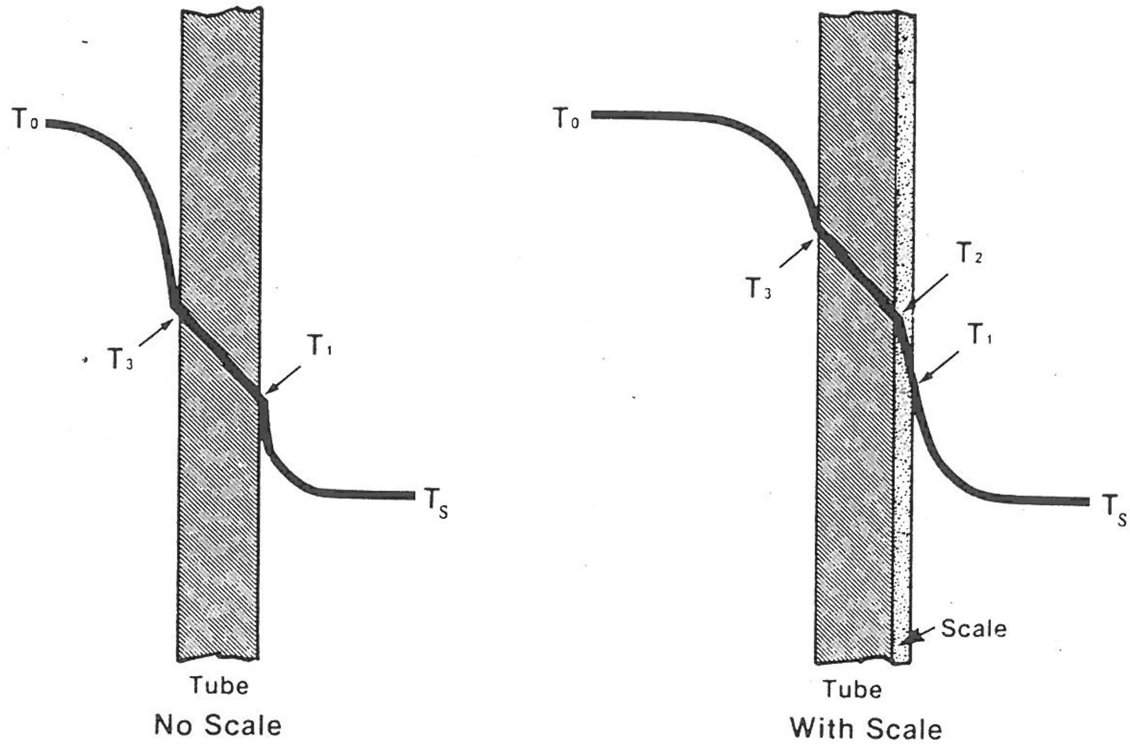
The thermal analysis is quite general and may be applied to superheaters and reheaters with steam-cooled tubes and water-walls with nucleate boiling heat transfer. Values of Q/A_0 will vary with location in the steam generator from 19,000-31,500 W/M^2-°C (6,000-10,000 Btu/hr-ft^2) for a reheater to more than 394,000 W/M^2°C (125,000 Btu/hr-ft^2) for water wall tubes in the burner area of the furnace. The table below gives the range of heat transfer coefficients normally encountered.



For a unit length of tube, the flow of heat, Q, is in a radial direction and is given by:

$$Q = U_0 A_0 (T_0 - T_S) \qquad (1)$$

Schematically, the temperature profile from flue gas, T_0, to bulk steam temperature, T_S is:



$$U_0 = \frac{1}{\frac{r_3}{r_i h_S} + \frac{r_3 \ln(r_2/r_1)}{k_1} + \frac{r_3 \ln(r_3/r_2)}{k_2} + \frac{1}{h_0}} \qquad (2)$$

The denominator of equation 2 has four terms, one for each of the thermal resistances:

$$\frac{r_3}{r_i h_S} = \text{steam side resistance}$$

$$\frac{r_3 \ln(r_2/r_1)}{k} = \text{scale resistance}$$

$$\frac{r_3 \ln(r_3/r_2)}{k_2} = \text{tube metal resistance}$$

$$\frac{1}{h_0} = \text{gas side film resistance}$$

Equation 1 may be rewritten:

$$Q/A_0 = \frac{T_0 - T_S}{\frac{r_3}{r_i h_S} + \frac{r_3 \ln(r_2/r_1)}{k_1} + \frac{r_3 \ln(r_3/r_2)}{k_2} + \frac{1}{h_0}} \qquad (3)$$

Equation 3 may be separated into its components as the quantity of heat that flows through each is the same.

$$Q/A_0 = \frac{T_1 - T_S}{\frac{r_3}{r_i h_S}}, \text{ temperature drop through steam film.} \qquad (4)$$

$$Q/A_0 = \frac{T_2 - T_i}{\frac{r_3 \ln(r_3/r_2)}{k_1}}, \text{ temperature drop through the scale.} \tag{5}$$

$$Q/A_0 = \frac{T_3 - T_2}{\frac{r_3 \ln(r_3/r_2)}{k_2}}, \text{ temperature drop through metal} \tag{6}$$

$$Q/A_0 = \frac{T_0 - T_3}{\frac{1}{h_0}}, \text{ temperature drop on gas side} \tag{7}$$

Dimensions in Metric Units

	h_i (W/M²-°C)	U_0 (W/M²-°C)	Q/A_0 (W/M²)
Economizer	5,678	28-40	15,773
Waterwalls	22,712-45,424	114-125	157,730-394,000
Reheater	1,703-2,271	62-97	19,000-31,500
Superheater	1,136-2,839	62-102	31,500-79,000

Dimensions in U.S. Customary Units

	h_i (Btu/hr-ft²-°F)	U_0 (Btu/hr-ft²-°F)	Q/A_0 (Btu/hr-ft²)
Economizer	1,000	5-7	5,000
Waterwalls	4,000-8,000	20-22	50,000-125,000
Reheater	300-400	11-17	6,000-10,000
Superheater	200-500	11-18	10,000-25,000

Figure 1 plots the increase in crown temperature as a function of inside scale thickness for several Q/A_0 values for steam-cooled tubes. The smaller values of Q/A_0 are typical of reheaters, the larger values of Q/A_0 are typical of superheaters. Figure 2 displays similar curves for water wall tubes with nucleate boiling heat transfer.

