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How to Avoid Problems with Superheaters and Reheaters

by

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HOW TO AVOID PROBLEMS
WITH SUPERHEATERS AND REHEATERS

by
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INTRODUCTION

The service conditions of a fossil-fired steam generator are among the most severe of any large engineered structure. Within the furnace, flame temperatures may reach 3000°F during the combustion of boiler fuels. The products of combustion will include many species that are corrosive to the materials of construction. Ideally, the inside of the boiler tubing would see only pure water and steam, but, in practice, this of course does not occur. The boiler feedwater is anything but pure H_2O and contains a host of chemicals deliberately added to make it less corrosive to the boiler tubing. The steam side environment for superheaters and reheaters is generally pure steam. However, even pure steam reacts with steel to form iron oxide:

$$3Fe + 4H_2O = Fe_3O_4 + 4H_2$$

Superheaters and reheaters see especially difficult operating conditions, particularly during start-up, when steam flow has not been fully established. The highest metal temperatures within the boiler are in the finishing legs of both superheaters and reheaters, metal temperatures in the neighborhood of 1100°F or higher. Since metal temperatures are the highest, the fire side oxidation and corrosion potential is the greatest. It is for these reasons that the actual life is about half that of the rest of the boiler, typically fifteen years or so.

The problems inherent to the operation of superheaters and reheaters are well known to the design engineer. It does not do justice to his task to summarize in one paragraph all of the design considerations that are involved. We can divide these considerations into the following:

1) *Steam Flow Considerations*
   A. High steam velocities are desirable as the higher the steam velocity the better the overall heat transfer is between the hot flue gas and the steam that is being heated and the cooler the tube will be. However, high steam velocities require large pressure drops, which cannot always be practically or economically achieved, especially within reheaters.

   B. Proper header design and sizing are necessary to insure even steam distribution to the tube bundles.

   C. Tube flow studies, orificing or tube shortening, are undertaken to insure uniform steam distribution within the tubes. The intent of all of these considerations is to have a uniform steam flow, tube to tube, whose final temperature meets the specifications.

2) *Flue Gas Considerations*

A. Flue gas velocities should be high from a heat transfer standpoint, but low enough so that tube OD erosion does not occur. This is especially true for coal fired units where the fly ash tube erosion becomes significant for flue gas velocities above about 65 feet per second.

B. The arrangement of superheaters and reheaters within the steam generator is considered to keep metal temperatures as low as possible and for protection during start-up. For example, an unprotected reheater would not be in the furnace proper, as start-up metal temperatures would be too high.

C. Start-up gas temperature limit 1000°F.

3) *Metal Studies*

Table I lists the alloys usually found in the superheaters and reheaters of utility boilers. Note that, for each alloy, there is an oxidation limit that restricts its use.

	%C	%Mn	%Mo	%Cr	%Ni	Other	Oxidation Limit
SA 210 A1	0.27 Max	0.80 Max.					850°F
SA 209T-1	0.10/0.20	0.30/0.80	0.44/0.65				900°F
SA 213-T11	0.15 Max.	0.30/0.60	0.44/0.65	1.0/1.5			1025°F
SA 213-T22	0.15 Max.	0.30/0.60	0.87/1.13	1.9/2.6			1075°F
SA 213-TP321H	0.04/0.10	2.00 Max.	17.0/20.0		9.0/13.0	*	1300°F
SA 213-TP347H	0.04/0.10	2.00 Max.	17.0/20.0		9.0/13.0	**	1300°F

*%Ti = 0.60 Max.
**%Ta + %Cb = 1.0 Max.

Table I Superheater and Reheater Tube Materials

4) *Overall Design Review*

A. Once the superheater and reheater have been designed, there is a review to study the sensitivity to unbalance, both in steam and flue gas flow, to determine if unbalances may impinge on design margins.

B. Are there anticipated start-up problems, especially in the reheater?

With all of the care that goes into the design of superheaters and reheaters in a new boiler, the life expectancy is about half that of the furnace or the economizer. The question is, why? What can be done to improve this from a design, operation and maintenance point of view?

It is instructive, I think, to look at a few superheater and reheater tube failures as examples of typical problems. For the most part these cases have not lasted more than 14 years or so, certainly not as long as anticipated when the boiler was purchased. Corrosion and oxidation on the fire side can lead to tube wastage and the associated wall thickness loss leads to premature failure. Steam side oxidation leads to increased thermal resistance which raises tube metal temperatures above the safe design limit. Depending on the design parameters and operational conditions, internal scale formation can increase peak tube temperatures by 75 or even 100°F. Higher metal temperatures than designed for increase the creep rate (decrease the creep life) and raise the oxidation rate (which in turn further raises the metal temperature). If ash corrosion occurs, higher metal temperature exacerbates the condition, and microstructural changes that lead to a weaker steel occur more rapidly.

The following four case histories illustrate the effects of internal scale buildup on tube metal temperature and the subsequent premature tube failure.

Case History No. 1

Metallurgical investigation of reheater tube samples.

Boiler Statistics:

Size:	1,600,000 lbs. steam/hr.
Steam Temperature:	1005°F/1005°F
Steam Pressure:	1975 psig
Fuel:	Pulverized Coal

This investigation covers several reheater-tube samples including a tube that has failed, Figures 1.1 and 1.2. The tubes are 1¾" OD × 0.150" wall, SA 213-T22 material.

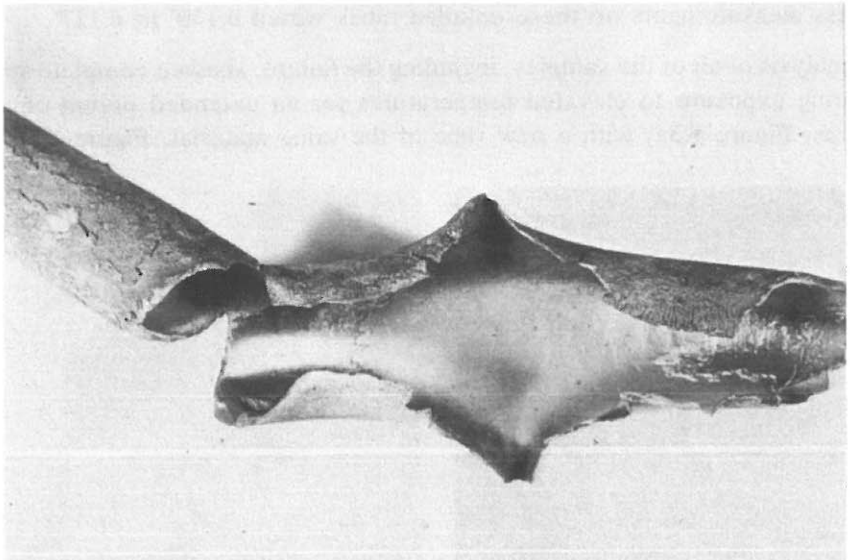


Figure 1.1 Failed Reheater Tube. Note the ID Scale and Thin Knife Edge Failure.

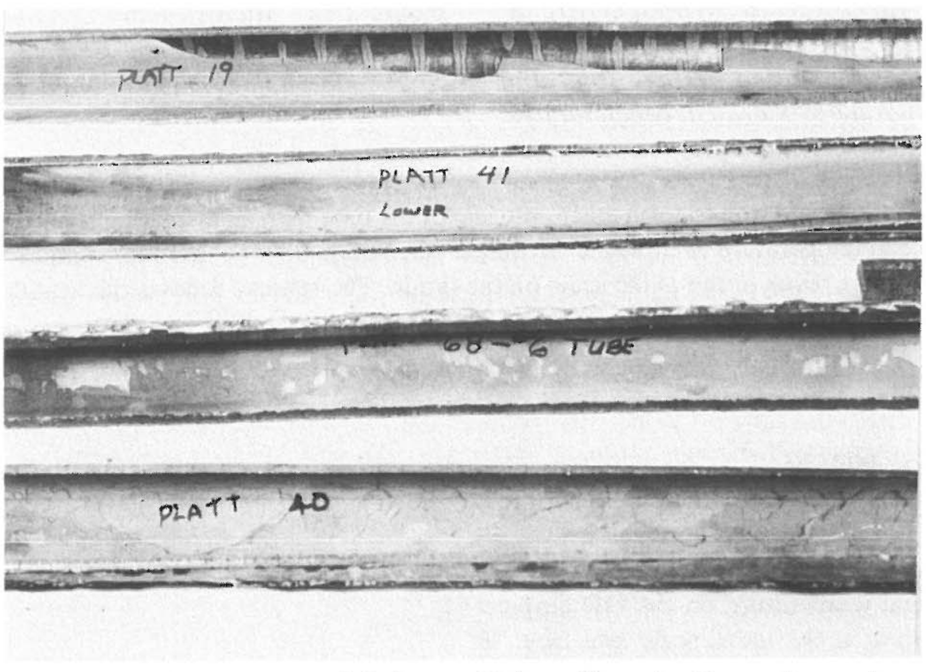


Figure 1.2 As-received Reheater Tubes. Note the Heavy Internal Oxide Scale.

