

FIRESIDE CORROSION AND EROSION PROBLEMS IN COAL BASED POWER PLANT

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Abstract

High temperature corrosion problems in coal/oil based power plants are discussed. The main corrosion problems in power plants are the water/steam side corrosion of the inner wall tubes of the boiler and the oxidation/sulphidation and hot corrosion of outer walls of boiler tubes. The former is well understood and can be controlled by controlling the chemistry of the feed water, the fireside corrosion is, however, least understood and is a function of several variables, both operating and material. These are discussed in detail with some of the data from the failure of plants as a result of fireside corrosion and erosion.

Introduction

High-temperature corrosion plays an important role in the selection of materials for construction of industrial equipments. The principal modes of high-temperature corrosion, frequently responsible for component failure are: oxidation, sulphidation, nitridation, carburization, hot corrosion and flyash erosion. Oxidation most often participates in the high-temperature corrosion process, regardless of the predominant mode of corrosion. In fact, alloys often rely upon oxidation reaction to develop a protective oxide scale to resist various high-temperature corrosion. Environment plays an important role in all types of corrosion attacks. The environments in coal/oil based power plants contain several corrosive species which may result in "oxidizing" (very high oxygen activity) or "reducing" (very low oxygen

activity due to combustion under stoichiometric or sub-stoichiometric conditions) atmosphere. The reducing atmosphere is generally more corrosive for corrosion modes, such as sulphidation, and ash/salt deposit corrosion. Moreover, the fuel contaminants can form ash/salt deposits on metal surfaces during high-temperature exposure which play significant role in the corrosion process. For example, sulphur from the fuel and NaCl from the ingested air may react during combustion to form salt vapour, such as Na_2SO_4 which at lower temperatures, deposits on the metal surfaces, resulting in accelerated corrosion, caused by the chemical reaction between the protective oxide scale and the salt deposit, leading to the breakdown of the scale. Such a corrosion process occurring in the presence of salt deposits is termed as "Hot Corrosion". The presence of large particles of quartz, FeS_2 or Al_2O_3 in the flyash causes yet another

problem known as "Flyash Erosion". Fireside oxidation/hot corrosion and flyash erosion are the major problems in coal-fired boilers. Boiler statistics^[1] for coal-based power plants indicate that flyash erosion accounts for about 28% of waterwall tubing failures and about 22% of superheater and reheater failures; fireside corrosion causes 0.5 and 1% of failures, respectively, in these areas. Problems with boiler pressure parts account for an equivalent availability loss of around 7.5% (waterwall and economizer tubes: 4% and superheater/reheater tubes: 2.2%). However, the determination of the availability loss, due to the causes mentioned above, is currently difficult because boiler tube damage and failure occur essentially in all regions of the boiler. Waterwalls suffer failures from both fireside corrosion and flyash erosion, as do superheaters and reheaters, whereas economizers usually suffer only erosion failures because of their position in the boiler. The objectives of this paper are to assess the importance, as related to availability, of boiler tube failures due to corrosion and to discuss the causes and mechanisms thereof. Attempts have also been made to examine the limitations of the current preventive and control technologies, and to provide direction for their improvement, more efficient implementation, or development of new technologies.

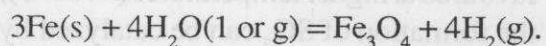
Corrosion Problems in Coal/Oil Based Power Plants

A fossil-fired steam power plant is illustrated in Fig. 1. Three fluid flow loops circulate through the system: fuel-air, water-steam, and condenser cooling. In the fuel-air loop, the fossil fuel is burnt in air and transfers its heat to a series of heat

exchangers. In the water-steam loop, clean feedwater is converted into superheated steam in a boiler, which expands through a series of turbines, converting its heat into mechanical energy. In the condenser-cooling loop, cold water is passed through the condenser and can be recirculated or is exhausted back to the source of the cooling water. Each fluid loop possesses its unique corrosion problems.

The fossil fuel is burnt in a very large chamber constructed of water walls (consisting of vertical or spiral tubes welded together in a web), where the feedwater is heated. In subcritical boilers, the saturated steam is superheated in tubular heat exchangers. In supercritical boilers, the liquid becomes superheated vapour without undergoing a phase change. The boiler fluid may become acidic or caustic, depending on the presence of corrosion deposits and flow interruptions. Under acidic conditions, the steel boiler tubes may be hydrogen embrittled; under caustic conditions, the tubes may be caustic gouged.

The corrosion in a steam boiler may be represented by the equation:



From the corrosion point of view, a boiler is nothing but a thin film of magnetic iron oxide supported by steel. This oxide film is continuously damaged and repaired during boiler operation, with simultaneous production of hydrogen. The superheater and reheater tubes suffer from steam oxidation of the inner surfaces and hot corrosion of the outer surfaces. The fire-side corrosion is a typical problem. In coal-fired boilers, it exhibits a maximum rate at 700 to 750°C, where the corrodent is

a liquid, and decreases to a minimum at high temperatures. Fig. 2 shows the main parts of a boiler susceptible to hot corrosion problems. There are essentially three distinct high-temperature corrosion problems in coal-fired boilers :

- Fireside Corrosion of Superheater/ Reheater and Waterwalls,
- Flyash Erosion of Waterwalls and Superheater/Reheaters,
- Steamside Oxidation in the Superheater/Reheaters.