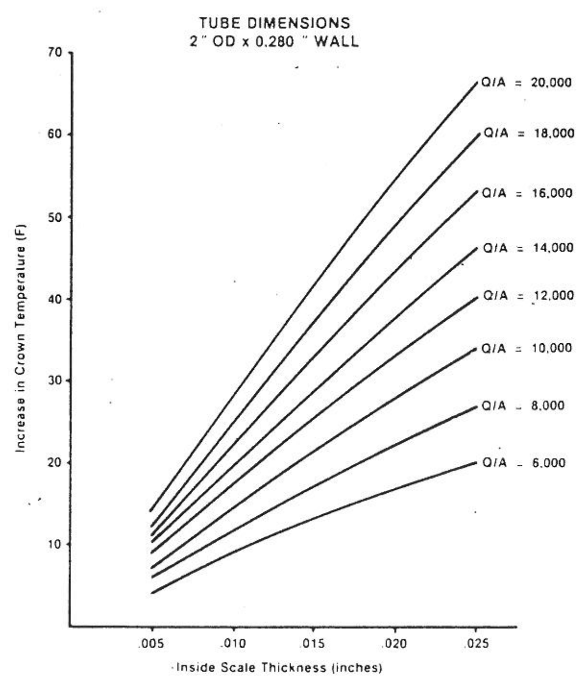


Figure 1 Increase in Crown Temperature As A Function Of Internal Scale Thickness For Steam-Cooled Tubes.

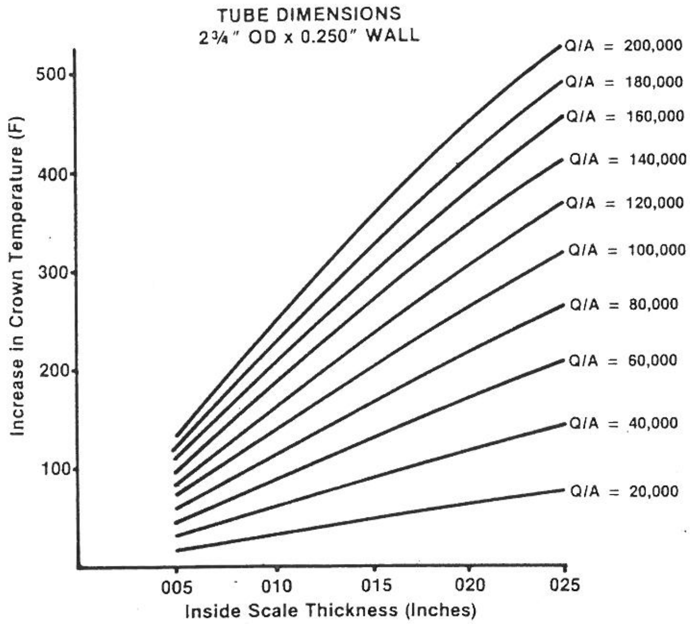


Figure 2 Increase in Crown Temperature As A Function Of Internal Scale Thickness For Waterwall Tubes With Nucleate Boiling Heat Transfer.

In all of these examples, the conductivity of the internal deposits or scale has been assumed to be .5765 W/M^2-°C (4 Btu-in./hr-ft^2-°F). Corrosion deposits are porous, composed of phosphates, carbonates, iron oxide particles formed elsewhere in the boiler treatment systems, and silica, among others. There is scant data in the literature on the thermal conductivity of deposits as noted.

While the exact conductivity is unknown for these deposits, it is likely that the value of iron oxide is an upper limit, correct for steam-cooled tubes and waterwalls in the absence of corrosion. Thus, the actual temperature increase for emulsion-cooled tubes will be higher than calculated. Figure 3A plots the change in tube metal temperature as a function of scale conductivity for Q/A_0 of 315,500 W/M^2 (100,000 Btu/hr-ft^2) and a scale thickness of .0254 cm (0.010 inches) for nucleate boiling heat transfer. Figure 3B plots ΔT as a function of internal scale conductivity for Q/A_0 of 56,780 W/M^2 (18,000 Btu/hr-ft^2) and a scale thickness of .0254 cm (0.010 inches) for steam-cooled tubes. Figure 3A is typical of waterwall tubes in the high heat release zones and Figure 3B is typical of superheater tubes.

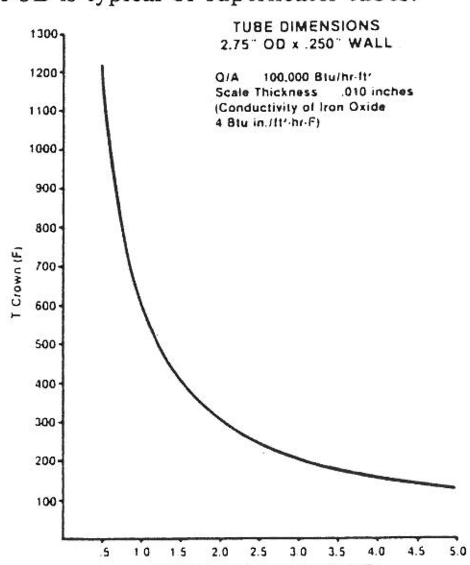


Figure 3A Change in Waterwall Tube Crown Temperature As A Function Of Internal Scale Conductivity.

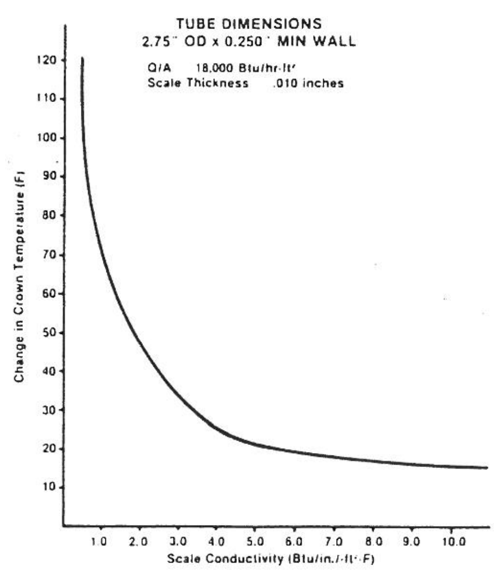


Figure 3B Change in Superheater Or Reheater Tube Wall Crown Temperature As A Function Of Internal Scale Conductivity.

Obviously, as the scale becomes more insulating, the increase in tube metal temperature is dramatic. Rapid tube failures have occured when film boiling occurs rather than nucleate boiling. At DNB (departure from nucleate boiling) a nearly continuous steam film or blanket forms of very low thermal conductivity. Metal temperatures of 760 - 816°C (1,400 - 1,500 °F) or higher can occur and tube ruptures inevitably follow.

Figure 4 displays the cross section of some typical deposits found in failed tubes. Note that the characteristics vary from dense, nearly void free iron oxide found in superheaters to porous water wall deposits that contain iron oxide, copper metal, and other boiler feedwater contaminants.

