

RECOVERY BOILER FIRESIDE DEPOSITS AND PLUGGING PREVENTION

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ABSTRACT

Massive deposit accumulation on tube surfaces in the upper furnace of a recovery boiler greatly reduces the boiler thermal performance and may lead to unscheduled boiler shutdowns due to plugging of flue gas passages. Understanding how deposits form, grow, become resistant to sootblowing, and ultimately plug the boiler, can help kraft mills devise better solutions to their specific plugging problems.

INTRODUCTION

Black liquor, on a dry mass basis, contains 40 to 50% inorganic materials, which upon combustion, form a low-melting temperature "ash" or smelt. The large quantity and the low melting temperature of the ash make black liquor one of the most troublesome industrial fuels used for steam and power generation. Deposition of fly-ash on tube surfaces in the upper furnace of recovery boilers is a persistent problem in many kraft pulp mills. Massive deposit accumulation greatly reduces the boiler thermal efficiency, may create a corrosive environment at the tube surface, and in severe cases, may completely plug the flue gas passages, leading to unscheduled shutdown of the boiler.

In recent years, advances in sootblower design and improved air delivery systems have helped markedly decrease problems associated with deposit build-up. However, as the boiler performance is improved, boilers are often pushed to higher liquor loads. This results in more fly ash, higher flue gas temperatures and more deposit build-up. This "moving target" makes deposit control a great challenge for recovery boiler operators.

This paper first reviews the basic characteristics of deposits, how they form, grow and ultimately plug the flue gas passages in different regions in the boiler, then discusses the possible preventive measures for each type of plugging. A more comprehensive discussion on this subject is available in Chapter 9 of the book, "Kraft Recovery Boilers", by Adams et al [1].

DEPOSIT FORMATION

Deposits are derived from three different sources: carryover, fume, and intermediate sized particles.

Carryover deposits are formed by inertial impaction on the tube surface of relatively large (0.01 to 3 mm) molten or partially molten smelt particles, and/or particles of partially-burned black liquor solids entrained in the flue gas. Carryover deposits are smelt-like; usually pink, fused and very hard (Figure 1).

Fume deposits are formed as a result of the condensation of vapours of sodium and potassium compounds in the flue gas. Condensation may occur in two ways: directly from the gas phase to form fine fume particles on the cooled surface, or indirectly to form fume particles in the flue gas stream, which are then transferred to the cool surfaces by turbulent deposition. Fume particles have a fairly uniform size distribution, varying from 0.1 to 1 μm . Fume deposits are white and usually soft (Figure 1).

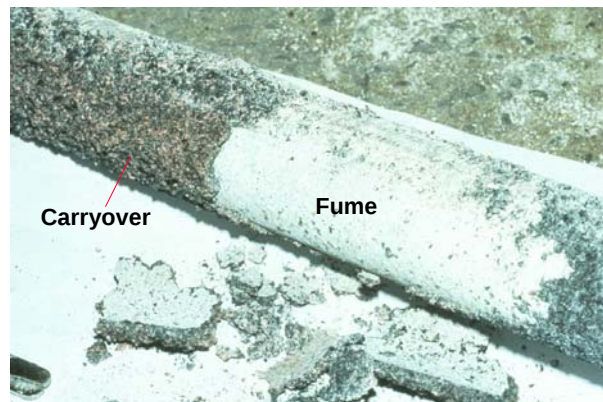


Figure 1. Carryover and fume deposits on an air-cooled probe in the superheater region.

Deposits are also derived from small, 1 to 100 μm , molten or partially molten smelt particles entrained in the flue gas. The formation mechanism of these Intermediate Sized Particles (ISP) is not well understood, although they are believed to form as a result of fragmentation of black liquor droplets during combustion and/or ejection of material from molten smelt pool during char burning [2,3]. Figure 2 shows a SEM photograph of ISP formed on an air-cooled probe in a char-burning apparatus (3). ISP deposits generally have a similar appearance as carryover deposits, although they are usually white or grey, and contain no char.

Due to the difference in particle size, carryover and ISP deposits tend to form on the leading edge (windward side) of tubes whereas fume deposits tend to form on the back or leeward side of the tubes.

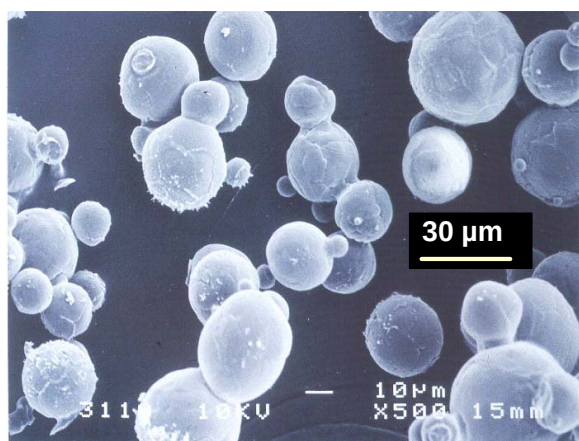


Figure 2. SEM photograph of intermediate sized particles on an air-cooled probe in a laboratory char burning apparatus.

Deposits are a mixture of carryover, ISP, and fume in proportions that vary with location in the furnace. In the lower superheater region near the bullnose, where the flue gas temperature is high and where most vapours do not condense due to the short residence time, carryover and ISP are the dominant types of deposits on the windward side of the tube (Figure 3). In the upper superheater region close to the generating bank inlet, the flue gas temperature is lower, allowing some vapours to condense to form fume. As a result, windward deposits in this region also contain some fume. In the back half of the generating bank and in the economizer region where the flue gas temperature is below 500°C, fume becomes dominant because i) most vapours condense to form fume, ii) a large amount of carryover and ISP particles has already been “screened out” by tubes upstream, and iii) carryover and ISP particles are completely solidified and do not stick readily to tube surfaces.

