Long Term test Burn of switch-grass co-fired with coal at OGS.

Corrosion and deposit tests.

Prepared	Jacob N. Knudsen, Jens J. Christiansen and Lars Lærkedahl, Elsam Engineering A/S, 26 May 2007
Checked	Lars Lærkedahl, Elsam Engineering A/S, 28 May 2007
Approved	Lars Lærkedahl, Elsam Engineering A/S, 28 May 2007

Doc. no. 277766
Project no. T012618.12

Table of Contents

Appendices

Appendix 1: “Deposit specimens exposed to 5% switchgrass + coal co-firing at Alliant, Iowa”. Melanie Montgomery, Technical University of Denmark and Jacob Knudsen, Dong Energy.

Appendix 2: “Corrosion and deposit investigations during large-scale co-combustion of switchgrass at a coal-fired power plant”. Jacob Knudsen et al, Proceedings Snowbird Conference 2006.

1. Introduction

Switchgrass - Panicum vigatum - is a native Iowa grass that grows well on marginal ground and it is seen as an alternative revenue generating crop for southern Iowa farmers. The goal for the Chariton Valley Conservation Reserve and Development Inc. (CVRCD) is to grow up to 200,000 tons of switchgrass (SWG) annually and by co-firing the biomass at the Alliant Energy's coal-fired power plant Ottumwa Generating Station (OGS) up to 5% of the coal used could be replaced annually.

As part of the Chariton Valley Biomass Project (a federally cost-share funded project coordinated by CVRCD) several co-firing tests have been conducted and the goal is a commercial system with a full design capacity of 25 tph (22.7 tonnes/hr), generating ~35 MWe of power from renewable energy sources.

The first test campaign was performed from November 2000 through January 2001 with non-commercial SWG handling equipment. The aim of the first test was to observe the effects on the boiler operation and emissions and to study the handling of the SWG. It was shown that co-firing of up to 16.8 tons/h (15.2 tonnes/h) - corresponding to a heat input of about 3% - is feasible without adverse operational problems.

From November through December 2003, the project's Interim Co-firing Test was completed. The purpose was to test and improve the processing equipment, to verify the emissions and performance information obtained during the first test campaign and to collect and characterize coal, SWG and ash samples.

The third and final stage of the project's development process was planned to be a 90-day (2,000 consecutive hour) continuous test burn of SWG co-fired with coal in the OGS boiler. The Long Term test Burn was conducted from February through May 2006 and 1675 running hours were achieved burning around 15,650 tons of SWG. The third test burn was intended primarily to assess long-term impacts of burning SWG in the OGS boiler.

For the Long Term test Burn Elsam Engineering was to manufacture the test coupons to be installed in the boiler, perform deposit probe tests during the test burn, and analyse and report the results.

2. Objectives

The scope of the third test campaign includes assessment of the long-term effects on the boiler operation with respect to corrosion and slagging/fouling as well as collection of high-quality data for evaluation of boiler efficiency, precipitator performance, emissions and ash characteristics.

Long term issues of most interest are:
- Slagging and fouling (build-up of molten ash material on boiler tubes and walls), and
- Potential corrosion impacts on the boiler.

This report summarizes the observations, results and evaluations from conducting corrosion and deposit test in the boiler during the 1675 hours test period.

3. Plant data

Ottumwa Generating Station, operated by Alliant Energy, is pursuing co-firing of SWG as a supplementary fuel in their 726 MWe (675 MWe, net plant output) tangentially fired pulverized coal boiler. This boiler, which went into commercial service in May 1981, is fired with low sulphur Powder River Basin (PRB) coal.

The boiler is a twin furnace design, without division walls. It has 8 firing corners. It is equipped with no sulphur removal equipment, and with a hot-side electrostatic precipitator.

The current capacity of the SWG processing facility is 12.5 tph. The SWG is transported pneumatically about 1000 feet from the processing building into two burners placed in the corners opposite of each other in the eastern part of the twin furnace, see Figure 1.