The visual examination of these tubes revealed the following:

A. The rupture was a wide open burst with the tube wall drawn to a knife edge at the failure.

B. The OD scale measured 0.011″ thick and the deposit from the products of combustion was 0.04″ thick.

C. The internal scale measured from 0.015″ to 0.026″ thick.

D. The tube wall thickness 12″ away from the failure and in the same plane, measured 0.127″. The tube wall thickness 180° from this point measured 0.171″.

E. The remaining reheater tube sections showed ID scale varying from 0.018″ to 0.021″ thick and OD scale and deposit up to 0.040″ thick.

F. Wall thickness measurements on these unfailed tubes varied 0.170″ to 0.127″.

Microstructural analysis of all of the samples, including the failure, showed complete spheroidization of the carbides indicating exposure to elevated temperatures for an extended period of time. Figure 1.3 compares the failures, Figure 1.3a, with a new tube of the same material, Figure 1.3b.

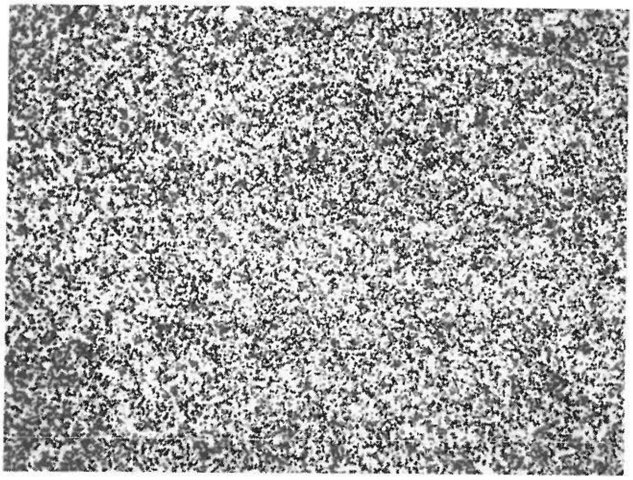


Figure 1.3a Microstructure Representative of All T-22 Reheater Tube Samples. The Structure is of Spheroidized Carbides and Ferrite, Typical of Long Term Exposure to Elevated Temperatures. (350×, Nital Etch)

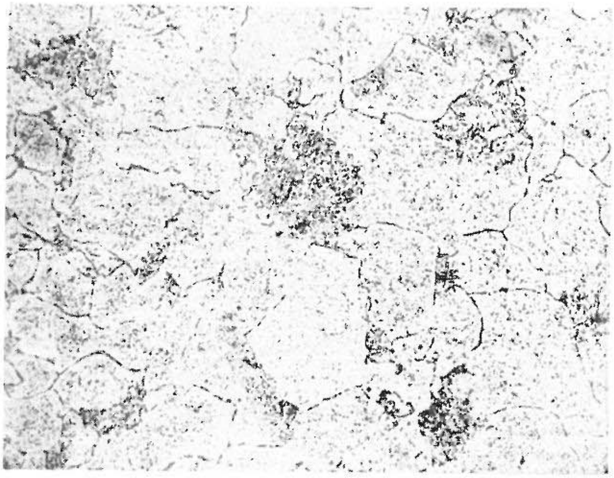


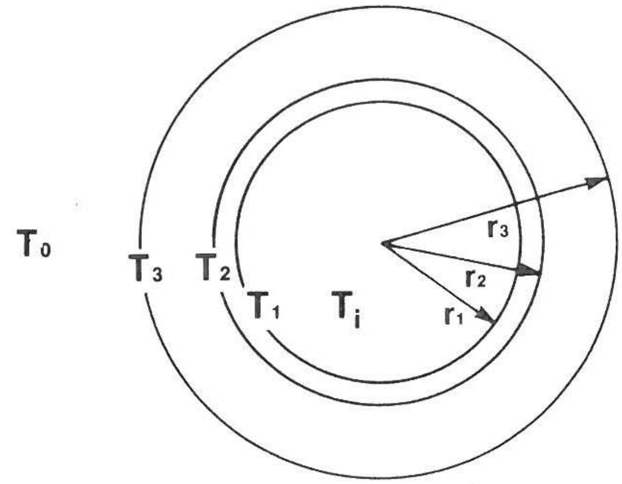
Figure 1.3b Microstructure of As-received New T-22 Tubing. Compare the Changes in Carbide Morphology. (350×, Nital Etch)

The reaction of steam and iron to form magnetite leaves the tube with an insulating layer on the ID which will cause the metal temperature to increase. A simple calculation may be done to estimate the peak tube metal temperature as a result of the oxide scale on the inside. The scheme follows the heat flow analysis of Kreith[1] for the steady state condition.

Nomenclature:

Q = heat flow, BTU/hr.
U_0 = overall heat transfer coefficient, BTU/hr./ft.^{2}/°F
A_0 = area of the outside tube surface, ft.^{2}
T_0 = flue gas temperature, °F
T_3 = tube metal temperature on the OD surface, °F
T_2 = temperature at the metal/scale interface, °F
T_1 = temperature at the ID of the tube, °F
T_i = bulk steam temperature, °F

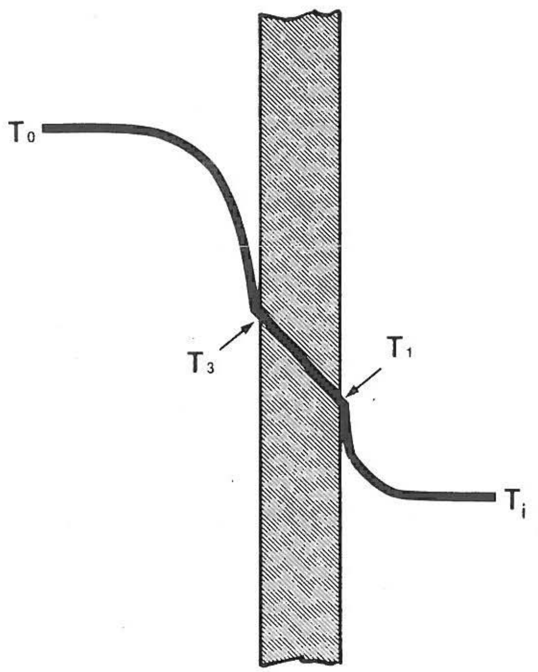
r_3 = radius of the tube, ft.
r_2 = radius of the ID of the tube metal, ft.
r_1 = radius of the tube ID, ft.
h_i = steam side heat transfer coefficient, BTU/hr./ft.^{2}/°F
k_1 = thermal conductivity of scale, BTU/hr./ft./°F
k_2 = thermal conductivity of tube metal, BTU/hr./ft./°F



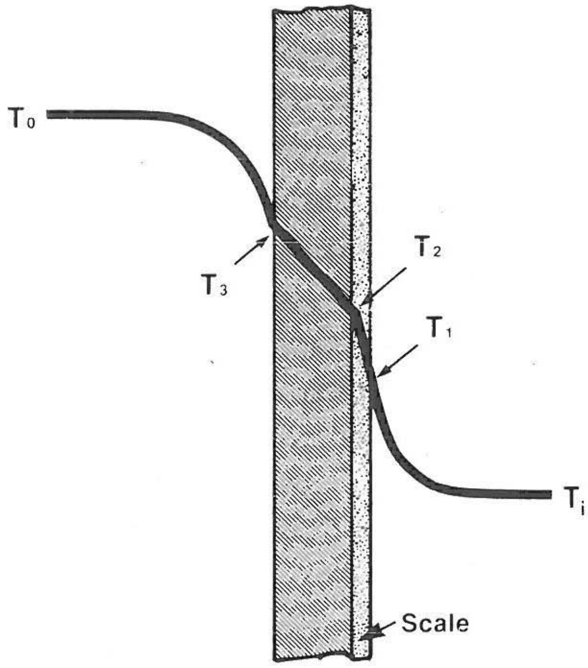
For a unit length of tube, the flow of heat, Q, is in a radial direction and is given by:

$$Q = U_0 A_0 (T_0 - T_i) \qquad \text{Equation 1}$$

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



No Scale



With Scale

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

The denominator of Equation 2 has four terms, one for each of the thermal components:

$$\frac{r_3}{r_i h_i} = \text{steam side film conductance}$$

$$\frac{r_3 \ln(r_2/r_1)}{k_1} = \text{scale conductance}$$

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

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

Equation 1 may be rewritten:

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

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

$$Q/A_0 = \frac{T_i - T_i}{\frac{r_3}{r_i h_i}}, \text{ temperature drop through steam film.} \qquad \text{Equation 4}$$

$$Q/A_0 = \frac{T_2 - T_i}{\frac{r_3 \ln(r_2/r_1)}{k_1}}, \text{ temperature drop through the scale.} \qquad \text{Equation 5}$$

$$Q/A_0 = \frac{T_3 - T_2}{\frac{r_3 \ln(r_3/r_2)}{k_2}}, \text{ temperature drop through the tube.} \qquad \text{Equation 6}$$

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

In order to calculate the surface temperature, T_3, as a result of scale formation on the tube ID, h_0 is first calculated from Equation 2 given the design parameters of U_0, r_3, r_1, h_i, and k_2 for the base tube condition. The scale conductance is zero and $r_1 = r_2$, no scale. Using this value of h_0, the design value of Q/A_0, and the design value of T_0, T_3 is calculated. In practice, during the initial design stage, T_3 is set at the practical limit plus a small margin; for T22 T_3 is 1075°F.

