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Ash Deposit Physical and Chemical Analysis

Volume 1—Literature Review of Past Work on Ash Deposits and Deposit Removal

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Technical Update, December 2010

EPRI Project Manager

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PRODUCT DESCRIPTION

As part of the Electric Power Research Institute's (EPRI's) ongoing Boiler Tube Failure Reduction (BTFR) program, this report has been compiled to discuss chemical and mechanical mechanisms that lead to the formation of ash deposits. Ash deposits are a known cause of a number of boiler tube failure mechanisms, which can not only impact plant performance, but lead to millions of dollars in lost revenue due to forced outages.

Results and Findings

This report represents a compilation of the available information on the chemistry of ash deposits, their formation, and how boiler conditions can affect the creation of these deposits. Ash deposits are highly dependent on operating conditions, the fuel combusted, as well as the boiler configuration. In the radiant section of the boiler, deposits tend to be more homogenous as a result of boiler temperatures being above the melting point for the constituents of the ash. In the convective section of the boiler, the deposits tend to be more heterogeneous as a result of lower temperatures. Also covered in this report is a review of the various methods of ash deposit removal, such as soot blowers, air blowers, water cannons, sonic horns, and pulse detonation ash removal, as well as the advantages and disadvantages for each device.

Challenges and Objectives

In the past, research has been done on various aspects of ash deposit formation, chemical makeup, and removal. This report brings together information from all of those prior reports and would be an asset to anyone in the utility industry looking for more information on ash deposits.

Applications, Value, and Use

The information in this report will be added to EPRI's BTFR program books and will be used in continuing research on austenitic damage, as well as future nondestructive evaluation research.

EPRI Perspective

This report familiarizes boiler engineers, corporate material scientists, and plant operators with the ash deposits created by Powder River Basin (PRB) coals,. It will allow them to make an educated decision on the ease of removal with available ash deposit–removal devices.

Approach

This report combines and summarizes papers written over the past 35+ years about the chemistry and the formation of ash deposits. From this research, information is gathered that can be used by utilities around the world to improve plant availability.

Keywords

Ash deposit
Boiler tube failures
Deposit formation
Soot blowers

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CHAPTER 1

Executive Summary

Ash deposition (or "slagging" and "fouling") on heat-transfer surfaces in coal-fired power plants has significant impacts on power plant performance. The chemical and physical properties of the ash-forming components in coal vary widely, and contribute to a wide range of deposit types and regions of deposition in coal-fired boilers. The properties of the deposits are highly dependent on coal composition and boiler types. Physical characteristics of a deposit that might form in a coal-fired boiler include: molten and flowing; plastic; highly-fused, glassy solid; metallic; highly-fused vesicular; highly-fused, dense crystalline; bonded; and powdery deposits.

Typically, deposits found in the radiant section of a utility boiler are more homogeneous as a result of assimilation of particles into a liquid (molten) phase. Such deposits are primarily silicate-based, and the physical characteristics of the deposit are dictated by the physical and chemical properties of the silicate liquid phases. As regional temperatures decrease, the degree of assimilation or melting of the deposited material will decrease. In addition, the extent of silicate-phase participation in deposit bonding will decrease.

At lower regional temperatures, the sulfate-based bonding mechanism becomes a factor in deposit formation. Sulfate-based bonding is characteristic of convective-pass fouling problems when firing coals containing high levels of alkali and alkaline-earth elements. A sulfated matrix can be very strong, and difficult to remove using sootblowing techniques.

The formation of deposits that are strongly bonded to heat transfer surfaces depends upon the following: characteristics of the reacted layers on the steel surface (formation of the reactive layers depends on the type of steel and the ash characteristics); steel surface temperature; ash particle melting behavior; and the thermal and chemical compatibility of the deposit and steel surface (surface layers of steel/residual ash).

Deposit strength development is due to sintering processes that involve the flow of liquid phase materials and condensation and/or reaction of gas phase species with deposited particles. The sintering process involves one or more stages–the first stage is neck growth between particles, which occurs when a thin liquid layer is formed between the deposited hollow, vesicular, or solid particles, and the meniscus tends to pull the particles together. This results in the rearrangement of particles by sliding and the formation of closed pores and voids. The degree to which sintering occurs will depend upon the temperature of the system, the reactivity of the deposited ash particles, the size distribution of the ash particles, the potential for crystallization, and the gaseous environment in the vicinity of the deposit.

Deposit thermal properties, including thermal conductivity, emissivity, and porosity, change as the ash deposit grows and matures. A deposit-free tube surface has a high emissivity. As ash is deposited, the emissivity decreases, but increases again as the deposit surface transitions to a flowing slag.

Thermal conductivity is a strong function of deposit temperature and its physical structure (porosity), and a weak function of the deposit chemistry. Temperature history (temperature changes over time) is important in that sintering among deposited ash particles will irreversibly result in porosity and/or density changes. Thermal conductivity would generally be low for the initial (porous) deposit layer, increase gradually to a moderate value for the middle sintered layer, and eventually reach a maximum value corresponding to the final outer slagging layer.

The thermal and mechanical properties of slags have significant impacts on the ability to remove deposits with various cleaning devices such as sootblowers. Deposits (water walls and convective pass) consist of complex materials that contain pores, unreacted ash particles, amorphous glassy phases, and crystalline phases. The characteristics of the deposited materials will depend upon the fuel composition, plant operating conditions, and location within the boiler.

Soot blowing relies on using a combination of thermal and mechanical shock to fracture the deposit. Crack propagation in slag is dependent upon a rapid change in temperature. The slag composition, crystallinity, and porosity will affect the ability to thermally shock a deposit to the point of fracture.

Thermal conductivity decreases with an increase in porosity, and increases with increasing temperature. Crack propagation is considered to be easier in highly porous, glassy slag deposits. A lower-porosity and higher-crystalline-content slag deposit would be more resistant to fracture. Slag compressive strength is also related to porosity. The resistance to fracture was found to decrease significantly for slags having a porosity of less than 25%.

There exist several methods of on-line ash deposit removal. They include sootblowers, water cannons, sonic horns, and pulse detonation technologies.

Sootblowers are used to clean radiant water walls and convective pass tubes in utility boilers. They can be wall blowers, which have a retractable lance that extends into the radiant section, or long retractable blowers to clean tube banks in the convective pass. Working fluids in sootblowers can be steam, air, or water. Steam sootblowers are the most common; the steam pressure is generally around 200 to 250 psig. Air sootblowers are not common; air pressure is usually around 180 psig. Steam is considered to be superior to air due to its higher kinetic energy at the same pressure. Water is also not extensively used for wall blowers, and rarely for long, retractable blowers. Water has the potential to provide high-impact energy and efficient cleaning, but it also carries the risk of tube damage and thermal shock failure.

The ability of a sootblower to remove deposits is related to the force of the sootblowing medium on the deposit. The measure of sootblower effectiveness is the peak impact pressure (PIP). This is the stagnation pressure along the nozzle centerline at a given distance from the outlet of the sootblower nozzle. The PIP decreases with distance from the nozzle. The force required for deposit removal can be estimated from the sootblower PIP, distance from the nozzle, the typical effective cleaning radius, and deposit tensile strength. The minimum cleaning radius for long retractable sootblowers is four feet (about 120 cm). At that minimum cleaning radius, indicative of deposits most difficult to remove, typical PIP values would range from 10 to 22 psi.

Ash deposit removal by sootblowers is related to the PIP that is delivered to the deposit, the deposit tensile strength, and the angle of impaction of the jet. The deposit tensile strength has an influence on the distance, and therefore, pressure, from the jet required to fracture the deposit. As

tensile strength increases, the pressure required to fracture the deposit also increases as a function of that strength. At a normal impaction angle, the PIP would need to be more than two times that of the deposit tensile strength. At another angle, the PIP would depend on the deposit tensile strength and the angle.

A water cannon or water blower is similar to a water sootblower, but it directs the water jet across the furnace box, and in a rastering pattern. Water pressure is typically around 175 psig; cleaning is due to a combination of water impact force and thermal shock. Water cannons have many advantages, especially with respect to the ability to adjust the settings (frequency, dwell time in certain locations, etc.) but also carry the concern for thermal shock, and damage, to the waterwall tubes.

Sonic horns, or acoustic sootblowers, became more popular during the past fifteen years. They operate by using sound pressure at about 150 decibels to acoustically shock deposits from tube surfaces. They are most effective with very loosely-sintered, or powdery, ash, and are therefore mainly used in very low-temperature regions of a boiler (such as the electrostatic precipitator, the baghouse, or selective catalytic reduction reactors). They require frequent operation in order to be effective; infrequent use can allow ash time to sinter and develop strength. They have advantages with regard to areas reached: they are able to remove deposits from all surfaces, and with regard to operating cost. They are not able to remove deposits with any degree of strength, however, and there is potential for damage or other upset from resonant vibrations.

Pulse detonation is an emerging technology, in which a pressure wave is used to remove deposits from boiler surfaces. It is similar in operation to a sonic horn, but uses a much higher peak pressure. This higher pressure allows pulse detonation to remove bonded and adhered deposits. The detonation wave is produced through the ignition of a fuel-air mixture in an external chamber. Pulse detonation technology has been successfully tested in several industrial boiler applications in Russia, and in utility boilers in Bosnia, and in air pre-heater surfaces of full-scale utility boilers in China. The detonation pulse should be able to effectively clean tube back-sides as well as sides facing the pulse, based on computation fluid dynamics analysis. Because of this, pulse detonation cleaning should be a good technology for cleaning large areas, and areas inaccessible to conventional sootblowing devices. Like sonic horns, there is the potential for tube damage from the pressure wave. Pulse detonation technology has been patented by several groups, and is commercialized by Pratt & Whitney.

Introduction

Ash deposition (or “slagging” and “fouling”) on heat-transfer surfaces in coal fired power plants has significant impacts on power plant performance. A recent study estimated the economic impact of coal quality and ash deposition on electric power generating plants to be over 1.2 billion per year (Harding and O’Connor, 2007). Impurities in coal, along with power system design and operation conditions, contribute to the formation of the deposits. The chemical and physical properties of the ash-forming components in coal vary widely, and contribute to a wide range of deposit types and regions of deposition in coal-fired boilers. Physical characteristics of a deposit that might form in a coal-fired boiler include: molten and flowing; plastic; highly-fused, glassy solid; metallic; highly-fused vesicular; highly-fused, dense crystalline; bonded; and powdery deposits. The properties of the deposits are highly dependent on coal composition and

boiler types (Benson and others, 1993). Methods of removing deposits include: sootblowing using air, steam, or water; load shedding; horns (acoustic); and detonation cleaning (Huque and others, 1998; ShockSystems, 2008).

The extent of wall slagging and convective pass fouling depends upon the quantity and association of inorganic constituents in the coal, boiler design, and combustion conditions. Figure 1-1 illustrates the general characteristics of deposits formed in pulverized coal fired boilers (Bryers, 1996). The inorganic constituents are distributed within the coal matrix in several forms, including: organically-associated inorganic elements; coal-bound, included minerals; and coal-free, excluded minerals (Benson and others, 1993). The forms of ash-forming components are coal-rank dependent. Low-rank subbituminous and lignitic coals contain mineral grains and organically-associated cations such as sodium, calcium, and magnesium. Higher-ranked bituminous and anthracites contain mainly mineral grains, and essentially no organically-associated cations.

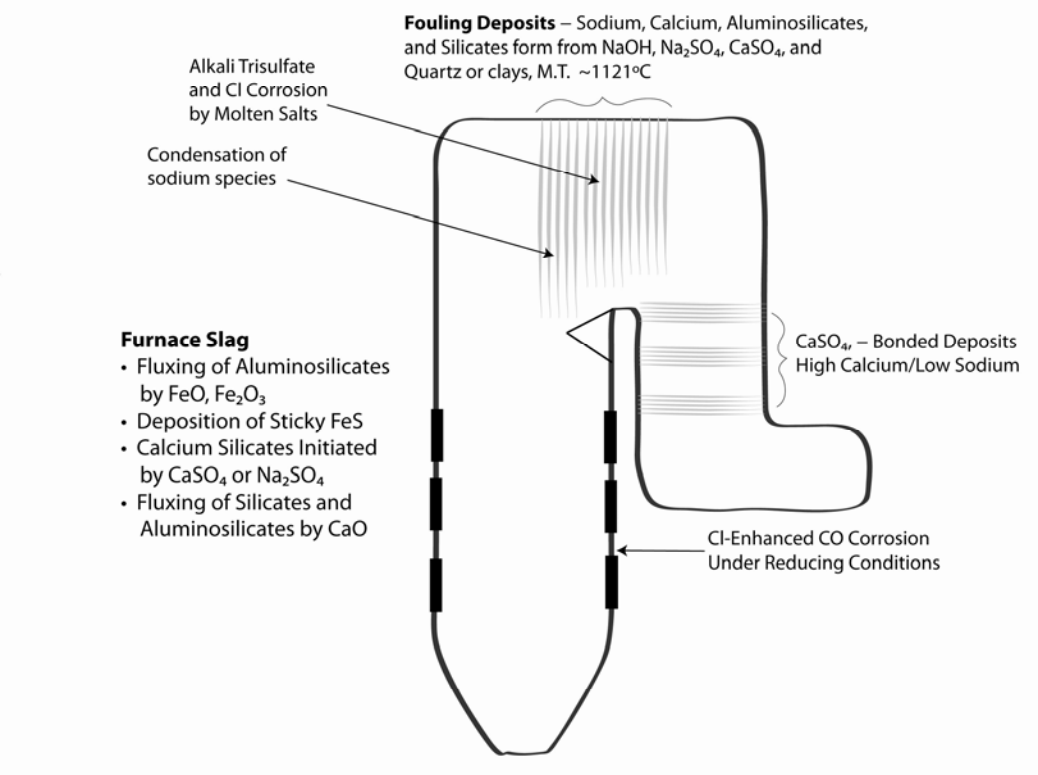


Figure 1-1
Generalization of boiler slagging and fouling (modified after Bryers, 1996).

During combustion, the inorganic materials are transformed into inorganic gases, liquids, and solids. Most of the minerals and other inorganic components are transformed into liquid or gas species in the flame and are transported with the bulk gas flow through the combustion system. As the heat is extracted, the particles solidify and the gas-phase species condense to form liquid or solid particles. The fly ash typically has a multimodal size distribution (Benson and Laumb, 2007). The submicron mode results from the condensation of gas phase species. The intermediate size fraction is due to organically-associated cations condensing or accumulating on

receding char surfaces as the carbon burns out. The larger size fraction consists of molten and solidified hollow, vesicular, and solid particles (Benson and Laumb, 2007).

The inorganic gases, liquids, and solids are transported to the heat-transfer surfaces by several mechanisms based on the state of the inorganic species (Raask, 1985). Submicron particles are transported to the surfaces by diffusion, thermophoresis, and electrophoresis. Larger particles are transported to the surface by inertial impaction.

The formation of deposits that are strongly bonded to heat transfer surfaces depends upon the following: characteristics of the reacted layers on the steel surface (formation of the reactive layers depends on the type of steel and the ash characteristics); steel surface temperature; ash particle melting behavior; and the thermal and chemical compatibility of the deposit and steel surface (surface layers of steel/residual ash) (Abbott and Austin, 1986; and Benson and Austin, 1990). Once a strongly bonded layer of ash particles forms on a surface, more ash particles, along with condensed and reacted vapor-phase components, will accumulate and particle-to-particle bonding will occur. In high-temperature regions of the boiler (such as the radiant section and furnace exit), the temperature of the surface of the ash layer will increase, producing a liquid-phase material that will effectively capture ash particles, leading to rapidly accelerated deposit growth.

The development of strength in deposits is due to sintering processes that involve the flow of liquid phase materials and condensation and/or reaction of gas phase species with deposited particles. The sintering process involves one or more stages–the first stage is neck growth between particles. Neck growth occurs when a thin liquid layer is formed between the deposited hollow, vesicular, or solid particles, and the meniscus tends to pull the particles together (Burke and Roslowski, 1976). This results in the rearrangement of particles by sliding and the formation of closed pores and voids. The early stages of sintering, neck growth between particles, have been effectively described by the early work of Frenkel (1945). Subsequent stages of sintering are described by two other models in the works of Mackenzie and Shuttleworth (1949) and Scherer (1977). The Mackenzie and Shuttleworth model is concerned with the shrinkage of isolated closed pores, and is able to predict densification kinetics in the later stages of sintering. The Scherer sintering model can be applied to all stages that occur in a sintering body. The degree to which sintering can occur will depend upon the temperature of the system, the reactivity of the deposited ash particles, the size distribution of the ash particles, the potential for crystallization, and the gaseous environment in the vicinity of the deposit.