Causes and Mechanisms of High-Temperature Corrosion

When coal particles are introduced into the flame, the moisture and the volatile species are driven off, the fixed carbon in the individual particles begins to burn. The contained mineral matter may be melted or vaporized, and is largely oxidized. The sulphur-containing compounds in the coal (such as FeS_2) are converted to oxides such as Fe_2O_3 , K_2O , Na_2O , SO_2 and SO_3 . The relative proportions of SO_2 and SO_3 in the flame depend on the available oxygen and the temperature. SO_2 is thermodynamically favoured at higher temperatures ($>700^\circ\text{C}$); the formation of SO_3 can be catalyzed by certain metal oxides, so that the proportion of SO_3 in flue gas may increase downstream of the burners. Thus the gaseous species released, as the coal passes through the flame, contain potential corrodents such as sulphur, vapour of alkali metal salts, and chlorine compounds (mostly HCl). The quality of coal used is very important. Raask^[2] has proposed a simple three-category ranking of the corrosiveness of coals based on the sum of the percentages of water-soluble sodium and potassium in the coal:

Water-soluble Na+K(Wt.%)	Corrosiveness
< 0.5	Low
0.5-1.0	Medium
> 1.0	High

A correlation has been found between the corrosion rate of superheater/reheater tubes and the chlorine content of the coal^[3]. Chlorine (more than 0.2 wt%) has been found to promote the release of both Na and K into the flame, and acts as a strong catalyst for the molten trisulphate attack. There is also evidence that HCl formed in the flame can destroy the Fe_2O_3 layer on a steel surface, thereby exposing it to additional oxidative attack^[4].

Fireside Corrosion Problems

The fireside corrosion of various components of a coal-fired boiler may be attributed to the following:

- Reducing (sub-stoichiometric) conditions caused by impingement of incompletely combusted coal particles and flames,
- Accelerated oxidation from overheating, and
- Molten salt or slag-related attack.

The fireside corrosion is generally localized to regions on the walls near the burners. The thick, hard, external scales formed often exhibit cracks which resemble an alligator hide as shown in the Fig.3. Reducing atmospheric corrosion can result due to direct reaction of the waterwall tubes with a sub-stoichiometric gaseous environment containing sulphur, or with partially combusted char containing FeS_2 . The reducing conditions have two main effects on corrosion. First, they tend

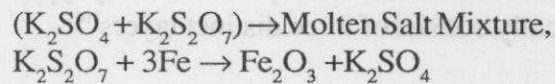
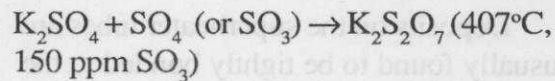
to lower the melting point of any deposited slag, increasing its ability to dissolve the normal oxide scales, and second, the stable gaseous sulphur compounds under these conditions include $H_2S^{[5-7]}$, which is more corrosive than SO_2 that predominates under oxidizing conditions. Fig.4 shows the cross-section of a 1.25 Cr-alloy waterwall tube removed from a boiler where it was exposed to "reducing" atmosphere corrosion. The scale is a mixture of sulphide and oxide, which suggests that the conditions in the combustion gas at the waterwall were close to those suggested by the Fe_3O_4/FeS boundary in the phase stability diagrams shown in Fig.5.

Overheating of the superheater is related to the poor design of the boiler, when slagging problems are experienced. Change in parameters such as the feed rate of coal to attain the desired steam temperature can cause overheating. Overheating of the reheaters can occur in rapid startup situations, when the combustion gas temperature at the reheater reaches its maximum value before full steam flow through the reheater is achieved. The overheating leads to accelerated oxidation of both the fireside and the steamside surfaces of the tubes to produce thickened, hard (alligator hide) scales. Above $570^\circ C$, a very non-protective scale of wustite (FeO) can be formed on iron which leads to the onset of rapid oxidation.

Mechanism of Molten Salt or Slag-Related Attack

Molten salt or slag-related attack takes several forms. Local disruption of the normal oxide film on the wall tubes can lead to either accelerated oxidation, or to

oxidation/sulphidation attack due to sulphur species in the slag. Alkali sulphates deposited on the waterwalls may react with SO_2 or SO_3 to form pyrosulphates such as $K_2S_2O_7$ & $Na_2S_2O_7$, or possibly complex alkali-iron trisulphates, the latter compounds being formed in thicker deposits after long times at about $482^\circ C^{[8]}$. The K_2SO_4 - $K_2S_2O_7$ system forms a molten salt mixture at $407^\circ C$ when the SO_3 concentration is 150 ppm. The above mechanism may be depicted by the following sequence of reactions:



By such a mechanism, the pyrosulphate can react aggressively with any protective iron oxide scales on the tubes, and lead to accelerated wastage through fluxing of the oxides and attack of the substrate metal. The corresponding sodium system can become liquid at $400^\circ C$ with about 2500 ppm of SO_3 . Such high concentrations of SO_3 is possible in the stagnant regions beneath deposits, so a similar attack by $Na_2S_2O_7$ may occur when a high-sulfur coal produces combustion gases containing high levels of sulphur oxides. Reid^[9] has pointed, however, that the levels of SO_3 present at this location in a boiler burning a typical coal are such that $K_2S_2O_7$ is unlikely to be found at temperatures above about $510^\circ C$, and $Na_2S_2O_7$ only up to about $400^\circ C$.

