Effects of Coal-bound Chlorine on Furnace-Wall Corrosion Under Low-NO_x Conditions



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Abstract

Since the late 1960s, United Kingdom (U.K.) studies have reported a correlation between the corrosion of utility boilers and the total amount of chlorine (Cl) in coals. These studies have indicated accelerated corrosion when Cl content of coal was 0.3% or greater. The experience in the United States, however, has indicated that the amount of Cl in high-Cl coals is not a major cause of corrosion. Nevertheless, because of the U.K. data, many U.S. boiler manufacturers have recommended a maximum Cl level of 0.3% for U.S. coals. This limit, however, decreases the market potential of the high-Cl coals of Illinois. In 1998, a joint study by the Illinois State Geological Survey (ISGS), McDermott Technology, Inc. (MTI), Illinois Clean Coal Institute (ICCI), and United States Department of Energy (U.S. DOE) focused on the high-temperature superheater and reheater tubewall corrosion that occurred in boilers under oxidizing conditions. Pilotscale tests of combustion corrosion were conducted with a high-Cl Illinois

Introduction

Many U.K. studies have associated accelerated fireside corrosion of tubes of utility boilers with the high-Cl content in coal (Bettelheim et al. 1980). Their corrosion data suggested that the corrosion rate of boiler tubes increased proportionately with increasing Cl concentration in coal. Based on the results of those studies, U.S. boiler manufacturers and utilities have considered coals containing more than 0.3% Cl to be potentially corrosive. The 0.3% limit was based primarily on engineering studies that extrapolated the U.K. coal data to the probable corrosive behavior of U.S. coal. The 0.3% limit on Cl has discouraged the burning of many Illinois Basin coals in utility boilers.

A survey jointly conducted by the EPRI and ICCI (Doane et al. 1994) indicated that some U.S. utilities have had decades of experience burning high-Cl coals in pulverized coal-fired boilers. Although fireside corrosion

coal, a high-Cl U.K. coal, and a low-Cl Illinois coal as the baseline. The results showed no correlation between coal Cl content and rate of corrosion, but the rate of corrosion and metal temperature were correlated. A joint study by PowerGen in the United Kingdom and the Electric Power Research Institute (EPRI) in the United States also recently concluded that, under oxidizing conditions, increasing the Cl content of the coal burned was not likely to increase the tube corrosion rate, and corrosion rates were dependent upon metal temperatures only.

The purpose of this research was to determine the effect of the Cl content of coal on the corrosion of the furnace wall under sub-stoichiometric (low-NO_x) combustion conditions. Two pilot-scale tests of combustion corrosion were conducted using high-Cl (0.41%) and low-Cl (0.10%) Illinois coals. The corrosion rates were measured using conventional probes made of T22 metal alloy for a duration that

problems have been reported, none of them could be directly related to the presence of Cl in coal. Furthermore, the corrosivity of two Illinois coals, one with a high-Cl content of 0.31% Cl and the other with a low-Cl content of 0.16%, was determined by Monroe et al. (1994) under pilot-scale combustion tests. Their results showed that the corrosion rate of the high-Cl coal was actually slower than the corrosion rate of the low-Cl coal. The tests used resistance corrosion probes instead of conventional probes, and corrosion rates were based on measurements of electrical resistance over the test period. Also, during the tests with the high-Cl coal, an equipment malfunction caused a high-temperature excursion, which increased the relative corrosion rates. Resistance probes are particularly sensitive to short temperature increases and to the temperature gradients along the probes. Temperature gradients in the

would give reliable comparisons. Tests with the high- and low-Cl coals showed no correlation between the coal Cl content and the corrosion rate of the test probe samples. The maximum amount of reduction in tube-wall thickness resulting from combustion corrosion was the same in the low-Cl and high-Cl coals. In addition, no chloride deposition was observed in the corrosion sample obtained from the high-Cl coal test.

The results obtained during coal combustion under the reducing conditions of this study were consistent with those of the previous study utilizing oxidizing conditions. Under both conditions, corrosion rate did not increase with increased Cl content. The relationship between corrosion rate and metal temperature was studied under oxidizing conditions, but the temperature dependence of the corrosion rate under reducing conditions was not a part of this study. The results of these studies could provide a comprehensive database that may help to convince boiler manufacturers to relax the limits on the Cl content of coals burned in their boilers.

probes were unavoidable during the tests in both oxidizing and reducing zones. The overall results showed that the high-Cl Illinois coal was less corrosive than the low-Cl coal under the test conditions. However, because of the uncertainties in the test results created by the high-temperature excursion and the sensitivity of the resistance probes to temperature variations, the results could not be used as the basis for redefining the recommended limits on Cl in coal imposed by boiler manufacturers to prevent corrosion.