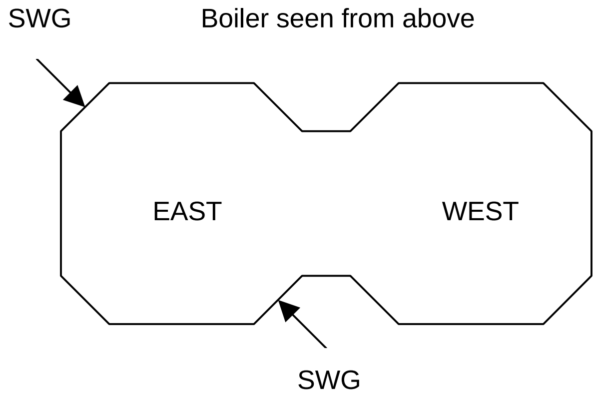

Figure 1: Twin furnace boiler with SWG co-firing in the eastern part.

4. Test plan

In order to quantify the effect of co-firing on emissions and ash characteristics, short-term test campaigns and long-term recording of CEM data has been performed.

The short-term tests are performed as 4-5 hours measuring campaigns with stable and well-defined operational conditions. This will ensure that complete and consistent data sets can be established. The scope of the sampling and analysis programme will allow calculation of mass balance closure and distribution of each element. SWG is only supplied to the eastern side of the boiler, and sampling of flue gas and fly ash from both sides of the flue gas system is recommended.

The number of tests to be performed depends on the number of relevant variable parameters to be investigated, such as boiler load, SWG consumption, SWG quality etc., assuming that SWG with a high and low content of alkali and chlorine can be obtained by early and late harvest. But as the bales collected for Long Term test burn have been accumulated over 3 years it has not been practical possible to tell them apart in the available stock. Therefore only the boiler load was used as variable parameter.

The general idea for the test plan was now to perform short-term tests at 100% boiler load and at 50% boiler load with the SWG capacity as close to 12.5 tph during the whole period. Both tests were repeated once. Furthermore a 24-hour test was made at “normal load conditions”. These tests were repeated later the same year during a period of “coal-only” in the boiler as a reference to the co-firing period. The following schedule was followed:

Table 1: Schedule for coal reference and SWG co-firing tests.

Test #	Date	Time	Boiler load	Exposure time (h)
Co-firing				
1	22 March 2006	9.00-14.00	100%	3
2	22-23 March 2006	23.00-04.00	50%	3
3	23 March 2006	09.00-14.00	100%	3
4	23-24 March 2006	23.00-04.00	50%	3
5	24-25 March 2006	04.00---04.00	“normal load”	24
Coal-reference				
1	3 July 2006	8.00-12.00	100%	3
2	3 July 2006	12.00-16.00	100%	3
3	4-5 July 2006	23.00-03.00	50%	3
4	5 July 2006	03.00-07.00	50%	3
5	5-6 July 2006	06.00---06.00	“normal load”	24

In the co-firing periods mentioned coal, SWG and ash samples were collected. In the coal-reference periods mentioned coal and ash samples were collected.

During these periods deposit probe tests were made in three (3) locations indicated as A, B and E in Figure 2 below.

In order to quantify the effect of co-firing on corrosion, long-term tests have been performed. The long-term tests were performed in two periods. From mid January 2006 to mid May 2006 and again from mid May 2006 to mid September 2006. The first period was with SWG co-firing and the last period was a coal-only period.

Tests coupons consisting of different kinds of materials were manufactured and build in the boiler in three (3) different superheater and reheater locations as indicated in Figure 2 below.