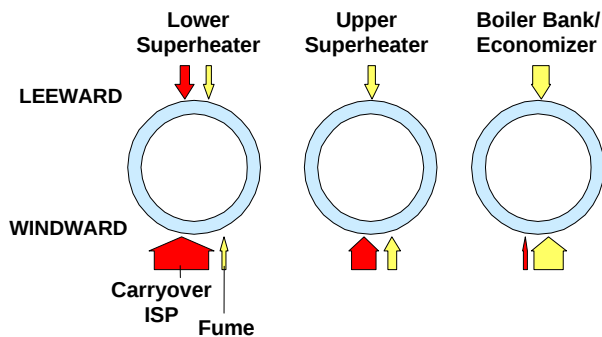


Figure 3. Preferential formation of carryover, ISP and fume deposits in a recovery boiler

Carryover, ISP and fume particles form a stream of dust, some of which is collected by ash hoppers at the bottom of the generating bank and economizer and/or by an electrostatic precipitator prior to discharge of the flue gas

to the atmosphere. The recovered dust is mixed with strong black liquor in the mixing tank and returned to the furnace (Figure 4). This internal dust recycle typically accounts for 2 to 10 wt% of the as-fired black liquor dry solids. A portion of the dust also ends up as deposits on tube surfaces; which are occasionally knocked off by sootblowers and fall to the char bed or into the ash hoppers. Only a small amount of the dust is lost as particulate emissions with the stack gas.

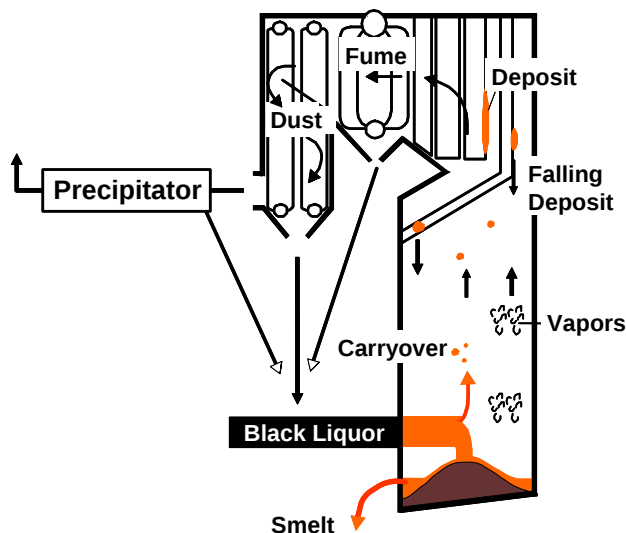


Figure 4. Internal recycle dust stream

Dust from the precipitator is usually very fine, consisting of mostly sub-micron sized particles since it results directly from condensation of vapours in the gas stream. Dust from ash hoppers is coarser because it also contains pieces of agglomerated, sintered deposits which have been removed from tube surfaces by sootblowers.

DEPOSIT CHEMISTRY

Deposits consist of more than 99 wt% water-soluble alkali compounds, mainly sodium sulphate (Na_2SO_4) and sodium carbonate (Na_2CO_3) with a small amount of sodium chloride (NaCl), and reduced sulphur compounds, such as Na_2S . Potassium (K) is also present as a substitute for sodium.

The composition of deposits depends on many factors, including the composition of as-fired black liquor, firing conditions in the lower furnace, location in the boiler, location on the tubes, as well as mechanisms by which the deposit is formed. For example, the potassium concentration in deposits may vary from 2 to 10 wt% K, depending on the type of wood being pulped at the individual mill [4]. Similarly, the NaCl concentration in deposits depends strongly on the Cl input to the mill. It may be as low as 0.5 wt% as Cl in some cases, and be higher than 10 wt% Cl at mills where sea-borne logs are used.

Because of the wide variation in composition of black liquors and deposits from mill to mill, there is no truly "typical" deposit composition. For example purposes below, the deposit composition that may be typical for a boiler at an inland mill operating at 28% white liquor sulphidity (on active alkali) and at a relatively hot char bed will be used. At such a mill, the as-fired black liquor would contain 18 to 20 wt% Na, 4 to 5 wt% S, 0.8 to 1.2 wt% K and 0.4 to 0.6 wt% Cl on dry solids.

Carryover Composition

As carryover particles travel to the upper furnace, where oxidizing conditions prevail, most of the Na_2S in the particles is oxidized to Na_2SO_4 . The composition of carryover deposits should initially be the same as oxidized smelt (Figure 5a). After deposition, a portion of the Na_2CO_3 content in the deposit may react with SO_2 and SO_3 in the flue gas to form Na_2SO_4 . Chlorides may be depleted slowly by vaporization and by conversion to sulphates.

A "typical" carryover deposit thus has a composition shown in Figure 5b. It contains much less carbonate, slightly less chloride, and much more sulphate than oxidized smelt. Since potassium would not change as a result of either oxidation or sulphation, the potassium content of the carryover deposit is essentially the same as in oxidized smelt.

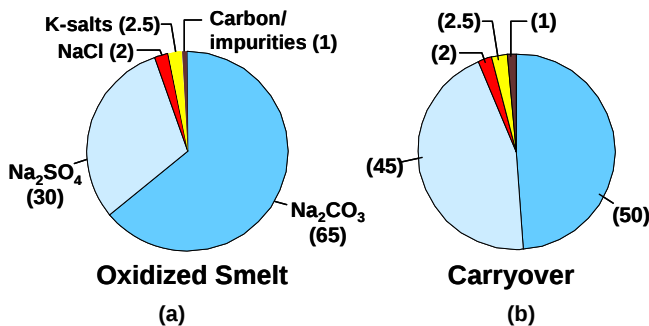


Figure 5. Composition (wt%) of oxidized smelt and carryover deposit

Fume Composition

Fume consists of sub-micron sized particles and so is very reactive. In the lower furnace, where reducing conditions and high temperatures prevail, the sulphur in the gas phase is mainly in the form of reduced sulphur gases such as H_2S . As shown in Figure 6a, Fume deposits contain significant amounts of alkali hydroxides (NaOH and KOH) and carbonates [5].

