Seghers Boiler Prism: a Proven Primary Measure against High Temperature Boiler Corrosion

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Abstract

This paper constitutes a follow-up on a presentation at NAWTEC 10 (2001) [1]. It contains novel insights regarding the operation of the Seghers Boiler Prism and its effectiveness as a primary measure against high temperature boiler corrosion in WtE plants. Starting from the currently available fundamental understanding on high temperature corrosion and the main features of the Boiler Prism, the operation as a primary measure is explained.

Since the previous presentation, three additional Boiler Prisms were successfully commissioned as a retrofit at a large WtE facility (3 x 705 tons/day at 4,700BTU/lb; 110 tons/hour steam at 1,450psi, 750°F) in the Netherlands. Together with the previously installed prisms, this brings the combined operational experience from all trains to more than 15 years.

The main data and experience of the retrofit project in the Netherlands are discussed and results regarding the performance of the prism are presented in detail. The latter are based both on existing process monitors as well as dedicated measurement campaigns and include:
- temperature and oxygen distribution in the 1st radiation pass,
- feedback on corrosion rates,
- influence on the combustion quality, and
- impact on the effectiveness of the mechanical cleaning equipment.

The results confirm the effectiveness of the prism as a primary measure against high temperature boiler corrosion and highlight the additional operational benefits.
Introduction

The European legislation's requirement for a flue gas residence time of at least 2 seconds at a temperature in excess of 1,562°F (850°C), together with the pursuit of higher energetic efficiencies of WtE boilers has obliged plants to operate at lower overall air excess ratios, higher combustion temperatures and elevated steam parameters [2]. In turn, this has resulted in a marked increase of high temperature boiler corrosion, an effect which was further exacerbated by an increase in the heterogeneity as well as the heating value of the waste due to the augmented implementation of selective garbage collection.

Along with problems related to boiler slagging and/or fouling and excessive wear of the refractory lining, [3] lists high temperature boiler corrosion as one of the main causes of more than 70% of WtE plant shutdowns. Despite intense research efforts and extensive experimental programs both on industrial and lab scales (e.g. within the European network on waste incineration 'PREWIN'), the topic of high temperature boiler corrosion remains subject to discussion. Evidence of this are the numerous seminars and congresses dedicated to this field each year. Although considerable progress has been made in identifying - what are currently thought to be - the main corrosion mechanisms, the true fundamentals of the phenomenon remain to be established. Nevertheless, current understanding enables the deduction of a series of general rules and guidelines for the limitation of the risk on corrosion.

Based on these understandings, the Seghers Boiler Prism was developed to eliminate or at least minimise the adverse effects of high temperature boiler corrosion.

This paper provides a concise explanation of high temperature corrosion, the operating principles of the Prism and a series of industrial scale results illustrating the success of the development in terms of corrosion reduction and also other operational aspects.

High Temperature Corrosion

In WtE plants, high temperature boiler corrosion typically occurs in a window with respect to the surface temperature of the involved components between 480°F (250°C) and 1020°F (550°C), a range associated with chlorine corrosion. Boiler corrosion below this range has been observed, but it typically concerns ‘dew-point’ corrosion caused by the condensation of sulphur components near the boiler exit. This particular type of corrosion is not considered in this paper.

High temperature corrosion in WtE boilers typically occurs in the following three areas (see also Figure 1):

1. top of the refractory lining in the 1st pass,
2. transition of the 1st to the 2nd pass (including the boiler roof), and
3. tube bundles of the evaporator and / or superheater at the entrance of the convective boiler pass.

The corrosion causes rapid wall thickness reduction in these areas and in some cases the failure of a single or multiple tubes, necessitating an immediate shutdown of the plant for repair.

Figure 1: High temperature corrosion areas in a WtE boiler

Although no general consensus has been established on the topic to date, two corrosion mechanisms seem to be emerging as the most relevant underlying phenomena. Both are discussed briefly below.
Active Oxidation [3,4]

The mechanism, also illustrated in Figure 2, is based on the diffusion of chlorine (Cl) towards the metal matrix through the oxide layer covering the boiler tubes. The chlorine was produced either by catalytic oxidation of hydrochloric acid in the flue gases (HCl) or by oxidation of previously formed metalchlorides. Once the chlorine reaches the metal matrix and provided oxygen is virtually absent (FeCl₂ is stable at very low oxygen vapor pressure), it will react to metalchloride and evaporate. In turn, the metalchloride diffuses to the gas/oxide interface and reacts with the available oxygen to metaloxide and chlorine. Part of the produced chlorine will diffuse once more to the metal matrix (see above) and cause more corrosion damage, while the remainder will enter the gas phase and react with water vapor to hydrochloric acid (HCl).