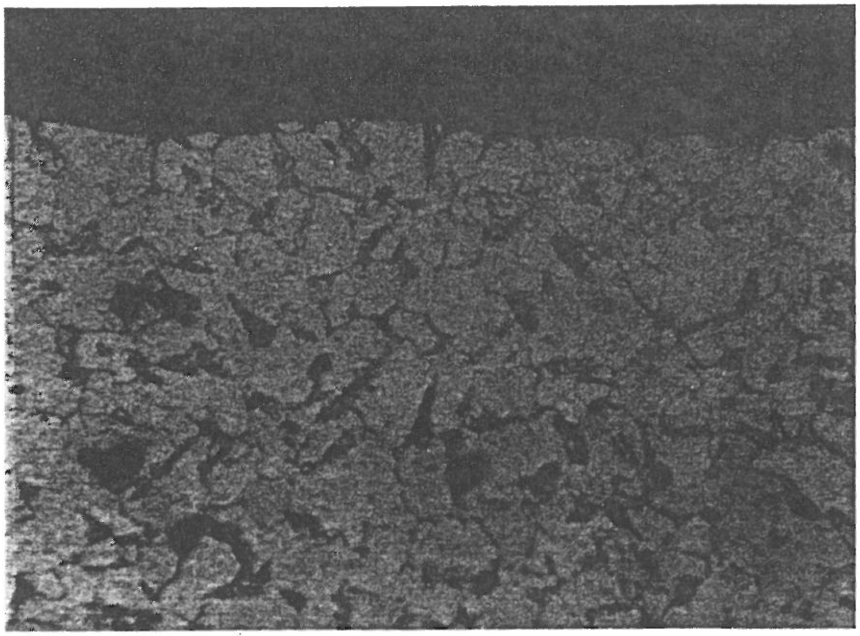


Figure 4A Internal Magnetite Scale From A Superheater Tube. Note The Dense, Nearly Pore-free Structure. Nital Etch, 500x.

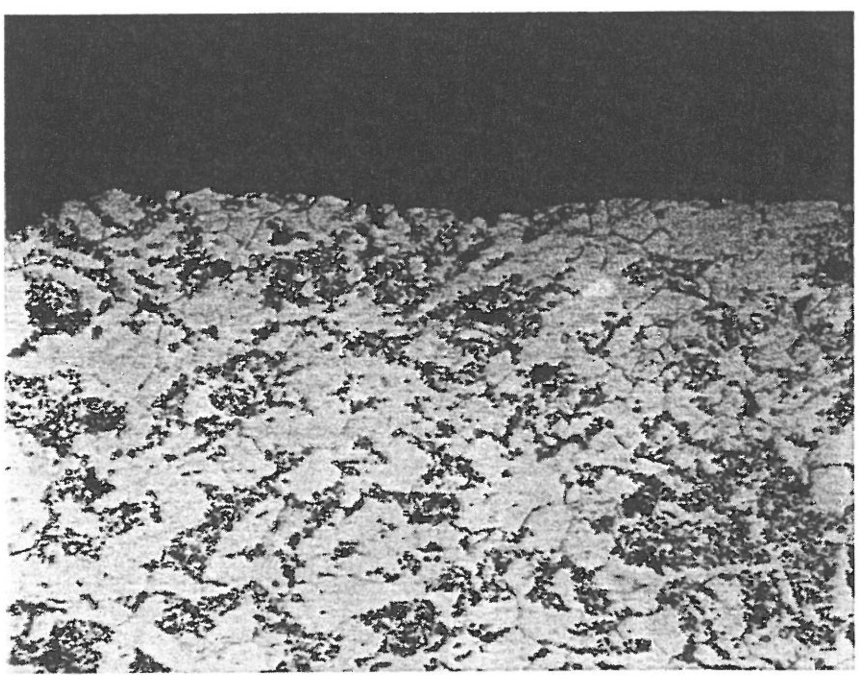


Figure 4B Internal Magnetite Scale From A Reheater Tube, Note The Porosity As Compared With Figure 4A. Nital Etch, 500x.

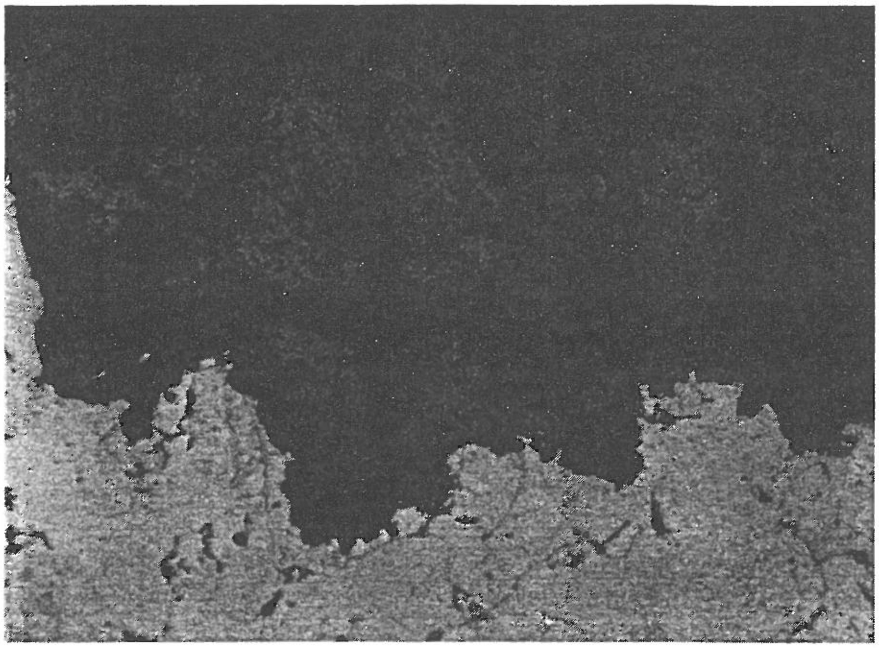


Figure 4C Internal Scale And Deposit From A Waterwall Tube. Note Porosity In The Oxide Layer Adjacent To The Metal And The Separation Between The Deposit And Oxide. Nital Etch, 500x.

Steam generating units need a periodic chemicial cleaning to maintain proper design metal temperatures. Figure 5 plots saturation steam temperature as a function of unit pressure. Since the maximum oxidation limit for carbon steel is 454°C (850°F) but some units use SA 209-T1 in the burner area, the figure 454°C (850°F) is chosen as the maximum safe operating temperature. The difference between 454°C (850°F) and the crown temperature of the tube is the temperature increase that a furnace wall tube may have before excessive tube failures occur. In these examples, the highest heat release areas are used, as these are the regions where internal deposits occur first, and subsequently, do the most damage. From Figure 5 and Figure 2, the amount of internal scale allowed before chemical cleaning is necessary may be determined. Figure 6 plots the amount of scale permissible as a function of pressure for several sets of furnace conditions.