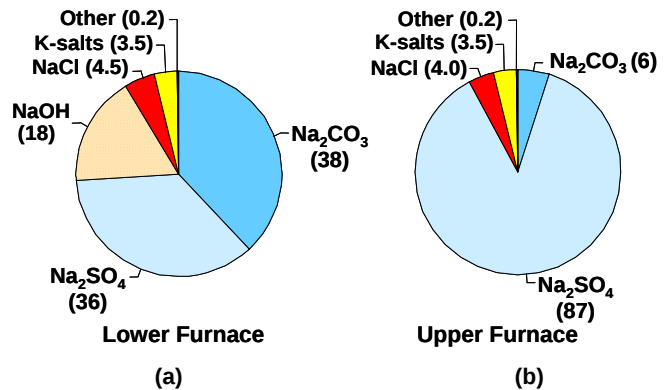


Figure 6. Composition (wt%) of fume deposits

In the upper boiler, the oxidizing atmosphere converts H_2S in the flue gas to SO_2 which in turn reacts with hydroxides to form sulphates. Most carbonates and some chlorides are also sulphated, but have a slower sulphation kinetics compared to the hydroxides. Fume deposits in the region from the bullnose elevation onward contain mostly sulphates, some carbonates and chlorides, and no hydroxides or reduced sulphur compounds (Figure 6b). Because of the sulphation reactions and the high volatility of NaCl and KCl in the lower furnace, fume deposits usually contain more sulphate, chloride, potassium, and less carbonate than carryover deposits.

ISP Composition

Since it is difficult to isolate ISP from carryover and fume, the exact composition of ISP is not known. However, because of the small particle size, ISP deposits are expected to have a composition similar to carryover deposits with lower chloride, lower potassium, lower carbonate, and higher sulphate contents, and with no sulphide.

Deposit Composition

The composition of deposits lies between that of carryover and fume, with sulphate and carbonate content varying widely with location in the boiler. In the lower superheater, where carryover and ISP are dominant, the deposit composition is closer to that of carryover. In the generating bank and the back side of the boiler where the flue gas temperature is low, fume becomes more significant and thus the deposit chemistry is closer to that of fume. Deposits may react with SO_2 and SO_3 in the flue gas, converting some carbonate and chloride to sulphate. Figure 7 shows typical compositions of deposits at various locations in the boiler. The carbonate content in deposits decreases dramatically toward the back side of the boiler.

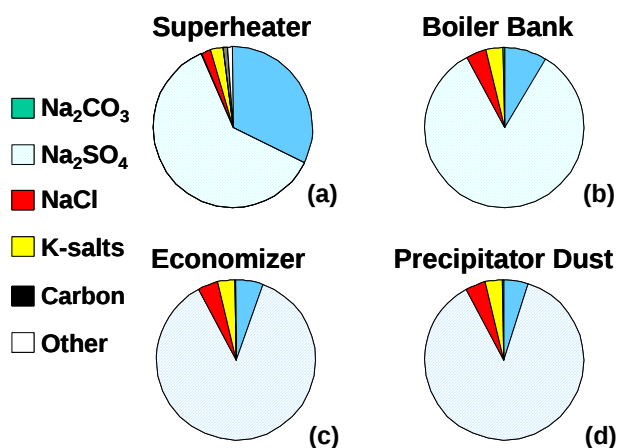


Figure 7. Compositions (wt%) of deposits at different locations

Precipitator Dust Composition

Precipitator dust is the portion of carryover, ISP and fume which has made its way through the boiler and is captured by the electrostatic precipitator. As carryover and ISP travels through the boiler, a significant portion of them is caught by superheater tubes and returned to the smelt bed (Figure 4); more is captured in the boiler bank and economizer and ends up in the ash hoppers. Only the finest particles (mostly ISP) travel all the way to the precipitator. On the other hand, fume, due to its small particle size, tends to follow the flue gas stream and is not captured by the tubes. It has been estimated that precipitator dust contains about 95 wt% fume and 5 wt% carryover and ISP. This makes the composition of the precipitator dust similar to that of fume in the upper boiler; it consists of Na_2SO_4 with some Na_2CO_3 , and is enriched in chloride and potassium (Figure 7d).

Fume composition is greatly influenced by the bed temperature in the lower furnace, the liquor sulphidity and by the concentration of the volatile components in the liquor. For example, boilers operating at high bed temperatures produce more fume and fume which contains more carbonate and less sulphate [6].

DEPOSIT MELTING BEHAVIOUR

Melting Temperatures

Like most mixtures of chemical compounds, recovery boiler deposits have two distinct melting temperatures. The first melting temperature is the temperature at which the deposit begins to melt and below which there is no liquid phase in the deposit. The complete melting temperature is the temperature above which the deposit is completely molten. Between these two extremes, lie two other important temperatures: the sticky temperature, T_{STK} , at which the deposit becomes sticky because it

contains 15 to 20% liquid phase, and the radical deformation temperature, T_{RD} , (or slagging temperature) at which the deposit contains about 70% liquid phase and is so fluid that it can run off due to its own weight.

These temperatures can be visualized with the aid of Figure 8, which schematically shows changes in appearance of a cone made of a typical superheater deposit as temperature increases.

The sticky temperature is an important parameter determining the rate of deposition in the region upstream of the generating bank. Stickiness is a strong function of deposit temperature, composition, particle size and velocity. Tube surface conditions also have a great impact on stickiness. Carryover particles are less sticky when they are covered with a layer of condensation, and/or when they are mixed with a large amount of unburned black liquor particles.

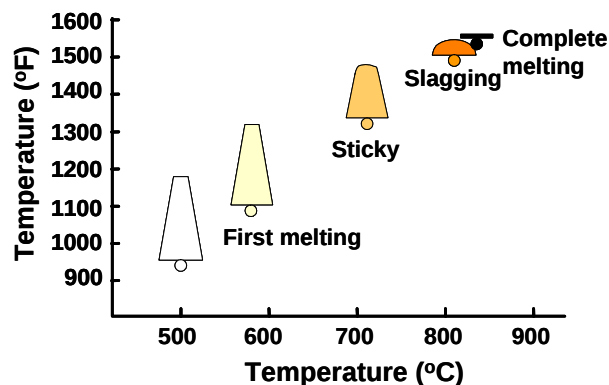


Figure 8. Appearance of a deposit cone at various temperatures

In order for a deposit to be sticky, it must contain a certain amount of liquid phase, which increases with both increasing temperature and chloride content at temperatures above the first melting temperature. As the amount of liquid phase in the deposit reaches 70% at the radical deformation temperature, deposit accumulation may cease because fresh deposits simply melt and run off [7].

Effect of Cl and K on Sticky Temperatures

Figure 9 shows the sticky temperature zone as a function of chloride content for a typical carryover deposit containing 5 mole% $\text{K}/(\text{Na}+\text{K})$. The sticky temperature zone is defined by the sticky temperature curve as a lower limit and the radical deformation temperature curve as an upper limit. In this zone, deposits are sticky, and so massive deposit accumulation is expected. Outside the sticky zone, deposits either have little liquid phase to be sticky, or have so much liquid phase that they slag and do not build up.