Research teams from the ISGS, MTI, ICCI, Sandia National Laboratories, and U.S. DOE (Chou et al. 1998, 2000) recently studied the effects of Cl on high-temperature superheater/reheater tubewall corrosion during coal combustion under oxidizing conditions. Pilot-scale combustion corrosion tests were conducted with a high-Cl Illinois coal and a high-Cl U.K. coal; a low-Cl Illinois coal was used as the baseline. The corrosion rates were measured using conventional probes under the oxidizing

combustion conditions that would normally be experienced by superheater tube walls in a conventional boiler. The results showed no evidence of a correlation between coal Cl content and the rate of corrosion. Evidence suggested that high-Cl Illinois coals, like low-Cl coal, could be successfully used in utility boilers if other coal components and boiler properties were understood and controlled. These findings were further confirmed by a joint study by PowerGen in the U.K. and the EPRI in the United States (Davis et al. 2000). They concluded that, under oxidizing conditions, increasing the Cl content of the coal burned was not expected to increase the tube corrosion rate, and corrosion rates were dependent only upon boiler tube metal temperatures.

A literature review (James and Pinder 1997) correlated the high corrosion wastage observed on the furnace wall of U.K. boilers with the high Cl in U.K. coal. However, the review also suggested that factors other than Cl should be considered as causes of accelerated corrosion and suggested that the accelerated corrosion took place primarily on the furnace wall where sub-stoichiometric combustion conditions and high heat flux coexisted.

The presence of reducing gases implies that insufficient oxygen was supplied to the combustion zone by improper mixing of air and coal. Also, high heat flux results in a high metal temperature on the furnace wall. Under conditions of insufficient oxygen, the sulfur in coal is primarily converted to hydrogen sulfide (H₂S) instead of sulfur oxide (SO₂). The H₂S gas is very corrosive and readily sulfidizes conventional furnacewall alloys. The sulfidization of the furnace-wall alloys is further escalated by high metal temperature. Therefore, when a large H₂S concentration and a high metal temperature coexist, accelerated corrosion wastage on the furnace wall is expected. A combination of these conditions could account for the majority of the corrosion wastage experienced on the furnace walls of U.K. boilers.

Contrary to the general consensus of the U.K. researchers, laboratory studies by MTI (Kung et al. 1994, 1996) sug-

gested that burning high-Cl coal would not cause additional corrosion on the furnace wall. In the MTI studies, HCl was added to the combustion gases at a level equivalent to burning high-Cl coal under sub-stoichiometric combustion conditions. The presence of HCl in the low-NO, combustion gas may retard sulfide attack. These results were consistent with those reported by U.K. researchers (Latham et al. 1991) for combustion under reducing conditions with the presence of H₂S. Up to 800 ppm of HCl (corresponding to 1.0% Cl in coal) had no effect on the corrosion of steel tubes at 400°C (752°F) or 500°C (932°F) (see also Doane et al. 1994). These findings are of potential importance to the Illinois coal industry. However, these corrosion data from simulated laboratory studies were insufficient to allow us to evaluate the potential beneficial effects from the Cl in coal on low-NO, burner applications.

This study focused on pilot-scale tests conducted with conventional probes to measure corrosion rates under the reducing/sulfidizing conditions that would be experienced by a water wall in a low- NO_x boiler. The results we obtained should help clarify the significance of Cl on furnace-wall corrosion when coal is burned sub-stoichiometrically.

Our study was designed to accomplish these specific tasks:

• Acquire two Illinois coal samples, one containing a high-Cl content (0.4% to 0.6%) and one containing low-Cl content (<0.20%), and pro cess

and distribute the samples for characterization and combustion tests.

- Characterize the properties of the coal samples used, including the occurrence of Cl, sulfur, and alkali metals and their roles, if any, that could affect the chemistry and mechanism of furnace-wall corrosion during combustion under substoichiometric conditions.
- Conduct two stoker-boiler burnerrig corrosion tests at MTI and collect samples for metallurgical composition and the rate of corrosion examinations.

- Perform metallographic examination of boiler scale and deposits and measure rates of corrosion from specimen cross sections.
- Interpret the sampling and analytical results and compare the rates of corrosion of the low-Cl coal with those of the high-Cl coal.