The corrosion rate is primarily determined by the evaporation and diffusion rate of the metalchloride. Since the former is insignificant at surface temperatures below 930°F (500°C), it can be concluded that this mechanism cannot be responsible for evaporator wall corrosion (wall temperatures typically below 570-590°F (300-310°C), depending on the steam parameters).

Salt Melt Induced Corrosion [4,5]

While cooling down in the boiler, part of the volatilised salts in the flue gases are deposited on the boiler walls and tubes. Given the right composition, these salts may form eutectics with melting points as low as 480°F (250°C) (in particular KCl-ZnCl₂ mixtures). At the saltmelt / metal interface, no oxygen is present and the metal will readily dissolve as metalchloride (Figure 3). After diffusing through the melt (driven by concentration gradients), the metalchloride is oxidised and the chlorine is liberated to repeat the cycle.

Figure 3: Salt Melt Induced Corrosion

It is thought that this mechanism is the main responsible for corrosion at relatively low wall temperatures, e.g. evaporator walls.

An essential reaction which is beneficial for avoiding corrosion concerns the sulphatisation of volatilised alkali / metal salts in the flue gases. In principle, it is a strongly exothermic reaction which transforms the chlorine salts into sulphate salts, after which the free chlorine reacts with water vapor to hydrochloric acid, e.g.

\[ 2 \text{KCl} + \text{SO}_2 + \text{O}_2 \rightarrow \text{K}_2\text{SO}_4 + 2 \text{Cl}\]
\[ 2 \text{Cl} + \text{H}_2\text{O} \rightarrow 2 \text{HCl} + \frac{1}{2} \text{O}_2 \]

Hence, upon condensation of the sulphatised salts less chlorine will be present in the deposits on the boiler components. In turn, this leads to less aggressive salts (sulphate corrosion occurs at higher temperatures) with a higher melting point (lower risk on the formation of salt melts) and therefore a reduction in corrosion. Sulphatisation typically occurs between 1,560-1,200°F (850-650°C) and requires well mixed flue gases and sufficient SO₂ and O₂.

As CO is typically a sign of the absence or shortage of O₂, in certain cases it should be interpreted as a possible indicator for increased corrosion potential.

In case of insufficient sulphatisation in the flue gases, the reaction will occur / continue in the deposits and may cause intense localised heating. It is clear that this might lead to the melting of salt mixtures with relatively high melting points and cause localised corrosion (so called 'pitting').

Furthermore, it has been observed that the velocity and flow direction of the flue gases with respect to the boiler tubes or walls constitutes a critical parameter. A high impact velocity (i.e. a strong component perpendicular to the boiler surface) typically leads to increased corrosion. This is readily understood when bearing in mind that corrosion constitutes a mass exchange phenomenon for
which the rate depends also on the availability of reaction partners. The latter will be more abundantly present in case of high impact velocities than when the flue gas flow is parallel to the boiler components. Based on this understanding, the typical corrosion diagram (so called ‘Flinger diagram’) has been extended to include different flue gas velocities.

The above understanding allows the formulation of a set of general rules and guidelines aimed at limiting high temperature corrosion:

1. **Promote sulphatisation by:**
   - limiting the flue gas temperature,
   - ensuring good mixing of the flue gases, and
   - supplying sufficient oxygen.
   In case of plants with a relatively high Cl/S-ratio in the waste, increasing the S-contents of the waste will also help the promotion of the sulphatisation of the volatilised salts.

2. **Minimise impact velocity, create a uniform flow pattern and a smooth transition from the 1st to the 2nd empty pass.**
   This is achieved by a proper design of the geometry of the combustion chamber and the boiler but also by ensuring good mixing of the flue gases without creating velocity components perpendicular to the wall.