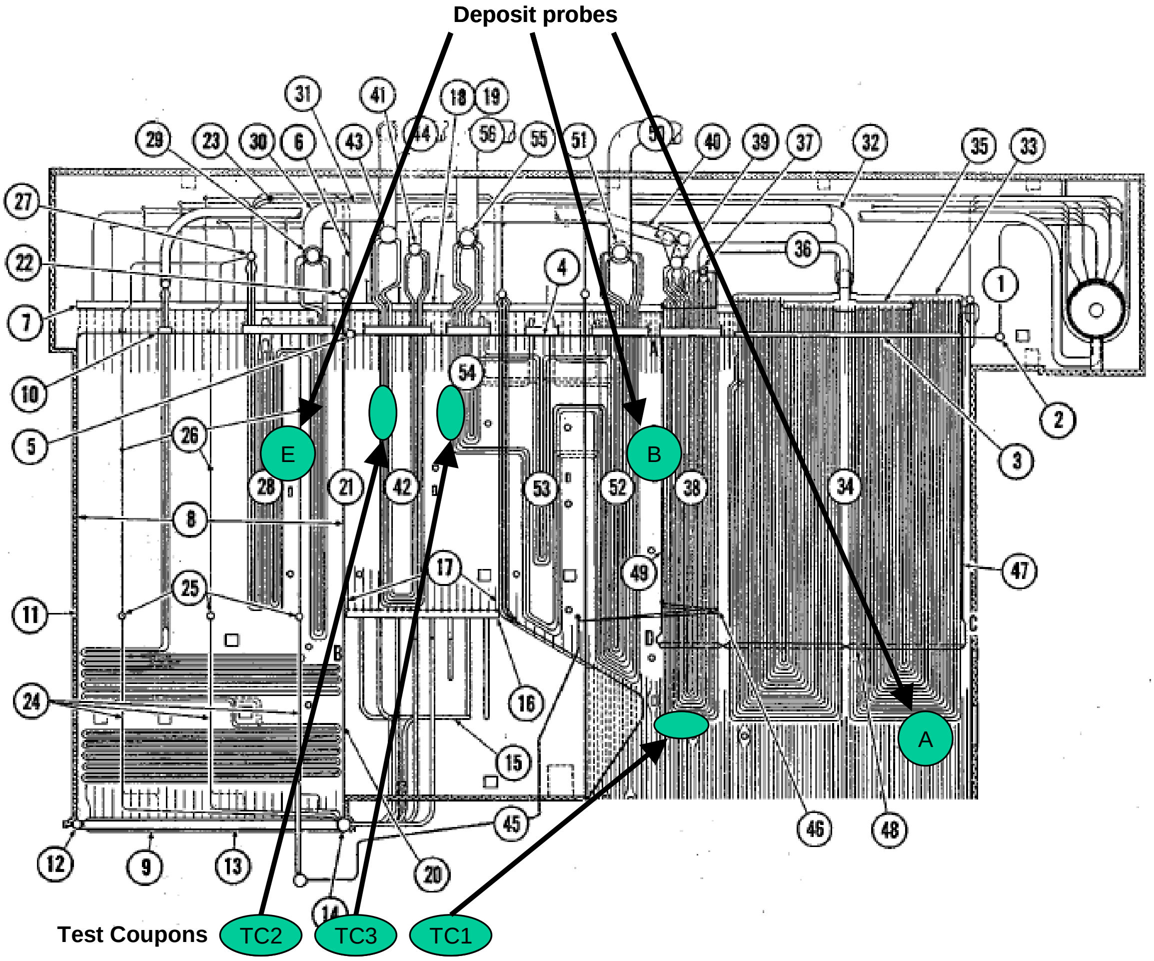

Figure 2: Locations for test coupons and deposit probes.

5. Test coupon specifications

Test coupon TC1 was built in the Superheater Pendant (SHP) area just above the combustion chamber. Test coupon TC2 was built in the Superheater Finishing (SHF) area between the combustion chamber and the 2nd draught of the boiler. Test coupon TC3 was built in the Reheater (RH) Finisher just in front of the Superheater Finisher. In each location three sets of test coupons were installed across the boiler. Eastside, Mid- and Westside of the boiler.

Locations are shown in Figure 2.

5.1 Test coupon materials and dimensions

In total 18 test coupons were manufactured. 9 coupons for the co-firing test period (3 sets of 3 coupons), and 9 coupons for the coal-only test period (3 sets of 3 coupons). Each coupon consists of 5 tubes each length 7.9” welded together. The different kinds of material, outer diameter (OD) and wall thickness (wt) of each tube are shown in Table 2.

Table 2: Material and dimension of each tube in the test coupons.

Test coupons no.	Tube no.	Material	Dimension [inch]	Dimension [mm]
			OD x wt	OD x wt
TC1.X.	1	347H	2 1/8 x 0.280	54.0 x 7.1
TC1.X.	2	10CrMo910	2 1/8 x 0.280	54.0 x 7.1
TC1.X.	3	13CrMo44	2 1/8 x 0.280	54.0 x 7.1
TC1.X.	4	304H	2 1/8 x 0.285	54.0 x 7.2
TC1.X.	5	347H	2 1/8 x 0.280	54.0 x 7.1
TC2.X.	1	347H	1 7/8 x 0.220	47.6 x 5.6
TC2.X	2	10CrMo910	1 7/8 x 0.220	47.6 x 5.6
TC2.X	3	13CrMo44	1 7/8 x 0.240	47.6 x 6.1
TC2.X	4	304H	1 7/8 x 0.238	47.6 x 6.0
TC2.X	5	347H	1 7/8 x 0.220	47.6 x 5.6
TC3.X	1	10CrMo910	2½ x 0.150	63.5 x 3.8
TC3.X	2	13CrMo44	2½ x 0.150	63.5 x 3.8
TC3.X	3	304H	2½ x 0.150	63.5 x 3.8
TC3.X	4	347H	2½ x 0.150	63.5 x 3.8
TC3.X	5	10CrMo910	2½ x 0.150	63.5 x 3.8