Methods and Materials

This 2-year project focused on determining the effect of Cl in coal on furnace-wall corrosion under substoichiometric combustion conditions. During the first year, a stoker boiler system (figs. 1 and 2) at MTI was specifically modified for conducting corrosion-rate studies that could be related to sub-stoichiometric (low-NO_x) conditions. The first pilot-scale combustion corrosion test was conducted on the low-Cl coal, and the second test was conducted on the high-Cl coal.

In our previous investigation (Chou et al. 1998, 2000), pilot-scale tests were conducted under oxidizing conditions to determine the effect of Cl in coal on superheater/reheater tube-wall corrosion. The coal samples tested included one low-Cl and one high-Cl Illinois coal. For the current investigation, coals from the same two Illinois mines were used as the low-Cl and high-Cl Illinois coals.

Before the tests, the two coal samples were ground and sieved into stokerboiler grade (0.25 to 1.0-inch diameter). Each coal sample was first screened to remove the >1 inch (>2.5 cm) material for further size reduction in a hammer mill. The size-reduced material then was screened and reprocessed, if necessary, until all of the sample was <1 inch in diameter. It was then remixed with the original <1-inch material. The processed sample (roughly 20 tons) was shipped by truck to MTI, Alliance Research Center, Alliance, Ohio. A 40-lb (18.2-kg) split of the coal sample was ground to -200 mesh (74 μ m) for coal characterization at the ISGS. Chemical characterization tests of the coal samples were conducted using ASTM methods (ASTM 2000); total Cl, total sulfur, ash, and metal oxide were among the substances analyzed (table 1).



Table 1 Chemical characterization of the two coals usedin the prior study and in this study (expressed as weightpercentage moisture-free dry coal basis).

	Low CI	Low Cl ¹	High Cl	High Cl ¹
Total Cl	0.14	0.13	0.44	0.43
Total S	4.48	3.89	1.22	1.13
Ash	9.38	9.16	7.90	6.89
SiO₂	4.17	4.27	3.88	3.60
Al_2O_3	1.63	1.60	1.85	1.63
Fe ₂ O ₃	1.75	1.85	1.00	0.84
CaO	0.48	0.43	0.24	0.19
MgO	0.07	0.08	0.10	0.08
Na₂O	0.13	0.12	0.11	0.09
K₂O	0.17	0.19	0.18	0.17
P_2O_5	0.02	0.02	0.02	0.02
TiO ₂	0.09	0.09	0.10	0.09
BaO	<0.01	<0.01	<0.01	<0.01
SrO	<0.01	<0.01	<0.01	<0.01
SO3	0.62	0.28	0.18	0.13

¹ Data obtained for samples in this study.

Figure 1 Overall schematic of the fireside corrosion testing facility.

Test Material and Corrosion Probe

The T22 metal alloy was used for the corrosion tests. The nominal composition of the T22 metal alloy is given in table 2. This low-alloy steel is MTI's standard material for construction of furnace walls in utility boilers. The corrosion behavior of T22 also resembles that of other low-alloy steels, such as SA213-T11 and SA213-T2, making it ideal for the corrosion study.

A special corrosion probe (figs. 3, 4, and 5) was designed for this study. The water-wall alloy T22 was assembled to form tube segments with 1-inch o.d. \times 1-inch length. The end of each segment was shaped to contain extruded and indented chamfers at 10° and 45°, respectively. The chamfers allowed multiple segments of samples to be connected to the probe without leakage of the cooling air. **Table 2** Nominal chemical composition of metal alloy T22.

Constituent	Max wt%	Min wt%
С	0.15	0.05
Mn	0.60	0.30
Р	0.02	ND ¹
S	0.01	ND
Si	0.50	ND
Cr	2.60	1.90
Мо	1.13	0.87

¹ND, not detected.

Mechanical pressure was applied from both ends of the probe so that a tight fit could be achieved during the sample segment installation. Type K chordal thermocouples were attached to one of the tube segments from inside the probe. The thermocouple junctions were embedded in the tube wall in a hole drilled in the sample's inner surface and secured by silver soldering.



flue gas exit

Figure 2 Schematic of the stoker-fired furnace in the fireside corrosion testing facility.