The addition of scale alters the heat flow; to calculate the effect of the scale, the scale term is added as in Equation 3.

Final calculation of T_3 is a two step procedure. Using h_0, just calculated, and appropriate values for the other terms in the denominator of Equation 3, h_i is nearly constant and for this calculation is assumed to be so, T_0 and T_i from design parameters, a new, smaller value of Q/A_0 is found. From Equation 7, T_3 is calculated from this smaller Q/A_0.

In this case history the conditions are as follows:

$$U_0 = 15 \text{ BTU/hr./ft.}^2$$
$$Q/A_0 = 7300 \text{ BTU/hr./ft.}^2\text{, see Table I}$$
$$T_0 = 1485°F$$
$$T_i = 1000°F$$
$$h_i = 300 \text{ BTU/hr./ft.}^2\text{, see Table II}$$

	h_i	U_0
Economizer	1000 BTU/hr./ft.^{2}	5-7 BTU/hr./ft.^{2}
Waterwalls	4000-8000 BTU/hr./ft.^{2}	20-22 BTU/hr./ft.^{2}
Reheaters	300-400 BTU/hr./ft.^{2}	11-17 BTU/hr./ft.^{2}
Superheaters	200-500 BTU/hr./ft.^{2}	11-18 BTU/hr./ft.^{2}

	Thermal Conductivity (1100°F)
Carbon Steel (SA-210 A1)	23.0 BTU/ft.^{2}/hr./°F/ft.
SA 209-T1	21.7 BTU/ft.^{2}/hr./°F/ft.
SA 213-T11	17.5 BTU/ft.^{2}/hr./°F/ft.
SA 213-T22	16.7 BTU/ft.^{2}/hr./°F/ft.
SA 213-TP321H	14.0 BTU/ft.^{2}/hr./°F/ft.
Fe_3O_4	0.342 BTU/ft.^{2}/hr./°F/ft.

Table II Range of Values for Heat Transfer Coefficients

Tubing is 1¾" OD × 0.150" wall, T22 material

$$k_1 = 0.342 \text{ BTU/hr./ft./°F}$$
$$k_2 = 16.7 \text{ BTU/hr./ft./°F}$$

From these data and Equation 2, h_0 is found to be 16.2 BTU/hr./ft.^{2} The formation of scale is assumed to occur half at the expense of the tube and half decreases the radius, r_1, of the tubing, thus:

$$r_3 = 0.875'' \ (0.0729 \text{ ft.})$$

The scale thickness is 0.019".

$$r_2 = 0.735'' \ (0.0613 \text{ ft.})$$
$$r_1 = 0.716'' \ (0.0597 \text{ ft.})$$

From Equation 3, the new Q/A_0 is found to be: 6700 BTU/hr./ft.^{2}. The higher T_3, from Equation 7, is 1072°F or about 40° higher.

It is instructive to calculate the various contributions to the overall flue gas to steam temperature each component makes:

	With Scale of 0.019"	Without Scale
Steam film	27°F	29°F
Scale	38°F	0
Tube	7°F	8°F
Gas side	412°F	449°F
Q/A_0	6700 BTU/hr./ft.^{2}	7300 BTU/hr./ft.^{2}

From this comparison it is evident that aside from the metallurgical implications of the higher tube metal temperatures, there is a slight loss of overall thermal efficiency of the boiler. The calculation is not meant to be precise, but to show the effects of scale on tube temperature. It is safe to say that if the original design limit was 1075°F, the present condition is some 40°F hotter or in the neighborhood of 1115°F.

Scale affects the tube metal temperature; Figure 1.4 plots the calculated temperature as a function of scale thickness for the present reheater tube study. Figure 1.5 shows the stress for the 1% creep in 10,000 and 100,000 for T22 material. Two things are evident from the samples:

1. The ID scale raises the crown temperature of the tube by about 40°F, and
2. Since the wall thickness has been reduced by oxidation or corrosion by 15% or so, the hoop stress in the tube wall will be correspondingly increased.

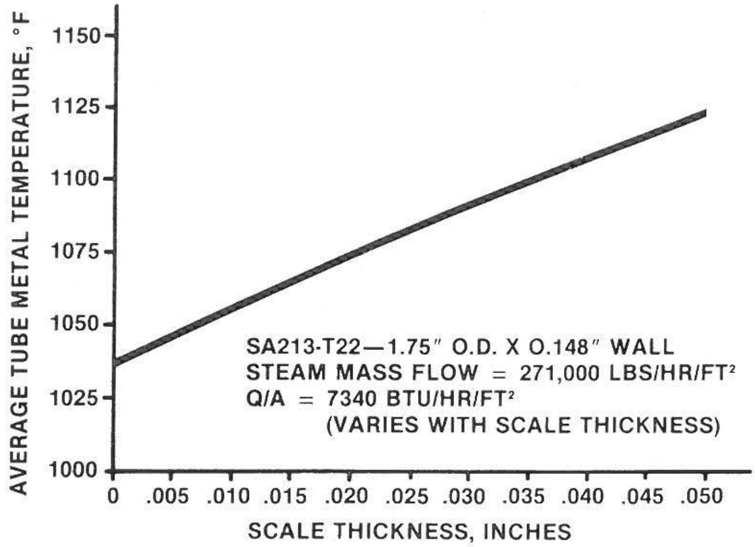


Figure 1.4 Tube Metal Temperatures as a Function of Scale Thickness of Reheater Tube Samples.

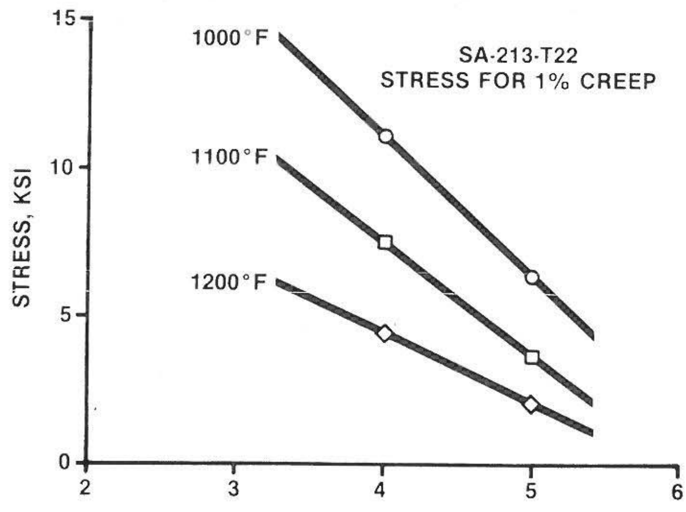


Figure 1.5 Stress for 1% Creep in SA 213-T22 Alloys.

Since the design stress for T22 per the ASME Code is 5800 psi at 1050°F, the actual operating conditions will be over 1100°F with a stress of 6700 psi. As can be estimated from figure 1.5, the time required to give a 1% creep deformation falls from about 100,000 hours for the design condition to about 10,000 hours for 1100°F and 6700 psi.

The inescapable conclusion for the cause of the failure of this reheat tube is a combination of higher temperature caused by the internal scale and severe wall thinning caused by either oxidation or corrosion which accelerated the creep deformation until the ultimate failure was by high temperature tensile strength. The unfailed tubes show that unless the reheater is chemically cleaned to reduce temperatures, increasing failures will occur. However, since the wall thickness has already been reduced by 15% or so, it would appear, if reliable full pressure operation is required, that the reheater section should be replaced.

Case History No. 2

Metallurgical investigation of superheater tubes.

Boiler statistics:	
Size:	650,000 lbs. steam/hour
Steam Temperature:	950°/950°F
Steam Pressure:	1675 psig
Fuel:	Natural Gas

This example deals with the investigation of several superheater sections taken from the high temperature superheater of a boiler that had been in service for approximately 15 years. No failures were observed in any of the samples and all tubes are 2″ OD × .300 wall, SA-213-T22, ferritic material.

The visual examination of these particular samples revealed the following:

A. All contained a thick tightly adhering scale on the OD surface, which measured 0.011″ to 0.030″ thick. The ID surface also exhibited a thick scale which measured 0.019″ thick. Figure 2.1 shows the as-received tube samples.