3. **Avoid hot spots by creating a uniform temperature distribution.**
   Essential for this are good mixing of the flue gases when leaving the combustion chamber, an adequate combustion control system and a homogeneous waste mix allowing stable process conditions.

4. **Limit the concentration of salts and heavy metals in the flue gases by operating at a moderate combustion temperature.**
   A good compromise between burnout and bottom ash quality on the one hand, and the amount of volatilised salts and heavy metals on the other, can be established by selecting an intermediate combustion temperature.

5. **Although it is often impossible in practice since the composition of the waste cannot be changed, limiting the chlorine concentration in the flue gases will also reduce the risk on high temperature corrosion.**

In principle, two different types of measures against high temperature corrosion are currently available.

The most common – so called ‘secondary’ – measures – attempt to extend the lifetime of boiler components by mitigating the adverse effects of corrosion. Widely used are protective layers aimed at shielding the boiler components from salt deposits and flue gases. Although some work is ongoing regarding non-metallic layers, the use of alternative alloys and innovative application methods, overlay welding with nickel based alloys (Alloy 625 / Inconel in particular) is by far the most common in Europe. Drawbacks of this approach are the high cost of the alloy, the variable success (depending strongly on the application process) and the limited temperature range, i.e. Alloy 625 does not provide protection above $750 - 840°F (400 - 420°C)$.

Other secondary measures include the injection of chemicals to facilitate the removal of deposits and decrease their corrosion potential, or to promote sulphatisation. Finally, some on-line cleaning methods such as water washing and explosive cleaning were developed in order to limit the build-up of deposits.

In contrast to the above, ‘primary’ measures seek to eliminate the actual cause of corrosion rather than only trying to mitigate its effects. The Seghers Boiler Prism constitutes such a primary measure and after a brief discussion of its main features, an explanation is provided on how it succeeds in avoiding high temperature corrosion.

**Seghers Boiler Prism: Key Features**

Since the prism was already discussed in detail elsewhere [1], only the key features are highlighted below.

The Seghers Boiler Prism constitutes a prism shaped dynamic mixer (i.e. with secondary air injection) inserted at the transition of the combustion chamber to the 1st radiant boiler pass (see Figure 4). It is water-cooled, refractory lined and integrated with the natural circulation system of the boiler. Therefore, when retrofitting an existing plant with a
prism, the heat exchanging surface near the combustion chamber will be enlarged and the flue gas temperature is expected to decrease.

Figure 4: Seghers Boiler Prism

The prism divides the flue gas channel into two sections (‘A’ and ‘B’ in Figure 4), in each of which secondary air is injected from two different locations (boiler wall and prism; positions ‘LA1’, ‘LA2’ and ‘LB1’, ‘LB2’ in Figure 4). Compared to a design without a prism, it allows for a more uniform injection of secondary air through multiple nozzles in the boiler walls and prism sides (ensuring high turbulence and optimal mixing) and for superior process control.

Based on the general rules and guidelines of the previous section, the manner in which the Seghers Boiler Prism eliminates or at least minimises high temperature boiler corrosion is discussed below:

- By limiting the flue gas temperature, ensuring intense mixing and providing a means for a highly uniform injection of secondary air, the prism creates optimal conditions for the sulphatisation reaction to take place. As discussed before, this will lessen the reactivity of the deposits in the considered temperature window and reduce the corrosion potential.

- Through a proper design of the geometry and position of the prism and boiler by means of detailed CFD simulations, a uniform and ‘well-behaved’ flow pattern of the flue gases is obtained.

- The intense mixing and the optimised injection of secondary air results in a highly uniform distribution of flue gas speed, temperature and oxygen in the cross sections of the 1st boiler pass shortly above the prism, i.e. hot spots are avoided.

- As stated before, the prism (cfr. the side walls of a combustion chamber with an integrated boiler) extracts heat from the combustion zone and aids to limit the combustion temperature. In turn, this reduces the volatilisation of salts and heavy metals and leads to less aggressive deposits.

Figure 5: Simulated Flue Gas Velocity Vectors

(no prism)  (with prism)
The above is also illustrated by means of Figure 5, which contains the simulated flue gas velocity vectors at comparable load cases in the cross section just above the transition of the incineration chamber to the 1st radiant boiler pass for a case with prism (figure on the right) and a case without prism (figure on the left). The two circles mark the position of the auxiliary burners. It is clear that the uniformity of the velocity distribution in the right figure (with prism) is far superior to the case without prism.