Combustion Conditions

Room-temperature compressed air was supplied to the corrosion probe to maintain the metal temperature. The airflow rate was regulated electronically by a controller that responded to signals from the probe thermocouples. To reproduce the conditions for furnace-wall corrosion, the metal temperature was maintained at 850°F (454°C), which is typical for a pulverized-coal-fired supercritical boiler with a steam temperature of 1005°F (541°C) at the steam outlet.

Post-Combustion Test Methods

Prior to the corrosion probe testing, the initial outer diameter of each tube sample was carefully measured. Following 800 hours of exposure in the fireside corrosion testing facility, the T22 corrosion samples were chemically cleaned. The chemical cleaning removed the coal ash that had been deposited on the sample surface as well as the corrosion scale formed during the fireside exposure. After the cleaning was completed, the final outer diameter was again measured.

Metallographic examinations were performed on the test samples after corrosion exposure. Each sample was cross sectioned, mounted, and polished using standard metallographic procedures. The morphology of the ash deposit and scale were examined using an optical microscope and a scanning electronic microscope (SEM) equipped with energy dispersive x-ray spectroscopy (EDS). Elemental mapping was performed on the sample with SEM-EDS when necessary to reveal the distribution of various corrosion species.

A sample of the coal ash deposit formed on the air-cooled corrosion probe was analyzed to determine the major constituents that might affect the corrosion mechanism in the coal ash layer adjacent to the alloy surface. The results of this analysis were helpful in identifying the amount of Cl involved in water-wall corrosion under conditions of sub-stoichiometric combustion.







Results and Discussion

Table 1 lists the results of analyses for total Cl, total sulfur, and ash contents as well as for metals contents, reported in oxide form, obtained for the coal samples during the prior study and for this study. The samples used in this study were very similar to those used in the previous study. Notably, the low-Cl coal contained a much higher sulfur content than did the high-Cl coal.

Data from the x-ray absorption near edge spectrum (XANES) analysis indicated that the Cl in these coals occurred in an ionic form. The effects of temperature and atmosphere on the forms of Cl in coals were followed by XANES analysis, and the results obtained were reported elsewhere (Chou et al. 1995). During the first test on the low-Cl coal, an effort was made to recondition the stoker boiler by removing the excess slag that accumulated. The time and cost spent on this extra effort were compensated by our finishing the test in 806 hours instead of the originally planned 1,000 hours. According to MTI, the 800-hour test was sufficient to complete the project goals. The second combustion corrosion test was also conducted for a duration of 800 hours. The corrosion samples obtained from both tests were analyzed, and the results were compared.



Figure 5 Arrangement of chamfered test samples on the probe.



Figure 6 Appearance of test sample after exposure to low-Cl coal combustion.



Figure 7 Appearance of test sample after exposure to high-Cl coal combustion.

Photographs of the corrosion samples obtained from the first test of the low-Cl coal and the second test of the high-Cl coal are shown in figures 6 and 7. The corrosion sample from the test firing with the low-Cl coal (fig. 6) had a much thicker surface deposit than did the sample (fig. 7) obtained from the test firing with the high-Cl coal. One sample from each of the tests was chemically cleaned to remove scale before the wall thickness was remeasured. Photographs of these two chemically cleaned samples are shown in figures 8 and 9. The wall thickness measurements before and after the combustion tests are compared in table 3.

For both tests, the thickness of metal tube wall lost on the hot-side centerline was 1 mil, and the maximum wall thickness lost was 3 mils, which would extrapolate to 33 mils per year of continuous running. The average wall thickness lost for the sample from the low-Cl coal test was 1.88 mils, which would extrapolate to an average of 20 mils per year. The average thickness lost for the sample from the high-Cl coal test was 1.13 mils, which would extrapolate to 12 mils per year. The data indicated that the maximum corrosion rate of the T22 samples was the same whether burning the low-Cl or high-Cl coal. However, the average corrosion rate obtained from burning the low-Cl coal was slightly greater than that for the high-Cl coal.

Examination of polished cross sections of the sample from the test with the low-Cl coal (figs. 10 and 11) showed that the sample had a coherent scale at the interface with the underlying metal. The average thickness of this scale was approximately 2.5 mils. Coal ash and other combustion deposits were found attached to, and above, the coherent scale.

The EDS was used to provide a semiquantitative analysis of the metal composition. The tube metal composition of the sample from the low-Cl coal test was examined. The data obtained at location 1, shown in figure 11, are given in table 4. The composition of the deposit at the interface between the scale and the underlying metal was also determined (table 5). At that location, the sulfur content was 5.36 wt%, and no chloride deposition was observed. An additional investigation was undertaken to determine whether chloride deposition might be found elsewhere at the interface. Some small, isolated pockets containing chloriderich deposits were found, and one of the pockets (fig. 12) showed a Cl content of about 0.73 wt% (table 6).