B. No wall thinning was noted in any of the tubes.

C. No swelling or bulging was observed on any of the tubes.

D. No significant corrosion from outside sources was noted on either the ID or the OD.

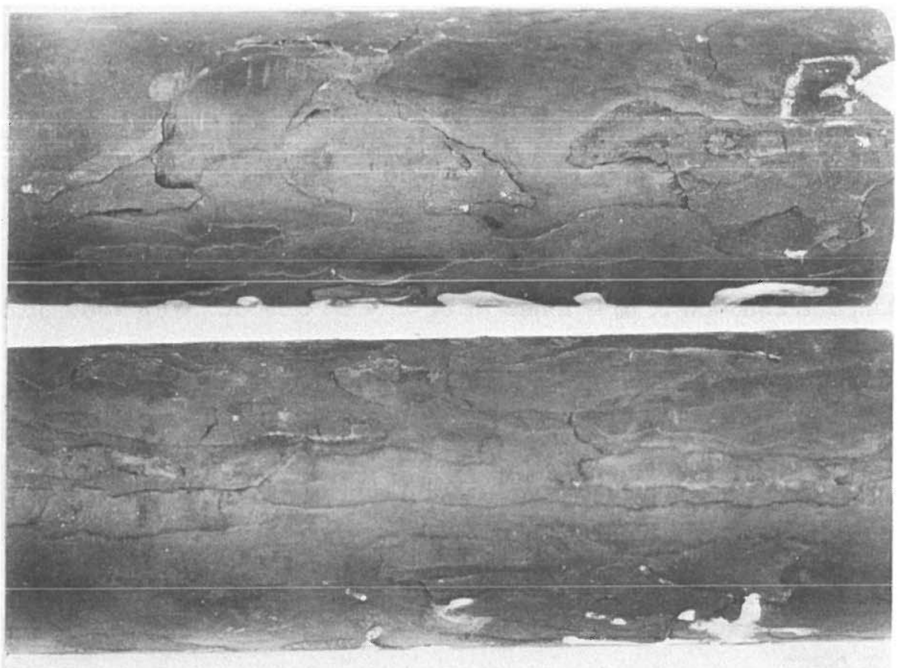


Figure 2.1 As-received Superheater Tubes of T-22. Note the Thick OD Scale.

The microstructures of all samples revealed complete spheroidization of the carbides in ferrite indicating exposure to high metal temperatures for prolonged periods of time, Figure 2.2. The microstructure can be attributed to nearly 15 years of service and the pearlite would be expected to have completely spheroidized. However, there is further danger in the insulating effect of the nearly 20 mils of scale observed on the ID surface. The thermal conductivity of magnetite is about 2 percent of that of steel.

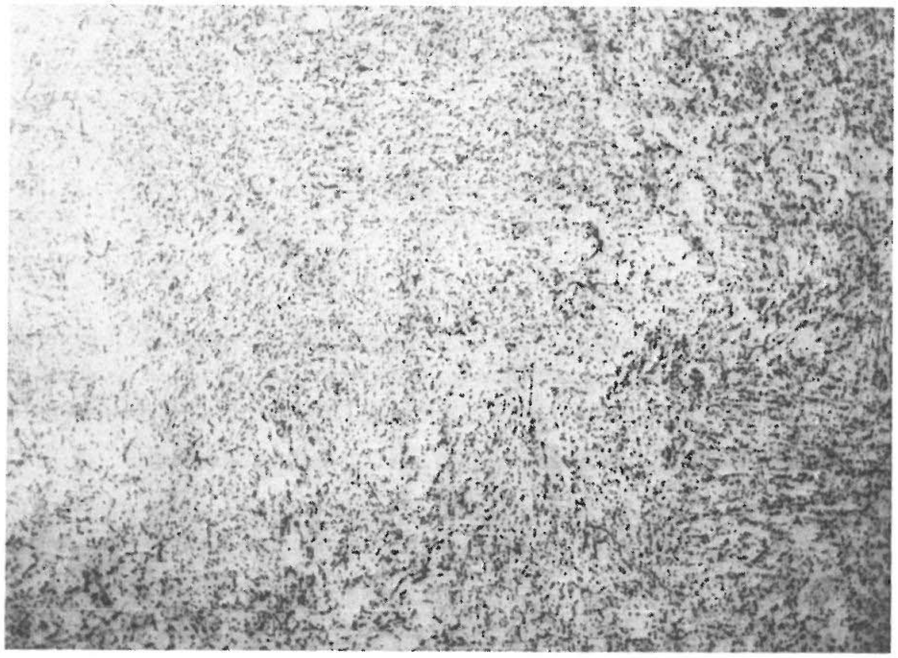


Figure 2.2 Microstructure of As-received T-22 Tubes; the Carbides are Completely Spheroidized. (500×, Nital Etch)

Using the thermal analysis of the previous case history, we can estimate the tube metal temperature increase due to the 0.019" scale. For this example the following data are used:

$$U_0 = 16 \text{ BTU/hr./ft.}^2$$
$$Q/A_0 = 15{,}000 \text{ BTU/hr./ft.}^2$$
$$T_0 = 2000°F$$
$$T_i = 950°F$$
$$h_i = 485 \text{ BTU/hr./ft.}^2$$

Tubing is 2" OD × 0.300" wall, T22 material

$$k_1 = 0.342 \text{ BTU/hr./ft./°F}$$
$$k_2 = 16.7 \text{ BTU/hr./ft./°F}$$

From these data and equation 2, h_0 is found to be 17.4 BTU/hr./ft.^{2} With 0.019" of scale: $r_3 = 1.0"$ (0.0833 ft.)

$$r_2 = 0.710" \ (0.0592 \text{ ft.})$$
$$r_1 = 0.691" \ (0.0576 \text{ ft.})$$

Equation 3 is used to calculate a new Q/A_0, 13,700 BTU/hr./ft.^{2} and from equation 7 is 1115°F or about 75° above the no scale condition.

The parameter $P = T(20 + \log t)$

where T is absolute temperature in °R (°F + 460°)
t is time in hours

has been used to describe changes in steel that are diffusion controlled. Larson and Miller[2] have used it in estimating stress rupture performance at 100,000 hours from high temperature tensile data and short time stress rupture data. It has also been used to relate microstructural changes, spheroidization, graphitization, etc., measured at high temperatures where these changes occur fairly rapidly with expected changes at lower temperatures.[3]

These superheater tubes are now operating 75°F above the no scale condition. For purposes of calculation, if the design assumes a 1 percent creep in 100,000 hours at 1040°F, then

$$P = 37{,}500 = (1040 + 460)(25).$$

At 1115°F, P is still 37,500 but "t" drops to 6,400 hours, less than one year.

Unless the thick ID scale is removed by suitable chemical cleaning procedures, these higher operating temperatures will cause creep failures with increasing frequency. Further complications arise from these higher metal temperatures and heavy scale:

1. The rate of OD oxidation increases with temperature, so increased metal wastage will occur.
2. The thick ID scale tends to spall off and tiny particles of iron oxide can lead to turbine blade erosion.
3. The decrease in heat absorption by the superheater leads to loss of thermal efficiency.

Case History No. 3

High temperature superheater tube failure.

Boiler Statistics:	
Size:	1,600,000 lbs. steam/hr.
Steam Temperature:	1005°F/1005°F
Steam Pressure:	1980 psig
Fuel:	Pulverized Coal

The high temperature superheater tube is SA-213-T22, 1¾" OD × 0.260" wall. The visual examination of the tube revealed the following:

A. The failure was a 1½" long longitudinal split, showing virtually no reduction in wall thickness; see Figure 3.1.

B. The wall thickness 1" away from the end of the failure and in the same plain measured 0.230".

C. The wall thickness 180° from the failure measured 0.300".

D. The OD scale and deposits measured 0.052"; the ID scale 0.012".

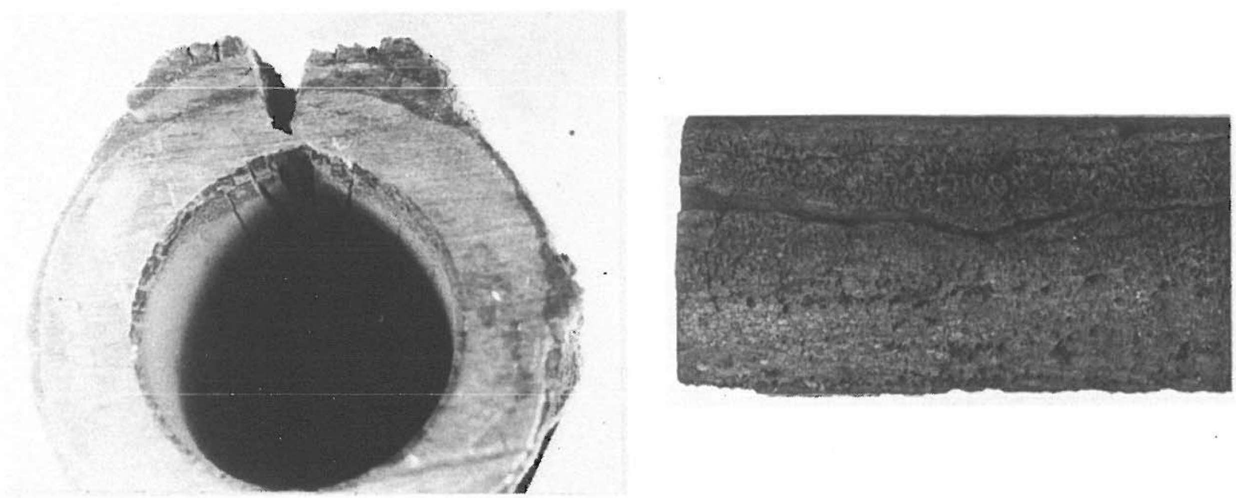


Figure 3.1 As-received Superheater Tube. The Failure is a Narrow Split about 1½ Inches Long. Note the ID Scale in the Transverse View.