Figure 10 shows the sticky temperature of carryover

deposits as a function of both chloride and potassium. The sticky temperature is significantly lowered as chloride content increases from 0 to 5 mole% Cl/(Na+K). The effect of potassium, on the other hand, is much less dramatic, particularly when the chloride content is below 1.5 mole% Cl/(Na+K).

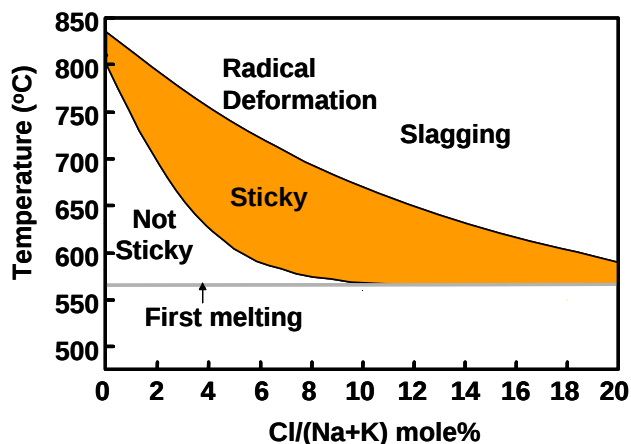


Figure 9. Effect of chloride on sticky temperature zone of deposits containing 5 mole% K/(Na+K)

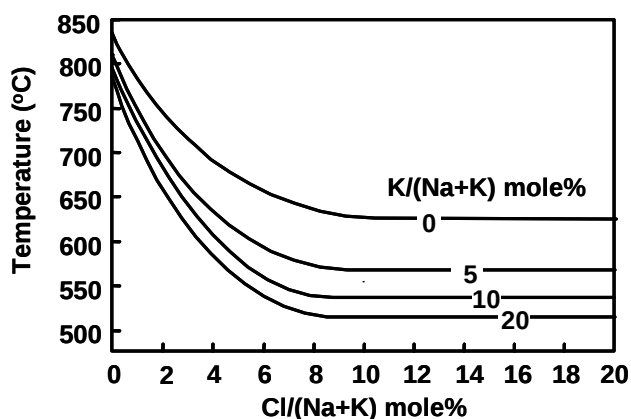


Figure 10. Effect of chloride on deposit sticky temperature at various potassium levels

As with sticky temperature, the radical deformation temperature is a function of the amount of liquid phase in deposits, and so is strongly influenced by the chloride content. This temperature is important because, together with steam temperature, it determines the thickness of deposits in the lower superheater where high flue gas temperatures prevail [1,7]. Increasing radical deformation temperature and/or decreasing steam temperature results in a thicker deposit.

It is important to note that Figures 9 and 10 should be used as a guideline only to assess the effects of Cl and K on recovery boiler fouling and plugging, and should not

be used in an absolute sense. This is because the data was obtained under static conditions in the laboratory [8,9]. In operating boilers, the deposit stickiness may be affected by many other factors; including particle temperature, tube surface condition and flue gas velocity. For example, when the deposition surface is covered with a layer of fume and/or a large amount of partially burned black liquor residue, a higher amount of liquid phase, thus a higher flue gas temperature, may be required to make carryover particles sticky. Further, since the ability of carryover particles to adhere usually increases with increasing flue gas velocity [10], increasing the black liquor firing load not only increases the flue gas temperature but also increases the gas velocity, which in turn, may cause carryover particles to deposit at lower temperatures.

Effects of Other Components

Since Na_2CO_3 and Na_2SO_4 are the major components in deposits, varying their relative concentration has little effect on deposit thermal properties. The phase equilibrium of the system Na_2CO_3 - Na_2SO_4 [11] suggests that in the absence of chloride, the deposit first melting and complete melting temperatures are very close to each other, in the range of 825 to 870°C (1520 to 1800°F) over the full range of carbonate content from 0 to 100 wt%. Laboratory tests [8,9] have also shown that the sticky temperature of a synthetic deposit made of Na_2SO_4 and Na_2CO_3 is about 825°C (1800°F), and is independent of the $\text{Na}_2\text{SO}_4/\text{Na}_2\text{CO}_3$ ratio.

Carryover particles may contain some Na_2S , particularly in the lower superheater where they are still burning. Above 740°C (1360°F), the first melting temperature of the Na_2SO_4 - Na_2S - Na_2CO_3 system, a higher Na_2S content can result in a larger amount of liquid phase and thereby resulting in a stickier deposit [12]. In the superheater region near the generating bank inlet, Na_2S is expected to have an insignificant effect on deposit stickiness. This is because of the flue gas temperature is usually lower than 700°C (1290°F), and oxidizing conditions prevail causing Na_2S to oxidize. In these regions, the effect of Cl and K becomes dominant.

Impurities may also lower the deposit melting temperature. Due to their low concentrations, <0.5 wt%, impurities are unlikely to have a significant effect on the amount of liquid phase, thus on the deposit sticky temperature [1].

DEPOSIT SINTERING

Fluffy, dust-like fume deposits may become hard and resistant to sootblowing through *sintering*, a diffusional process that can occur at temperatures below the first melting point of the fume. During a sintering process, particles become bonded together; and a grain boundary replaces the two original surfaces of the touching particles in order to reduce the total surface energy. Material diffuses

initially along the particle surfaces to points of contact, forming "bridges" between particles (Figure 11). Subsequent diffusion of material causes densification and an appreciable increase in strength.