Deposit-related molten salt attack of the pendant tubes concerns the development of conditions beneath a surface deposit which are conducive to the formation of a low melting salt of the type

(Na, K)₂Fe(SO₄)₃. Catalytic oxidation of SO₂ in stagnant zones beneath a layer of deposit can lead to nearly equilibrium levels of SO₃, so that conditions are favourable for the formation of trisulphates in deposits up to about 704°C. Above this temperature, the required SO₃ concentrations cannot be sustained, and the trisulphates become unstable, decomposing to the alkali sulphates which are solid. There is wide acceptance that compounds of this type play a critical role in the corrosion of superheater tubes.

Deposits on the superheater tubes are usually found to be tightly bonded to the tubes at the room temperature. They typically consist of three distinct layers^[10]:

- i. A hard, brittle and porous outer layer, which is the bulk of the deposit and has a composition similar to the boiler flyash.
- ii. A white intermediate layer. When this layer has a chalky consistency, corrosion is found to be mild or non-existent. When it is fused and semi-glossy, corrosion is found to be severe. Compounds identified in this layer include complex alkali sulphates, and the alkali-iron trisulphates.
- iii. A black, glossy inner layer, composed primarily of oxides and sulphides of iron.

The typical appearance of a corroded superheater tube is illustrated in Fig.6. The thickened, non-protective scale formed beneath such deposits comprises of mixed layers of iron oxides and sulphides as is evident from Fig.7.

Fireside Erosion Problems

Light erosion damage is usually main-

fested by polishing of the affected surface. The eroded area is often quite clean and free of deposits. Thinned and flattened areas result from more severe erosion. Erosion tends to be localized to particular areas of the boiler, and to particular parts of a given tube bank. Fig.8 shows the typical appearance of flyash erosion damage on an economizer tube.

The factors in coal which contribute to fireside erosion problems are large particles of dense minerals such as quartz, or FeS₂, and those mineral constituents which may be converted during combustion to hard/abrasive compounds such as alumina and silica based oxides.

System variables (such as flyash particle velocity and the angle of impingement), and operating variables (which define the size, shape, hardness and number density of the flyash particles), are very important. The rate of erosion loss is usually found to be proportional to:

- the impact velocity raised to a power between 2 and 4, and
- the number of individual impacts by the flue gas.

Erosion damage is, therefore, a potential problem at any point on the fireside of the boiler where the ash-laden flue gas contacts boiler tubes or internal support structures at velocities and with particle loadings above some minimum values. Flyash erosion of waterwall tubes is generally encountered in the areas around the top of the rear wall of the furnace, where the flue gas is turned to flow through the rear pass. Erosion results largely from turbulence created by the change in flow direction, and by flow around pendant tube bundles.