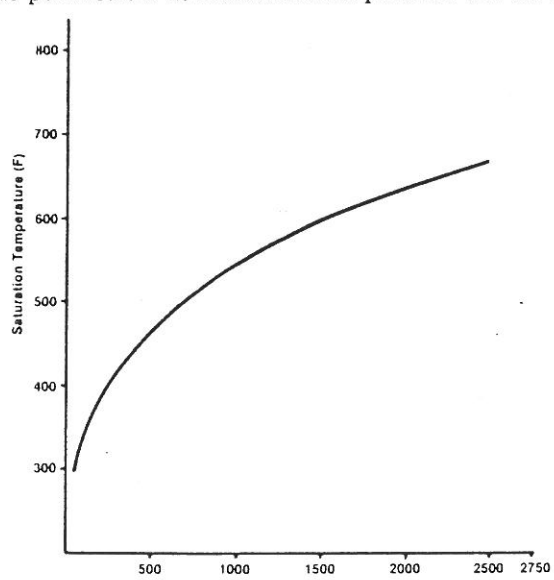


Figure 5 Saturation Temperature As A Function Of Pressure.

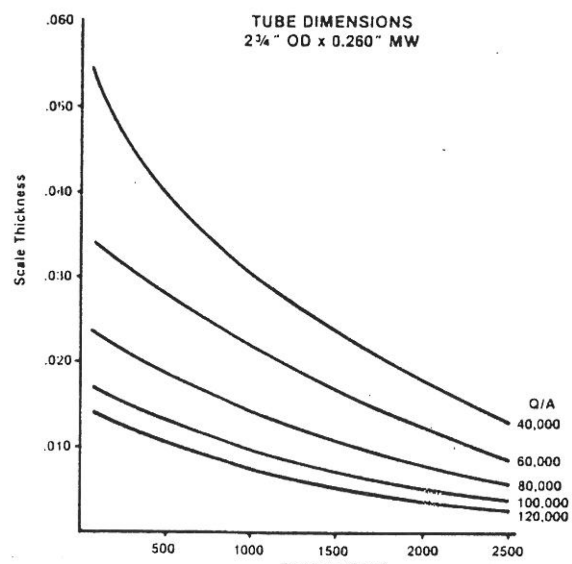


Figure 6 Scale Thickness Required To Raise Crown Temperature To 454°C (850°F) From Saturation As A Function Of Pressure For Various Q/A For Waterwall Nucleate Boiling Heat Transfer.

Similar arguments apply for superheaters and reheaters. Internal scale raises steam-cooled tube metal temperature above safe operating limits also. However, the scale induced temperature rise is less per mil of internal scale than for furnace tubes: Q/A_0 is typically much less. However, the concept in limiting tube metal temperature increases to the oxidation or design limit is the same. While no easy predictions are possible, it appears desirable to hold temperature increases under 14°C (25°F) or 17°C (30°F). For most units, this means a scale thickness of about .0254-.0305 cm (10-12 mils) in a reheater and about .013-.0203 cm (5-8 mils) in a superheater before chemical cleaning should be done.

Studies have been presented on the amount of scale, in mg per cm^2, before chemical cleaning is necessary; see, for example, the work of Atwood and Hale[5]. For comparison, their recommendations for subcritical units 1,800 psig and up, are:

Clean Surfaces	Moderately Dirty Surfaces	Very Dirty Surfaces
less than 15 mg/cm²	15 - 40 mg/cm²	more than 40 mg/cm²

If we assume that a furnace deposit is composed of silica, SiO_2, magnetite, Fe_3O_4, and copper of 4.5 and 3.0 gms/cm³ density and pure Fe_3O_4 of 5.3 gms/cm³ density, the Atwood and Hale definitions become:

Dimensions in Metric Units

Density (gms/cm³)	Clean Surfaces (cm)	Moderately Dirty Surfaces (cm)	Very Dirty Surfaces (cm)
3.0	.0051	.0051 - .0135	More than .0135
4.5	.0033	.0033 - .0089	More than .0089
5.3	.0028	.0028 - .0076	.More than .0076

Dimensions in U.S. Customary Units

Density (gms/cm³)	Clean Surfaces (mils)	Moderately Dirty Surfaces (mils)	Very Dirty Surfaces (mils)
3.0	2.0	2.0 - 5.3	More than 5.3
4.5	1.3	1.3 - 3.5	3.5
5.3	1.1	1.1 - 3.0	3.0

Clearly, as the porosity increases, the thermal conductivity of the particular deposits will decrease. The effect is that a "very dirty surface" with .0076 cm (3.0 mils) of Fe_3O_4 (40 mg/cm²) will have a lower tube metal temperature than will an equally dirty surface composed of 0.135 cm (5.3 mils) of SiO_2, Fe_3O_4, and copper (40 mg/cm²).

It is generally much easier for metallography laboratories to make a determination of the scale/deposit thickness than to measure the loading in mg/cm² or gms/ft² as usually performed. The effort here has been to correlate internal scale/deposits with a heat flow analysis as an aid in understanding the thermal damage that may occur if design conditions are not maintained. Without putting too fine a point on this excercise, chemical cleaning of the entire steam generator, superheater, reheater, and the furnace is necessary and desirable to keep tube metal temperatures at or below design limits.

Examples have been presented to cover some boiler operations, but certainly not all conditions of tube dimension, materials, Q/A, steam flow, etc. have been covered. The procedures have been outlined and limits set for a calculation to determine whether a particular unit needs to be chemically cleaned.

The final section describes three examples of boiler tube failures that show the effects of internal scale or deposit on metal temperatures. All may be explained by the thermal analysis just presented. All show severe deprivation or failure and micro-structural degradation. For further examples of metallurgical failures, see reference 6.

Case History No. 1: Metallurgical Investigation of Several Waterwall Tubes

Boiler Statistics:

Size:	1,270,000 Kg/hr (2,800,000 lbs. steam/hr)
Pressure:	16,550 KPa (2,400 psig)
Temperature:	541/541°C (1005/1005°F)
Fuel:	Pulverized Coal

The following example deals with the investigation of five waterwall tubes, four of which showed expansion of the tube diameter, wall thinning, and the thermal distress effects of internal scale and deposits. None of the tubes were ruptured; all tubes were originally 6.35 cm OD by .66 cm (2½ inch OD by 0.260 inch) minimum wall, SA 210-A1 carbon steel. Figure 1.1 shows three of the as-received tubes.