The microstructure of the failed area showed a complete spheroidized structure; see Figure 3.2. The surface of the tube shows an intergranular penetration of the OD oxide; see Figure 3.3. Figure 3.4 shows creep voids in the vicinity of the failure.

Using equation 4, the temperature increase is calculated to be 80°F.

At the time of failure, the outer skin temperature was about 1200°F. The failure appearance is a classic example of creep failure; many voids preceding the failure crack. At high temperatures the grain boundary is a source of weakness. Where planes of atoms are in disarray, the binding energy between atoms is a little

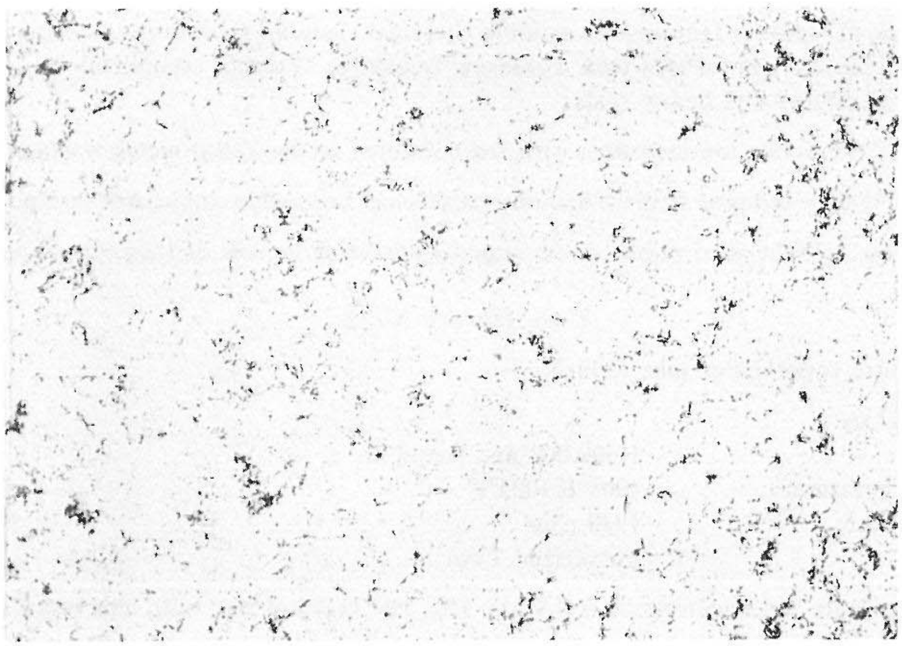


Figure 3.2 Microstructure Shows Spheroidized Carbides and Ferrite. (500×, Nital Etch)

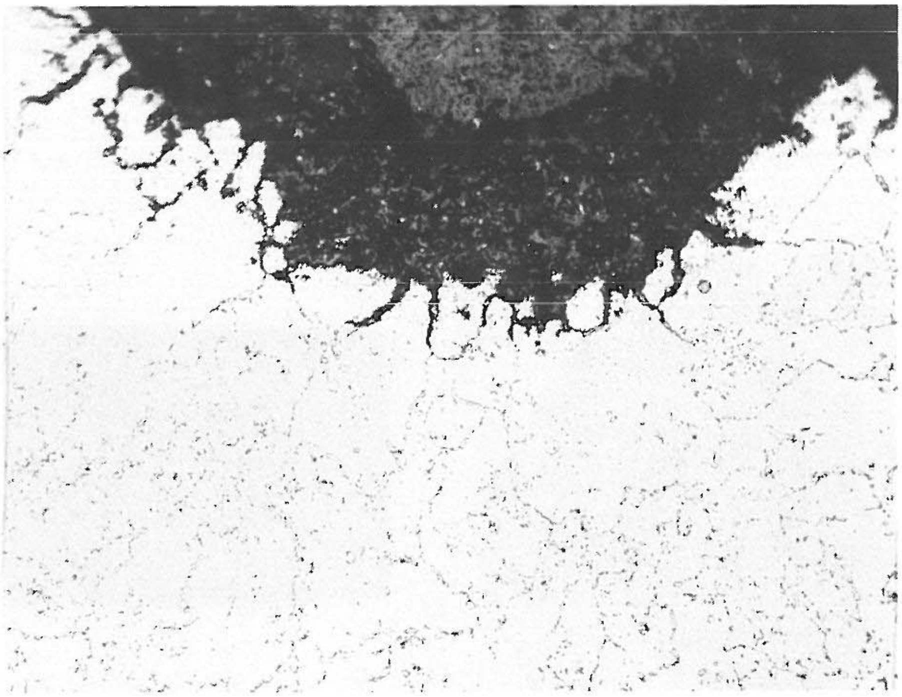


Figure 3.3 The OD Scale Exhibits Some Minor Grain Boundary Attack. (500×, Nital Etch)

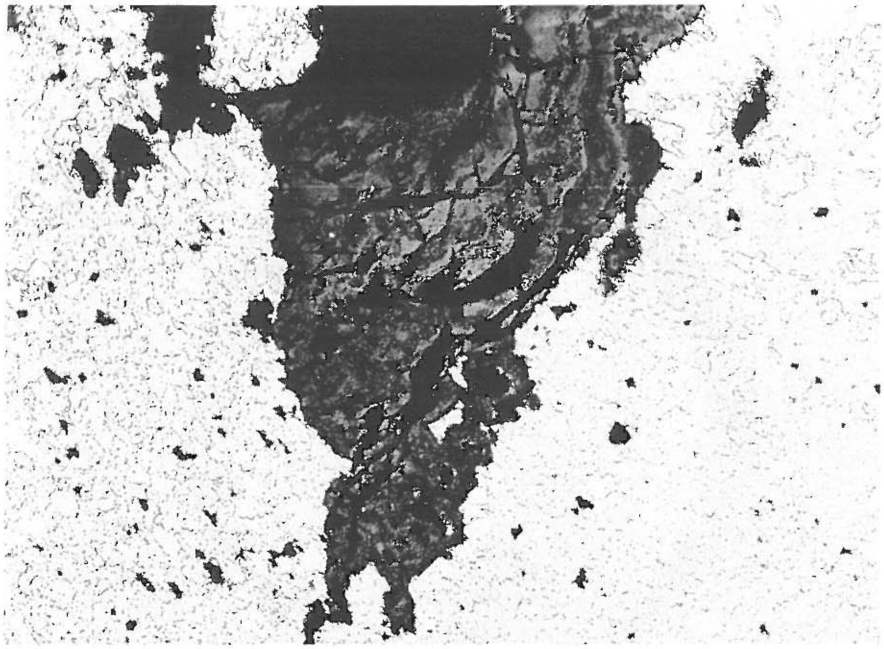


Figure 3.4 The Structure at or near the Tip of the Failure. Note that the Crack is Completely Filled with Oxide Scale. The Black Specks in the Metal are Voids Indicative of a Creep Failure. (500×, Nital Etch)

less than the regular arrangement within crystals. Adjacent grains slide and where three grains come together, a void will start. Grain boundary sliding is accompanied by dislocation movement; dislocations are defects of atomic size that make up the grain boundary. At the triple point these atomic size defects collect, pile up, to form the void.

The cause of failure is by creep. Thick ID scale decreases the overall thermal conductivity of the tube so that tube metal temperatures are increased sharply, 80°F. Tube metal temperatures above 1200°F for T22 for an extended period of time led to the failure of this tube.

Case History No. 4

Metallurgical investigation of a reheater tube.

Boiler Statistics:	
Size:	550,000 lbs. of steam per hour
Steam Temperature:	1005°F/1005°F
Steam Pressure:	1875 psig
Fuel:	No. 6 Fuel Oil

This example deals with the failure of a reheater tube from a small municipal power plant. The reheater tube is SA-213-T22 2″ OD × 0.148″ wall. Visual examination of the tube revealed the following:

A. The tube was heavily coated with a thick deposit and scale.

B. The inside of the tube contained a tightly adhering magnetite scale, 0.015″ thick.

C. The tube was thinned for a considerable distance. See Figure 4.1.

D. Micrometer measurements showed the wall thickness to be 0.020″ at the thinnest portion of our sample.

E. The wall thickness at the lug measured 0.152″.

The microstructure shows complete spheroidization of the pearlite and a carbide network around the ferrite grains; see Figure 4.2.