Chemical and physical characteristics of deposits found in utility boilers vary widely from being homogenous, amorphous slag to highly heterogeneous, bonded deposits. Under a microscope, true amorphous slag is a homogeneous melt phase in which complete assimilation and melting of ash constituents has occurred, without crystallization. Heterogeneous, bonded deposits consist of pores, unreacted ash particles, a liquid-phase matrix bonding material, and crystalline material. The types of liquid-phase bonding materials that will form depend upon temperature, due to the stability of the chemical species comprising the phase. The degree of deposit heterogeneity changes with temperature, and therefore, location in the boiler. High-temperature deposits usually contain more liquid-phase silicate-based matrix material, depending upon the composition of the ash particles, and lower-temperature deposits contain more sulfate-based bonding material.

Typically, deposits found in the radiant section of a utility boiler are more homogeneous, as a result of assimilation of particles into a liquid (molten) phase. Such deposits are primarily silicate-based, and the physical characteristics of the deposit are dictated by the physical and chemical properties of the silicate liquid phases. Iron-rich phases that include silicates, sulfides, oxides, and metallic iron also contribute to the formation of slag deposits. As regional temperatures decrease, the degree of assimilation or melting of the deposited material will decrease. In addition, the extent of silicate-phase participation in deposit bonding will decrease. Some participation of sulfate bonding may occur at the deposit-tube interface, even when silicate-based bonding mechanisms are dominant.

At lower regional temperatures, the sulfate-based bonding mechanism becomes a factor in deposit formation. This sulfate-based bonding is characteristic of convective-pass fouling problems when firing coals containing high levels of alkali and alkaline-earth elements. Sulfate-bonded deposits can also contain silicate-rich fly ash particles.

Ash Forming Components in Coal

Inorganic elements in coal occur as discrete minerals, organically-associated cations, and cations dissolved in pore water. Lower-ranked subbituminous and lignitic coals have bonding sites for cations (such as sodium, magnesium, calcium, potassium, strontium, and barium–other minor and trace elements may also be associated in the coal in this form). In higher-ranked coals, bituminous and anthracite, the inorganic components consist mainly of minerals.

Mineral grains are usually the most abundant inorganic component in coals. Major mineral groups found in coals include silicates, oxides, carbonates, sulfides, sulfates, and phosphates. In order to understand and predict the behavior of the inorganic constituents during combustion, detailed information must be obtained on the abundance, size, and association of mineral grains in the coal. Table 1 lists the major minerals and organically associated elements found in coals.

Table 1-1
Major mineral types and organically-associated inorganic elements found in coal.

Mineral Name	Formula
Quartz	SiO_2
Kaolinite	$Al_2Si_2O_5(OH)_4$
Illite	$K(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,H_2O]$
Montmorillonite	$(Al,Mg)_8(Si_4O_{10})_5(OH)_{10}\cdot 12H_2O$
Pyrite	FeS_2
Calcite	$CaCO_3$
Dolomite	$CaMg(CO_3)_2$
Gypsum	$CaSO_4\cdot 2H_2O$
Barite	$BaSO_4$
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$
Hematite	Fe_2O_3
Rutile	TiO_2

Organically associated inorganic elements: Na^+, K^+, Ca^{2+}, Mg^{2+}, Ba^{2+}, Sr^{2+}

Physical and Chemical Transformations of Inorganic Constituents

The physical and chemical transformations of inorganic constituents in coal will depend on the inorganic composition of the coal and combustion conditions. Inorganic components illustrated in Figure 1-2 can consist of organically-associated cations, mineral grains that are included in coal particles, and excluded mineral grains. There are many possible combinations of mineral–mineral, mineral–coal, mineral–cation–coal, and mineral–mineral–cation–coal associations in coal. These associations are unique to each coal sample. Figure 1-2 illustrates the types of transformations that are likely to occur during the coal combustion process.

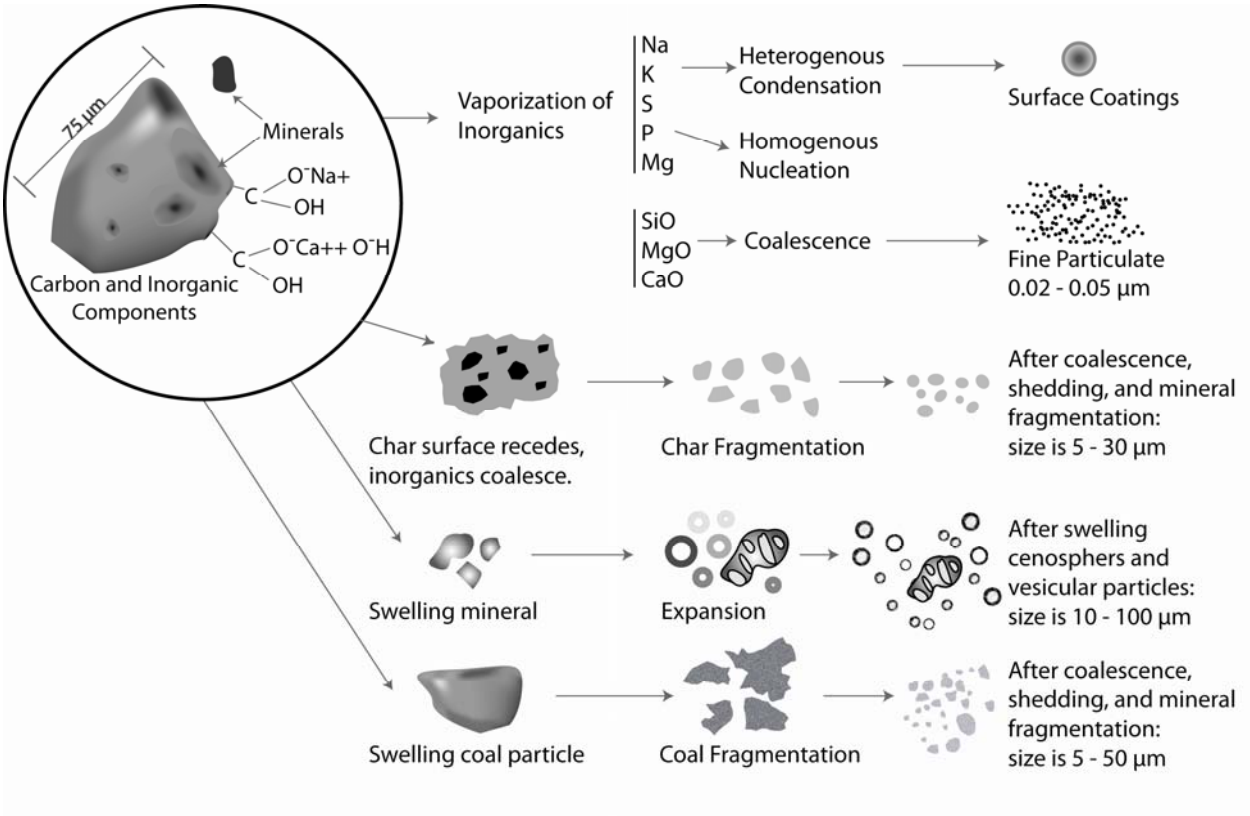


Figure 1-2
Transformation of inorganic components present in coal during combustion.

The physical transformations involved in fly ash formation illustrated in Figure 1-2 include: 1) coalescence of individual mineral grains within a char particle; 2) shedding of the ash particles from the surface of the chars; 3) incomplete coalescence due to disintegration of the char; 4) convective transport of ash from the char surface during devolatilization; 5) fragmentation of the inorganic mineral particles; 6) formation of cenospheres and vesicular particles; and 7) vaporization and subsequent condensation of the inorganic components upon gas cooling.

As a result of these interactions, the ash mass distribution (as a function of size) that is typical of lignite and subbituminous coals is shown in Figure 1-3. The particle size distribution is

multimodal, with a submicron fraction originating from condensed vapor phase species, a two-micrometer mode derived from more refractory, organically-associated cations, and a larger size (10 to 15 microns) mode for ash materials derived from the major mineral components.

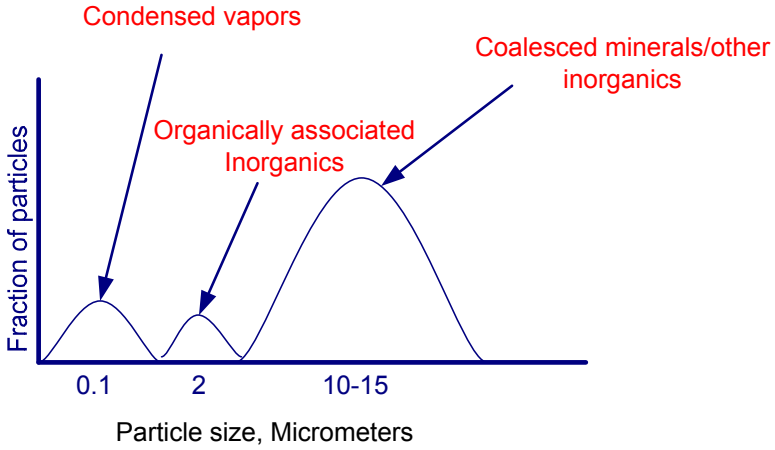


Figure 1-3
Particle size distribution of entrained ash particles (Benson and Laumb, 2007).

Figure 1-3 shows the chemical composition of ash size fractions from a subbituminous coal, illustrating that smaller size fractions are rich in alkali and alkaline earth sulfate materials, and larger size fractions contain more aluminosilicate materials.

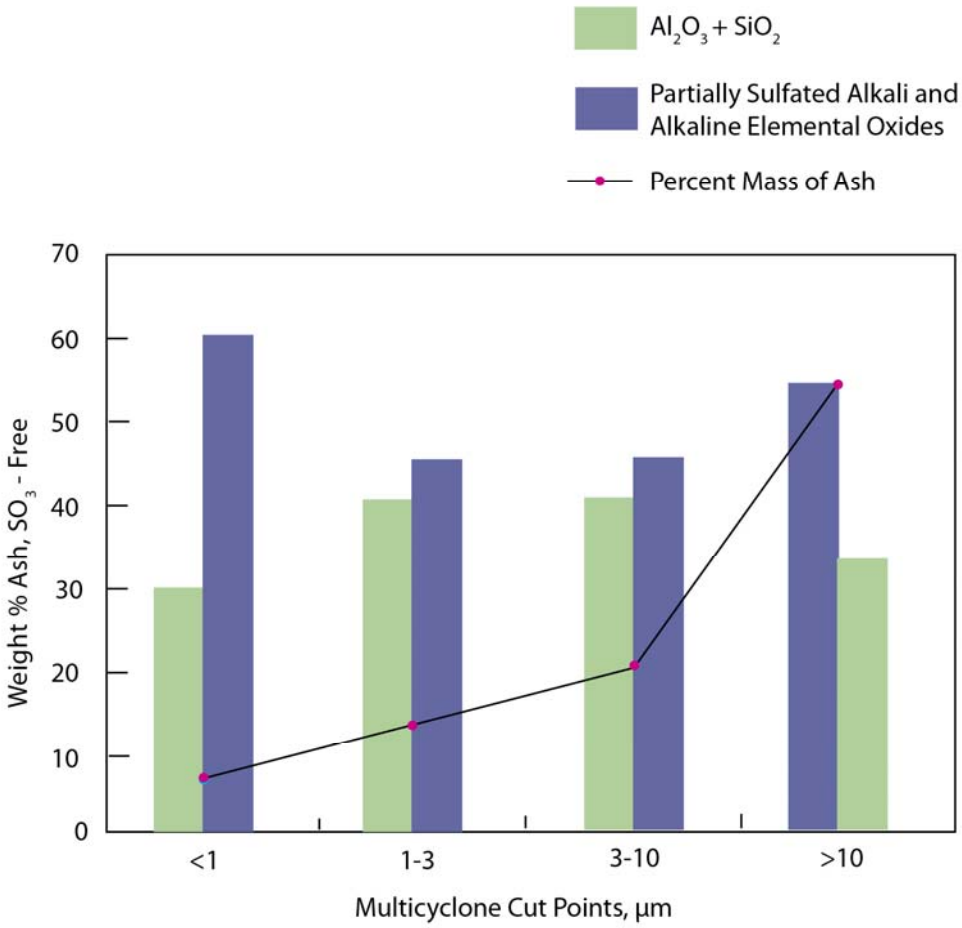


Figure 1-4
Ash particle size composition distribution produced during combustion (Benson and other, 2004).

Several chemical systems are important relative to the characteristics of fly ash materials and their ability to produce deposits in combustion systems. These include the aluminosilicates, silicates, metal oxides, metals, sulfates, phosphates, chlorides, and sulfides systems.

The silicate and aluminosilicate fraction of the fly ash consists mainly of glass (a non-crystalline, amorphous material) that ranges from hollow (cenosphere) to solid particles. The silicate and aluminosilicate fraction is produced from clay minerals and quartz. The characteristics of the glass (liquid) material are important because they have the most significant impact on high-temperature slag and convective pass deposits that form at temperatures above about 2000°F. The chemical and physical properties of the silicate- and aluminosilicate-derived ash particles impact the liquid phase formation, sintering, and crystallization behavior that ultimately impact the overall porosity and strength of high temperature deposits.

The characteristics of glass-forming systems relative to high-temperature silicates have been defined by Kingery and others (1976). Glass-forming oxides, also referred to as network formers, have the ability to build and form three-dimensional, random networks. Good network formers include of SiO_2, B_2O_3, GeO_2, P_2O_5, and AsO_4. These network formers form highly covalent

bonds with the oxygen atoms. For the silicate system in slagging and fouling deposits, pure forms of silicate and aluminosilicate have high melting points and high viscosities.

The addition of modifying oxides such as sodium, magnesium, calcium, potassium, and sometimes iron, can weaken the network through the addition of oxygen to produce non-bridging oxygens. For example, the addition of Na_2O to a silicate glass causes the formation of two non-bridging oxygen atoms, one contributed by Na_2O; the sodium ion balances the charge. The addition of a network modifier to a silicate glass reduces its viscosity and increases its thermal expansion coefficient.

Some intermediate oxides are not capable of forming a glass, but can take part in the glass network by substituting for silica. A good example of an intermediate oxide is alumina. Iron can act as a network modifier or an intermediate substance. In coal ash systems, the effect of iron on the silicate glasses is extremely important. The oxidation state of the iron will dictate whether iron will exist as a network modifier or an intermediate. Iron present as FeO (Fe^{2+}) will act as a network modifier, resulting in the formation of nonbridging oxygens and weakening the network. Iron present as Fe_2O_3 (Fe^{3+}) will act as an intermediate.

Pyrite (iron sulfide) in combustion systems can produce a range of species that include: reduced iron, iron oxides, and iron sulfides. Iron sulfides will contribute to the production of wall slag deposits under conditions that limit the oxidation of the FeS_2 to FeO to Fe_2O_3 or Fe_3O_4. If low melting point intermediate phases such as FeS and FeO form, particles rich in FeO and FeS can stick to the heat-transfer surfaces.

Deposit Growth

Deposit formation consists of two distinct phenomena. The first is the transport of ash species to the heat-transfer surface. The second is the process of adhesion that causes the particles to remain on the heat-transfer surface. These two processes are dependent upon the chemical and physical properties of the surface and the precursor forms of the depositing species.

Transport mechanisms

Transport of ash particles to heat transfer surfaces involves several processes that are related to the physical state and size of the ash forming components in the flue gas, gas velocity, and system geometry. The primary processes are summarized below and are illustrated in Figure 1-5.

1. Vapor phase and small particle diffusion
   a. Less than 1 um–characteristically rich in elements that have been flame volatilized and condensed–Na_2SO_4/ K_2SO_4

   b. Condensation takes place in the stagnant gas boundary layer next to the heat transfer surface and involves nucleation and growth of submicron particles. The diffusion mechanisms include:

      - molecular level–Fick diffusion
      - particles suspended in a host liquid–Brownian diffusion
      - turbulent systems–Eddy diffusion
2. Thermophoresis–heavy molecules and particles less than 10 micrometers in diameter experience a force in a temperature gradient in the direction from hot to cold, producing a movement of the particle to a relatively cold surface. This mechanism is important for particles that are less than 10 micrometers in diameter.
3. Electrophoresis–particles can acquire electrostatic charge as a result of flame ionization. Charged particles can be deposited due to an electrostatic field.
4. Inertial Impaction–particles greater than 5-10 micrometers are inertially impacted on surfaces. This process accounts for most of the mass of the deposit, and is the dominant transport mode of particles to heat transfer surfaces in utility boilers.