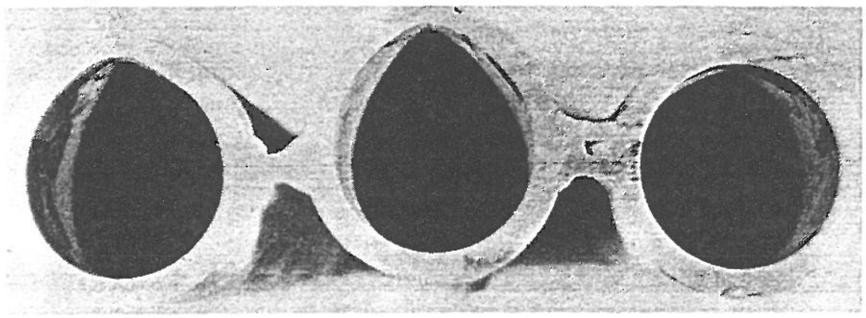
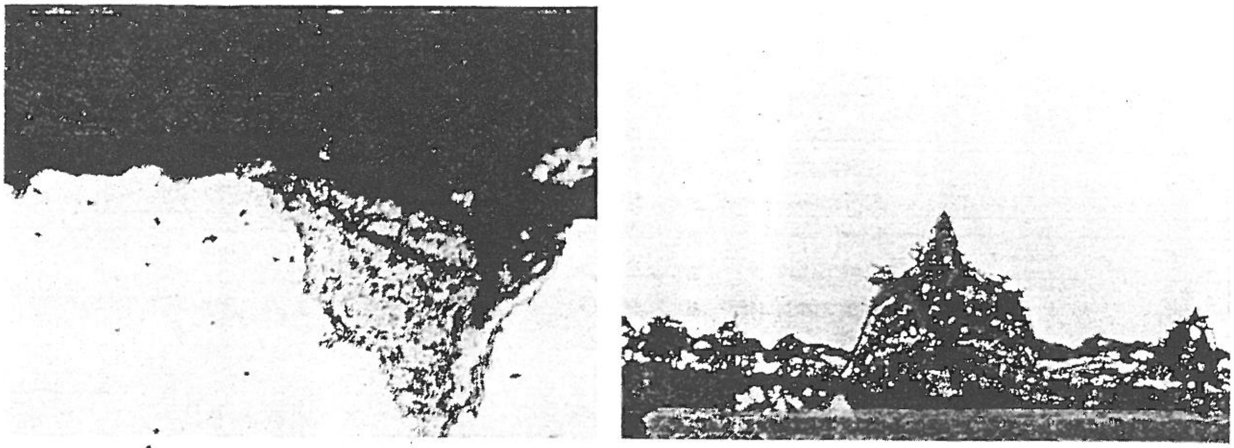


Figure 1.1 As-received Water Wall Tubes.

Visual examination showed the following:

1. Caliper measurements of the expanded tube diameters varied from 6.43 cm ($2\frac{17}{32}$ inch) to 6.91 cm ($2\frac{23}{32}$ inch) depending on the sample and location. One tube measured the original 6.35 cm (2½ inch) OD.
2. Wall thickness measurements on the fire side varied from .452 cm (0.178 inch) to .734 cm (0.289 inch) depending on sample and location. The location 180 from the fire side had a wall thickness of .737 cm (0.290 inch) and is assumed to be the original wall thickness.
3. The thickness of the internal scale was measured to be .025 to .028 cm (0.010 to 0.011 inch) thick and contained quite a bit of copper. See Figure 1.2.
4. The fire side scale and deposit was .025 cm (0.010 inch) thick, tightly adhering, and glassy in appearance.
5. A sulfur print showed the presence of sulfides indicating the early stages of liquid ash corrosion.

The microstructure of the fire side of all these tubes showed the effects of overheating to varying degrees. In the most severe cases of elevated temperature exposure, the iron carbide had spheroidized with some decomposition to graphite present. Toward the steam side of the fire side, the effects of thermal distress are less evident, an insitu breakdown of the carbide but the pearlite colonies are still clearly evident. Figure 1.3 shows the most severe case of degradation on the fireside, spheroidized carbides, graphite, and ferrite. Figure 1.4 shows the steam side conditions of the same tube, an in situ breakdown of the iron carbide but the shape of the pearlite colonies is still clearly discernible. The gradient in structure is caused by the temperature gradient through the tube, the fireside is about 56°C (100°F) hotter than the metal in contact with the steam. On the backside of the tube, 180° from the fireside, the microstructure shows the normal ferrite and lamellar pearlite, note Figure 1.5.



OD ID

Figure 1.2 OD And ID Surface. Note Layered Appearance Of ID Scale And Deposit. Deposit Contains 4.4% Copper That Shows Up As Light Colored Zones In The Deposit. The Dark Spots In The Metal At The OD Are Graphite. Unetched, 100x.

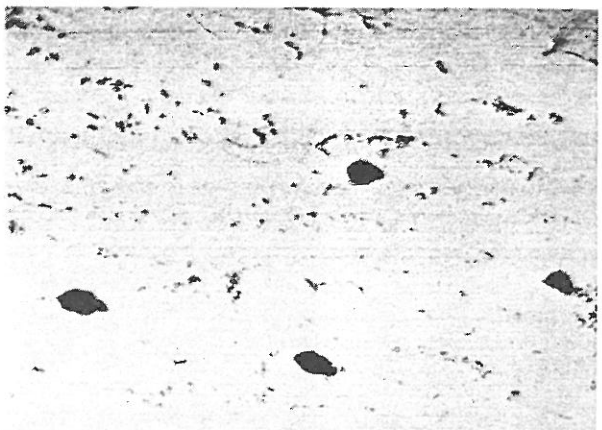


Figure 1.3 Microstructure At The OD Of The Tube. Large Black Spots Are Graphite. Nital Etch, 500x.

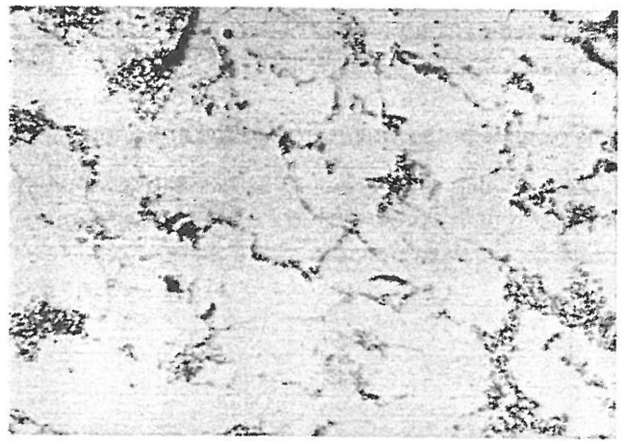


Figure 1.4 Microstructure At The ID Of The Waterwall Tube. The Pearlite Has Completely Spheroidized But The Pearlite Colonies Are Still Intact. Nital Etch, 500x.