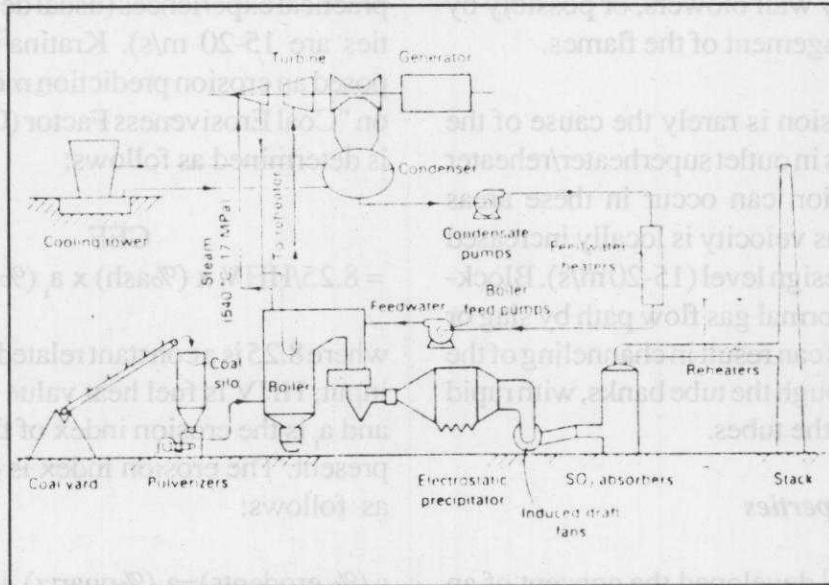


Fig. 1 : The schematic of a coal-fired power plant

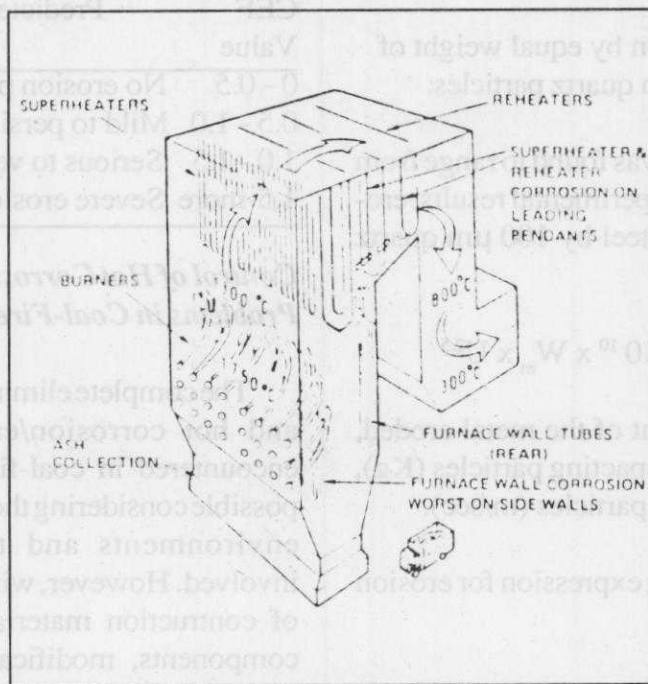


Fig. 2 : The schematic of a coal-fired boiler showing the main parts susceptible to hot corrosion

Other type of erosion in the regions of the waterwalls occurs from ash or slag entrained by wall blowers, or possibly by direct impingement of the flames.

The erosion is rarely the cause of the tube failures in outlet superheater/reheater tubes. Erosion can occur in these areas when the gas velocity is locally increased above the design level (15-20 m/s). Blockage of the normal gas flow path by slag or ash deposits can result in channeling of the flue gas through the tube banks, with rapid thinning of the tubes.

Flyash Properties

Raask^[11] developed the concept of an "Erosive Index" for coals relating the erosivity to the quartz content of the flyash, which he has defined as:

$$\text{INDEX}(I) = \frac{\text{Erosion by flyash}}{\text{Erosion by equal weight of 100 } \mu\text{m quartz particles.}}$$

The value of I was found to range from 0.2 to 0.4. From experimental results, erosion rate of mild steel by 100 μm quartz grains is given as:

$$W_e = 9.5 \times 10^{-10} \times W_m \times U^{2.5}$$

where W_e = weight of the metal eroded, W_m = weight of impacting particles (Kg), U = velocity of the particles (m/sec).

The corresponding expression for erosion by flyash is:

$$W_e = 9.5 \times 10^{-10} \times I \times W_m \times U^{2.5}$$

Using these calculations, one can say that at velocities around 35 m/s, erosion

can cause the tube failure in 10,000-50,000 hrs., which is in good agreement with practical experiences (usual design velocities are 15-20 m/s). Kratina^[12] has proposed an erosion prediction method based on "Coal Erosiveness Factor (CEF) which is determined as follows:

$$\text{CEF} = 8.25/\text{HHV} \times (\% \text{ash}) \times a_1 (\% \text{erodents}),$$

where 8.25 is a constant related to unit heat input, HHV is fuel heat value (in B ThU) and a_1 is the erosion index of the erodents present. The erosion index is determined as follows:

$$a_1 (\% \text{erodents}) = a_1 (\% \text{quartz}) + a_2 (\% \text{SiO}_2) + a_3 (\% \text{Al}_2\text{O}_3) + a_4 (\% \text{Fe}_2\text{O}_3).$$

Interpretation of CEF value for tube bank velocities in the range of 16 to 21 m/s are as follows :

CEF Value	Predicted Erosion
0 - 0.5	No erosion problem
0.5 - 1.0	Mild to persistent erosion
1.0 - 1.5	Serious to very serious erosion
1.5-more	Severe erosion

Control of Hot Corrosion/Erosion Problems in Coal-Fired Boilers

The complete elimination of oxidation and hot corrosion/erosion problems encountered in coal-fired boilers is not possible considering the complexity of the environments and the mechanisms involved. However, with proper selection of construction materials and design of components, modification of operating conditions, use of good quality coals, and applications of various heat-resistant coatings, the problems can be effectively checked to a great extent.

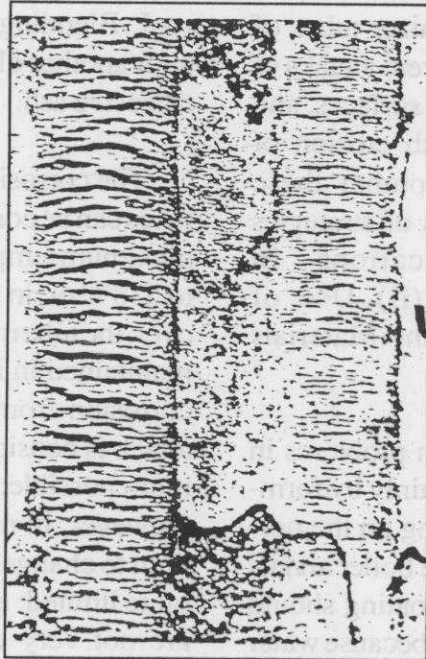


Fig. 3 : The thick, hard scale on waterwall tubes showing the cracks which resemble an alligator hide