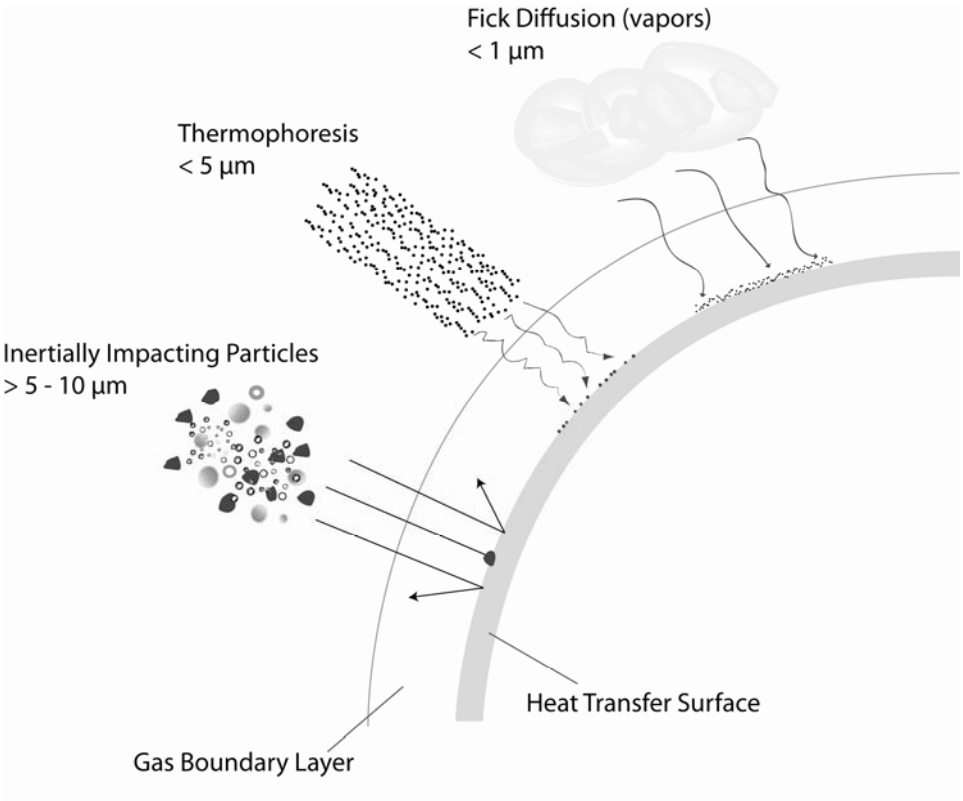
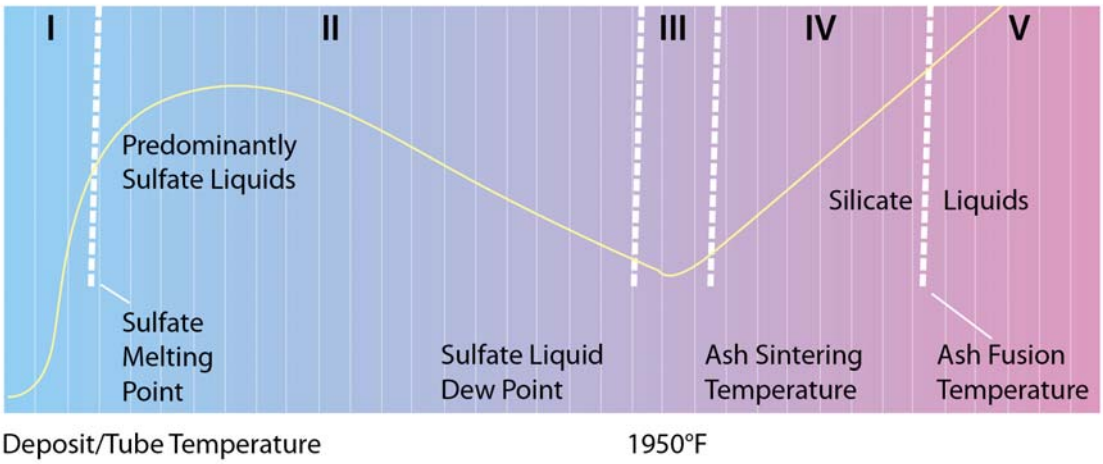


Figure 1-5
Vapor phase and particle transport mechanisms in utility boilers.

Ash deposits in utility boilers sometimes have layered structures. Initial layers are typically rich in small particles that contain high levels of flame-volatilized species such as sodium and sulfur. The transport mechanisms for these initial layers are due primarily to small particle and vapor-phase diffusion and thermophoresis. While small particles are being transported to the surface, larger particles are impacting the surface to form intermediate and outer layers. The condensed flame-volatilized species on the surface may provide a sticky (near- or fully-molten) surface for trapping the inertially-impacting, larger, non-sticky particles. The initial layers can provide fluxing materials that will cause larger particles in the intermediate and outer layers to melt.

Through this process, these initiating deposit layers begin as individual particles, impacting, sticking, and providing sites for the formation of "islands" of particles. The initial islands of particles are the precursors to the more massive, upstream deposits that form in the secondary superheater and reheater sections of a utility boiler. Coatings of condensed and reacted flame-volatilized species form on the surfaces of entrained-ash particles. The condensates react with the surface of the particles to form a molten or plastic surface. Condensation can also occur on the surfaces of deposited ash particles. These "puddles" of liquid-phase material contribute to the thickening bonds between particles. The dominant phases (as a function of increasing temperature) that are critical to deposit formation in coal-fired boilers are illustrated in Figure 1-6.



Deposition Regimes:

1. Dry-sticking regime: no glue
2. Vapor orthermophertically deposited liquid glue
3. Glue produced by heterogenous chemical reactions at vapor-ash interface
4. Ash particle softening on impact
5. Wet limit (sticking coefficient nearly unity)

Figure 1-6
Relationship between chemical phases, bonding, and temperature for liquids that contribute to deposit formation in utility boilers firing coal.

Figure 1-7 illustrates the differences in the sintering of a fouling and non-fouling coal fly ash as a function of temperature. The fouling coal fly ash develops strength at a much lower temperature than a non-fouling coal fly ash. Ash fusion measurements for the fouling and non-fouling coal fly ash show similar fusion temperatures, but do not compare well with the actual observed sintering behavior of the fly ash.

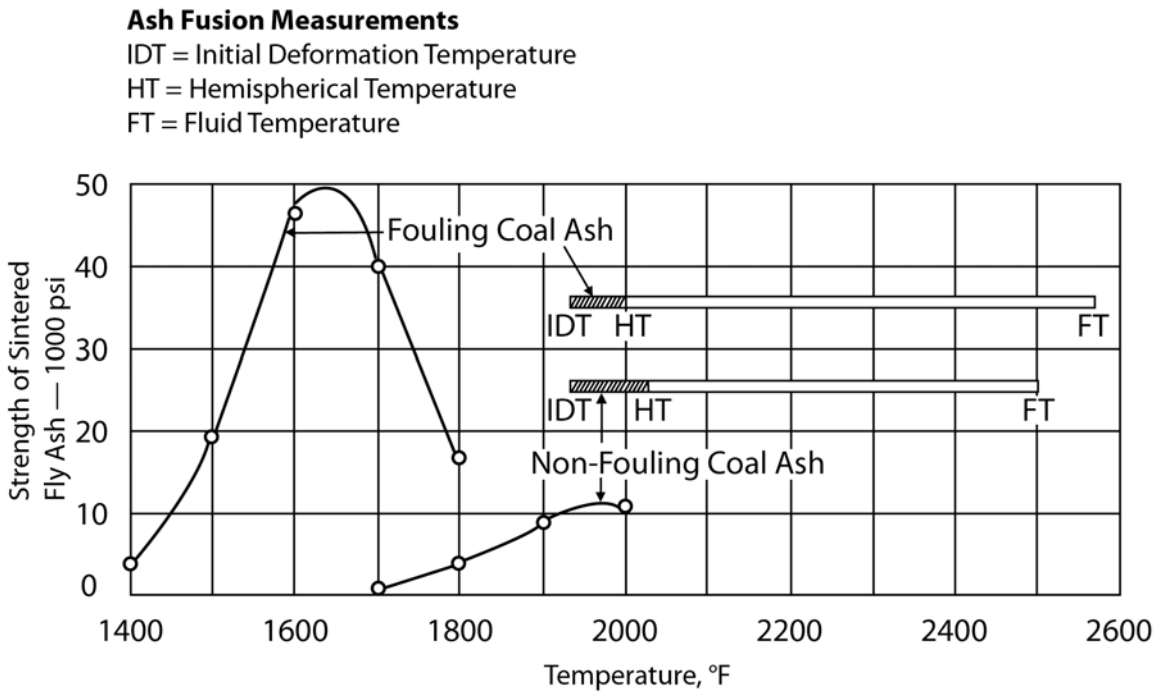


Figure 1-7
Relationship between the strength of sintered fly ash and ash fusion temperatures for a fouling and non-fouling coal as a function of temperature.

Formation of the outer layers of ash deposits result from larger ash particles impacting and sticking to the surface. As the outer surfaces become more insulated from the steel, the temperature of the deposit increases. This increase in deposit temperature will increase the quantity of liquid-phase components by melting the ash deposit materials. These liquid-phase components act as a efficient collectors of impacting fly ash particles. This process is especially important where silicate-bonded phases are being accumulated on water walls and high-temperature convective pass heat transfer surfaces (typically at temperatures above 2000°F).

Low-temperature fouling deposits are produced from lignite and subbituminous coals that contain high levels of calcium and sometimes sodium. Formation of these deposits is dependent upon the availability of small calcium oxide particles and the sulfation process. Based on detailed field testing to determine the mechanism by which low-temperature deposits form, Hurley and others (1991) identified that deposit characteristics are related to the size and composition of the entrained ash. Samples representing both upstream (windward side of tube) and downstream (back side of tube) deposits were collected. In all cases, the sulfation process occurred after the particles were deposited; very little sulfation took place while the particles were entrained in the gas stream.

Ash Adhesion

The forces responsible for initially holding ash particles to heat-transfer surfaces include Van der Waals, electrostatic, and surface tension (Raask, 1985). Very small particles are held in place by Van der Waals and electrostatic forces. Small particles transported by diffusion and

thermophoretic mechanisms are rich in flame-volatilized species and are usually concentrated in the initial layers of ash deposits. These initial layers likely contribute to the formation of strong bonds between the steel and the deposit.

Factors that influence the adhesion of an ash deposit to a heat-transfer surface include:

1. Temperature of the steel surface.
2. Thermal compatibility between the deposited material and the heat-transfer surface.
3. Chemical compatibility between the initiating particles and the heat-transfer surface.
4. Surface tension of the ash droplet.

Both the temperature of the steel and the gaseous environment, in terms of gas temperature and composition, can influence the adhesion of an ash deposit to a heat-transfer surface. Presence of a liquid phase significantly increases the ability of an ash deposit to adhere. Particles that impact and spread over the deposit surface provide initial contact and adhesion. The spreading effect is a function of the particles surface tension. The initial spreading of the particle provides the contact between the deposit and steel for chemical and mechanical bonding. High temperatures, localized reducing zones, and chemical composition of the deposited material are all factors that affect liquid-phase formation and deposit adhesion.

In the high-temperature radiant section of the utility boiler, molten ash particles may impact on the waterwalls, resulting in the formation of a deposit. The initiating layers next to the heat-transfer surfaces may contain condensed, flame-volatilized species that are rich in alkali and alkaline-earth sulfates. Particles impacting this layer may incorporate some alkali and alkaline-earth elements. The alkali and alkaline-earth elements will cause the formation of lower melting point phases that can contribute to increased bonding with the heat transfer surface.

Thermal and chemical compatibility between the steel surface and the deposit influences the ability of the deposit to stick and remain adhered during normal cycling of the utility boiler. If the thermal characteristics (i.e., thermal expansion coefficients) of the heat-transfer surface and the depositing material are similar, the deposit will not shed easily when the unit is cycled. On the other hand, if the thermal expansion coefficients of the ash and the surface are different, the deposits will shed much more easily during cycling. The chemical composition and thermal characteristics of the ash layer on the heat-transfer surface markedly affect the strength of the adhesion bond between the oxide and ash layer. Materials that have similar thermal expansion coefficients will likely form strong bonds that will not break during cycling of the unit.

Chemical bonding between the ash deposit and the steel surface provides for the formation of the strongest bonds. Good adherence is related to the level of metal oxide in the glass. For example, the level of iron in the glass is a good indication of the deposit to form a strong bond with a heat-transfer surface.

Detailed fundamental studies of factors that influence the sticking of coal ash slags to heat-transfer surfaces were conducted by Austin and others (Moza and Austin, 1982; Moza and others, 1980; Abbott and others, 1985; Moza and Austin, 1981; Abbott and Austin, 1982;Abbott and others, 1981; Tangsathitkulchai and Austin, 1985), who developed a simplified apparatus to produce molten droplets of slag that would fall on, and stick to a boiler steel coupon that was held at a controlled temperature. The information generated with this apparatus led to an

understanding of the factors that influence the sticking behavior of slag droplets on boiler steel surfaces. The factors influencing sticking behavior included: slag droplet composition; droplet temperature; nature of the steel surface; and steel temperature. With increasing steel substrate (or "coupon") temperature, the contact angle of the droplet decreased, causing increased wetting of the surface and increased adhesion strength. The strength of adhesion was increased exponentially with increasing substrate temperature; mild steels exhibited an interaction of the glass or slag droplet with oxide layer on the steel, resulting in a strong bond. Ash droplet interaction with stainless steels exhibited poor wetting and low adhesion strengths up to 863 K (1094°F). Limited chemical reaction occurred, and initial layers that had high levels of Na_2SO_4 or NaCl decreased the sticking temperature. The adhesion force decreased as a result of decreasing substrate temperature and thermal cycling of the substrate temperature.

In further studies on the adhesion of ash particles to boiler steel substrates, a laminar flow furnace or drop-tube furnace system was constructed in order to simulate the ash-forming properties and residence times of full-scale combustors (Abbott and Austin, 1986). In this laboratory apparatus, a thin ray of coal was combusted in a tube heated to simulate the temperature history of a utility boiler. The resultant ash was accelerated and impacted in a cooled boiler steel substrate. This system has been used to study deposit initiation (Benson and Austin, 1990) and to examine deposit growth and strength development (Tangsathitkulchai and Austin, 1985; Conn and others, 1987).

The particles that formed strong bonds with boiler surfaces were studied using a laminar-flow, drop-tube furnace system that was equipped with a deposition probe to simulate the temperatures of steels in utility boilers (Benson and Austin, 1990). The strongly bonded particles were sheared from the substrate, and the adhesive strengths were measured. In addition, the particles were examined with a scanning electron microscope/microprobe to image and determine the chemical composition of the droplet. The particles that formed strong bonds included those that were rich in the following: iron and silicon; iron and sulfur; iron, calcium, and sulfur; barium and sulfur; barium, strontium, and sulfur; and calcium and phosphorus.

Deposit Thermal Properties

The absorption of heat in a utility boiler that has deposits on the surfaces involves several processes. The heat-transfer process involves radiative, convective, and conductive heat transfer. The first process to be considered is the radiative heat transfer to the surface of the deposit, and the second is the conductive heat transfer through the deposit. Finally, convective heat transfer to the cooling fluid within the tube will also be considered.

Deposit thermal properties, including thermal conductivity, emissivity, and porosity, change as the ash deposit grows and matures. The expected property changes in thermal conductivity and emissivity (or absorptivity) are described by Figure 1-8, as reported by Wall and others, 1979. This generalized model of ash deposit growth represents the growth and maturation processes for a silicate-based bonding mechanism. Bonding of very small particles with sulfate-based phases forms an extremely dense enamel-like material on the heat transfer tube surface that is very difficult to remove.

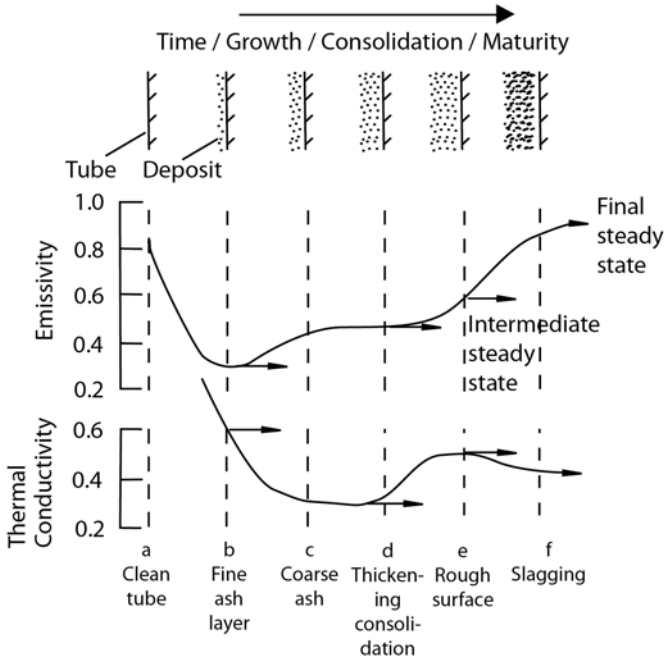


Figure 1-8
Expected trends in deposit thermal properties during deposit growth, reported by Wall and others (1979).

In general, a deposit-free tube surface has a high absorptivity of around 0.8. The initial layer of deposit is expected to be fine, condensable ash. For a layer of 2-μm particles, the absorptivity may be as low as 0.3. As the initial layer thickens, deposit surfaces become stickier and larger, less-sticky ash particles can be captured (these less-sticky ash particles would normally tend to rebound upon impaction on less-sticky deposit surfaces). The layer of less-sticky, particulate coarse ash particles would develop, and would have an absorptivity of about 0.4–0.5. As this particulate layer grows in thickness, the deposit surface absorptivity will gradually increase until a flowing slag layer is produced.