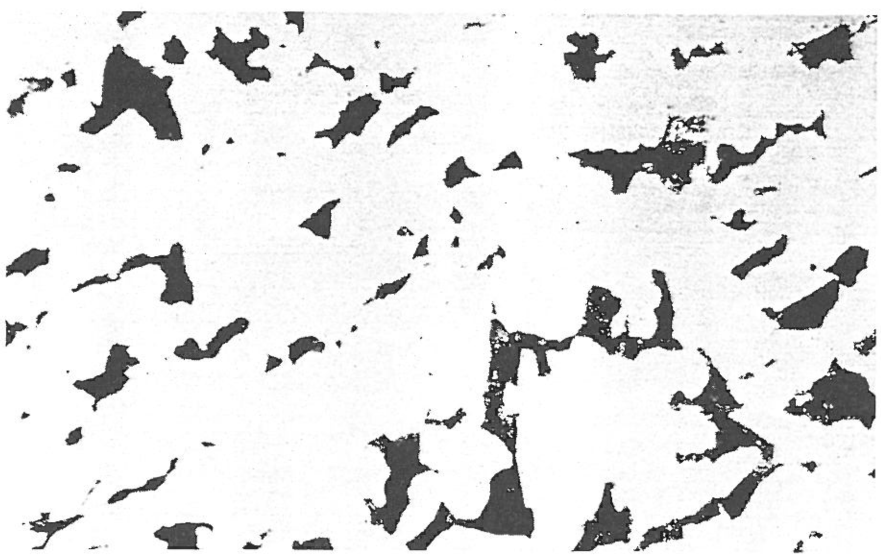


Figure 1.5 Microstructure Of The Back Side Of The Tube. The Structure Is Pearlite (Dark Areas), And Ferrite (Light Areas), And Is The Normal, Expected Structure For SA 210 A1. Nital Etch, 500x.

Chemical analysis of the ID deposit shows primarily iron oxide and copper (about 98 + %) with trace amounts of other impurities. See Table 1-A.

Phosphorus	as	P_2O_5	None detected
Sulfur	as	SO_3	0.35%
Sodium	as	Na_2O	0.04%
Silicon	as	SiO_2	1.85%
Iron	as	Fe_2O_3	94.4%
Calcium	as	CaO	0.05%
Magnesium	as	MgO	0.22%
Chlorine	as	Cl	50 ppm
Copper	as	Cu	4.4%
Aluminum	as	Al_2O_3	.05%

Table 1-A Internal Scale Deposit of Waterwall Tubes

We can conclude that the overheating of the tube is caused by the internal scale. In the pre-boiler system, containing copper alloys, a leak developed, the copper corrosion products dissolved in the boiler feedwater, and plated out on the steel boiler tubes in the lower portion of the boiler where steam is first generated. The net reaction is:

$$Cu^{++} + \underline{Fe} \quad Fe^{++} + \underline{Cu}$$

The result is both iron (as iron oxide) and copper (as metal) are deposited on the furnace tubes, see Figure 1.2.

Any ID deposit will act as an insulating layer, reduce the overall heat transfer and raise the tube metal temperature, as presented in the previous section. Figure 1.6 plots ΔT vs scale thickness for this particular example. Internal deposits of 0.011 inches can raise the crown temperature up to 111°C (200°F).

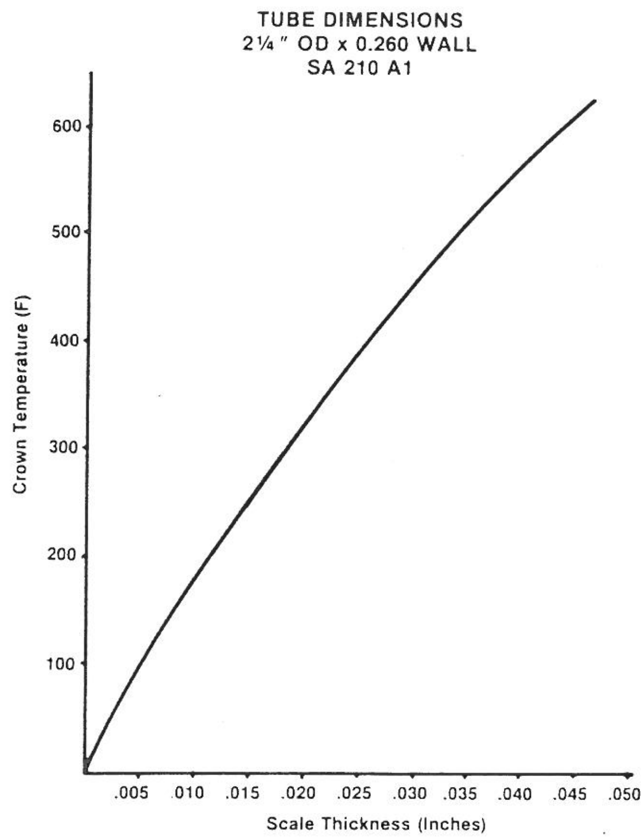


Figure 1.6 Change In Crown Temperature As A Function Of Scale Thickness For This Example And Location In The Furnace.

The microstructural variations across the fireside from OD to ID can be explained by the internal scale and heat flow analysis presented. The temperature drop through the tube is, from equation 8, about 50°C (90°F). A clean tube crown temperature is about 421°C (790°F). With an internal scale thickness of .025 cm (0.010 inch) the OD crown temperature rises to nearly 538°C (1,000°F) and the ID is over 454°C (850°F). Hence, the microstructure will show varying degrees of thermal damage from OD to ID.

Case History No. 2: Metallurgical Investigation of a Ruptured Superheater Tube.

Boiler Statistics:

Size:	1,451,000 kg/hr (3,200,000 lbs steam/hr)
Pressure:	17,926 KPa (2,600 psig)
Temperature:	541/541°C (1005/1005°F)
Fuel:	No. 6 Fuel Oil

This second example is of a superheater tube failure. The tube in question is 4.45 cm OD by .66 cm (1¾ inch OD by 0.260 inch) minimum wall SA 213-T22 (2¼% Cr - 1% Mo). Similar behavior in steam-cooled tubes may be expected as a consequence of internal iron oxide scale, that is, tube metal temperatures will increase. Iron reacts with steam to form magnetite:

$$3\ Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$$

The reaction is inevitable and proceeds over the entire life of the boiler.

Visual examination showed the following:

1. The failure was a narrow split with little or no tube swelling at the failure, see Figure 2.1.
2. On the bore of the tube, longitudinal stress cracks were clearly evident in the iron oxide scale, see Figure 2.2.
3. Internal scale was measured at .114 cm (0.045 inch).

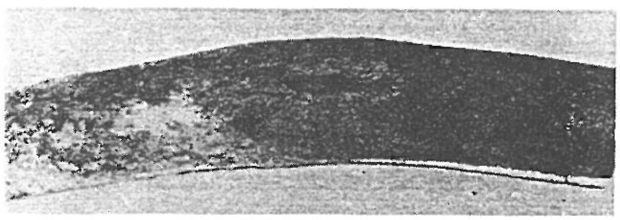


Figure 2.1 As-received Superheater Tube. Note Fissure And Almost Total Lack Of Expansion Or Ductility.