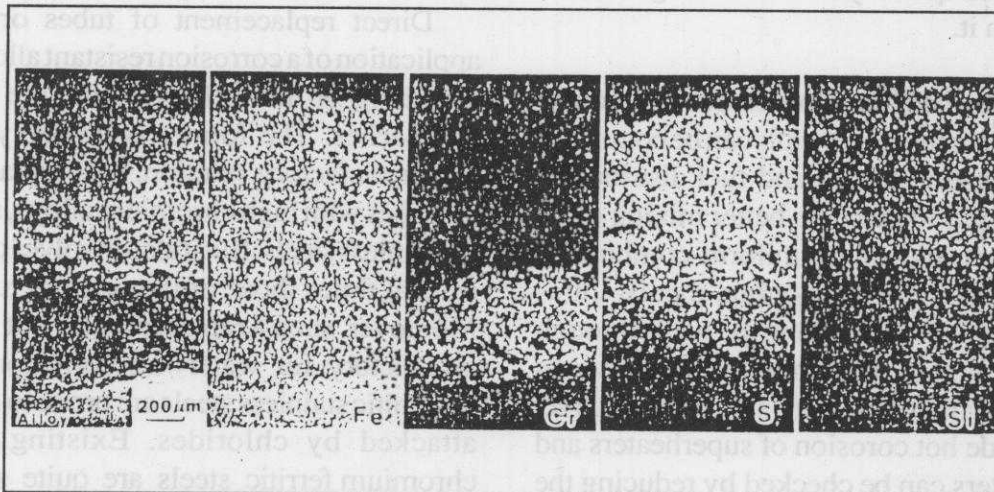


Fig. 4 : Cross-section of the corroded face of a waterwall tube subjected to a "reducing" atmosphere. X-ray maps show that the inner scale contain iron and chromium from the alloy, and sulphur.

From the discussion in preceding sections, it is clear that waterwalls, superheater/reheater and economizer tubes of the boiler suffer from the severe attacks of steam oxidation of the inner surfaces, and fireside hot corrosion/flyash erosion of the outer surfaces. To combat these problems mainly two types of strategies are adopted: (i) Modifications in Operation Parameters, (ii) Use of Corrosion/Erosion-Resistant Materials and/or Coatings.

The waterside corrosion problems in boilers can be controlled mainly by forming a good magnetite coating on the normally used steel walls of the boiler and its maintenance. The applied coating should be least permeable to water, because water is the species responsible for the continuous damage of the thin magnetite film formed on the steel during the operation. Purity of feed water is also an important factor from the corrosion point of view. Hence, the chemistry of feed water should be monitored and efforts be made to reduce the quantity of dissolved gases and salts in it.

Fireside Corrosion "Reducing" conditions near the water walls can be countered by adjusting the air and fuel distribution to burners to promote better mixing of air and fuel and more uniform combustion conditions. Air blanketing, that is, introducing flow of air along the walls through openings in the membrane between waterwall tubes, can also be effective. Fireside hot corrosion of superheaters and reheaters can be checked by reducing the levels of the chemical species in the coal. This is done by blending of coal types and coal washing which improve the stoichiometric balance of the coal and air flow to each burner. Standard coal washing

can remove approximately one-half the sulphur and alkali metal content of the coal. Blending a known corrosive coal with another also helps to produce a less corrosive ash.

The corrosion of superheater/reheater tubes can be controlled also by limiting the maximum temperature of steam generated to 538°C or, in some cases, 556°C. Moreover, the tube metal temperature should be maintained in a regime where the rate of corrosion from alkali-iron sulphate-type attack is considerably less than the maximum possible; this is illustrated in Fig. 9. However, in normal circumstances freedom to change the operating conditions is quite limited; and sometimes the changes are not very effective. Thus the above modifications in operational parameters do not provide a long-term solution to corrosion problems.

Use of More Corrosion Resistant Materials

Direct replacement of tubes or the application of a corrosion resistant alloy as a coating on the affected tube are two approaches. The former is probably the most satisfactory solution, e.g., replacing the tubes with high chromium alloys, such as stainless steels. But it also involves costs several times those of the original tubes. Moreover, such a replacement is not very satisfactory for waterwall corrosion, as austenitic stainless steels are prone to be attacked by chlorides. Existing low chromium ferritic steels are quite satisfactory. Thus a replacement which satisfies the waterwall corrosion and for which the existing chromium concentration is sufficient, an outer Cr-rich alloy is needed to combat fireside corrosion. The