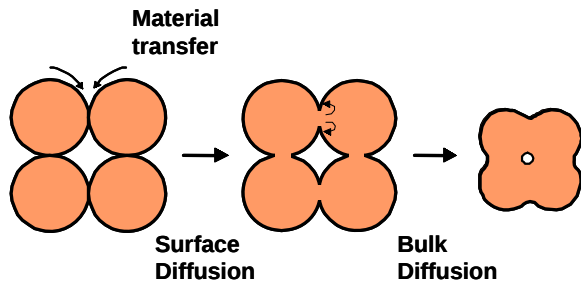


Figure 11. Schematic of the sintering process

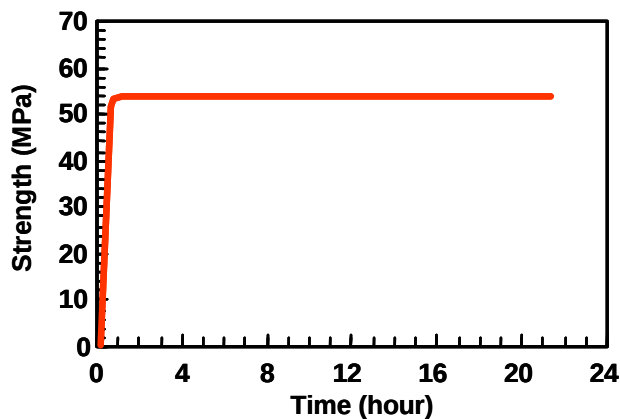


Figure 12. Compressive strength of dust pellets sintered at 500°C for various lengths of time

Fume, due to its submicron size, can sinter rapidly. Laboratory and field tests [13] using precipitator dust have shown that the dust starts to sinter at about 300°C (570°F) and becomes very hard in less than one hour if it is exposed to temperatures above 500°C (930°F) (Figure 12). A comparison of compressive strengths of sintered dusts and other familiar materials indicates that a sintered dust can be as hard as cement (Figure 13).

Material	Compressive Strength MPa
Glass	800 – 2000
Fired brick	70
Cement	30 – 60
Sintered dust	50
Insulating brick	7
Unsintered dust	<2

Figure 13. Compressive strength comparison

DEPOSIT MECHANICAL PROPERTIES

As shown in Figure 14, deposits are brittle below their first melting temperature, which varies between 520°C and 600°C, depending mainly on the potassium content. At higher temperatures, the deposit becomes fluid or "plastic", and consequently cannot be removed readily by sootblowers [14].

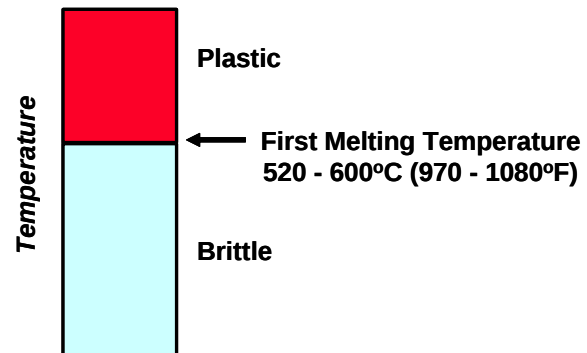


Figure 14. Deposit Mechanical Properties

OCCURRENCE OF PLUGGING

Since the deposit chemistry, deposit formation mechanisms and flue gas flow characteristics vary greatly with location in the boiler, and between boilers, there is no plugging pattern which is applicable to all cases. Plugging occurs differently throughout the boiler depending on how deposits form and grow, and how they are removed by sootblowers. For this reason, the occurrence of plugging, which is generalized below, may be somewhat different.

Plugging in the Superheater

In the lower superheater, the flue gas temperature is usually higher than 820°C (1510°F). Carryover particles may still be burning (sparklers) and be at a higher temperature than the surrounding flue gas. Carryover and ISP are molten droplets, which strike and solidify on the tubes to form fused and hard deposits. As the deposit grows thicker, the outer surface temperature increases until it reaches the radical deformation temperature at which point the surface becomes fluid, slags and thus stops growing. Under such conditions, deposit thickness is self-limiting, that is, no accumulation occurs after the deposit reaches a certain thickness. Plugging thus does not occur in this region despite the fused, hard and adherent nature of underlying deposits.

In the higher superheater and in the region closer to the boiler bank, the flue gas temperature falls within the deposit sticky temperature zone (Figure 9). Carryover particles and ISP are always sticky, forming deposits that will continue to grow and will not be self-limiting, since their surface temperature is lower than the radical deformation

temperature. In this region, therefore, massive deposit accumulation likely occurs if sootblowing is insufficient. The deposits usually form heavily on the tube leading edge due to the impaction of molten/partially molten carryover particles. They may eventually bridge the spacing between adjacent superheater platens (Figure 15).

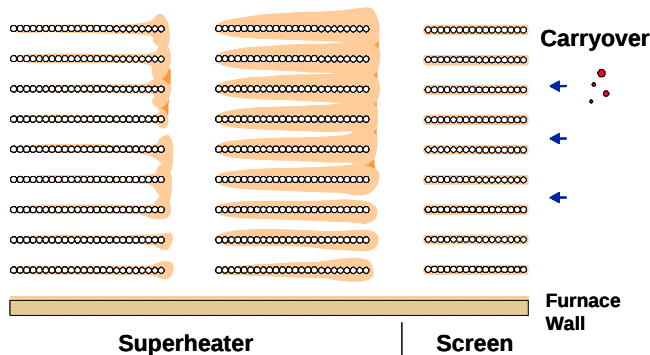


Figure 15. Deposit accumulation pattern in superheater region

Plugging in the Generating Bank

The most commonly experienced plugging is the one that occurs at the boiler bank inlet. This is primarily due to the narrow tube spacing that causes a sudden restriction of the flue gas flow at this location.

The flue gas temperature is typically in the range of 550 to 700°C (930 to 1290°F), depending on the degree of fouling in the superheater. Carryover particles may or may not be sticky depending on their composition and whether or not they are mixed with fume. Plugging in this region is highly likely if the carryover is sticky, due to either high flue gas temperatures or high chloride content.

Plugging at the boiler bank inlet is often a result of high flue gas temperature caused by the severe fouling in the superheater region. Figure 16 schematically shows how fouling in the superheater may lead to plugging at the boiler bank inlet. When the boiler is clean (just after a waterwash, for example), the sticky temperature (T_{STK}) curve and the radical deformation temperature (T_{RD}) curve, which define the massive deposit accumulation zone, are located in the lower superheater (Figure 16a). As deposits accumulate in the sticky zone, the flue gas temperature in this region increases and thus shifting the T_{STK} curve toward the boiler bank. The T_{RD} curve is also shifted in the same direction but only slightly. This is because the flue gas temperature in the region upstream of the T_{RD} curve is high and thus the deposit thickness remains more or less constant, resulting in the same heat transfer to the waterwall and heat transfer surfaces.