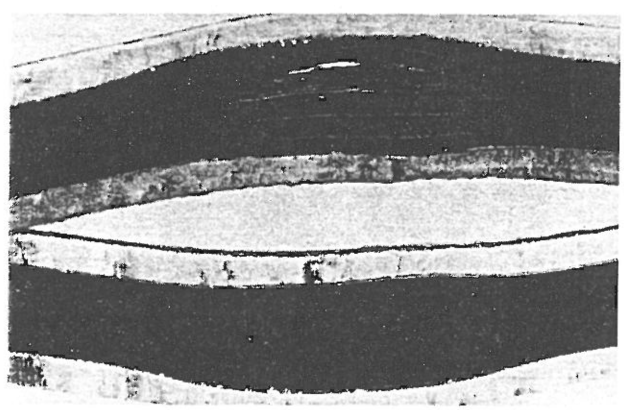


Figure 2.2 Same Tube As Figure 2.1 Cut Open To Illustrate ID Scale And Longitudinal Stress Cracks In The Scale.

Microstructural analysis showed a complete coalescense and agglomeration of the carbides, indications that a long time at elevated temperature, well above safe design limits, has occurred, see Figure 2.3.

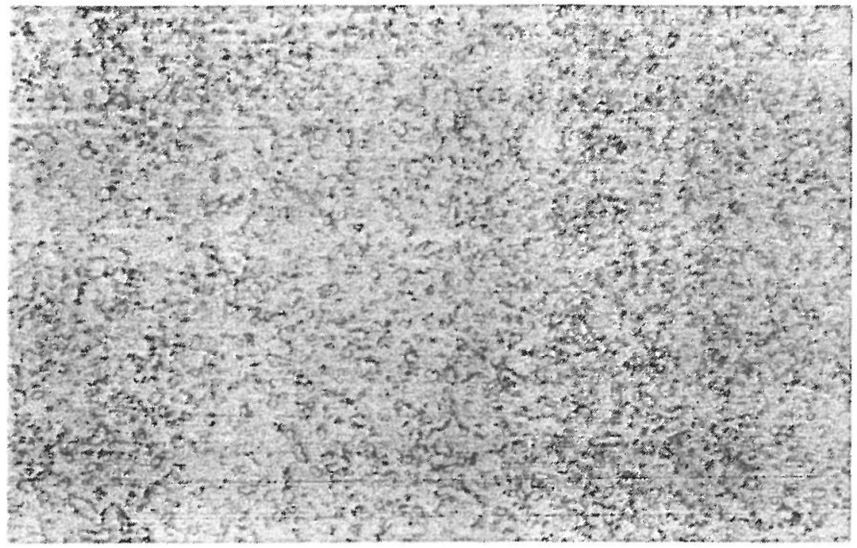


Figure 2.3 Microstructure At The Failure. Note The Complete Spheroidization Of The Carbide.

The thermal analysis presented in the first section for steam-cooled tubes shows, from Figure 2.4, that tube metal temperature is expected to increase by nearly 111°C (200°F) for .114 cm (0.045 inch) thick ID scale at a Q/A_0 of 163,000 W/M^2 (20,000 Btu/hr-ft^2). Thus, it is not surprising that the microstructure is completely spheroidized and the tube failed by a creep mechanism. If the normal tube temperature is expected to be 552 -566°C (1,025 -1,050°F) the final days of this tube saw a peak metal temperature of more than 649°C (1200°F).

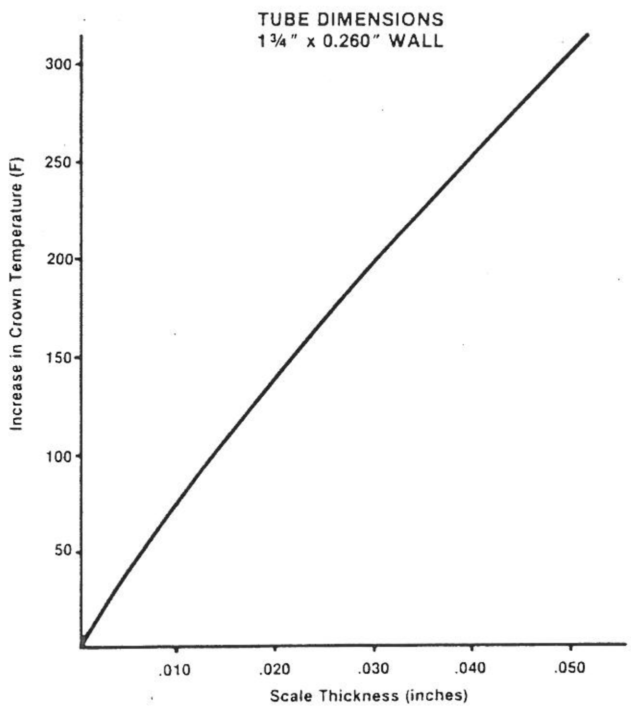


Figure 2.4 Increase In Crown Temperature As A Function Of Scale Thickness For This Example Of A Steam-cooled Superheater Tube.

Case History No. 3: Metallurgical Investigation of Waterwall Tube

Boiler Statistics:

Size:	45,400 kg/hr (100,000 lbs steam/hr)
Pressure:	2,137 KPa (310 psig)
Temperature:	163°C (325°F)
Fuel:	Oil/Gas

This example is of a water-wall tube failure from a small industrial packaged boiler. The tube is from the convection pass toward the rear. The tube is 5.08 cm by .241 cm (2 inch OD by 0.095 inch) minimum wall SA 178-A material. The failure is a small, narrow fissure about two inches long with very little swelling or wall thinning associated with the rupture, see Figure 3.1. Visual examination revealed the following:

1. The inside of the tube was nearly plugged with deposit, thickness was more than .318 cm (1/8 inch). See Figure 3.2.
2. Very little wall thinning was noted.
3. No external corrosion was observed.
4. Actual wall thickness removed from the failure was .279 cm (0.110 inch).

The actual stress S, in this tube is, from Section I of the Boiler and Pressure Vessel Code:

$$S = \frac{P}{\dfrac{2t - 0.0\ ID}{D - (t - 0.005\ D)}}$$

where P is pressure, psig, t is tube wall thickness, inches, and D is tube diameter, inches. For 2,137 KPa (310 psig) operating pressure and 5.08 cm OD by .279 cm (2 inch OD x 0.110 inch) actual wall, the calculated stress is 2,950 psi. SA 178-A has an allowable stress of 20,300 KPa (2,950 psi) at a temperature of about 504°C (940°F), well above the oxidation limit for a plain carbon steel.

Figure 3.1 As-received Waterwall Tube From An Industrial Boiler. Rupture Is A Narrow Fissure.