Thermal conductivity is a strong function of deposit temperature and porosity, and a weak function of the deposit chemistry; that is, the higher the temperature and the lower the porosity, the higher the thermal conductivity is. Also, the temperature history (temperature increases or decreases with time) is important in that sintering among deposited ash particles will irreversibly result in porosity and/or density changes. The expected thermal conductivity would be low for the initial layer, increase gradually to a moderate value for the middle sintered layer, and eventually reach a maximum value corresponding to the final outer slagging layer.

The ash chemical and physical characteristics influence radiative and conductive processes. The ability of the deposit to reflect or re-radiate the radiant energy from the flame is primarily due to its physical characteristics. If the deposit is not molten, it will have a rough surface that will scatter the radiant energy, causing a high deposit emission. If the deposit is molten, the chemical composition of the deposit will influence its color and, therefore, the ability of the deposit to absorb or reflect heat.

The thermal conductivity of a deposit is related to the physical structure and chemistry of the deposit. A deposit that is highly porous and composed of insulating materials will have a low thermal conductivity, while low-porosity materials that containing iron will have higher thermal conductivity. Thermal conductivity levels for deposits have been measured by Wall and others (1979) and Benson and others (1990). Deposit properties that influence heat transfer are emissivity and thermal conductivity, which vary with temperature, particle size, chemical composition, and density/porosity of the deposit.

Deposit Strength Development

The development of strength in deposits can be explained through sintering theory. A good description of sintering theory can be found in Kingery and others (1976). Sintering of a material is defined as a densification process that results from heat treatment. Strength development in ash deposits is a dynamic and complex process. In most cases, strength development involves the formation of a liquid phase. Much of the discussion on strength development will focus on liquid-phase sintering or viscous-flow sintering. Other sintering mechanisms such as solid-state sintering may be involved, but may not be dominant.

Sintering in ash deposits involves complex physical and chemical transformations. An understanding of the mechanisms of sintering will allow for predicting strength development and for identifying possible ways to weaken deposits. Ash particles that produce a deposit vary in size and composition. Particle size and composition distribution of the deposited ash material provides an indication of the relative reactivity of the ash particles with each other and the gas-phase components. Assessment of the reactivity of deposited ash particles gives further insight into determining the ability of the deposit to form a liquid phase. The reactivity and ability to form a liquid can be ascertained by examining the base-to-acid ratio distribution of the entrained-ash particles. An entrained ash with a high potential for liquid-phase formation would have both acid- and base-rich components. Once deposited, the basic and acidic species could react, forming low melting point particles. A low potential for liquid phase formation is indicated by dominance of either basic or acidic components. Little potential for liquid-phase formation exists if only one component is present.

Sintering mechanisms involve solid-state and viscous flow. In solid-state sintering, the densification process is a result of the decrease in surface area and lowering of the free energy by eliminating porosity. Solid-state sintering mechanisms include vaporization and condensation, bulk diffusion transfer, and surface diffusion. Viscous or plastic flow occurring where two particles are beginning to sinter is illustrated in Figure 1-8. The liquid phase component is the primary contributor to deposit strength development. Abundance and viscosity of the liquid phases are primary factors needed to assess sintering potential. The liquid phase can be described as being reactive or nonreactive with the solid components in the melt. A reactive liquid readily dissolves the solid particles. A nonreactive liquid is one in which the solid particles are insoluble. Physical characteristics of the liquid phase can be changed appreciably by crystallization or decomposition. In nonreactive viscous flow, sintering by the liquid phase does not dissolve the solid components. For example, in low-temperature sulfate-based deposits, the sulfate liquid phases bond the silicate-rich particles together, with little or no reaction occurring between the silicate particles and sulfate liquid phases. Viscous flow sintering with a reactive liquid phase

results in the formation of large amounts of liquid. There is an appreciable solubility of the solid particles in the liquid and good wetting of the solid by the liquid.

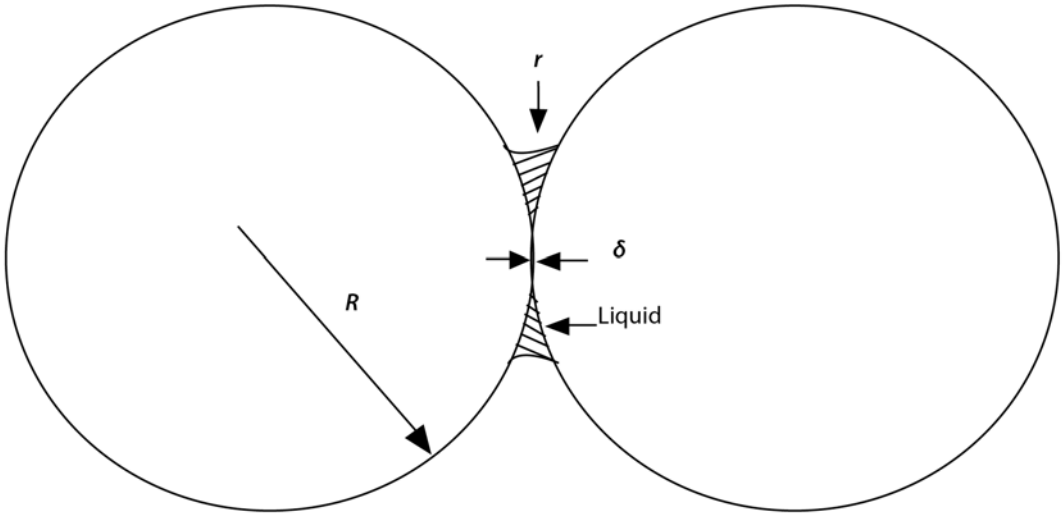


Figure 1-9
Viscous-flow sintering of two particles.

The driving force for densification is derived from the capillary pressure of the liquid phase between the particles. When two particles that are coated with a liquid phase are in contact with each other, the inter-particle space becomes a capillary in which substantial pressure can develop. For example, in silicate systems containing capillary diameters between 0.1–1 μm, pressures can range from 1.2–12.1 mPa (174–1755 psi) (Kingery and others, 1976). The capillary pressure increases densification through the following processes:

1. Rearrangement of the particles causes more effective packing.
2. The number of contact points between particles is increased.
3. Ostwald ripening (the process involving the dissolution of smaller particles producing larger particles) occurs.
4. High pressure causes the liquid to penetrate between particles and increases the solubility of the solid. The material is transferred away from the particle contact points, allowing the particle centers to become closer.
5. Crystallization will influence the melt by changing the composition of the liquid phase and the production of solid grains, thus slowing the densification process.

Frenkel (1945) developed a relationship that defines the sintering or coalescence of particles. He defined these in terms of measurable parameters, including particle size, viscosity, and surface tension. When two particles are in contact, the initial deformation of the particles is the result of surface tension forces pulling the particles together, resulting in viscous flow and the diffusion of material. The growth of the interface between two particles can, therefore, be defined as follows:

$$x^2 = \frac{3r\gamma t}{2\eta} \qquad \text{[Eq. 1]}$$

where χ is the radius of the interface, r is the radius of the particles, γ is the surface tension, t is the time, and η is the viscosity.

Raask (1985) has made relationships between the degree of sintering and the ratio of the neck-bond radius to the particle radius. Equation 1 has been changed to:

$$\frac{x}{r} = 1.225\left(\frac{\gamma}{\eta r}\right)^{1/2} t^{1/2} \qquad \text{[Eq. 2]}$$

This equation is applicable when $x/r < 0.3$. The rate of deposit strength development with respect to time can be expressed as follows:

$$\frac{ds}{dt} = -3/2 \qquad \text{[Eq. 3]}$$

where s is the strength value, and k is the constant.

Final stages of sintering are not well-represented by the Frenkel (1945) and Raask (1985) sintering models. The deposit produced during the sintering process contains pores. The final stages can be represented by the Mackenzie and Shuttleworth (1949) model, which is concerned with the shrinkage of pores.

Relationships were developed between the chemical composition of coal ash slags and physical properties. Nowok and Benson (1992) performed sintering experiments with homogeneous coal ash slags in order to relate the base-to-acid ratio (chemical composition) to the surface tension-to-viscosity ratio (γ/η). The homogeneous slags were crushed and sized-fractionated. Pellets were prepared and sintered under controlled conditions. Crushing strengths of the resulting ash pellets were measured. Figure 1-9 is a plot of the measured γ/η versus the base-to-acid ratio. The results indicated that γ/η is clearly related to the chemistry of the system. A linear relationship was obtained when determined in air. When determined in CO/CO_2, an exponential increase was observed. This is due to the change in oxidation state of the iron, causing it to decrease the viscosity of the liquid.

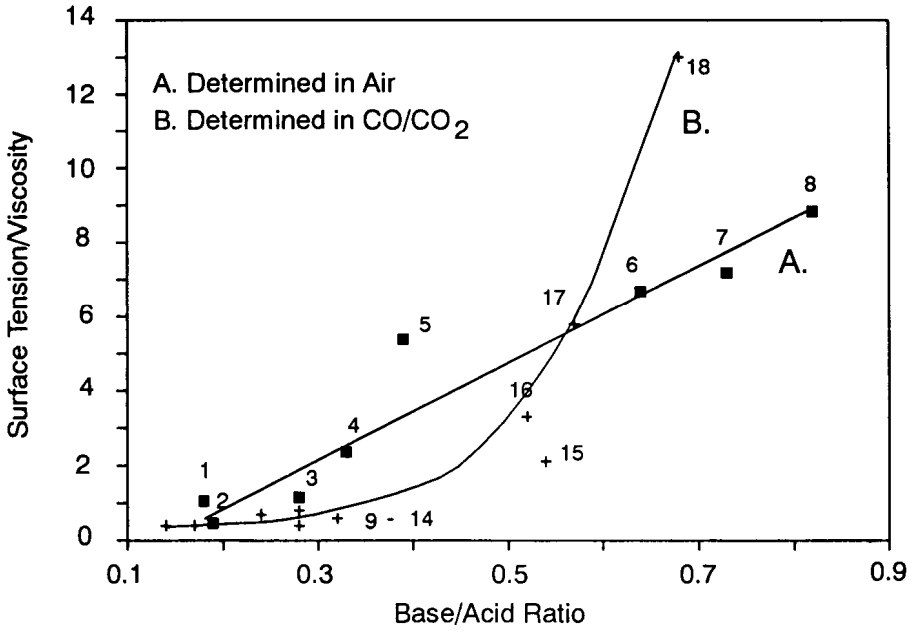


Figure 1-10
Measured surface tension/viscosity ratio versus base/ash ratio for homogeneous slags determined in air and a CO/CO_2 atmosphere above the temperature of activated viscosity (Benson and Nowok, 1992).

Compressive strengths were determined for selected homogeneous slag pellets that were sintered at 1370 K (2000°F) in air. The results are shown in Figure 1-10. As the surface tension-to-viscosity ratio increased, the strength of the pellet increased. This is consistent with the Frenkel and Raask models for strength development due to viscous flow sintering.

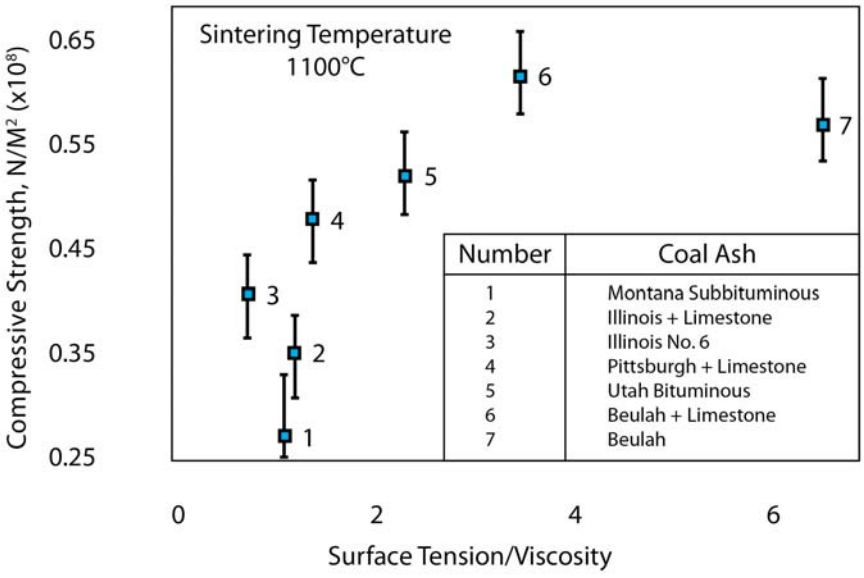


Figure 1-10
Measured surface tension/viscosity ratio versus compressive strength for homogeneous slags determined in air and a CO/CO_2 atmosphere above the temperature of activated viscosity.

Porosity shows a different trend than sintering when the ash deposit grows. Initially, porosity is high for the particulate layer due to a large fraction of continuous gas phase present in a defined volume. As the deposit transitions from the particulate layer to the sintered layer, and transitions further to the slagging layer, porosity tends to diminish because of an increasing volume fraction of solid or viscous materials.

Sulfate phase-based bonding materials become more stable at temperatures below 2000°F, and are typical of coals that have high levels of calcium and sodium. The sulfate-based bonding process involves the deposition and capture of alkali and alkaline earth element-rich particles along with silicate-rich particles. After deposition, the alkali and alkaline earth element-rich particles are sulfated, causing the formation of a matrix. Unlike high-temperature deposits, the silicates do not participate in the bonding of ash particles. The silicate particles remain largely unreacted. The primary contributors to the formation of low-temperature deposits are the very small alkali and alkaline earth element-rich particles that are produced as a result of combusting coal. These small particles are readily sulfated and can create a matrix that is very strong and difficult to remove using sootblowing techniques.

Sulfates are formed primarily by the vaporization and condensation processes. During combustion, sulfur oxides form from the oxidation of sulfides and organic sulfur in the flame. At the high flame temperatures, sulfur dioxide (SO_2) forms first, followed by the formation of sulfur trioxide (SO_3). At lower temperatures, equilibrium favors the formation of SO_3. Sulfur oxides can interact with the surface of fly ash particles. It has been shown that the maximum amount of reaction occurs between sulfur oxides and ash at approximately 1400 to 1600°F and is dependent upon the quantity of alkali and alkaline-earth oxides in the ash (Benson and Kalmanovitch, 1989). The exact mechanisms by which alkali and alkaline earth-rich sulfates form in combustion systems are poorly understood. It is assumed that the alkali and alkaline-earth elements volatilize in the flame and are converted to oxides. The alkali and alkaline-earth oxides then react with SO_2 and O_2 or SO_3 to form sulfates. It has been postulated that sulfates form in the gas stream and condense on the surfaces of materials such as fly ash particles or boiler steel surfaces. Another, more likely pathway for the reaction is on the surface of entrained fly ash particles where an alkali layer (NaOH) is first deposited, followed by the sulfur oxide interaction.

Low-temperature fouling deposits are sometimes produced from subbituminous coals that contain high levels of calcium. The formation of these deposits is dependent upon the availability of small calcium oxide particles and the process of sulfation. In addition, the process of sulfation in the convective pass is dependent upon temperature, as shown in Figure 1-11 (Mulligan and others, 1989). Based on detailed field testing to determine the mechanism by which low-temperature deposits form, Hurley and others (1991) identified that the deposit characteristics are related to the size and composition of the entrained ash. The strength due to sintering by sulfates is illustrated in Figure 1-12 (Hurley and others, 1998). This shows the higher strength development was observed at about 1640°F.

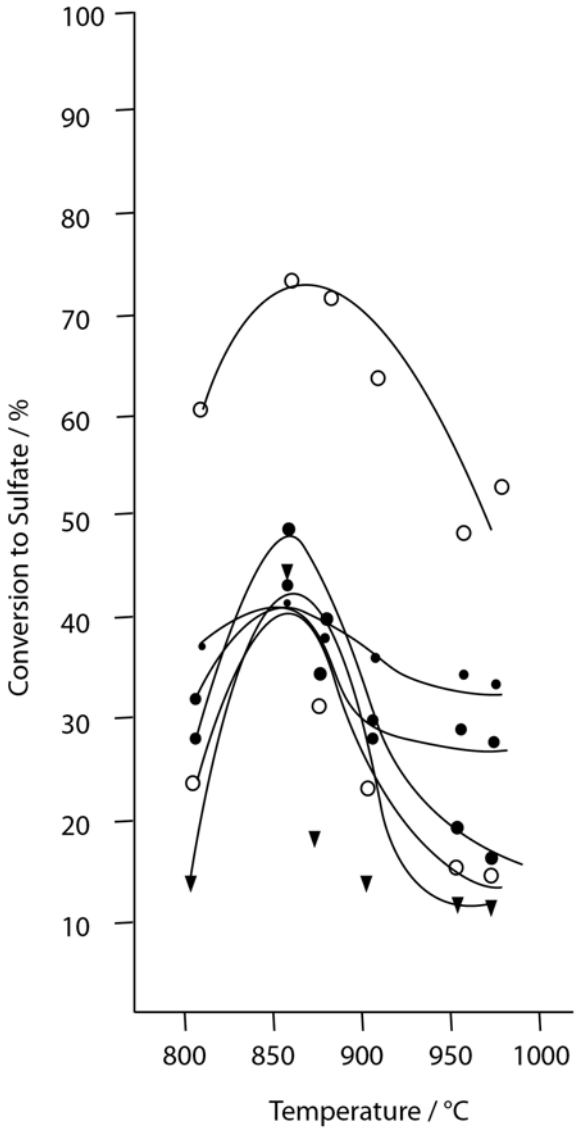


Figure 1-11
Sulfation of CaO-rich materials derived from a range of limestone samples as a function of temperature (Mulligan and others, 1989).