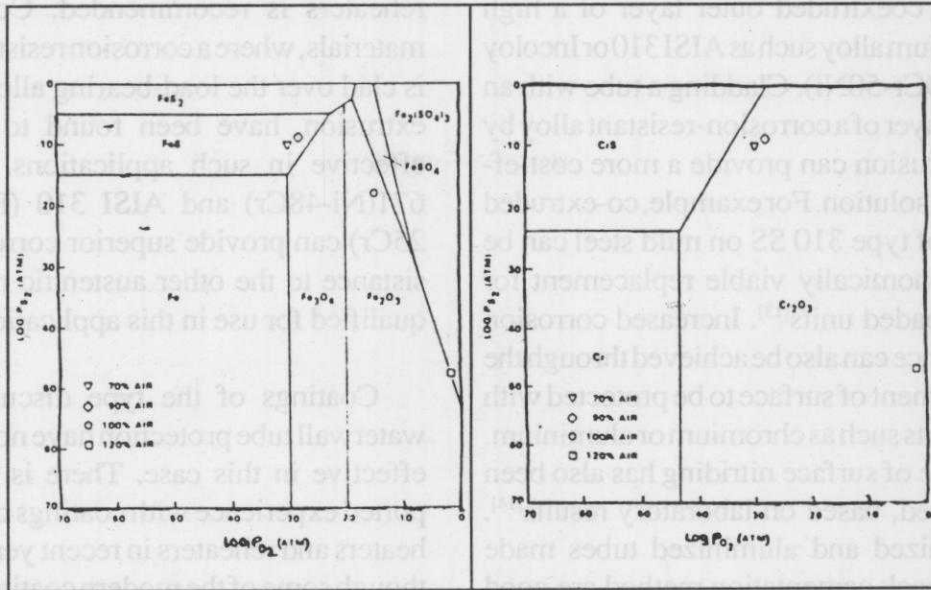


Fig. 5 : Phase stability diagrams at 482°C indicating the stable corrosion products as a function of percentage stoichiometric combustion air

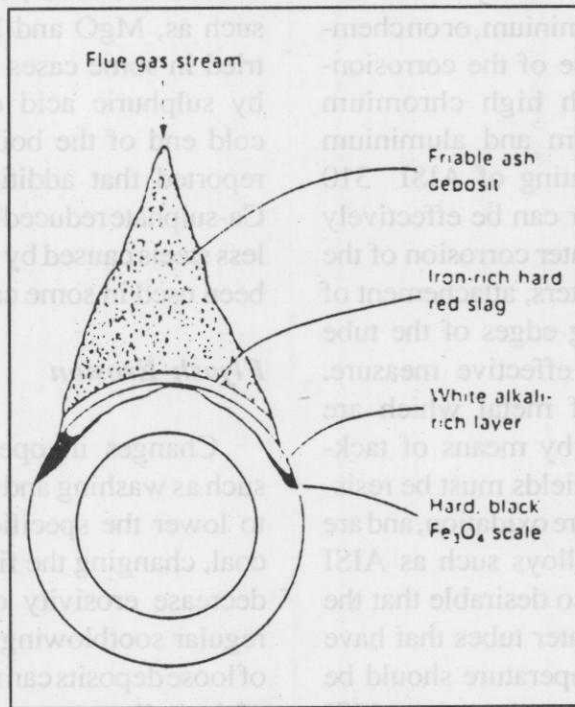


Fig. 6 : Typical cross-sectional appearance of a superheater tube which has fireside corrosion

materials choice is probably between thicker-walled carbon steel tubes and tubes with a coextruded outer layer of a high chromium alloy such as AISI 310 or Incoloy 671 (50Cr-50Ni). Cladding a tube with an outer layer of a corrosion-resistant alloy by co-extrusion can provide a more cost-effective solution. For example, co-extruded tubes of type 310 SS on mild steel can be an economically viable replacement for base-loaded units^[13]. Increased corrosion resistance can also be achieved through the enrichment of surface to be protected with elements such as chromium or aluminium. The use of surface nitriding has also been proposed, based on laboratory results^[14]. Chromized and aluminized tubes made using pack cementation method are good options for control of corrosion^[15].

Flame-or-plasma-spraying is also used to apply corrosion-resistant alloys into waterwall tubes. The alloys used are typically based on aluminium, or on chemistries similar to those of the corrosion-resistant alloys with high chromium contents or chromium and aluminium contents. Plasma coating of AISI 310 stainless steel powder can be effectively employed. To encounter corrosion of the superheaters or reheaters, attachment of shields to the leading edges of the tube affected, can be an effective measure. Shields are strips of metal which are attached to the tube by means of tack-welded straps. The shields must be resistant to high-temperature oxidation, and are usually made from alloys such as AISI 309 (25% Cr). It is also desirable that the superheater and reheater tubes that have the highest metal temperature should be fabricated of stainless steels such as AISI 304, 321, 347.

In boilers operating at 566°C steam,

use of corrosion-resistant alloys for some of the tube rows in the superheaters and reheaters is recommended. Composite materials, where a corrosion-resistant alloy is clad over the load-bearing alloy by co-extrusion, have been found to be cost effective in such applications. Inconel 671 (Ni-48Cr) and AISI 310 (Fe-20Ni-25Cr) can provide superior corrosion resistance to the other austenitic materials qualified for use in this applications^[16].

Coatings of the type discussed for waterwall tube protection have not proved effective in this case. There is little reported experience with coatings on superheaters and reheaters in recent years, even though some of the modern coatings (such as FeCrAlY-types) may be effective.

Very little is known regarding the use of additives to combat corrosion in coal-fired boilers. However, Mg-Based additives, such as, MgO and Mg(OH)₂ have been tried in some cases to prevent corrosion by sulphuric acid condensation in the cold end of the boiler. Also, Rahmel^[17] reported that addition of either Mg or Ca-sulphate reduced the corrosion of stainless steels caused by K₂SO₄. CaO has also been used in some cases.