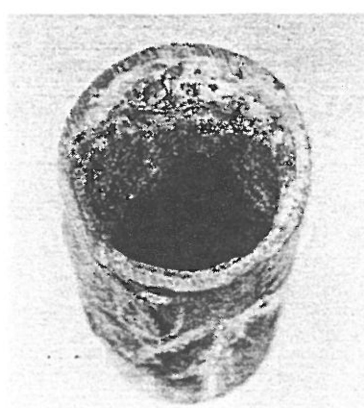


Figure 3.2 Cross Sectional View Of The Tube Shown In Figure 3.1. Note The Virtual Pluggage With Deposit.

The thermal analysis may be used to calculate the approximate temperature increase of the tube as a result of the more than .318 cm (⅛ inch) internal deposit. For this example, Q/A_0 is about 176,000 W/M^2 (40,000 $Btu/hr\text{-}ft^2$). From Figure 2, the temperature increase, $\triangle T$, as a function of scale thickness, x; for x in mils, may be approximated by:

$$T = 5.6x$$

For 125 mils thick deposit, assuming the same thermal conductivity as iron oxide, (not exactly true, but close for this exercise), the temperature increase is 389°C (700°F). At the time of rupture, the crown metal temperature was well over 538°C (1,000°F), a creep failure, then, is not surprising.

Microstructural analysis showed the fire side of the tube to be completely decarburized. Figure 3.3 displays the microstructure at the OD, mid-wall and ID of the fireside. For comparison, Figure 3.4 shows the microstructure of ferrite and pearlite found on the rear of the tube. There is, to be sure, an in situ breakdown of the pearlite çolony still plainly visible.

Figure 3.3 These Three Microstructures Show Complete Decarburization Of The SA 178-A Tube Material.

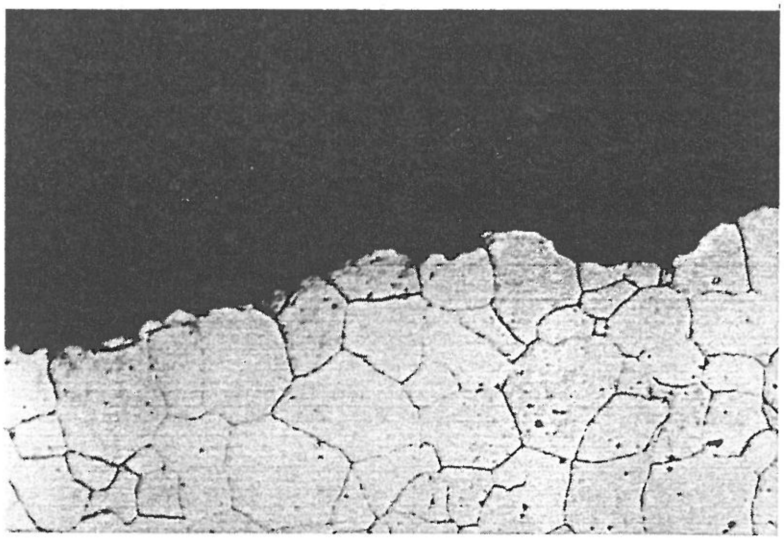


Figure 3.3A Microstructure At The OD Of The Tube In The Neighborhood Of The Failure. Nital Etch, 500x.

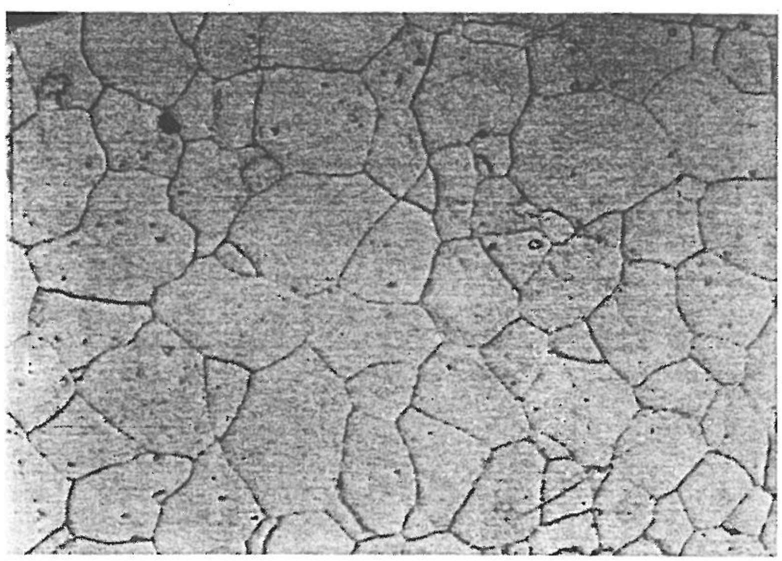


Figure 3.3B Mid-wall Microstructure Of The Same Metallographic Specimen As Figure 3.3A. Nital Etch, 500x.

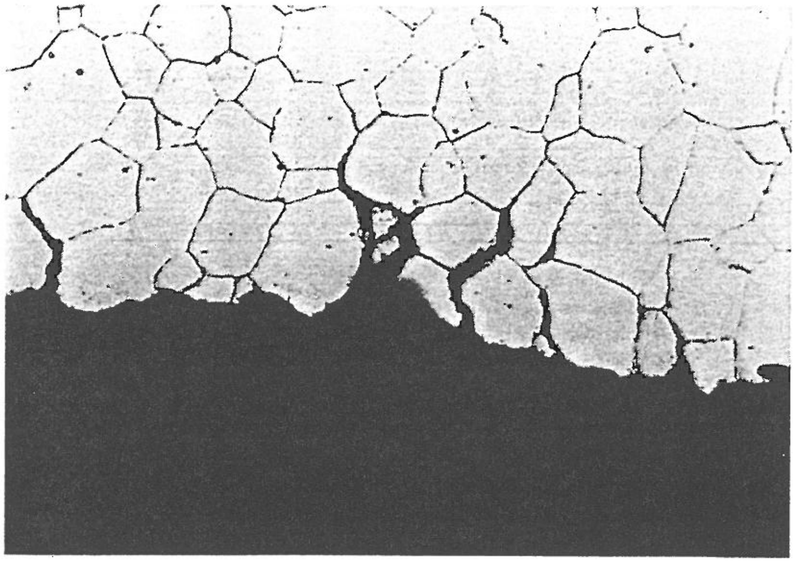


Figure 3.3C Microstructure At The ID Of The Same Samples As Figure 3.3A and B. Nital Etch, 500x.

Figure 3.4 The Microstructure Of The Same Tube Taken From The Rear Of The Tube, 180° From The Rupture, The Structure Is Pearlite With An In Situ Spheroidization Of The Carbide Phase, And Ferrite. Nital Etch, 500x.

In conclusion, the creep failure is caused by the internal deposit. Chemical analysis of the deposit gave the following:

Silicon	as SiO_2	74.20%
Iron	as Fe_2O_3	16.30%
Phosphorus	as P_2O_5	2.98%
Sulfur	as So_3	1.55%
Sodium	as Na_2O	0.85%

Clearly the problem is related to silica and poor boiler feedwater control.

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