It is obvious that the Seghers Boiler Prism can be implemented in new designs as well as in existing plants as a retrofit.

The remainder of this paper discusses the implementation of a Boiler Prism in three WtE trains of an existing plant and presents the results of the project in terms of high temperature boiler corrosion reduction as well as other operational aspects.

Retrofit of AZN: Project Description

The WtE plant of Afvalverbranding Zuid-Nederland (AZN) in Moerdijk, the Netherlands, comprises three trains of 81 MWth which treat a total of 700,000 tons of municipal waste per year. It is equipped with three identical WtE boilers, each producing 110 tons/hour of superheated steam at 1,450 psi (100 bar) and 750°F (400°C) for the adjacent CHP plant.

The combustion takes place on a forward acting grate, comprising three parallel grate tracks with a total area of 893 ft² (83 m²). The layout of the grate and boiler is illustrated by means of Figure 6. The incineration of waste started in 1997.

During the first years after the start-up, the following observations were noted:
- high flue gas temperature at the outlet of the radiant pass (up to 1740°F (950°C)),
- high corrosion rate at the boiler roof and walls in the radiant pass, as well as at the evaporator and final superheater bundles in the horizontal boiler pass,
- frequent tube failures,
- high maintenance and repair costs,
- excessive production of boiler- and flyash, and
- an availability of approximately 7,500 hrs.

In order to try and correct the above problems, AZN initiated an elaborate revamp program of all three lines in 2001. This program involved the following modifications:
- implementing the Seghers Boiler Prism,
- replacing part of the air-cooled grate with a water-cooled grate,
- optimising the primary air distribution system,
- implementing a new combustion control concept,
- replacing the evaporator and superheater bundles,
implementing a new refractory lining concept (so called ‘MOKESA’ system), and increasing the primary air preheater capacity.

After more than one year of close observation and detailed analysis of the performance of the retrofitted train #2, AZN decided to conduct the same revamp on the remaining two trains (#1 and #3) in 2003.

The scope of the works for the Seghers Keppel Technology Group for each train involved:
- implementing the Boiler Prism,
- modifying the secondary air and flue gas recirculation injection nozzles as well as the corresponding boiler walls,
- modifying the secondary air and flue gas recirculation ducting,
- replacing the secondary air fans,
- installing an on-line nozzle cleaning system, and
- improving the water-cooled grate.

Figure 7: Hoisting of the Prism

Figure 8: Mounting of the Prism
During the engineering phase, prior to the actual construction of the prism and ducting, the position, geometry and size of the prism was meticulously determined by means of detailed CFD analyses by in-house specialists of Seghers Keppel Technology Group. Both the situation before and after implementation of the prism was simulated and the results were assessed in terms of velocity, oxygen, CO and temperature distribution in different cross sections. In order to approximate reality as closely as possible, separate boundary conditions were used for each of the three grate tracks. This project phase was completed in approximately one month.

Once the geometry and the position (including that of the secondary air and flue gas recirculation nozzles) had been fixed, all remaining engineering parameters such as pressure drop, strength analysis, internal circulation, ... were verified. At the same time the main components were purchased, constructed and inspected. Verification of these parameters, purchasing and construction took approximately four months.

The actual work on site, requiring a shutdown of the particular train, lasted typically less than one month (25 days). As illustrated by Figures 7 and 8, the prism was mounted through the boiler roof. Before this could commence, refractory lining, ducts, auxiliary burners, specific pressure parts, and parts of the boiler wall and roof had to be removed as well as welds had to be prepared. After mounting the prism, the boiler was pressure tested, the secondary air and flue gas recirculation nozzles and corresponding boiler walls were replaced, the refractory lining was re-applied and the boiler roof was closed.

The total project for the implementation of the last two prisms, from the signing of the contract until the actual start-up of the first retrofitted train took less than six months.

Performance of the Seghers Boiler Prism at AZN

The performance of the Seghers Boiler Prism at AZN was validated and monitored by means of existing on-line equipment on the one hand and by means of dedicated measuring campaigns on the other. Results of both are presented below.