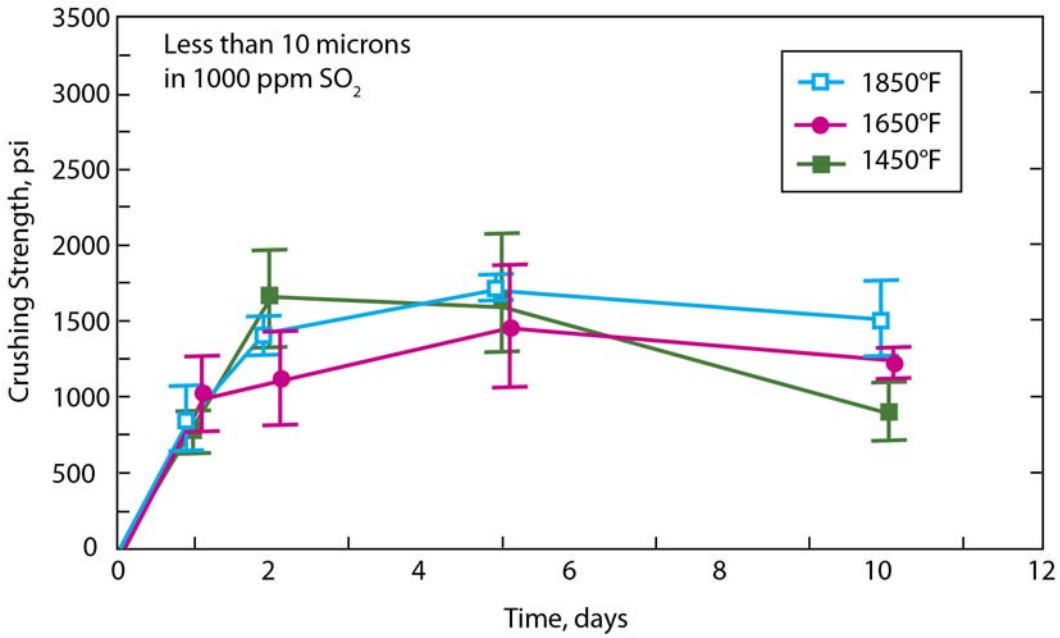


Figure 1-12
Sintering of a calcium rich fly ash that is less than 10 micrometers at selected temperatures (Hurley and others, 1998).

When firing Powder River Basin coals containing high levels of calcium, enamel-like layers can form on heat transfer surfaces. These enamel-like layers are very difficult to remove. In these coals, particles rich in alkali and alkaline earth elements are deposited and subsequently sulfated, resulting in the development of deposit strength. Microscopic examination of these enamel layers indicated that they consist mainly of highly-sulfated particles that are less than three microns in aerodynamic diameter. These layers result from thermophoresis/electrophoresis or simple diffusion of small particles.

Deposit Types

Wall Slag

Slag or water wall deposit compositions can include reduced phases (such as sulfides and reduced metal oxides), metallic materials, and silicates. The reduced phases result from impingement of partially-converted iron sulfide particles on heat transfer surfaces. Figure 1-13 shows a cross-section of a deposit that is bonded by sulfide materials.

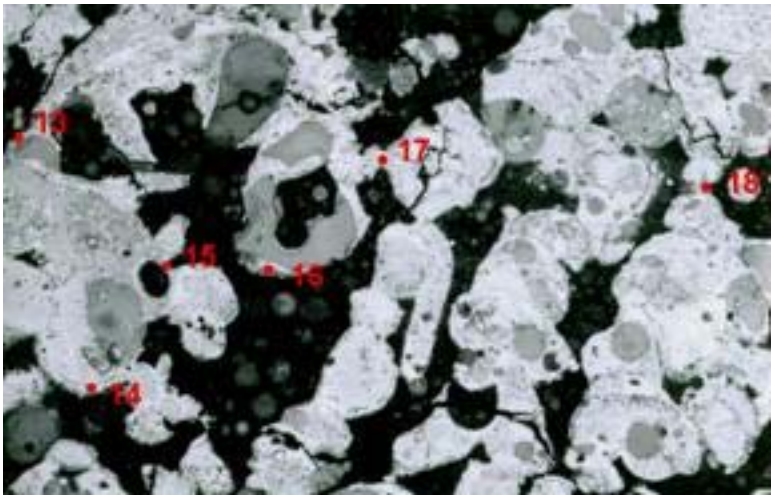


Figure 1-13
An un-oxidized, pyrite-based slag deposit at 140x magnification. Bright areas are rich in the iron and sulfur species that bond the deposit.

Metallic-like slag is produced in a reducing environment. This slag type is rich in reduced iron phases. Figure 1-14 shows a polished cross-section of a metallic slag deposit. These slags have a metallic luster and are usually associated with the combustion of pyrite rich coals, in which reduced metals separate from the silicate-based slag materials.

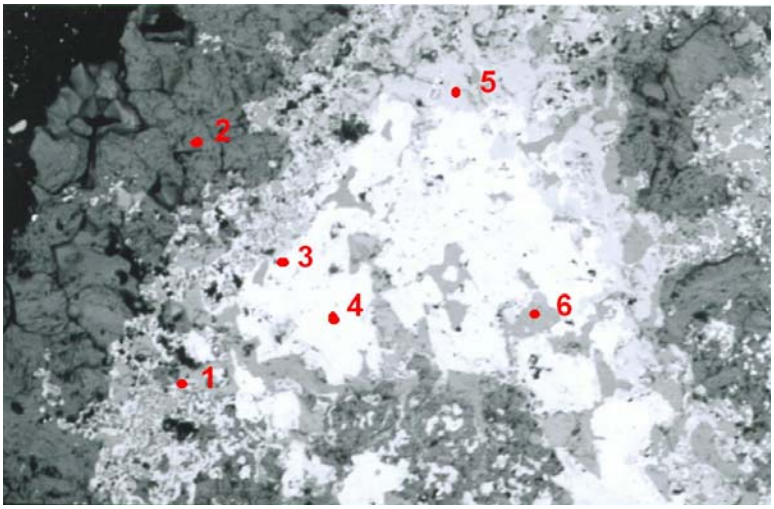


Figure 1-14
A reduced-iron-rich, metallic-like slag deposit at 250x magnification. The bright region in the middle of the image is rich in iron, with very little oxygen. The outer gray regions contain more oxygen.

Aluminosilicate-based slag deposits include homogeneous amorphous slags, vesicular slag, vesicular crystalline slag, and highly crystalline slag materials. The amorphous slag materials form at high temperatures, and have undergone complete melting and reaction of the ash particles to form a homogeneous melt phase. Figure 1-15 shows a polished cross-section of a homogeneous slag.

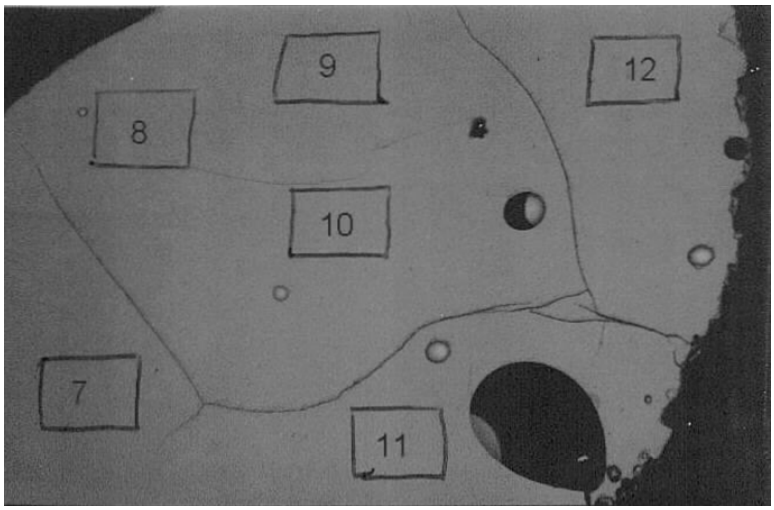


Figure 1-15
A homogeneous, glassy slag deposit that contains few pores, at 22x magnification.

An example of a vesicular slag deposit is shown in Figure 1-16. Vesicular slags form from materials that are decomposing and outgassing during the melting process. The result is the abundance of pores in the deposit. The pores typically weaken ash deposits. In some cases, highly-vesicular deposits will crystallize. The crystallization is related to the composition of the slag and the availability of nucleating agents. A crystalline vesicular deposit is shown in Figure 1-17. In most cases, crystallization of the slag materials results in strengthening of the deposit materials. However, the presence of crystals can change the composition of the residual melt phase, increasing the viscosity, and will reduce sintering. In addition, the crystallization can create heterogeneity in the slag, leading to crack propagation as a result of different thermal expansion coefficients between the crystalline materials and residual liquid. Figure 1-18 shows a denser, highly crystalline slag deposit.

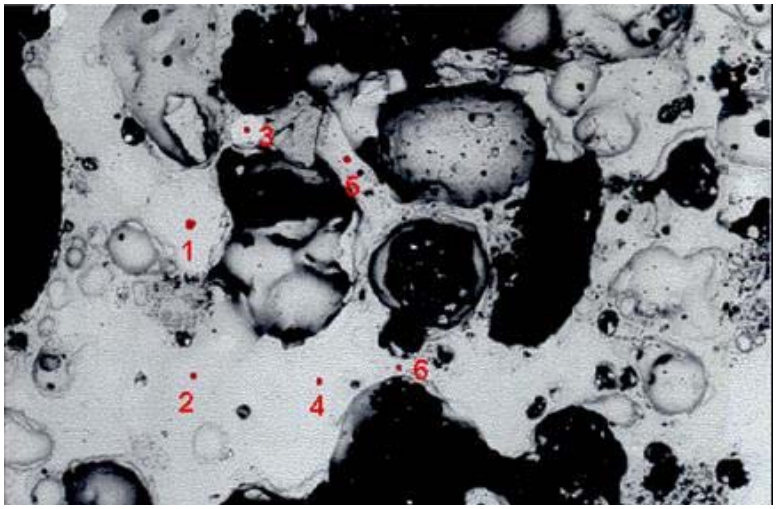


Figure 1-16
A vesicular slag deposit with a homogenous composition, at 200x magnification.

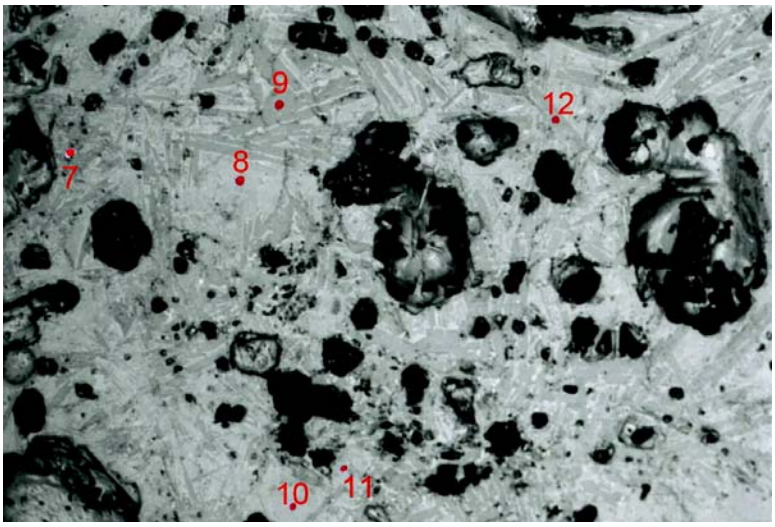


Figure 1-17
A highly crystalline, vesicular slag at 95x magnification.

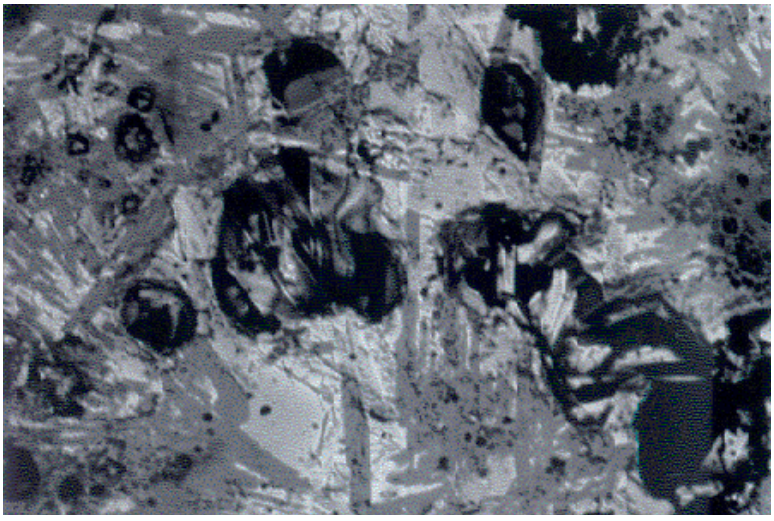


Figure 1-18
A highly crystalline, low-porosity slag, at 500x magnification.

High-Temperature Fouling

High-temperature fouling occurs in regions of the utility boiler where temperatures exceed the maximum temperature for the stability of sulfate-bearing phases, and silicate phase dominate particle bonding. In most cases, high-temperature fouling deposits are layered. Innermost layers, next to the tube, are rich in flame-volatilized species. Subsequent layers contain larger, liquid-bearing particles that impact and stick, as shown in the micrograph in Figure 1-19. The deposit in Figure 1-19 is highly porous, with particle bonding due to surface coatings and bonding of vesicular particles. Bonding is enhanced by the condensation of flame-volatilized species on the surfaces of the particles, causing them to sinter and develop strength. As the deposit grows, it has

an insulating effect on the tube, and outer deposit layers will increase in temperature. The higher temperature leads to melting and further interaction of the particles, and ultimate results in the formation of a liquid phase. Once a liquid phase has formed on the outside of a deposit, it becomes an efficient collector of ash particles, regardless of the melting characteristics of those particles. The type of liquid phase that dominates the deposit processes is temperature-dependent.

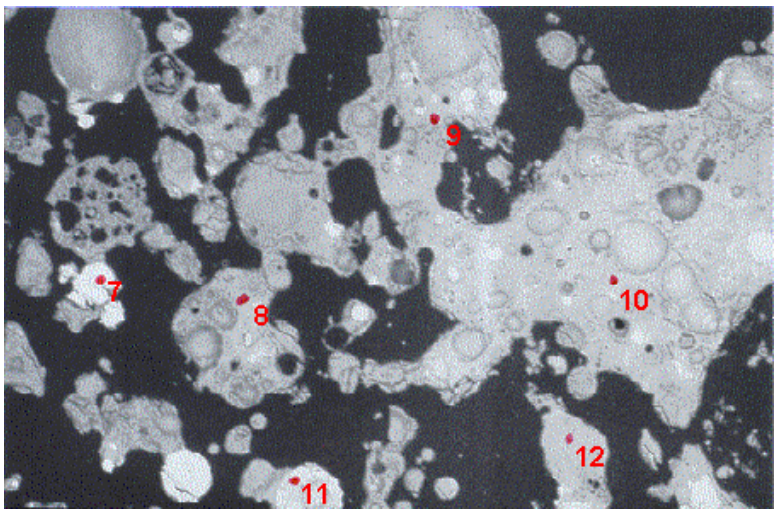


Figure 1-19
A partially sintered, highly porous high-temperature silicate-based deposit, at 250x magnification.

Low-Temperature Fouling

Low-temperature ash deposition occurs at temperatures below about 1800°F. In the low-temperature fouling system, sulfate phases are the dominant matrix or bonding material between particles. Examples of sulfate-bonded deposits are shown in Figures 20 and 21. Detailed examinations of sulfate-bonded deposits have been conducted, and the sulfate-based bonding mechanism may proceed as follows: coals containing high levels of organically-associated calcium produce very small particles, which are sulfated either on the tube surface after deposition through small-particle transport processes, or in the gas stream. The sulfated small particles can then produce very dense deposits (Figure 1-20) or a dense bonding matrix (Figure 1-21). The very small, calcium-rich particles that are produced from combusting coal containing organically-associated calcium are the primary contributor to the formation of low-temperature deposits. These small particles are readily sulfated, and can create a matrix that is very strong and difficult to remove using sootblowing techniques.