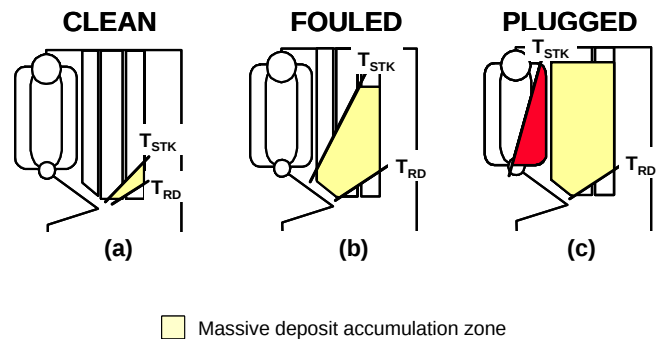


Figure 16. Spreading of deposit sticky zone with time

This shift of the sticky temperature curve toward the back side of the boiler causes the deposit accumulation zone to “spread out” with time (Figure 16b). Plugging eventually occurs as the deposit accumulation zone spreads to the boiler bank where the flue gas passages are much narrower than in the superheater area (Figure 16c). Figures 17 and 18 respectively show massive deposit accumulation on superheater platens and complete plugging of flue gas passages at the boiler bank inlet.

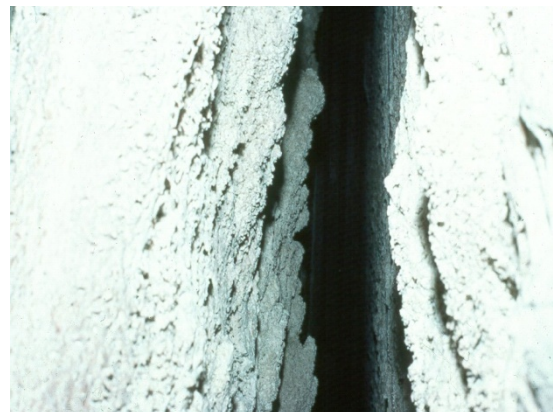


Figure 17. Massive deposit accumulation pattern on superheater platens



Figure 18. Complete plugging at the generating bank inlet

Plugging at the center of the generating bank has been experienced at several mills. It may occur as follows. Consider the case of a 6200 KPa (900 psi) steam pressure boiler where the flue gas temperature entering the boiler bank is 600°C (1110°F), and leaving is about 400°C (730°F). The tube surface temperature is lower than 300°C (570°F) due to the saturated steam temperature inside, 278°C (531°F). This low temperature allows fume to form directly on the tube surface. As the deposit layer thickens, its outer surface temperature rises and sintering occurs (Figure 19). The outer layer may become hard while the inner layer adjacent to the tube remains unsintered and soft. Such deposits can still be removed from the tubes by sootblowers because of the weak bonding between the soft, friable inner layer and the tubes.

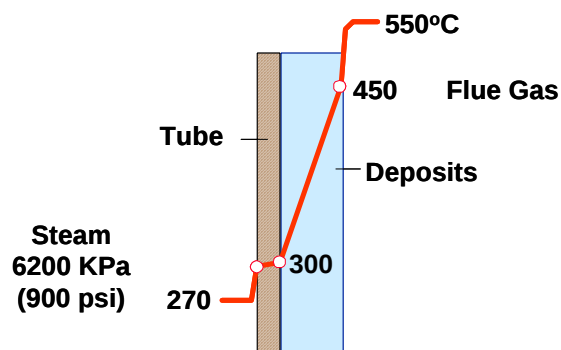


Figure 19. Temperature across a generating bank tube and deposit layer

However, sintering can occur rapidly in cases where deposits are not effectively cooled by the tubes:

- *"Jammed" deposits* - Large pieces of deposits, which have been removed from the tubes in the upper part of the boiler by sootblowers, fall and lodge between tubes in the lower part (Figure 20).
- *Twisted deposits* - Long columns of deposits may be twisted and separated from the tubes as a result of vibration caused by sootblowers.
- *Deposits on stabilizing bars* - These horizontal bars are not cooled.
- *Deposits on sealed tubes* - Some boiler bank tubes may have been deliberately plugged in response to tube leakage. These tubes are not cooled since there is no steam flowing inside.
- *Deposits on mud drum* - The mud drum is a common place for falling deposits to accumulate.



Figure 20. Jammed deposits between tubes in the generating bank

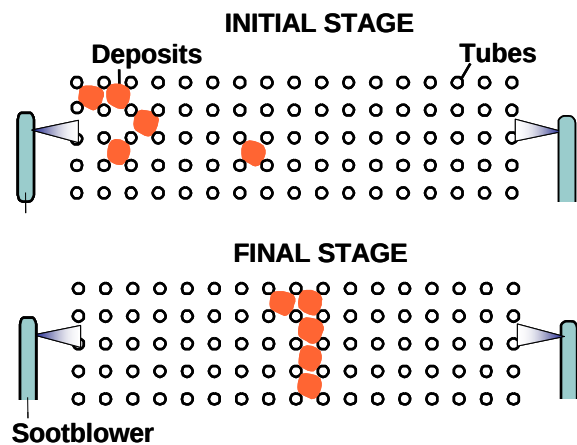


Figure 21. Progression of deposit buildup in the middle of the generating bank

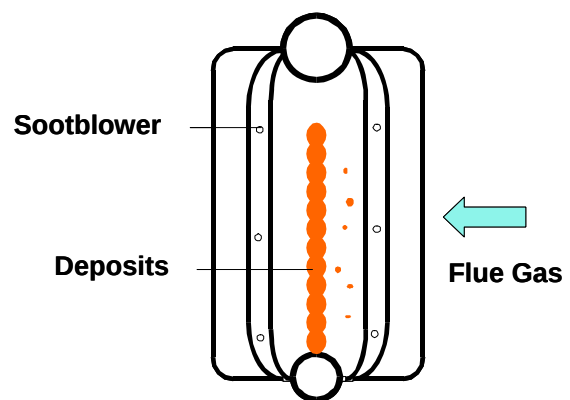


Figure 22. Formation of deposit "curtain" in the middle of the generating bank



Figure 23. Complete plugging in the middle of the generating bank

These deposits receive little or no cooling from the tubes and will sinter. Jammed deposits may be "pushed" toward the center of the boiler bank by sootblowers on both sides of the boiler mid-bank (Figure 21). This forms a "curtain" in the center of the generating bank which collects more deposits and leads eventually to complete plugging at this location (Figures 22 and 23)

Single-drum boilers have also experienced plugging in the generating bank. The problem is usually a result of sintering of fume deposits on uncooled stabilizing bars.