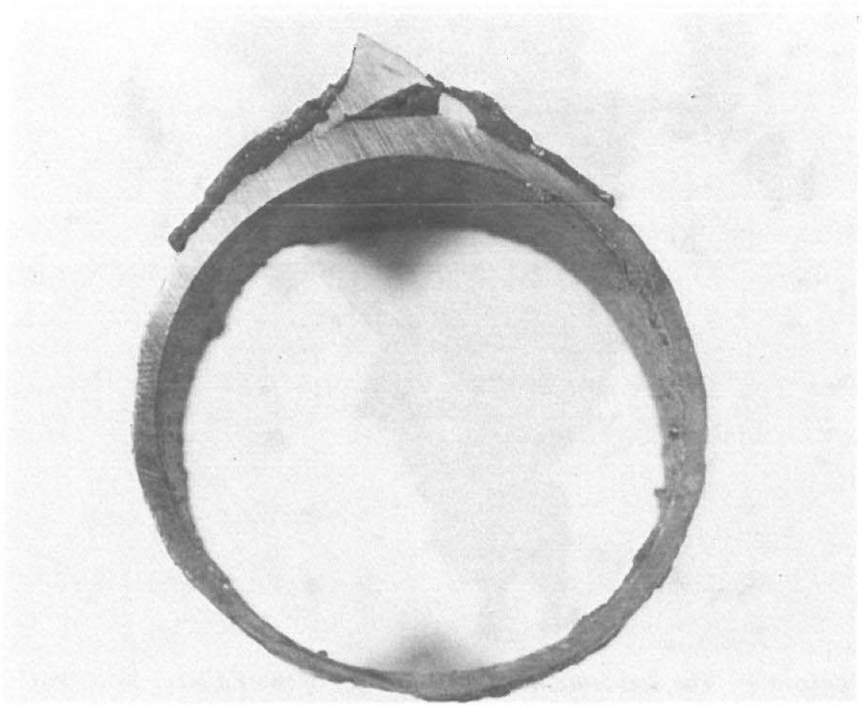


Figure 4.1 Cross-sectional View of an As-received T-22 Reheater Tube. Note the Extensive Metal Wastage in the Lower Portion of the Photograph.

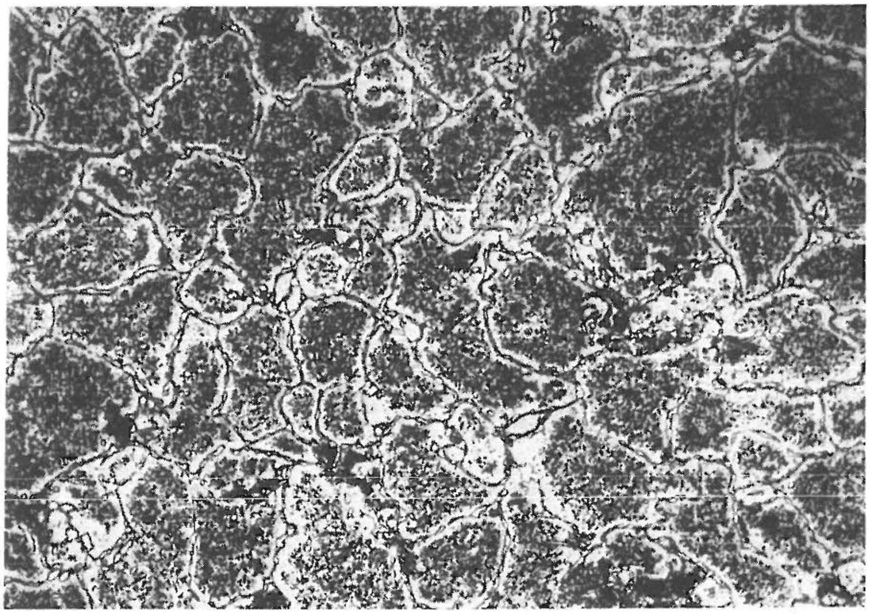


Figure 4.2 Microstructure Of the Tube Sample. Observe the Spheroidized Carbides and the Carbide Network Surrounding Each Ferrite Crystal. (500×, Nital Etch)

The extensive wall thinning indicates a severe OD corrosion problem, and the chemical analysis of the deposits confirms the presence of vanadium, sulphur, and sodium; see Table III. The presence of these elements suggests the tube wastage is by liquid ash corrosion.

Mixtures of vanadium and sodium oxides have melting points as low as 1050°F; mixtures of vanadium pentoxide (V_2O_5) and sodium sulfate (Na_2SO_4) have melting points below 1000°F.[4] In the presence of carbon, the corrosion of superheaters and reheaters in oil fired boilers is by sulfidation and the formation of metallic sulfides.[5]

Using the thermal analysis presented in Case History No. 1 shows that for this particular reheater the 0.015" thick magnetite scale on the ID raises the crown temperature of the tube by nearly 50°F. The OD corrosion condition is exacerbated by the higher metal temperature resulting from the ID scale.

Vanadium	as V_2O_5	39.2%
Sulphur	as SO_3	13.9%
Sodium	as Na_2O	12.2%
Iron	as Fe_2O_3	31.2%
Carbon		0.4%

Table III Chemical Analysis of OD Deposit

SUMMARY

The preceding four case histories illustrate the effects of excessive ID scale buildup on the service condition of superheaters and reheaters. We have seen that as the ID scale thickness increases, it acts as an insulation barrier to heat flow from the hot flue gas to the steam. By insulating the ID of the tube, the tube metal temperature increases and these higher operating temperatures lead to shortened operating life for the following reasons:

1. Increase the creep rate, or reduce the creep life. Figure 1 plots the ASME Code Section I allowable stress for T-22 as a function of temperature. Note the sharp drop off in allowable stress above about 1000°F; this stress drops from 5,800 psi at 1050°F to 4200 psi at 1100°F. Relatively small temperature increases will sharply reduce the time to reach a 1% expansion caused by creep.

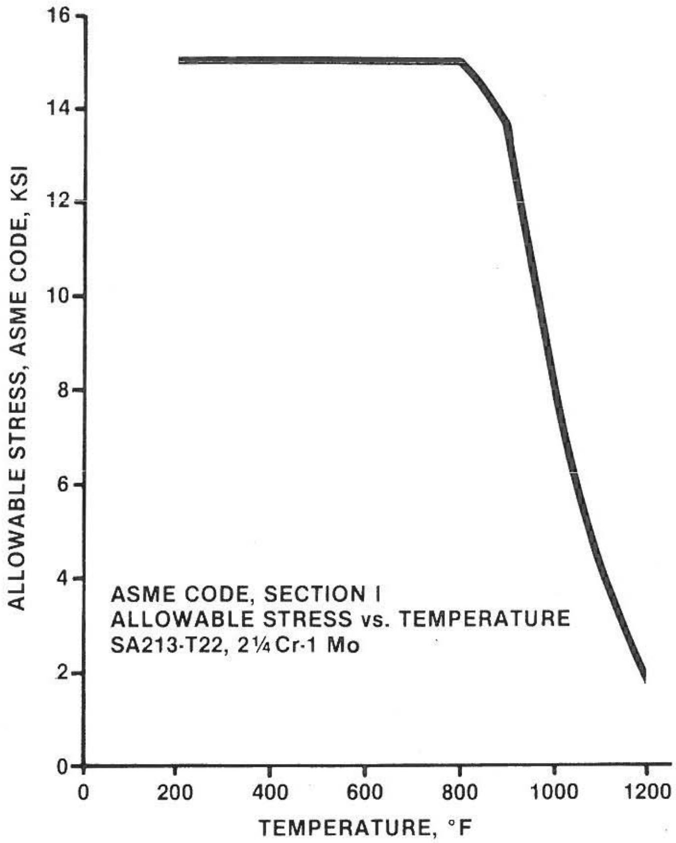


Figure 1 A Plot of the Allowable Stress Per ASME Code Section I Versus Temperature for SA 213-T22. Note the Sharp Drop in Allowable Stress Above 1000°F.

2. Increase the fire side corrosion rate. Figure 2 shows the corrosion rate vs temperature for SA 213-TP321 in a coal ash [$Na_3Fe(SO_4)_3$] environment. Note that within the temperatures of interest, 1050-1150°F, the rate of corrosive attack increases with temperature. Similar behavior exists for corrosion rate as a function of temperature for oil ash.

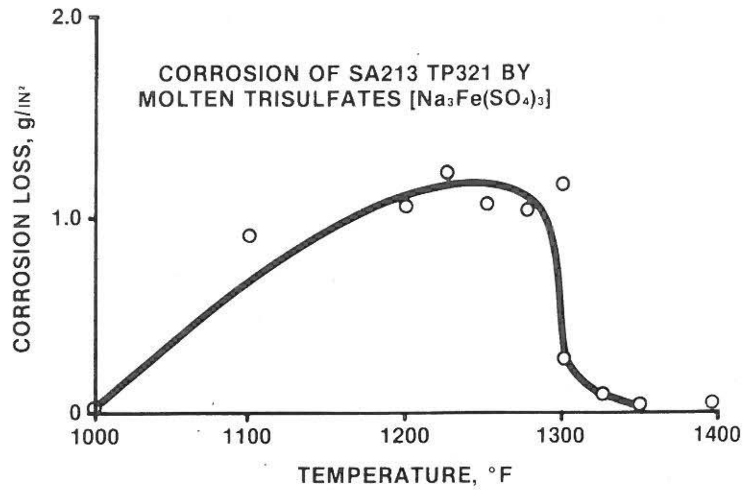


Figure 2 Corrosion Rate Versus Temperature for SA 213-TP321 in a Coal Ash Environment, from Reference 4.