Each train is equipped with an on-line and continuous acoustic temperature mapping system (AGAM-system from the company 'Bonnenberg&Drescher', Germany), located approximately 15ft (4.5m) above the top of the Boiler Prism. It comprises eight transceivers that allow the calculation of the average temperature along 22 different paths in the horizontal cross section of the boiler. Based on this information, an on-line two-dimensional temperature distribution is established, which is also available in the control room as a contour mapping. The standard deviation of the temperatures along these 22 different paths accurately reflects the uniformity of the temperature profile across the boiler section. Typical results of the standard deviation for the temperatures on a train with and a train without prism are compared in Figure 9. During the considered periods, both trains were operated at identical conditions (thermal load & throughput).

The above figure (Figure 9) illustrates clearly that the prism succeeds in increasing the uniformity of the temperature profile to such an extent that the standard deviation on the
train with prism is almost half that of the train without prism. It should be noted that the above results were obtained relatively short after the start-up of the retrofitted train and that fine tuning of the control system was still ongoing. More recently, days with an average standard deviation on the 22 temperature paths of 64°F (18°C) have been obtained.

Furthermore with respect to the temperature in the 1st empty pass but also at the entrance of the horizontal pass (see Figure 6), it was observed that the average flue gas temperature has decreased by about 86°F (30°C) compared to the situation prior the retrofit. Note that this observation agrees well with measurements at the Bonn plant [1], at which a temperature drop of 77 – 86°F (25-30°C) was registered. According to AZN's estimates and assuming that the plant could be operated safely at the same temperature level as before the implementation of the prism, this decrease in temperature along with the increased uniformity of the temperature profile would allow an increase in throughput of 6 – 10%. However, due to restrictions on the flue gas cleaning equipment of the current plant the actual increase in throughput cannot be realised.

In addition to the observations based on the existing process monitoring equipment, a series of dedicated measurement campaigns by independent labs were conducted. A particularly relevant campaign was performed in September – October 2003. At this time, train #3 ('L3') of the facility had been fully retrofitted while on train #1 ('L1') everything had been completed except for the implementation of the Boiler Prism (see description of the revamp program earlier). During the campaign, both trains were operated at the same load conditions. The measurements on the two trains were not conducted simultaneously, but care was taken to feed both with the same type of waste. The campaign consisted of the continuous measurement of temperature, oxygen and carbon monoxide during six hours and in six different points in a cross section approximatively 27ft (9m) above the top of the Boiler Prism.

At the same time the dust at the boiler exit as well as the flyash captured in the electrostatic precipitator downstream the boiler were sampled by the company CheMin GmbH (Augsburg, Germany) to assess the corrosion potential based on the chemical composition of these samples.

![Figure 10: Temperature [°C] distribution with (right figure) & without prism (left figure) (cross section approx. 27 ft (9m) above prism)](image)

![Figure 11: Oxygen [vol%] distribution with (right figure) and without prism (left figure) (cross section approx. 27 ft (9m) above prism)](image)
At the time of writing of the draft paper, only partial results were available. Complete results are expected by the end of January 2004 and will be included in the final paper and the oral presentation.

The main results available to date include the temperature and oxygen distribution.

The results of the temperature measurements indicate that while the distribution on the train with prism (L3) is more variable than on the train without prism (L1), the average profile is considerably more stable and uniform. In fact, the train without prism exhibited a clear hot spot in one particular corner of the 1st boiler pass throughout the entire campaign. These observations are illustrated by means of Figure 10, which shows a contour plot for the train with (L3) and the train without prism (L1), based on the average temperature in the six measurement locations (MP1 - MP6) in the considered cross section. These plots allow the following observations with respect to the train with prism (L3) and compared to the train without prism (L1):

- the span (difference between maximum and minimum) of the temperature measurement is lower by almost a factor two,
- the temperature on nearly half of the cross sectional area between the measurement varies less than ± 50°F (10°C), and
- the contour plot does not show hot spots (while on L1 point 4 (MP4) constituted a hot spot throughout the entire test measurement campaign).

The fact that the overall average temperature on the train with prism was slightly higher than on the train without prism stemmed from a difference in oxygen concentration (see also below) and is not deemed significant.