Plugging in the Economizer

Plugging may occur in the economizer, particularly when there is no sootblower at the economizer entrance (Figure 24). The exact cause of plugging in this region is not clear, although it cannot possibly be carryover because the amount of carryover in this region is small and the flue gas temperature is too low to make carryover sticky.

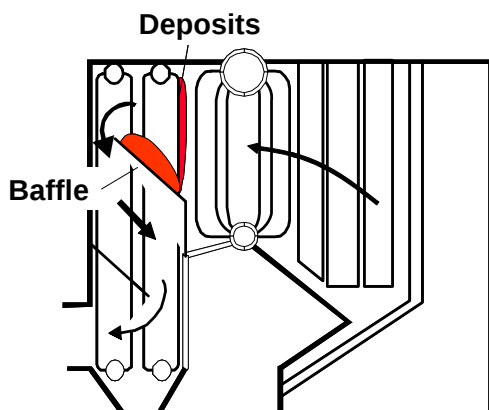
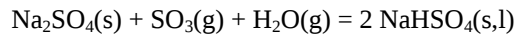


Figure 24. Plugging in the economizer

A possible explanation is that it may be caused by acidic sulphates, mainly sodium bisulphate (NaHSO_4) formed as a result of the reaction between the Na_2SO_4 in the fume and the SO_x and water vapour in the flue gas [15,16], i.e.



This reaction is preferred under high SO_2/SO_3 concentration in the flue gas, particularly in boilers that burn high sulphidity liquor and have low bed temperatures [6]. The resulting acidic sulphates may form a stable molten phase at temperatures prevailing in the economizer region, making the dust sticky and promoting deposit accumulation and sintering.

Plugging may also occur at the entrance to the first path of the economizer by impaction, since there is an abrupt change in the flue gas flow direction due to a baffle, and particularly when the flue gas temperature is higher than 400°C . Deposits accumulated on the uncooled baffle may sinter and harden.

DEPOSIT CLEANING

Sootblowers

The principal means of on-line deposit removal is sootblowers which periodically blast deposits with high pressure steam. During boiler outages, hot water, rather than steam, is sprayed through sootblower nozzles to wash off deposits.

A sootblower consists of a lance tube inserted into, and rotated in the spacing between tube banks. The lance tube has two opposing nozzles at its working end (Figure 25). The ability of a sootblower to remove deposits is correlated with the peak impact pressure (PIP) of the jet, which is the stagnant pressure measured along the nozzle centreline downstream of the nozzle. PIP decreases rapidly in the jet axial direction due to the turbulent entrainment of surrounding fluid and consequent decay of the jet kinetic energy.

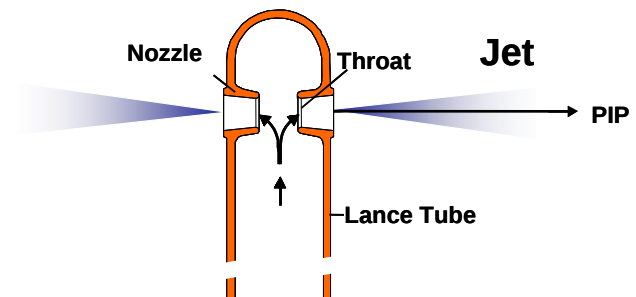


Figure 25. Schematic of a sootblower lance tube

For old type, Hi-PIP nozzles (Figure 26a), the steam velocity at the nozzle throat is supersonic. As the steam jet passes through the throat, it expands and accelerates to a velocity well above the speed of sound, and its pressure decreases in a manner controlled by the geometry of the divergent section of the nozzle. The divergent section of the nozzle and the short distance between the throat and the nozzle exit make it impossible for the jet to adjust its exit pressure to the ambient pressure. The jet is said to be “underexpanded”, and thus must complete its expansion outside the nozzle through a series of oblique expansion and compression waves, known as *shock wave*. As a result, a substantial proportion of the jet kinetic energy is converted into internal energy, causing a significant decrease in PIP [17].

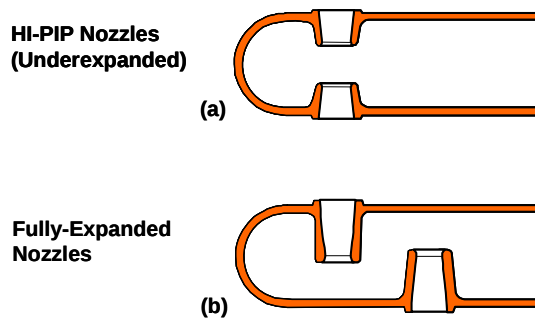


Figure 26. Schematic of sootblower nozzles

Over the past decade, several new types of sootblower nozzles have been developed which allow the jet to achieve full (or close-to-full) expansion before it exits the nozzle [18,19]. Fully expanded nozzles (Figure 26b) differ from underexpanded nozzles in that the distance between the throat and the nozzle exit is much longer, and the contour of the divergent section is carefully designed instead of just being a conical shape. Since fully expanded nozzles have much smaller jet kinetic energy losses, they provide a much greater PIP than underexpanded nozzles (Figure 27).

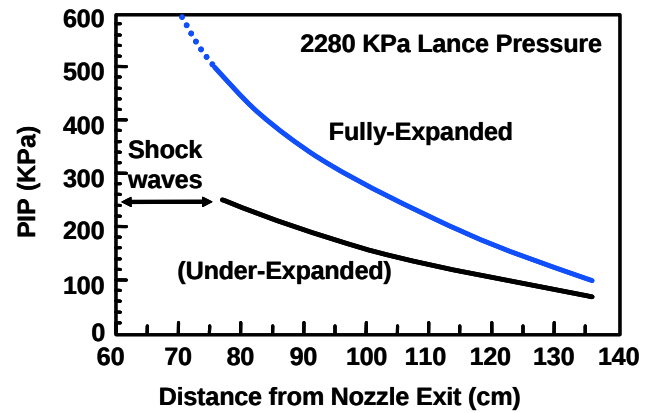


Figure 27. Peak Impact Pressure versus distance from nozzle exit

Sootblowing Optimization

Deposit removal efficiency and steam savings can be maximized by optimizing sootblowing operation [18, 19,20]. In planning a strategy for sootblowing, the variations in deposit chemistry and accumulation characteristics with location in the boiler must be taken into consideration. The principal rules are listed below:

- Sootblowing is not needed in regions such as screen tubes and the lower superheater where the flue gas temperature is higher than 820°C (1500°F). This is because deposits will not grow further after reaching a steady state thickness, and besides they are too hard and too tenacious to be removed by the sootblowers anyway.
- In the higher superheater where massive deposit accumulation normally occurs, sootblowing must be performed more frequently in this region in order to lower the flue gas temperature entering the generating bank.
- In the first half of the generating bank, deposits are difficult to remove because of the narrow tube spacing, and thus maximum sootblowing energy is required.
- In the economizer, sootblowing can be less frequent and low-energy sootblowing is more than sufficient.