Additional analyses were performed to evaluate the remainder of the deposit. The composition of the coherent scale (table 7) showed a sulfur content of

 Table 3
 The loss of wall thickness resulting from fireside exposure of alloy samples.

		Wall thic	kness (ir	nches) at	o'clock p	position		
	12:00	1:30	3:00	4:30	6:00	7:30	9:00	10:30
Low-Cl coa	al: 806 h	r, 850°F						
Initial Final Change	0.121 0.120 0.001	0.121 0.119 0.002	0.121 0.118 0.003	0.121 0.120 0.001	0.122 0.120 0.002	0.122 0.120 0.002	0.122 0.120 0.002	0.122 0.120 0.002
High-Cl co	al: 800 ł	nr, 850°F						
Initial Final Change	0.119 0.119 0.000	0.118 0.119 0.0001	0.118 0.119 0.0001	0.118 0.118 0.000	0.119 0.118 0.001	0.120 0.117 0.003	0.120 0.117 0.003	0.120 0.118 0.002

¹ Final measurement exceeding initial measurement may have resulted from residual scale, small axial thickness variations, and/or rounding effects. In any case, these circumstances were counted as zero thickness loss. In the low-Cl coal test, the 12 o'clock position was at the hot-side centerline, whereas in the high-Cl test, the 6 o'clock position was the hot-side centerline.



Figure 8 The low-CI coal combustion sample after chemical cleaning.



Figure 9 The high-CI coal combustion sample after chemical cleaning.

F22-3 sample



Figure 10 SEM of a polished cross section at the external surface of the low-Cl coal combustion sample.

F22-3 sample showing EDS locations 1-7



Figure 11 Appearance of scale and deposit on the low-Cl coal combustion sample.



Figure 12 Isolated chloride-rich deposits found at the tubescale interface of the low-Cl coal combustion sample.

Table 4 EDS analysis of the chemical composition ofthe tube metal (at location 1, shown in fig. 11) of asample from the low-Cl coal test.

Element	Atom %	Weight %	Error (±)	Norm %
Si	1.54	0.78	0.10	0.78
Cr	2.31	2.16	0.13	2.16
Mn	0.72	0.72	0.11	0.72
Fe	94.74	95.15	0.66	95.16
Мо	0.69	1.19	0.20	1.19
Total	100.00	100.00		100.00

Table 5 EDS analysis of the chemical composition ofthe tube-scale interface (at location 2, shown in fig. 11)of a sample from the low-Cl coal test.

Element	Atom %	Weight %	Error (±)	Norm %
0	78.34	53.80	0.73	53.80
AI	0.23	0.26	0.02	0.26
Si	0.86	1.04	0.09	1.04
S	3.90	5.36	0.11	5.36
Cr	2.51	5.60	0.16	5.60
Fe	14.16	33.93	0.41	33.93
Total	100.00	100.00		100.00

Table 6 Analysis of combustion deposits (pocket location indicated by arrow in fig. 12).

Element	Atom %	Weight %	Error (±)	Norm %
0	74.67	48.11	0.69	48.11
AI	0.26	0.28	0.02	0.28
Si	0.82	0.93	0.09	0.93
S	3.41	4.40	0.10	4.40
CI	0.51	0.73	0.06	0.73
Cr	1.09	2.27	0.12	2.27
Fe	19.25	43.27	0.45	43.27
Total	100.00	100.00		100.00

Table 7 EDS analysis of the chemical composition ofthe coherent scale deposits (at location 3, shown in fig.11) of a sample from the low-Cl coal test.

Element	Atom %	Weight %	Error (±)	Norm %
0	75.11	50.79	0.67	50.79
Al	0.22	0.26	0.02	0.26
Si	0.66	0.78	0.09	0.78
S	8.27	11.20	0.13	11.20
Cr	1.21	2.66	0.11	2.66
Fe	14.53	34.31	0.39	34.31
Total	100.00	100.00		100.00

F22-2 sample



Figure 13 SEM of a polished cross section at the external surface of the high-Cl coal combustion sample.



F22-2 sample showing EDS locations 1-4

Figure 14 Appearance of coherent scale and deposit on the high-Cl coal combustion sample.