3. Increase the rate of ID scale formation. This is a vicious circle; ID scale raises metal temperatures which in turn increase the rate at which the scale forms.

4. Increase exfoliation. In general, the thicker the ID scale the more readily it will spall and lead to turbine blade erosion by small particles of scale entrained in the steam.

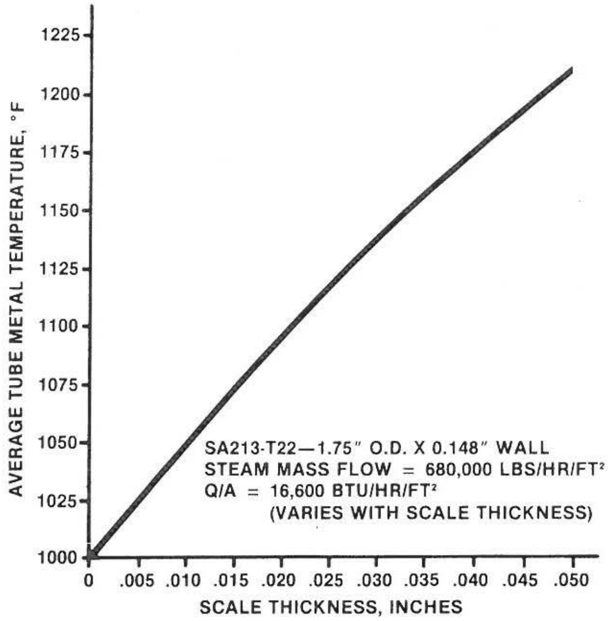
5. Decrease thermal efficiency. Higher metal temperature implies a slight, but real, loss of thermal efficiency.

RECOMMENDATIONS

Recommendations to prevent the inevitable ID scale buildup from causing serious long term problems fall into two categories, operational and design. The two are not necessarily independent although once a boiler is placed in service it is too late for design considerations to be of help. Design alternatives should be considered at the time the boiler is purchased or during major surface replacement.

On the operational side, exercise greater care during service, especially during start-up. Keep within the specified temperature limits as even short term overheating has a cumulative adverse effect. What is true for superheaters is doubly true for reheaters. During start-up the reheater is the last to be cooled by steam flow, and furthermore, the first steam from the turbine may be 300-400°F and effectively shock the reheater tubes at metal temperatures of 800°F or more.

Chemically clean when scale buildup raises operating metal temperature by 15-20°F above the safe design limit. At the annual outage, the high temperature portion of the superheater and reheater should be checked for scale buildup. The thickness of scale that will be required to increase the tube metal temperature by 15-20°F above the safe design limit depends on the design parameters. Figures 3, 4 and 5 show the calculated wall temperatures as a function of scale thickness for several cases. Note the wide variation expected. However, even this modest 15-20°F increase in tube metal temperature will reduce the time for 1% creep expansion by almost a factor of 2.



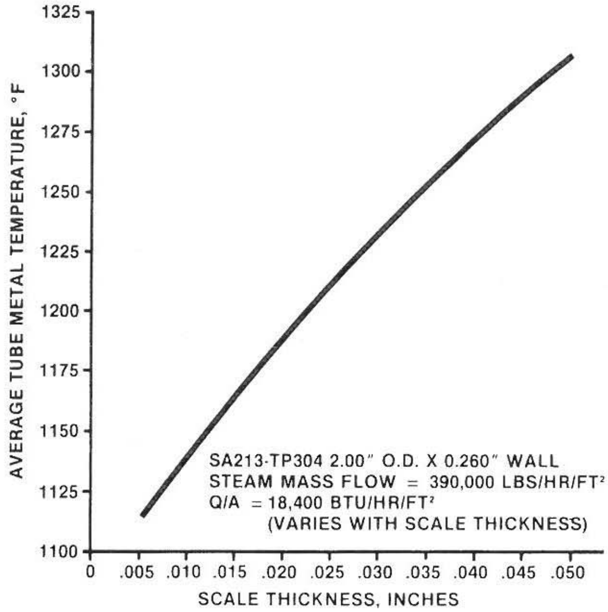


Figure 3 Tube Metal Temperature as a Function of ID Scale Thickness. 2" OD × 0.300" Wall, T-22.

Figure 4 Tube Metal Temperature as a Function of ID Scale Thickness. 2" OD × 0.260" Wall, 304.

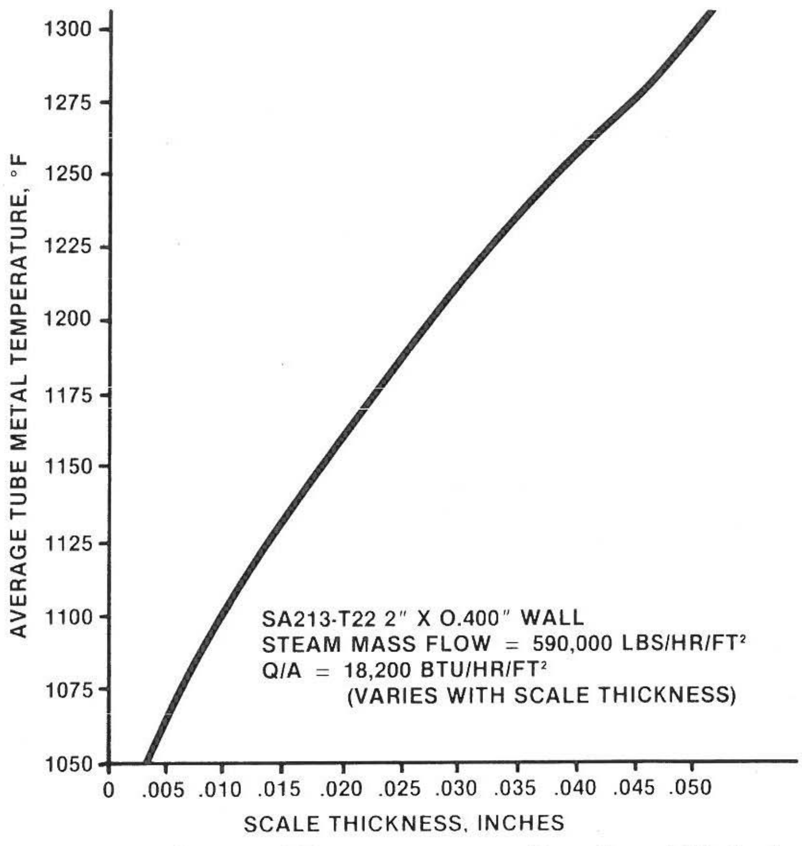


Figure 5 Tube Metal Temperature as a Function of ID Scale Thickness. 2" OD × 0.400" Wall, T-22.

The ease with which a unit can have a superheater and reheater chemically cleaned is related to design; these portions of the boiler should be completely drainable. Figures 6 and 7 compare two recent Riley Stoker contracts of about the same capacity, nearly 4½ million pounds of steam per hour. One has a pendant type SH and RH and is not drainable; the other has horizontal SH and RH and is drainable. By designing units with drainable superheaters and reheaters, chemical cleaning is facilitated.

The other design change that will provide long trouble-free service is to use more alloy tubing, T-22 where T-11 and 321 where T-22 are now used. In effect this lowers the oxidation limits for ferritic materials. The use of more stainless steel will extend the time between chemical cleanings. Careful measurements on T-22 and 321H from a 15 year old unit on either side of the weld that had the same temperatures and service shows that the scale thickness on T-22 was 0.013 inches and on the 321H 0.005 inches. Using the thermal analysis presented, a comparison of thick walled T-22 (1¾" OD × 0.254" wall)