Flyash Erosion

Changes in operational parameters, such as washing and blending of the coals to lower the specific ash content of the coal, changing the fineness of the coal to decrease erosivity of the coal, and the regular sootblowing to prevent plugging of loose deposits can reduce flyash erosion of the boiler components.

The typical coal fineness specification is 70 percent passing through 200 mesh.

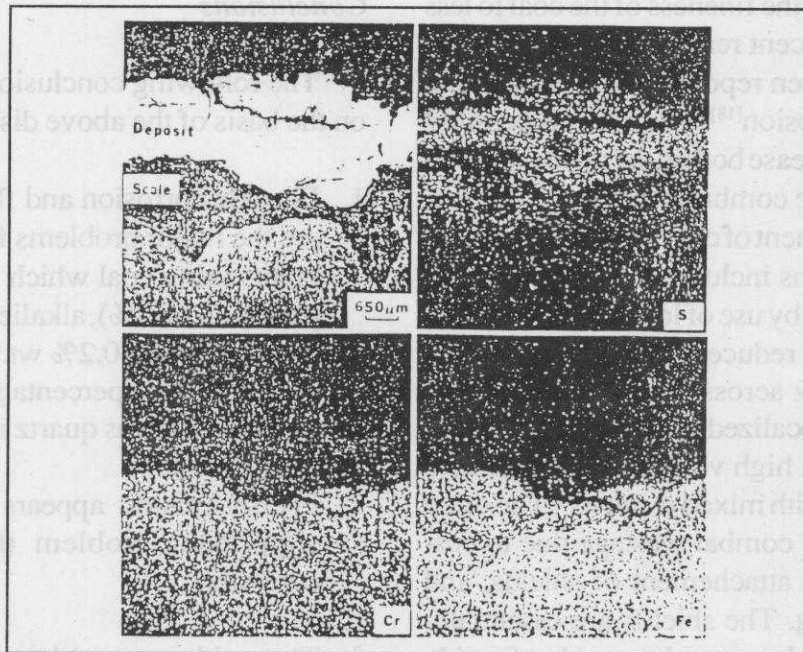


Fig. 7 : Details of the deposit and scale on a fireside corroded superheater tube

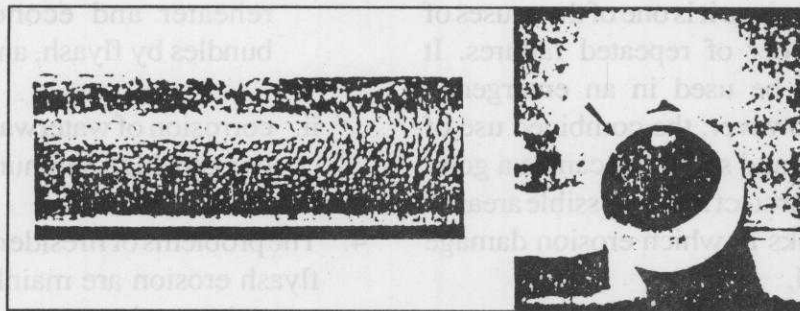


Fig. 8 : Typical appearance of flyash erosion damage on an economizer tube

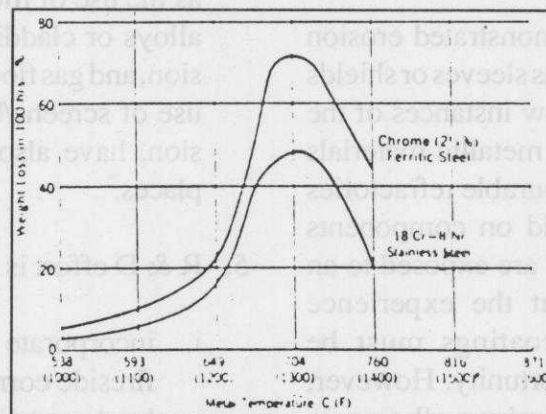


Fig. 9 : The bell-shaped curves showing the effect of metal temperature on corrosion rate

A change in the fineness of the coal to less than 0.5 percent remaining on a 50 mesh sieve has been reported to be effective in reducing erosion^[18]. The effect is possibly due to a decrease both in the residence time for complete combustion and the number of impingement of char on the walls. Other modifications include: reducing the bulk gas velocity by use of lower excess air and operating at reduced load, and control of the gas flow across the boiler section to eliminate localized turbulent region. To reduce local high velocities, baffles have been used with mixed results^[19]. The other measures to combat wastage due to erosion are the attachment of shields, and pad-welding. The shields are essentially the same as those used to combat fireside corrosion of the superheaters and reheaters.

In general, pad-welding should be discouraged, since it is one of the causes of a large number of repeated failures. It should only be used in an emergency situation. However, the combined use of pad-welding and shielding can be a good approach to protect less accessible areas of the tube banks in which erosion damage has occurred.