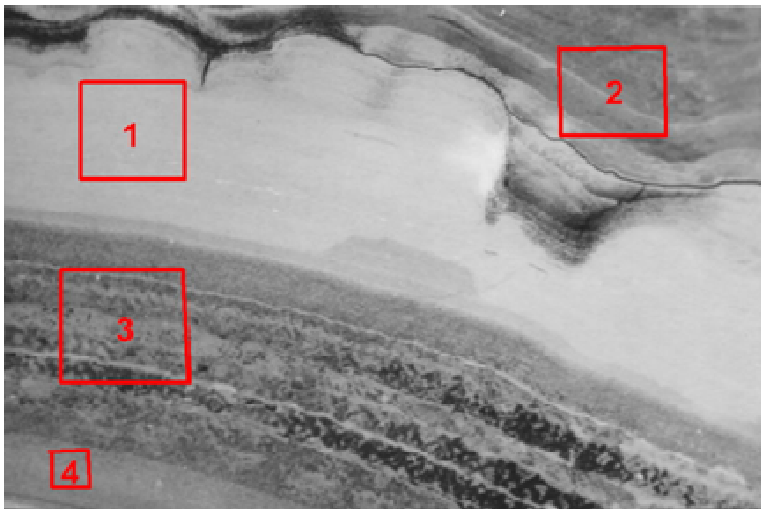


Figure 1-20
A dense, layered sulfate-based deposit, at 20x magnification.

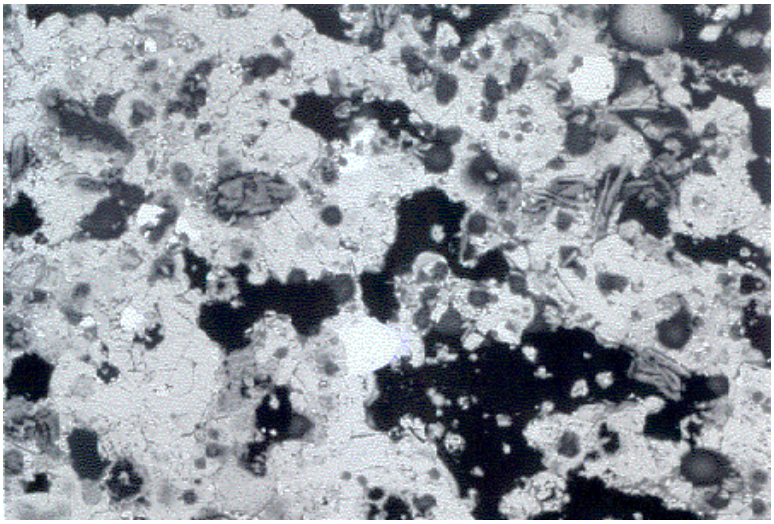


Figure 1-21
Another low-temperature, sulfate-bonded deposit at 500x magnification.

Thermal Mechanical Properties of Deposits

The thermal and mechanical properties of slags have significant impacts on the ability to remove deposits with various cleaning devices such as sootblowers. Deposits (water walls and convective pass) consist of complex materials that contain pores, unreacted ash particles, amorphous glassy phases, and crystalline phases. The characteristics of the deposited materials will depend upon the fuel composition, plant operating conditions, and location within the boiler. Wain and others (1992) examined the compressive strength, elastic modulus, thermal conductivity, and coefficient of expansion for slag deposits, and made relationships to slag deposit composition, crystallinity, and porosity. Their efforts were focused on developing a tool that could provide an indication of sootblower effectiveness.

Soot blowing relies on using a combination of thermal and mechanical shock to fracture the deposit. Crack propagation in slag is dependent upon a rapid change in temperature. In Wain's model, deposits are assumed to be brittle materials consisting of glass and crystalline material below the glass transition temperature, and the thermal stress generated in deposits can be defined by the thermal shock parameter:

$$\sigma = \frac{E \cdot \alpha \cdot \Delta T}{(1-\upsilon)}$$

where σ is the fracture stress, E is the elastic modulus, ΔT is the temperature change and υ is Poisson's ratio. The equation can be re-written to find the temperature change ΔT required to reach the fracture stress σ.

Various ceramic/glass materials can be ranked in terms of temperature change or energy required to generate stress to initiate crack propagation. Thermal shock parameters, R and R', can be determined from the measurement of thermal and mechanical properties of slag. The properties depend upon slag composition, crystallinity, and porosity.

$$R = \frac{\sigma \cdot (1-\upsilon)}{E \cdot \alpha} \quad \text{and} \quad R' = \frac{\sigma \cdot (1-\upsilon) \cdot k}{E \cdot \alpha}$$

where k is the thermal conductivity of the slag.

Wain and others (1992) measured the thermal and mechanical properties of ten slag samples from selected pulverized coal-fired boilers. They found that the thermal conductivity of the slags was related primarily to its porosity, and the slag composition and crystallinity had little impact. The relationship between slag thermal conductivity and porosity is shown in Figure 1-22. They were not able to identify relationships between chemical composition, crystallinity, or porosity and thermal expansion, but found that slag compressive strength could be related to the porosity by the relationship

$$\sigma = \sigma_0 \exp^{-nP}$$

where σ_0 is the compressive strength of the material with zero porosity, σ is the strength at porosity level P, and n is a curve fitting parameter.

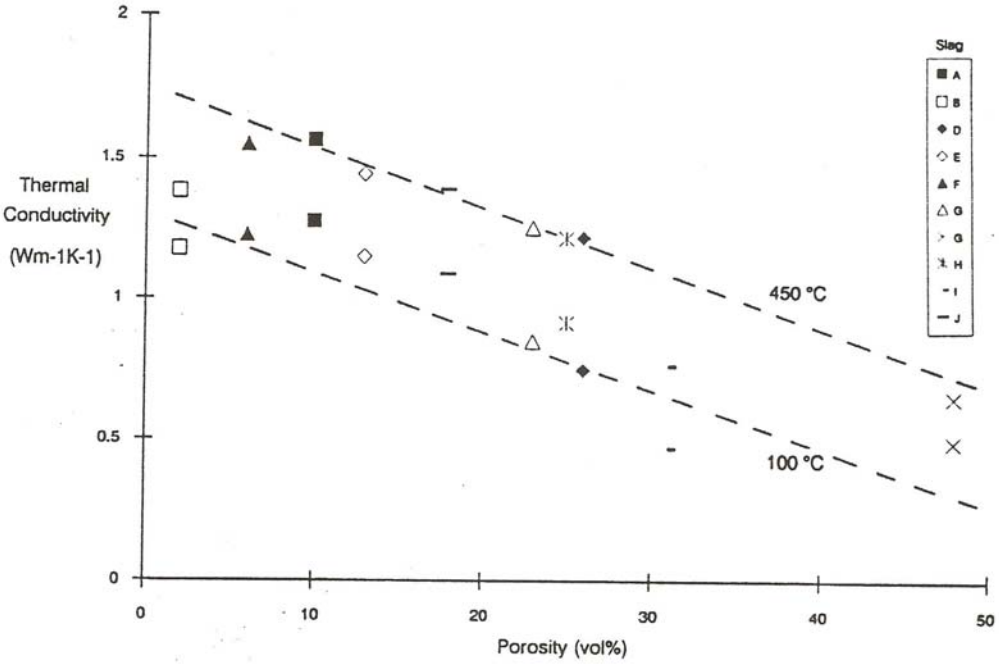


Figure 1-22
Relationship between slag thermal conductivity (k) and porosity.

Rezaei and others (2000) compared measurements of thermal conductivity to show that the physical structure of deposits has a significant impact on thermal conductivity. Figure 1-23 illustrates the variation of thermal conductivity and ash porosity at temperatures between 350 and 800°C (662 and 1472ºF). Thermal conductivity decreases with an increase in the porosity, and increases with increasing temperature.

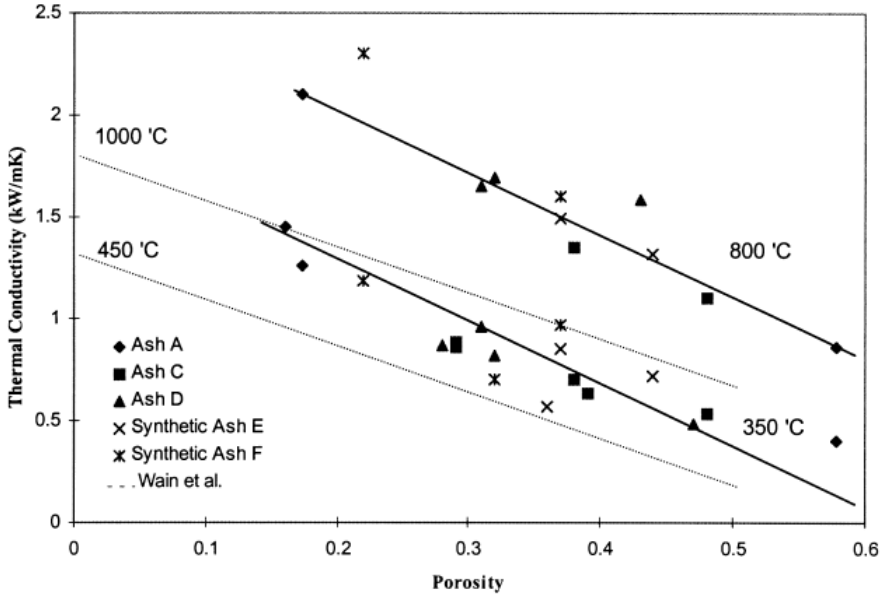


Figure 1-23
Thermal conductivity and porosity based on work conducted by Rezaei and others (2000).

Thermal shock resistance, R and R' were calculated from a combination of thermal and mechanical properties (Wain and others, 1992). The thermal shock resistance (R) as a function of porosity is illustrated in Figure 1-24. Based on the work by Wain and other, crack propogation would be easier in highly porous, glassy slag deposits. A lower porosity and higher-crystalline-content slag deposit would be more resistant to fracture. The resistance to fracture was found to decrease significantly for slags having a porosity of less than 25%.

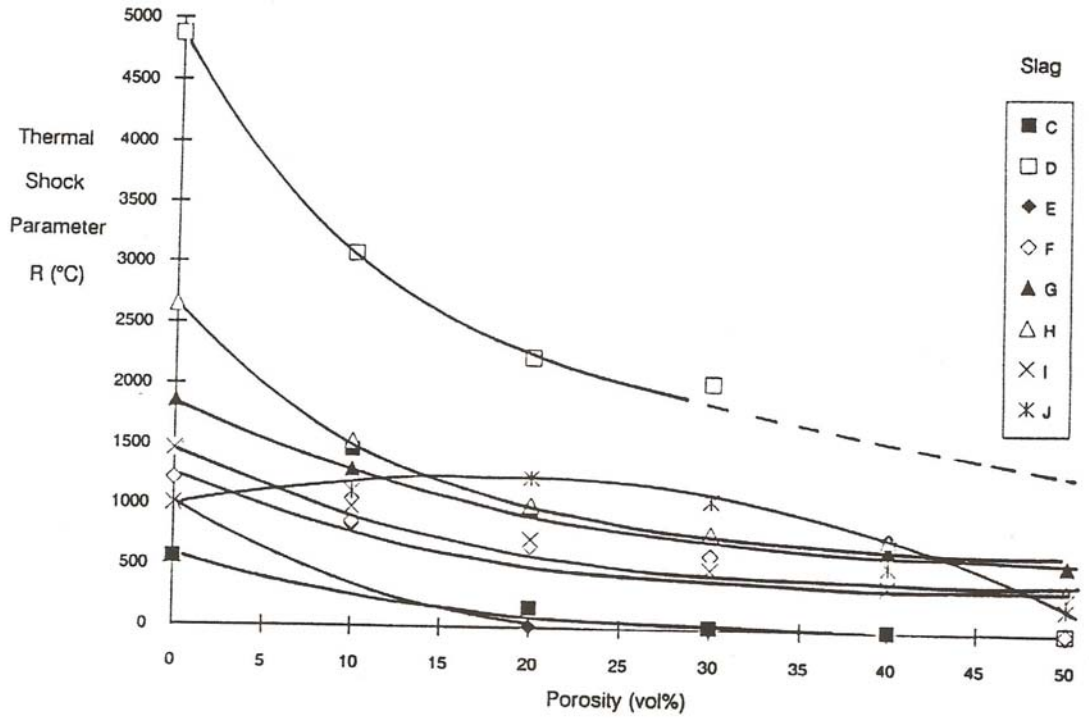


Figure 1-24
Relationship between shock parameters and slag porosity (Wain and others, 1992).

Measurement of porosity in deposit is a critical component. Abd-Elhady and others (2007) have used scanning electron microscopy to measure porosity of deposits, as shown in Figure 1-25. Figure 1-25 illustrates the changes in porosity as a function of location (from tube-side to gas-side) in the deposit.

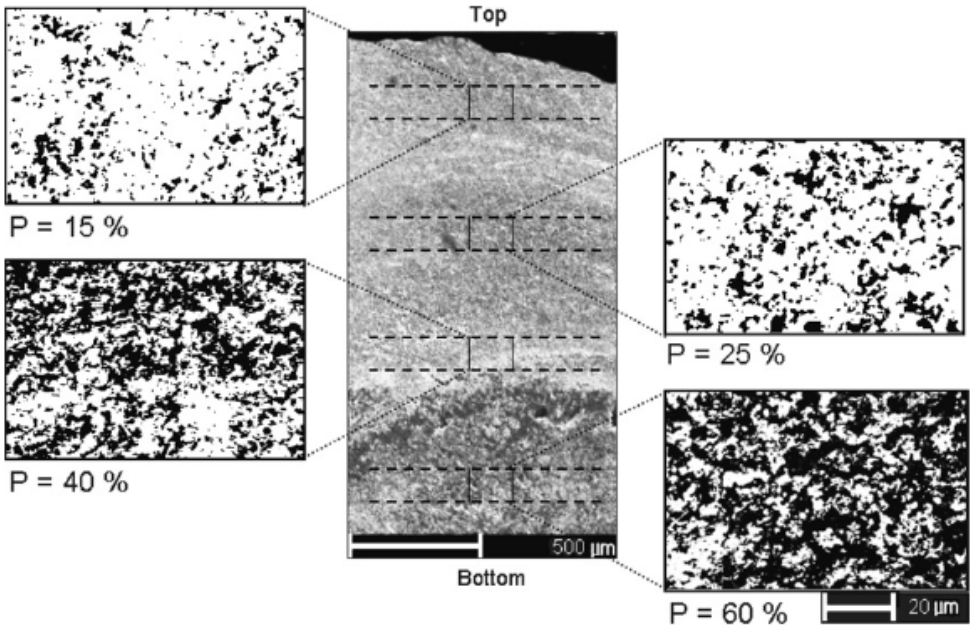


Figure 1-25
Porosity measurements of a fouling ash deposit from the convective pass of a combustion using a scanning electron microscope (Abd-Elhady and others (2007).

Online methods of ash deposit removal

Sootblowers

Sootblowers are used to clean the radiant water walls and convective pass tubes in utility boilers. Wall blowers consist of a retractable lance that can extend into the unit approximately 1 to 2 inches. The lance has a nozzle that directs steam or air tangentially against the furnace wall while it rotates about its axis. Typically, wall blowers are able to break the bonds between the deposit and heat transfer surface, resulting in removing the deposit. Each wall blower cleans a region that ranges from 8 to 12 feet in diameter.

Long, retractable sootblowers are used to clean tube banks in the convective pass. These include the tubes in the superheater, reheater, and economizer regions of the boiler. These long sootblowers are retracted outside the boiler wall when not in use. In operation, the retractable sootblower rotates as it is inserted into the boiler. Two opposed nozzles direct steam or air in a helical pattern as the sootblower extends into the boiler between tube banks. Typically, the nozzles are installed perpendicular to the sootblower axis. The retractable sootblower is capable of cleaning in a radius of 4 to 9 feet (1.2 to 2.7 m) from the sootblower centerline, the degree of penetration into the tube bank is dependent upon the degree of fouling and tube spacing.

The working fluid in both types of sootblowers (wall blowers and retractable sootblowers) can be either steam, air, or water. Steam sootblowers are the most common, due to the availability of steam. Dry steam is generally used at 200°F (111°C), at a pressure of 200 to 250 psig (1.38 to

1.735 mPa). Steam has the advantage of providing twice the kinetic energy of air at the same pressure, but with the disadvantage of having the potential to introduce excessive moisture into the combustion gas.

Air sootblowers are considered to be superior to steam sootblowers, mainly because a minimal amount of moisture is introduced into the combustion gas. As noted, air has less kinetic energy than steam at a given pressure. The air pressure in air sootblowers is normally about 180 psig (1.240 mPa). The use of air sootblowers also requires the installation of compressors to provide the necessary air.