11.2 wt%, but again, no chloride deposition was detected. Analyses to verify the composition of the combustion deposits that covered the coherent deposit also showed no evidence of chloride deposition.

Polished cross sections through the tube-metal sample exposed to test firing with the high-Cl coal (figs. 13 and 14) were also examined. This sample had a coherent scale that was somewhat thinner than the sample obtained from the low-Cl firing test (1.0 mil instead of 2.5 mils). Much less coal ash and smaller other deposits were found on top of the coherent scale. The transition to these deposits was more gradual than that for the sample from the low-Cl coal test. Again, the EDS analysis was used to provide a semiquantitative measure on the metal tube

composition of the sample from the high-Cl coal test. The data obtained at location 1 of the sample shown in figure 5 are given in table 8.

The composition of the deposit at the interface between the scale and the underlying metal (table 9) showed an enrichment of sulfur (3.54 wt%), but no chloride deposition.

Table 8 EDS analysis of the chemical composition ofthe tube metal (at location 1, shown in fig. 14) of asample from the high-Cl coal test.

Element ¹	Atom %	Weight %	Error (±)	Norm %
Si	1.18	0.59	0.10	0.59
Cr	2.34	2.18	0.12	2.18
Fe	95.55	95.63	0.61	95.63
Мо	0.93	1.60	0.19	1.60
Total	100.00	100.00		100.00

¹ Mn was not detected at this location.

Table 9 EDS analysis of the chemical composition ofthe tube-scale interface (at location 2, shown in fig. 14)of a sample from the high-Cl coal test.

Element	Atom %	Weight %	Error (±)	Norm %
			· · /	
0	81.09	57.38	0.66	57.68
Al	0.26	0.31	0.02	0.31
Si	0.76	0.94	0.08	0.94
S	2.50	3.54	0.08	3.54
Cr	1.05	2.42	0.09	2.42
Fe	14.34	35.41	0.34	35.41
Total	100.00	100.00		100.00

Additional searching revealed no significant evidence of chloride deposition at the scale-metal interface. Analysis of the coherent scale itself revealed a sulfur content (0.34 wt%) for the high-Cl coal test (table 10) that was significantly lower than that for the sample from the low-Cl coal test (11.2 wt%) (table 7). Again, in no case was chloride deposition found either in the scale or in the combustion deposits on this sample.

The results of this study showed that the maximum corrosion rate of the T22 metal samples was the same whether samples were exposed to low-Cl or high-Cl coal combustion. However, the average corrosion rate of the test alloy exposed to combustion gases from the low-Cl coal was greater than that from the high-Cl coal. Sulfur content was greater in the scale produced from burning the low-Cl coal. This difference appeared to be related to the sulfur content in the coal. The sulfur content of the low-Cl coal was much greater than that of the high-Cl coal. There was no evidence of chloride deposition at the interface or in the scale produced from burning the high-Cl coal. Some isolated chloride-rich pockets were observed at the interface of the sample obtained from the low-Cl coal test. The sources of these chloride deposits were not obvious. There was, however, no indication of increased corrosion in the areas near and adjacent to these deposits. This observation supports the view that chloride deposits may not be a source for increasing the rate of metal surface corrosion.

Conclusions and Recommendations

Under low NO conditions, combustion of the high-Cl coal resulted in essentially the same corrosion rate of the tube metal alloy as with the low-Cl coal. Indeed, the corrosion rate based on average wall-thickness loss from the burning high-Cl Illinois coal was actually slightly less than that from burning low-Cl coal. Also, there was no evidence of chloride deposition in the scale that formed during the high-Cl coal test. The results of this study, obtained from combustion of coal under reducing conditions, were consistent with those of the previous study conducted using oxidizing conditions. Under either oxidizing or reducing conditions, corrosion rate did not increase as the Cl content of the coal increased. The results of this study suggest that the Cl content limits on coal set by boiler manufacturers are not necessarily applicable in all cases and that futher investigations to build a comprehensive database that confirms these findings may help boiler manufacturers to relax the limits on the Cl content of coals burned in their boilers.

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Table 10 EDS analysis of the chemical composition ofthe coherent scale deposits (at location 3, shown in fig.14) of a sample from the high-Cl coal test.

Element	Atom %	Weight %	Error (±)	Norm %
0	82.10	57.06	0.64	57.06
Al	0.18	0.21	0.02	0.21
S	0.24	0.34	0.05	0.34
Fe	17.47	42.39	0.36	42.39
Total	100.00	100.00		100.00

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