Use of Materials and Coatings

Materials with demonstrated erosion resistance can be used as sleeves or shields in critical areas, but few instances of the extensive use of such metallic materials have been reported. Pourable refractories are sometimes overlaid on components such as headers which are exposed to an erosive gas flow, but the experience suggests that such coatings must be renewed at every opportunity. However, embedding of economizer elbows in refractory cement has proved effective in some cases.

Conclusions

The following conclusions are drawn on the basis of the above discussion:

1. Fireside corrosion and flyash erosion are the major problems for the power plants using coal which has high sulphur (>2.5 wt.%), alkalies (>0.5 wt.%) and chlorine (>0.2% wt.%), or which contains high percentage of erosive minerals such as quartz in the ash.
2. Flyash erosion appears to be more significant problem than fireside corrosion.
3. The problems requiring most attention are:
 - i. erosion of back pass superheater/reheater and economizer tube bundles by flyash, and
 - ii. corrosion of waterwalls by the low oxygen, high sulphur conditions.
4. The problems of fireside corrosion and flyash erosion are mainly tackled by extensive maintenance; though permanent and long-term measures, such as the use of more corrosion resistant alloys or cladding for fireside corrosion, and gas flow modifications by the use of screens/baffles for flyash erosion, have also been taken at many places.
5. R & D effort is needed to:
 - i. incorporate permanent solution to fireside corrosion problems either by the application of proper coating of waterwall/superheater tubes by a high chromium alloy or by

using co-extruded tubes or tubes of better materials, and

- ii. establish correlation from actual failure analyses.

References

1. G.C. Thomus, W.H. Clyton and V. Llinares, Jr., "C.E Availability data Program", Proc. of the American Power Conference, 42, 86-94 (1980).
2. E. Raask. "Mineral Impurities in Coal Combustion", Hemisphere Publishing Corp., Washington, D.C., 342-343 (1985).
3. "The Control of High Temperature Fireside Corrosion", Second Edition, Central Electricity Generating Board, London (1977).
4. P. Mayer and A.V. Manolescu, "Influence of Hydrogen Chloride on Corrosion of Boiler Steels in Synthetic Flue Gas", Corrosion, 36, 369-373 (1980).
5. I.P. Ivanova and L.A. Svistunova, "Corrosion of 12Kh1MF Steel and Various Corrosion Resistant Coatings in a Medium of Flue Gases during combustion of Anthracite", Teploenergetika, 18, 60-63 (1971).
6. I.P. Ivanova, V.P. Kaminskii and A.G. Belyaeva, "High Temperature Corrosion of Waterwall Tubes in Supercritical Boilers Burning Anthracite Fines", Teploenergetika, 19, 16-18 (1972).
7. I.P. Ivanova and Yu. L. Marshak, "High-Temperature Corrosion of Screens During Combustion of Anthracite Clum", Teploenergetika, 22, 15-18 (1975).
8. R.C. Corey, H.A. Grabowski and B.J. Cross, "External Corrosion of Furnace Wall Tubes-III. Further Data on Sulphate Deposits and Significance of Iron Sulphide Deposits", Trans. ASME, 71, 951-963 (1949).
9. W.T. Reid, "External Corrosion and Deposits-Boilers and Gas Turbines", Elsevier, New York, (1971).
10. A.J. Blazewicz and M. Gold, "High-temperature Gas-Side Corrosion in Coal-Fired Boilers",
11. E. Raask. "Particle Impaction Erosion in Coal-Fired Boiler Plant", VGB Conf. on Flue Gas Corrosion and Deposits in Thermal Power Plants, Essen (1977).
12. P. Kratina and J. McMillan, "Flyash Erosion in Utility Boilers-Prediction and Protection", Presented at Canadian Electrical Association Conf., Regina, Sask, Oct. (1982).
13. T. Flatley, E.P. Latham and C.W. Morris, "Co-extruded Tubes Improve Resistance to Fuel Ash Corrosion in U.K. Utility Boilers", Materials Performance, 20, 12-17 (1981).
14. D.J. Lees, "Selection of Corrosion Resistant Coatings for Boiler Tube Applications", Surface Treatments for protection, 10, 174-182 (1978).
15. W.A. McGill and M.J. Weinaum, "Alonized Heat Exchanger Tubes

- Give Good High Temperature Service*", Materials Performance, 20, 16-207 (1978).
16. E.P. Latham, T. Flatley and C.W. Morris, "Comparative Performance of Superheated Steam Tube Materials in Pulverized Fuel-Fired Plant Environment, in Corrosion Resistant Materials for Coal Conversion Systems", (eds. D.B. Meadowcroft and M.I. Manning), Applied Science, pp.137-156, (1983).
17. A. Rahmel, "Influence of Calcium and Magnesium Sulphates on the High-Temperature Oxidation of Austenitic Chrome-Nickel Steels in the Presence of Alkali Sulphates and SO_3 ", in Mechanisms of Corrosion by Fuel Impurities, Butterworth, London 556-570, (1903).
18. "Personal Communication", W.P. Apblett, Jr., Foster Wheeler Development Corp., 1985.
19. G. Thimot, "Erosion & Abrasion in Coal-Fired Steam Generators and Auxiliaries", Presented at ASTM/ASME Forum on Practical Erosion Problems in Fluid System & Machinery, Niagra Falls, June (1979).