Water is not extensively used as a medium for wall blowers, and almost never for long, retractable sootblowers. Although the density of a water jet has the potential to provide very high-impact energy, and efficient cleaning, there is great concern about tube damage and failure due to thermal shock (Rahimi and others, 2003). The amount of moisture introduced is a concern.

Water Cannon

The Clyde Bergemann-type water cannon or water blower is different from conventional wall blowers for furnace-box cleaning (Clyde Bergemann, 2008). The water cannon directs a water jet across the furnace box, where it impinges on, and removes slag from the opposite boiler wall. Operating water pressure is typically around 175 psi. The cleaning action is a combination of water impact and thermal shock. Deposit removal is performed by rastering the water jet across the boiler wall. An advantage to this process is that openings or other sensitive areas can be skipped by the rastering pattern, and dwell time is adjustable for the degree of slagging present. The water cannon is easily adapted to automated control, with wall heat flux monitors providing feedback to help determine the timing and duration of the cleaning required at different areas of the walls. As with water sootblowers, there is concern about the effect of thermal shock on water-wall tubes.

Sonic Horns

Sonic horns or acoustic sootblowers began to be more widely utilized by the power industry during the last 15 years (Schimmoller , 1994). The operating principle is in the use of sound pressure on the order of 150 decibels (dB) to remove deposits. Two ranges of frequency are used: above 75 hertz (Hz) to avoid resonance with other plant components; and the infrasonic or near-infrasonic frequency range of 10 to 35 Hz. Sonic horns are effective in removing loose ash and very lightly sintered deposits. Typically, they are used in the economizer, air pre-heater, and electrostatic precipitator (ESP) or baghouse regions of a boiler, and for cleaning selective catalytic reduction (SCR) reactors used for NO_x control. Their use in areas such as the economizer allows for cleaning of closely-spaced heat exchange tubes, where conventional sootblowing is not effective. Sonic horns must be operated frequently, on the order of once every 20 to 30 minutes, to ensure that loose ash in these areas does not sulfate to form a non-removable deposit. An advantage of sonic horns is their ability to reach areas that are inaccessible to other removal technologies, and their relatively low operating cost. The major disadvantages to sonic horns are their inability to remove hard deposits, and the potential for resonant vibrations.

Pulse Detonation

Pulse detonation is another alternative to conventional sootblowing technologies. Pulse detonation involves the use of a pressure wave to remove deposits from boiler surfaces. The pressure wave of the pulse detonation technology is analogous to the action of a sonic horn, but with a much higher peak pressure. Because of the higher pressure, pulse detonation is able to remove bonded and adhered deposits, in addition to weakly-bonded or loose ash. Ignition of a fuel-air mixture in an external chamber produces the detonation wave, which is introduced into the boiler via pipes or ducts.

Podimov (1979) examined the use of pulse detonation methods to remove deposits; the method examined used a valve-less pulse-jet to provide a repetitive pressure wave similar to that of a sonic horn. The pulsed detonation technology was successful in several industrial boiler applications in Russia. Pulse detonation with controlled pressure waves was tested using a laboratory model and in two full-scale, 300-MWe utility boilers in Bosnia (Hanijalić and Smajević,1991; 1993; 1994a; and 1994b). The pulsed devices were used to clean tubes in the convective pass and economizer regions of the boilers. No cleaning was performed in the main furnace box. The results showed good cleaning performance, with no adverse effects on boiler tubes after 18 months of operation.

Pulse detonation has also been tested for cleaning rotary air pre-heater surfaces in several full-scale utility boilers in China (Fan and others, 2002; Yu and others, 2001).

Several patents for pulse detontation technologies have been filed; two by Smajevic and Hanjalic (1990 and 1991) for power and other boiler types and for high-pressure gasification. Hunter (1997) holds a patent for the use of a pulse detonation device to remove particulate build-up on candle filter systems in coal gasifiers.

The U.S. Department of Energy sponsored a project performed by Prairie View A&M University, Lockheed Martin, and Microbeam Technologies Inc. to evaluate slag removal using pulse detonation (Huque and others, 1998). The project involved both computational fluid dynamics (CFD) calculations and experiments using a small pulse detonation apparatus. The CFD calculations indicated that when the detonation pulse interacted with multiple tubes, the resulting shock waves produced would effectively clean tube back sides as well as the sides facing the pulse wave. This was not the case when a single tube was modeled. In tube bundles, detonation waves are reflected from tubes, resulting in build-up on the back side of the lead tube. This indicates that the technology has the potential to clean the back sides of tubes. A pressure gradient plot illustrating shock formations around the heat exchanger tubes is shown in Figure 1-26. Tests with the pulse detonation apparatus on actual slag and fouling deposit samples from Xcel Energy (Northern States Power) power plants were tested. The results of testing indicated that up to 95% of soft air heater deposits would be removed from the front, side, and back of a simulated tube that was 7.8 inches (20 cm) from the detonator pulse exit. Removal of hard slag deposits was effective at shorter distances, and that a threshold pressure is required to remove hard deposit. The threshold pressure allowing for effective removal of slag deposits is required.

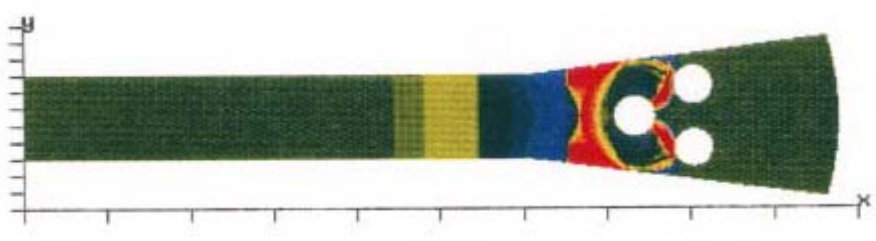


Figure 1-26
CFD modeling of the shock waves around tubes illustrating the shock function based on pressure gradients (Huque and others, 1998).

Based on past work, pulse detonation cleaning has the potential to remove hard deposits as well as loose ash. Additionally, a pulsed detonation device may be able to clean large areas and areas inaccessible to conventional soot blowing devices. A concern with pulse detonation is the possibility of tube damage due to the detonation pressure wave.

The pulse detonation technology has been commercialized by Pratt & Whitney (www.shock-system.com). The Pratt & Whitney's SHOCKSystem™ claims to be able to reduce or eliminate deposits from the lower-temperature regions of a coal-fired utility boiler. The technology has been installed in several locations and the results appear promising.

Deposit Removal Force

Conventional Air or Steam Sootblowing

The ability of a sootblower to remove deposits is related to the force of the sootblowing medium on the deposit. The measure of sootblower effectiveness is the peak impact pressure (PIP). This is the stagnation pressure along the nozzle centerline at a given distance from the outlet of the sootblower nozzle (Kashitani and others, 1998). The PIP decreases with distance from the nozzle.

Several researchers have performed detailed numerical modeling of sootblower nozzle jets to determine PIP at a selected distance from the nozzle. Kaliazine and others (1997) developed relationships to calculate the PIP, as follows:

$$V/V_{ex} = 1 - \exp\{-1/[k_v(\rho_4/: \rho_{ex})^{1/2} \cdot \chi/R_{ex}-0.7]\}$$

and

$$(H_x - H_{ex})/(H_o - H_{ex}) = 1 - \exp\{-1k_H(\rho_4/:\rho_{ex})^{1/2} \cdot \chi/R_{ex}-0.7]\}$$

where χ is the distance from nozzle exit, V_{ex} is the jet velocity at the nozzle exit, H_{ex} is the stagnation enthalpy at the nozzle exit, H_o is the enthalpy of the surrounding medium, R_{ex} is the nozzle exit radius, ρ_4 is the ambient gas density, ρ_{ex} is the nozzle exit gas density, M_{ex} is equal to $V_{ex}/V\gamma RT_{ex}$, and is the Mach number at the nozzle exit, and γ is equal to c_p/c_v, or the ratio of specific heat capacities for the jet gas.

The main mechanical factor that influences the removal of the deposit is the stagnation pressure due to the deceleration of the jet when it slows by hitting the deposit surface (Kaliazine and others, 1999). The stagnation pressure at the jet axis is called the peak impact pressure, P. Using these equations the peak impact pressure can be calculated at any distance from the nozzle for a fully expanded jet:

$$P/P_{ex} = [1 + M^2(\gamma - 1)/2]^{\gamma/\gamma - 1}$$

$$P/P_{ex} = [(\gamma+1)/2]^{(\gamma+1)/(\gamma-1)}\, M^2[\gamma-(\gamma-1)/2M^2]^{-\gamma/(\gamma-1)}$$

where P_4 is the ambient pressure.

Figure 1-27 shows the relative performance of a conventional high-PIP nozzle to that of a fully-expanded nozzle on PIP, as a function of distance (Jameel and others, 1994). Based on experimental work, a theoretical fully-expanded nozzle would have a higher PIP at a greater distance than an experimental high-PIP conventional nozzle.

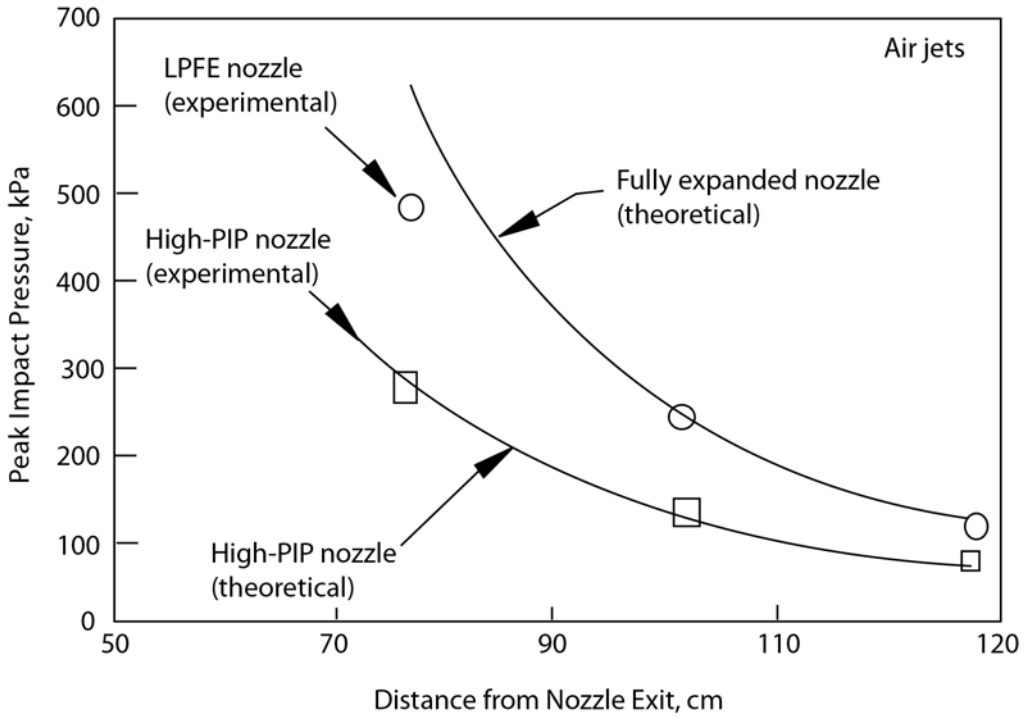


Figure 1-27
PIP as a function of distance from nozzle exit (Jameel and others, 1994).

The PIP decreases with distance from the sootblower nozzle, as shown in Figures 28 and 29. The presence of heat-exchange surfaces impacts the PIP, as shown in Figure 1-30 where the PIP for a free jet and for a jet confined between simulated platens are compared (Kermani and others, 2001). In this experiment, the PIP of the confined jet was approximately fifty percent higher than that of the free jet, at distances greater than 29.5 inches from the nozzle.

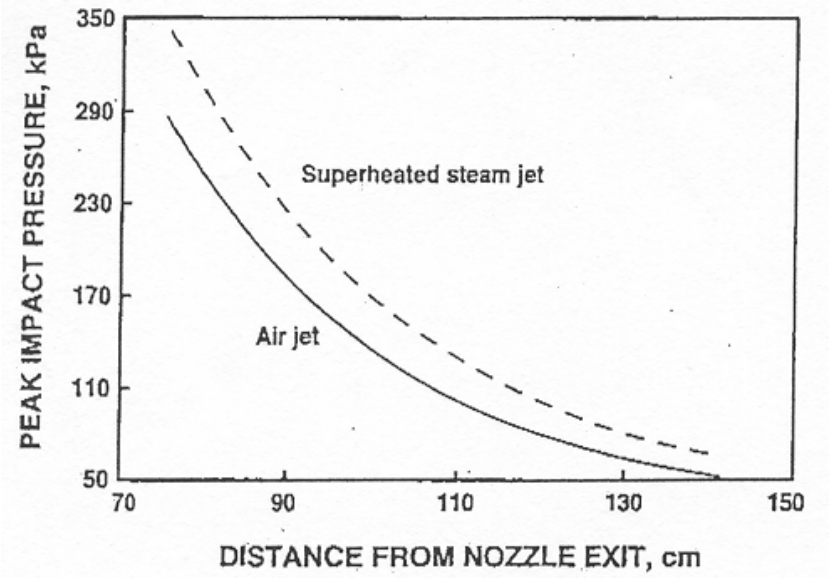


Figure 1-28
PIP as a function distance from the nozzle for air and steam (Jameel and others, 1994).

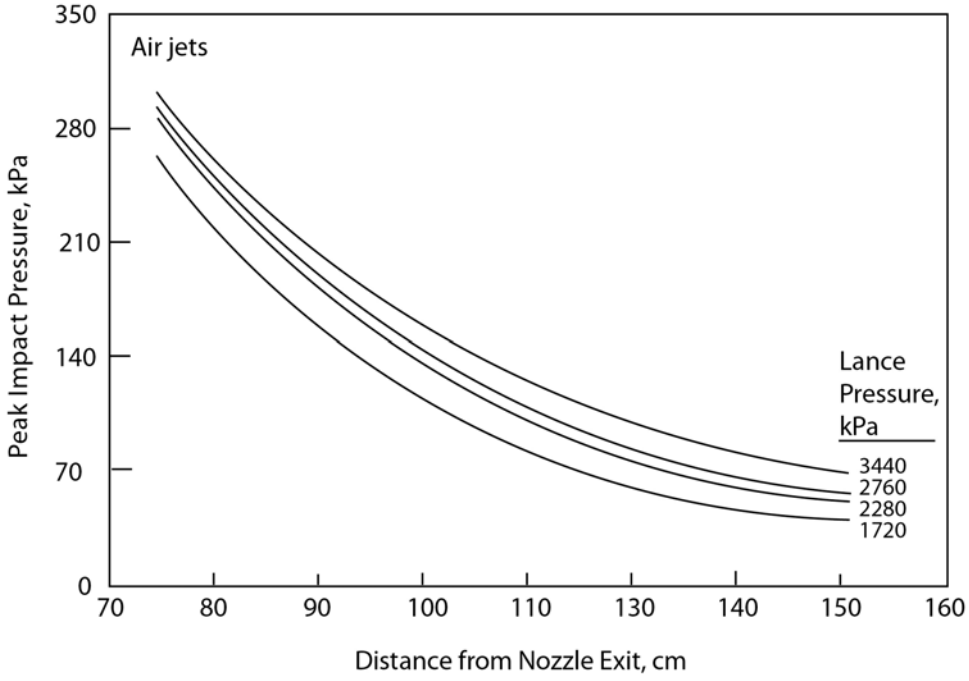


Figure 1-29
PIP as a function distance from nozzle exit for various lance pressures (Jameel and others, 1994).

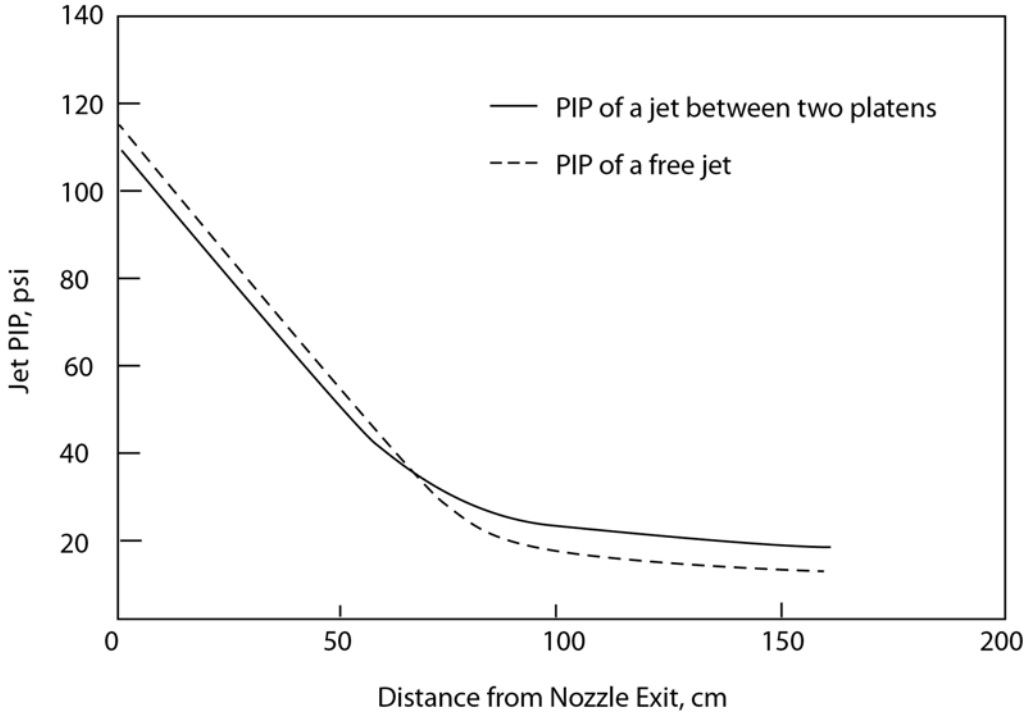


Figure 1-30
PIP profiles for a free jet and between platens (Kermani and others, 2001).