Deposit Cleaning by Thermal Shock

In order to prolong the time between washouts, many mills employ a “*Thermal Shock*” practice to remove deposits. The practice involves turning off the black liquor flow in order to rapidly cool the deposits. This causes deposits to contract, crack, and become separated from the tubes so that they can easily be blown off by sootblowers [21].

Thermal shock is inevitably carried out in all boilers when there is a sudden reduction in firing load, from a power failure or from problems at other parts of the boiler or the mill. Since such an event may also cause unnecessary "shock" to the tubes, proper procedures must be followed so that deposits can be effectively removed with minimum tube damage. The procedure for each boiler may be somewhat different due to large differences in boiler design, and due to sootblowing system and steam production constraints. It may be designed with the following considerations:

- There is no need to turn off all liquor flow to the boiler. A 50 to 75% reduction for 2 to 3 hours is often sufficient.
- The tube temperature should be maintained as constant as possible throughout the thermal shock event to minimize shocks to the tubes. This can be achieved by decreasing steam flow, while co-firing black liquor with gas or oil to maintain the saturated steam pressure and superheated steam temperature.
- Thermal shock is most effective in the superheater region for three main reasons: the wider spacing between platens which allows deposits to fall freely when dislodged by sootblowing; the greater flue gas temperature drop as a result of liquor load reduction; and the dense deposits which are prone to cracking due to the large temperature change.
- In the boiler bank and economizer regions, deposits are porous, thus are less prone to thermal shock.
- There is no need to carry out a thermal shock event for more than 3 hours since most deposits in the superheater region fall during the first 2 hours. Also, since more deposits fall during the heating cycle than during the cooling cycle, sootblowing in the superheater region should be continued for at least 3 hours after the boiler has resumed full load.
- A thermal shock event is more effective if it is carried out in the early stages of superheater fouling and periodically repeated throughout the running period.

PLUGGING PREVENTION

It is apparent from the above discussion there are three types of deposits which are principally responsible for plugging at various locations in the boiler:

- Sticky carryover and ISP deposits in the superheater region and at the generating bank inlet;
- Sintered fume deposits in the generating bank;

- Sticky fume deposits in the economizer region which result from the high SO_2/SO_3 content in the flue gas.

Since plugging occurs only when the rate of deposit formation exceeds the rate of deposit removal, it is important to identify the exact type and location of plugging so that appropriate preventive measures can be taken. Listed below are the main causes and preventative measures for the three types of plugging.

Plugging Due to Sticky Carryover and ISP

Main Causes:

1. Excessive carryover and ISP formation
2. High flue gas temperature

Preventive Measures:

1. Minimizing the amount of carryover through:
 - lowering liquor firing load, if possible;
 - optimizing firing conditions to stabilize the char bed;
 - modifying air and liquor delivery systems, to ensure better bed control and combustion, and to minimize the flue gas channelling effect;
 - installing improved monitoring systems such as bed imaging cameras, bed pyrometers and carryover monitoring devices to obtain timely feedback
2. Reducing the stickiness of carryover through:
 - lowering the Cl content in the black liquor;
 - lowering flue gas temperatures
3. Lowering flue gas temperatures through:
 - optimizing firing conditions to keep the combustion in the lower furnace;
 - increasing heat transfer surface area;
 - increasing sootblowing frequency in the region upstream of the affected areas;
 - periodically carrying out thermal shock or "chill-and-blow" to remove deposits in the superheater region
4. Maximizing deposit removal by:
 - lowering the Cl content in the black liquor;
 - increasing sootblowing frequency in the affected area;
 - optimizing sootblowing sequence/frequency;
 - using fully-expanded sootblower nozzles

Plugging Due to Fume Sintering

Main Causes:

1. Excessive fume

2. Ineffective sootblowing
3. High flue gas temperature

Preventative Measures:

1. Minimizing the fume quantity by
 - increasing heat transfer surface area;
 - lowering bed temperature;
 - operating a char bed with uniform temperature [22]
2. Lowering flue gas temperatures through:
 - optimizing firing conditions to keep the combustion in the lower furnace;
 - increasing heat transfer surface area;
 - increasing sootblowing frequency in the region upstream of the plugged sites;
 - periodically carrying out "chill-and-blow" to remove deposits in the superheater region
3. Maximizing deposit removal by:
 - installing additional sootblowers and/or increasing sootblowing frequency in the affected area;
 - using advanced sootblower nozzles;
 - removing, if possible, uncooled deposition sites, such as stabilizing bars, baffles and sealed tubes

Plugging due to Sticky Fume

Main Causes:

1. Low carbonate content in fume
2. High SO₂/SO₃ content in the flue gas
3. Ineffective sootblowing

Preventative Measures

1. Increasing the carbonate content in the fume or decreasing the SO₂/SO₃ content in the flue gas through:
 - operating the boiler at a high bed temperature;
 - lowering the black liquor sulphidity;
 - avoiding burning of elemental sulphur directly in the boiler
2. Maximizing deposit removal by installing additional sootblowers and/or increasing sootblowing frequency in the affected area.
3. Removing a section of the baffle (if applicable) to avoid the abrupt change of flue gas direction and to decrease the flue gas velocity.

SUMMARY

The properties and formation mechanisms of fireside

deposits in a kraft recovery boiler vary greatly with location in the boiler. They may also differ from boiler to boiler. It is critically important to identify the exact location where massive deposits accumulate and to understand how deposits form, grow and become resistant to sootblowing at that location, so that better solutions to the problem can be devised.

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