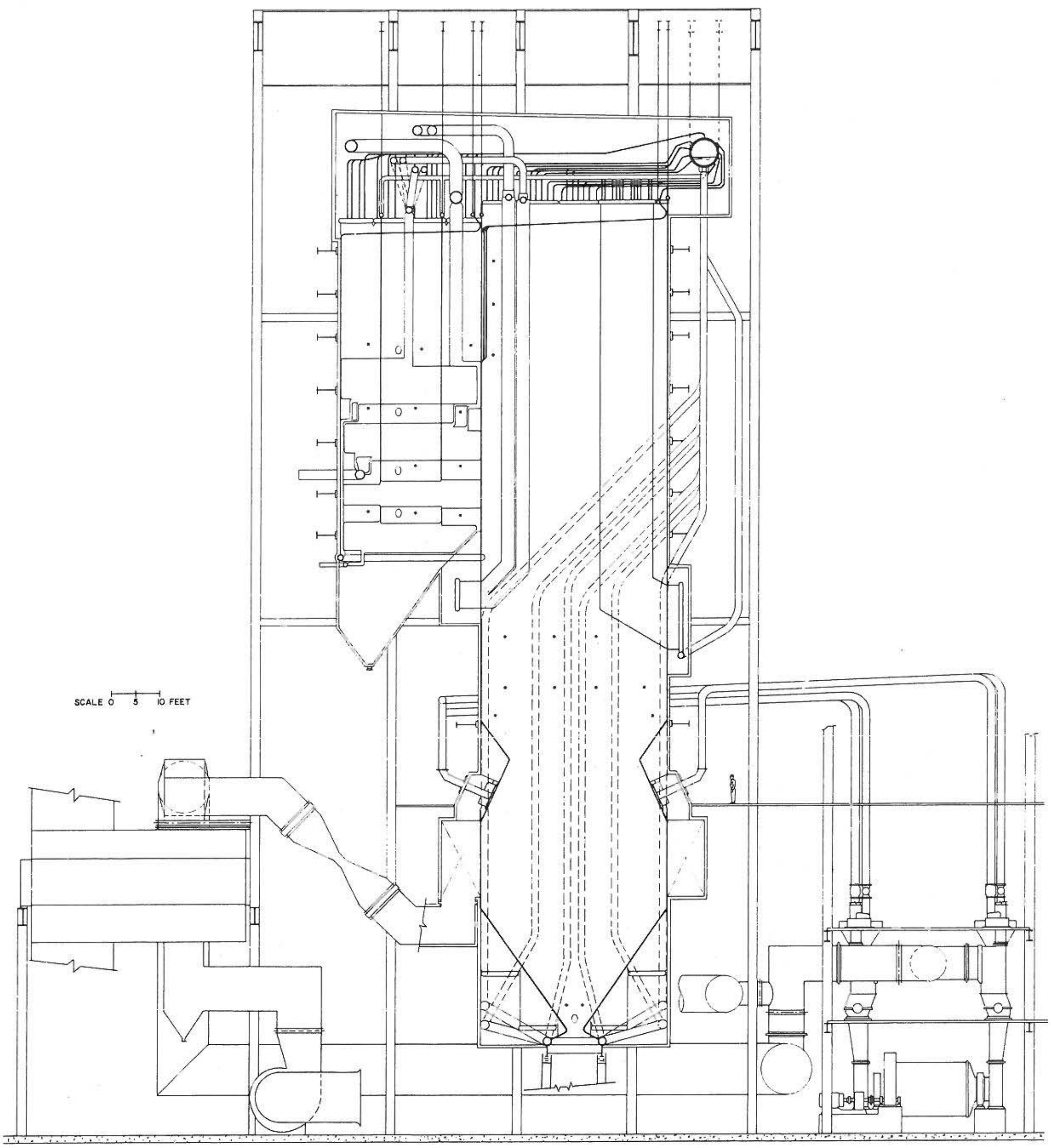


Figure 6 A Recent Riley Stoker Corporation Boiler with Drainable Superheater and Reheater.

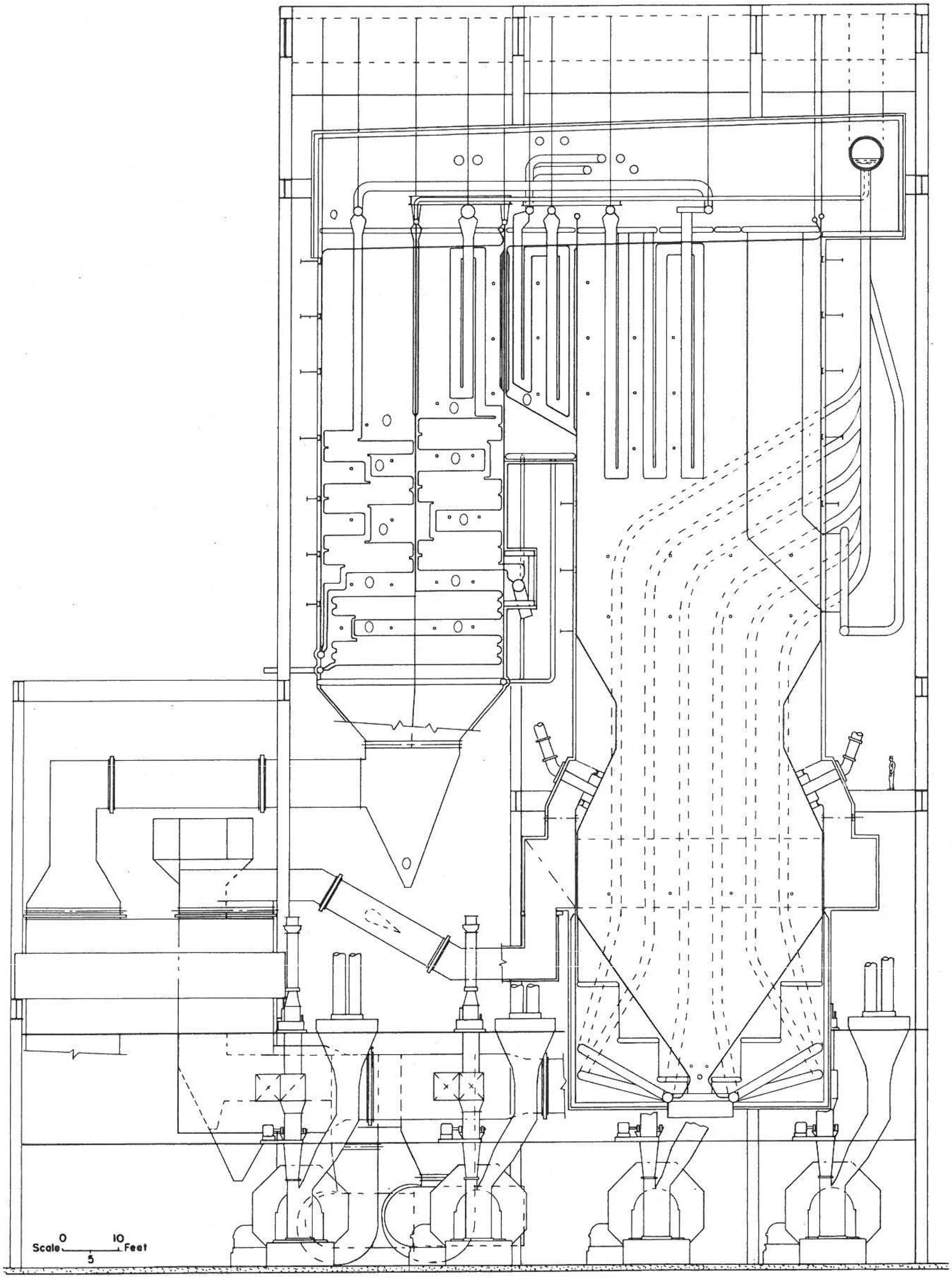


Figure 7 A Recent Riley Stoker Corporation Boiler Designed with Pendant Type Superheater and Reheater.

with 321H (1½" OD × 0.170" wall) shows the 0.013" scale on T-22 raises the temperature about 75°F while the 0.005" scale on 321 raises the temperature by 20°F. Figures 8a and 8b compare the morphology of these two oxides; note the smoothness of the oxide/metal interface on T-22 and the deep penetration of the oxide into the 321H. Since the stainless steel oxide is "keyed" into the base metal, there is less tendency for spalling to occur and thus less tendency for turbine blade erosion to occur.

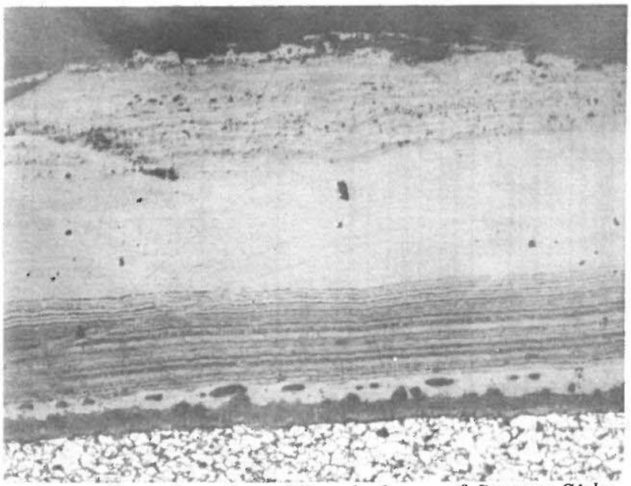


Figure 8a Interface Morphology of Steam Side Oxide on SA 213-T22 Tubing. The Scale/Metal Boundary is Planar With No Grain Boundary Penetration of the Oxide. (70×, Nital Etch)

Figure 8b Interface Morphology of Steam Side Oxide on SA 213-TP321 Tubing. Note the Unevenness to the Scale/Metal Interface. (70×, Unetched)

However, since we all work and try to sell in a very competitive atmosphere and these design improvements are more expensive, unless we shall receive credit for these changes or the specifications so state, our offerings will not likely include them. At the time purchase specifications are written, more attention should be given to the operational and maintenance problems you people will live with and have for the next three or four decades. The lowest first cost is not necessarily the lowest life cost.

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