Ash deposit removal by sootblowers is related to the PIP that is delivered to the deposit, the deposit tensile strength, and the angle of impaction of the jet. Kaliazine and others (1997) utilized a criterion for deposit removal, in which the PIP needs to be greater than twice that of the deposit tensile strength, in order for impaction normal to the deposit to occur:

$P > 2\ S_t$

where P is the PIP, and S_t is the deposit tensile strength.

Using a series of model deposits of known tensile strength, Kaliazine has formulated an approximate expression that accounts for jets impacting at an oblique angle (Kaliazine and others (1997):

$P > 2\ S_t / \cos^2(a)$

where a is the angle of the jet, relative to the deposit surface.

The influence of deposit tensile strength on the distance (or pressure) from the jet required to fracture the simulated deposit is illustrated in Figure 1-31. As tensile strength of the deposit increases, the pressure required to fracture the deposit also increases as a function of its strength. The angle of incidence required to remove a simulated deposit, as a function of the deposit tensile strength, is shown in Figure 1-32 (Kaliazine and others, 1997).

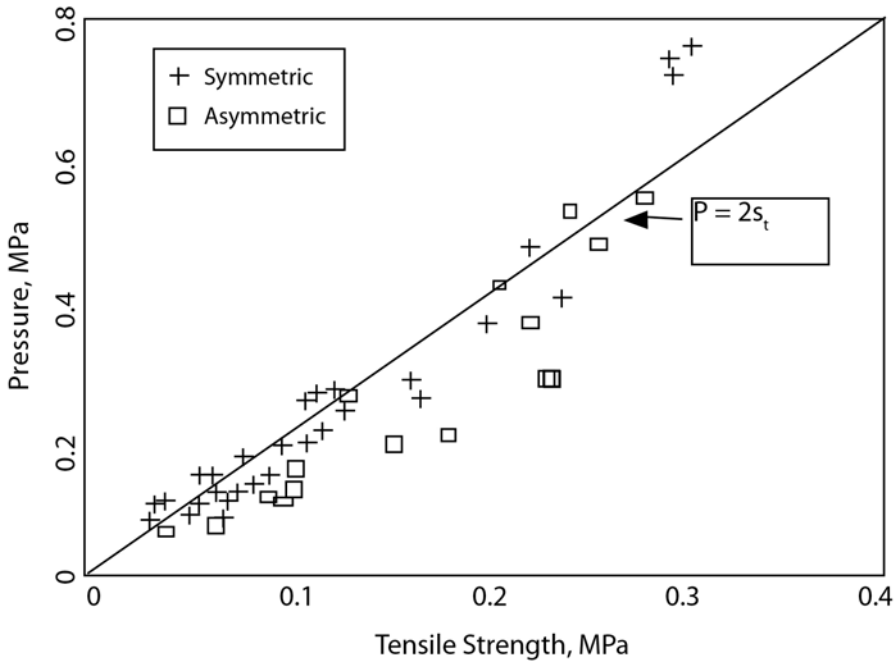


Figure 1-31
PIP versus tensile strength required to break simulated deposit (Kaliazine and others, 1997).

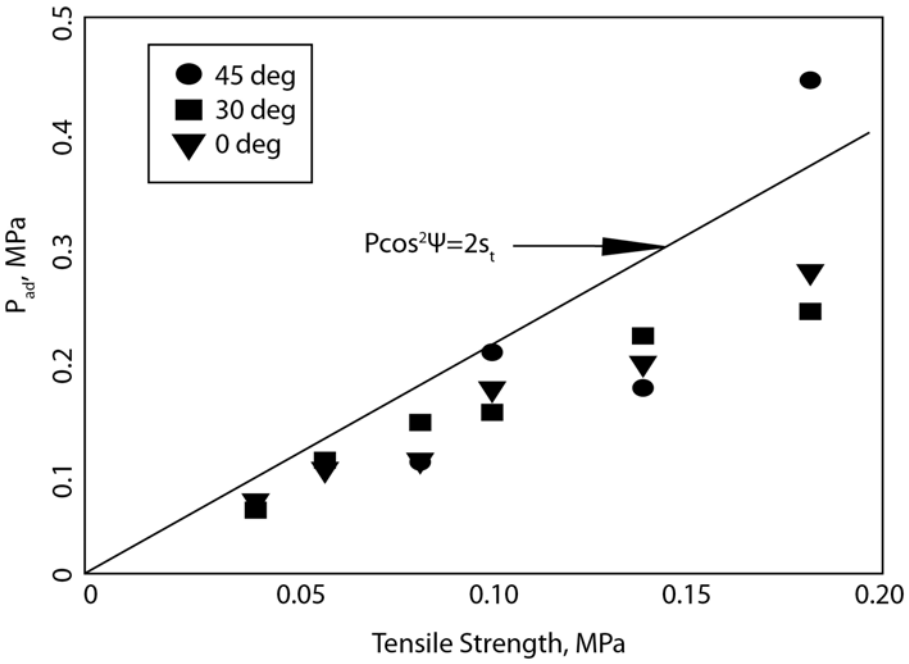


Figure 1-32
PIP required to remove the deposit versus tensile strength for different attack angles (Kaliazine and others, 1997).

Kermani and others (2001) developed a numerical model based on concurrent laboratory measurements. The model relates the drag force on the deposit (from the sootblower jet) to the stress induced in a deposit:

$s = F/A$

where s is the deposit adhesion strength, F is the drag force imposed on the deposit by a sootblower jet, and A is the contact area of the deposit with the underlying tube surface. Deposit removal will occur if the stress exerted within the deposit is greater than the adhesion strength of the deposit. In this case, the size of the deposit is important–the drag force increases with the deposit size. The influence of deposit height and distance from nozzle on drag force was also examined, as illustrated in Figure 1-33.

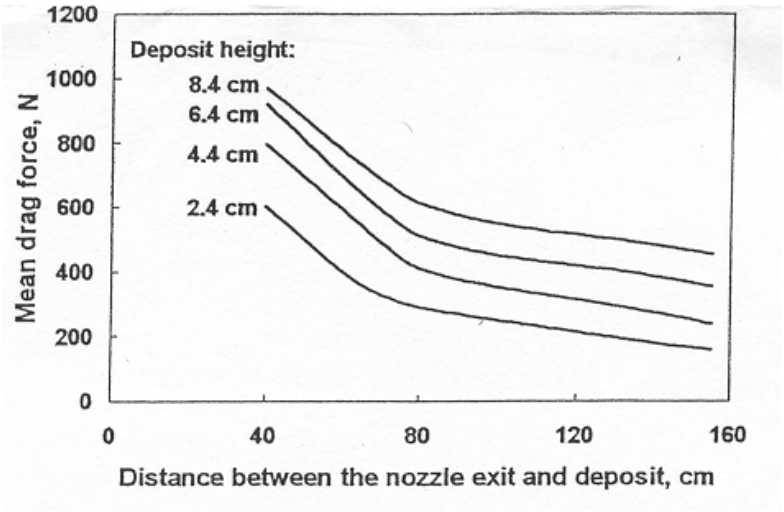


Figure 1-33
Drag force as a function of distance between nozzle and deposits of different heights (Kermani and others, 2001).

The force required for deposit removal can be estimated from the sootblower PIP, distance from the nozzle, the typical effective cleaning radius, and deposit tensile strength. The minimum cleaning radius for long retractable sootblowers is four feet (about 120 cm). At that minimum cleaning radius, indicative of deposits most difficult to remove, typical PIP values (estimated from Figures 27, 28, and 30) ranged from 10 to 22 psi.

Sonic Horns

Sonic horns, or acoustic sootblowers, operate with a sound pressure of approximately 150 dB, equivalent to only 0.09 psi. This pressure is significantly less than measured values of deposit tensile and adhesion strengths. Because of the lower pressure, acoustic sootblowing can only remove loosely-bonded or powdery ash material, and is not effective on materials that have developed any strength.

Water Cannons

Water cannons utilize a high-pressure water jet in which the pressure is estimated to be two to three orders of magnitude higher than the pressure of a steam jet at the same velocity. The higher

pressure is due to the greater density of water in its liquid form, and, as a result of this higher pressure, water cannons are capable of removing water wall slag and high-temperature fouling deposits on platens.

Pulse Detonation

Pulse detonation is an emerging technology that has the potential to remove deposits by sending high pressure waves at the deposit. Experiments in a test furnace have indicated that the pressure wave produced is between 14.5 at 43.5 psi, at a distance of 39.4 to 45.9 feet from the base of the detonation chamber (Hanijalić and Smajević, 1993, 1994). This pressure appears to be significantly higher than a steam or air sootblower jet at a comparable distance**.**

Summary and Conclusions

Ash deposition (or "slagging" and "fouling") on heat-transfer surfaces in coal-fired power plants has significant impacts on power plant performance. The chemical and physical properties of the ash-forming components in coal vary widely, and contribute to a wide range of deposit types and regions of deposition in coal-fired boilers. The properties of the deposits are highly dependent on coal composition and boiler types. Physical characteristics of a deposit that might form in a coal-fired boiler include: molten and flowing; plastic; highly-fused, glassy solid; metallic; highly-fused vesicular; highly-fused, dense crystalline; bonded; and powdery deposits.

Typically, deposits found in the radiant section of a utility boiler are more homogeneous as a result of assimilation of particles into a liquid (molten) phase. Such deposits are primarily silicate-based, and the physical characteristics of the deposit are dictated by the physical and chemical properties of the silicate liquid phases. As regional temperatures decrease, the degree of assimilation or melting of the deposited material will decrease. In addition, the extent of silicate-phase participation in deposit bonding will decrease.

At lower regional temperatures, the sulfate-based bonding mechanism becomes a factor in deposit formation. Sulfate-based bonding is characteristic of convective-pass fouling problems when firing coals containing high levels of alkali and alkaline-earth elements. A sulfated matrix can be very strong, and difficult to remove using sootblowing techniques.

The formation of deposits that are strongly bonded to heat transfer surfaces depends upon the following: characteristics of the reacted layers on the steel surface (formation of the reactive layers depends on the type of steel and the ash characteristics); steel surface temperature; ash particle melting behavior; and the thermal and chemical compatibility of the deposit and steel surface (surface layers of steel/residual ash).

Deposit strength development is due to sintering processes that involve the flow of liquid phase materials and condensation and/or reaction of gas phase species with deposited particles. The sintering process involves one or more stages–the first stage is neck growth between particles, which occurs when a thin liquid layer is formed between the deposited hollow, vesicular, or solid particles, and the meniscus tends to pull the particles together. This results in the rearrangement of particles by sliding and the formation of closed pores and voids. The degree to which sintering

occurs will depend upon the temperature of the system, the reactivity of the deposited ash particles, the size distribution of the ash particles, the potential for crystallization, and the gaseous environment in the vicinity of the deposit.

Deposit thermal properties, including thermal conductivity, emissivity, and porosity, change as the ash deposit grows and matures. A deposit-free tube surface has a high emissivity. As ash is deposited, the emissivity decreases, but increases again as the deposit surface transitions to a flowing slag.

Thermal conductivity is a strong function of deposit temperature and its physical structure (porosity), and a weak function of the deposit chemistry. Temperature history (temperature changes over time) is important in that sintering among deposited ash particles will irreversibly result in porosity and/or density changes. Thermal conductivity would generally be low for the initial (porous) deposit layer, increase gradually to a moderate value for the middle sintered layer, and eventually reach a maximum value corresponding to the final outer slagging layer.

The thermal and mechanical properties of slags have significant impacts on the ability to remove deposits with various cleaning devices such as sootblowers. Deposits (water walls and convective pass) consist of complex materials that contain pores, unreacted ash particles, amorphous glassy phases, and crystalline phases. The characteristics of the deposited materials will depend upon the fuel composition, plant operating conditions, and location within the boiler.

Soot blowing relies on using a combination of thermal and mechanical shock to fracture the deposit. Crack propagation in slag is dependent upon a rapid change in temperature. The slag composition, crystallinity, and porosity will affect the ability to thermally shock a deposit to the point of fracture.

Thermal conductivity decreases with an increase in porosity, and increases with increasing temperature. Crack propagation is considered to be easier in highly porous, glassy slag deposits. A lower-porosity and higher-crystalline-content slag deposit would be more resistant to fracture. Slag compressive strength is also related to porosity. The resistance to fracture was found to decrease significantly for slags having a porosity of less than 25%.

There exist several methods of on-line ash deposit removal. They include sootblowers, water cannons, sonic horns, and pulse detonation technologies.

Sootblowers are used to clean radiant water walls and convective pass tubes in utility boilers. They can be wall blowers, which have a retractable lance that extends into the radiant section, or long retractable blowers to clean tube banks in the convective pass. Working fluids in sootblowers can be steam, air, or water. Steam sootblowers are the most common; the steam pressure is generally around 200 to 250 psig. Air sootblowers are not common; air pressure is usually around 180 psig. Steam is considered to be superior to air due to its higher kinetic energy at the same pressure. Water is also not extensively used for wall blowers, and rarely for long, retractable blowers. Water has the potential to provide high-impact energy and efficient cleaning, but it also carries the risk of tube damage and thermal shock failure.

The ability of a sootblower to remove deposits is related to the force of the sootblowing medium on the deposit. The measure of sootblower effectiveness is the peak impact pressure (PIP). This is the stagnation pressure along the nozzle centerline at a given distance from the outlet of the

sootblower nozzle. The PIP decreases with distance from the nozzle. The force required for deposit removal can be estimated from the sootblower PIP, distance from the nozzle, the typical effective cleaning radius, and deposit tensile strength. The minimum cleaning radius for long retractable sootblowers is four feet (about 120 cm). At that minimum cleaning radius, indicative of deposits most difficult to remove, typical PIP values would range from 10 to 22 psi.

Ash deposit removal by sootblowers is related to the PIP that is delivered to the deposit, the deposit tensile strength, and the angle of impaction of the jet. The deposit tensile strength has an influence on the distance, and therefore, pressure, from the jet required to fracture the deposit. As tensile strength increases, the pressure required to fracture the deposit also increases as a function of that strength. At a normal impaction angle, the PIP would need to be more than two times that of the deposit tensile strength. At another angle, the PIP would depend on the deposit tensile strength and the angle.

A water cannon or water blower is similar to a water sootblower, but it directs the water jet across the furnace box, and in a rastering pattern. Water pressure is typically around 175 psig; cleaning is due to a combination of water impact force and thermal shock. Water cannons have many advantages, especially with respect to the ability to adjust the settings (frequency, dwell time in certain locations, etc.) but also carry the concern for thermal shock, and damage, to the waterwall tubes.

Sonic horns, or acoustic sootblowers, became more popular during the past fifteen years. They operate by using sound pressure at about 150 decibels to acoustically shock deposits from tube surfaces. They are most effective with very loosely-sintered, or powdery, ash, and are therefore mainly used in very low-temperature regions of a boiler (such as the electrostatic precipitator, the baghouse, or selective catalytic reduction reactors). They require frequent operation in order to be effective; infrequent use can allow ash time to sinter and develop strength. They have advantages with regard to areas reached: they are able to remove deposits from all surfaces, and with regard to operating cost. They are not able to remove deposits with any degree of strength, however, and there is potential for damage or other upset from resonant vibrations.

Pulse detonation is an emerging technology, in which a pressure wave is used to remove deposits from boiler surfaces. It is similar in operation to a sonic horn, but uses a much higher peak pressure. This higher pressure allows pulse detonation to remove bonded and adhered deposits. The detonation wave is produced through the ignition of a fuel-air mixture in an external chamber. Pulse detonation technology has been successfully tested in several industrial boiler applications in Russia, and in utility boilers in Bosnia, and in air pre-heater surfaces of full-scale utility boilers in China. The detonation pulse should be able to effectively clean tube back-sides as well as sides facing the pulse, based on computation fluid dynamics analysis. Because of this, pulse detonation cleaning should be a good technology for cleaning large areas, and areas inaccessible to conventional sootblowing devices. Like sonic horns, there is the potential for tube damage from the pressure wave. Pulse detonation technology has been patented by several groups, and is commercialized by Pratt & Whitney.

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