Similar observations were obtained from the oxygen measurements. The distribution on the train without prism (L1) was fairly steady but strongly non-uniform. The train with prism (L3) exhibited a more variable but on average much more uniform O₂-profile across the 1st radiant pass. Figure 11 contains contour plots for the considered cross section which represent the average oxygen distribution during the 6 hour measurement periods. From these measurements it is shown that the train with prism (L3) was operated at a slightly lower oxygen concentration than the train without prism (L1).

In addition to the above observations during dedicated measurement campaigns and based on the existing acoustic temperature mapping system, the following important operational benefits were noted:

1. Since the first Boiler Prism was taken into operation on train #2 (L3, commissioned in 2001), the corresponding train has not had any corrosion related shutdown. In fact, during a recent visual inspection (June 2003) of the boiler roof (typically the location where corrosion rates used to be the highest) no sign of wear or material loss has been noted. Similar observations were made with respect to the superheater bundles (significantly less pitting on the trains with prism). Based on this, AZN expects a considerable increase in lifetime of the corresponding boiler components.

2. The on-line mechanical cleaning devices on the boiler (so called 'rappers' in the horizontal boiler pass) are operating more efficiently. While analyses of boiler ash samples are ongoing, this already indicates that the prism has also influenced the characteristics of the deposits such that their removal has been facilitated. The improved cleaning efficiency has allowed the period between off-line boiler cleaning (so called 'reisezeit') to be increased from less than one year to more than 12,000 hours (1.5 year). It is clear that this improvement leads to considerable cost savings and revenue increase.

3. Prior to the implementation of the prism, the combustion of waste on the grate was frequently and significantly hindered by relatively large ash and dust deposits on the sidewalls of the incineration chamber. After the retrofit and due to the lower combustion temperature which was primarily brought about by the prism, these deposits are not observed any longer. In turn, this has resulted in increased combustion stability and capacity. As stated before, to date the latter cannot be realized due to restrictions on the capacity of the flue gas cleaning system.

4. Similarly, the deposits on the boiler walls in the region of the secondary air injection nozzles have been reduced dramatically since the implementation on the prism. Furthermore, these deposits are easier to remove and cause less damage to the refractory lining.
5. The implementation of the prism has lead to an improved burnout of the gases. This statement is based on visual observations in the 1st radiant pass. Prior to the implementation of the prism, flames could frequently be noted up to the entrance of the 2nd pass. With prism this is reduced to below halfway up the 1st pass.

Note that the above observations agree well with those from the WtE plant in Bonn, which were described earlier [1].

Finally, some unpublished results of deposit analyses at the Bonn WtE plant deserve attention. It concerns deposit samples at different positions in the 1st radiation pass (at different elevations with respect to the combustion grate) that were taken during a shutdown. The sampling was performed on two trains, both treating the same waste, one of which was equipped with a prism. Sampling and analysis was performed by CheMin GmbH (Augsburg, Germany). The results of the deposit analyses clearly indicate that sulphatisation on the train with prism started significantly earlier than on the train without prism. Note that these observations are in good agreement with the expectations based on the fundamental understanding of high temperature corrosion and the operation principles of the Seghers Boiler Prism.

When combining the operation time of all trains in both plants (Bonn and AZN), more than 15 years of operational experience with the Boiler Prism has been compiled.

Conclusions

As a result of changes in waste composition, operator’s focus and legislation, high temperature boiler corrosion has significantly gained importance and has compromised plant economics considerably.

Although the fundamental understanding of the phenomenon is not yet complete, a set of guidelines aimed at the reduction of high temperature corrosion has been formulated. Based on these rules and the operating principles of the Seghers Boiler Prism, its effectiveness as a primary measure against high temperature boiler corrosion was explained.

In the period of 2001 – 2003, three additional boiler prisms were commissioned in a large WtE facility in the Netherlands. Together with the feedback from previously installed prisms (i.e. Bonn WtE facility), a combined operational experience of +15 years has been established.

The efficiency of the Seghers Boiler Prism in avoiding high temperature corrosion was proven by means of experimental results and operational observations. Both existing process monitors as dedicated measurement campaigns and analyses were used.

Based on all of the above, it is fair to state that the Seghers Boiler Prism as an effective primary measure against high temperature corrosion is a fully developed and proven technology.

References