347H = Stainless steel TP 347H, 304H = Stainless steel 304H, 10 Cr Mo 910 ~ T22, 13 Cr Mo 44 ~ T11

5.2 Co-firing coupons numbering and location in boiler

Table 3 shows the stamped mark in each tube, the coupon location in the boiler (SHP, SHF and RH areas) and the orientation of the single tube when they were welded in for the co-firing tests.

Table 3: Co-firing coupon numbers and location.

	Fluegas flow side	Tube no.	Tube no.	Tube no.	Tube no.	Tube no.	Panel Bundle tube no.	Location in boiler
Material		**347H**	**10Cr**	**13Cr**	**304H**	**347H**	**SHP**	
TC 1.1	Lee	<=111	<=112	<=113	<=114	<=115	5	East
TC 1.2	Wind	<=121	<=122	<=123	<=124	<=125	20	Middle
TC 1.3	Lee	<=131	<=132* (>	<=133	<=134	<=135	37	West
Material		**347H**	**10Cr**	**13Cr**	**304H**	**347H**	**SHF**	
TC 2.1	Lee	<=211	<=212	<=213	<=214	<=215	5	East
TC 2.2	Lee	<=221	<=222	<=13Cr **	<=224	<=225	83	Middle
TC 2.3	Lee	<=231	<=232	<=233	<=234	<=235	161	West
Material		**10Cr**	**13Cr**	**304H**	**347H**	**10Cr**	**RH**	
TC 3.1	Wind	<=311	<=312	<=313	<=314	<=315	5	East
TC 3.2	Wind	<=321	<=322	<=323	<=324	<=325	83	Middle
TC 3.3	Wind	<=331	<=332	<=333	<=334	<=335	161	West

<= Steam flow-direction

* (> 132 and 10Cr is clock wise rotated 270 degrees

** Mark is rotated 180 degrees

5.3 Coal-only coupons numbering and location in boiler

Table 4 shows the stamped mark in each tube, the coupon location in the boiler (SHP, SHF and RH areas) and the orientation of the single tube when they were welded in for the coal-only tests.

Table 4: Coal-only coupon numbers and location.

	Fluegas flow side	Tube no.	Tube no.	Tube no.	Tube no.	Tube no.	Panel Bundle tube no.	Location in boiler
Material		**347H**	**304H**	**13Cr**	**10Cr**	**347H**	**SHP**	
TC 1.4	Lee	<=145	<=144	<=143	<=142	<=141	5	East
TC 1.5	Lee	<=155	<=154	<=153	<=152	<=151	20	Middle
TC 1.6	Lee	<=165	<=164	<=163	<=162	<=161	37	West
Material		**347H**	**304H**	**13Cr**	**10Cr**	**347H**	**SHF**	
TC 2.4	Lee	<=245	<=244	<=243	<=242	<=241	5	East
TC 2.5	Lee	<=255	<=254	<=253	<=252	<=251	83	Middle
TC 2.6	Lee	<=265	<=264	<=263	<=262	<=261	161	West
Material		**10Cr**	**347H**	**304H**	**13Cr**	**10Cr**	**RH**	
TC 3.4	Lee	<=345	<=344	<=343	<=342	<=341	5	East
TC 3.5	Lee	<=355	<=354	<=353	<=352	<=351	83	Middle
TC 3.6	Lee	<=365	<=364	<=363	<=362	<=361	161	West

<= Steam flow-direction

6. Measurement technique

6.1 Test coupons

In order to evaluate the influence of SWG co-firing on the corrosion rate of boiler tubes, corrosion test coupons have been installed in the boiler during periods of co-firing 5 % SWG (February – May 2006) as well as 100 % coal firing (May-September 2006). In both cases, the test coupons were exposed for approximately 4 months.

The corrosion test coupons have been installed at boiler positions TC1 (SH pendant), TC2 (SH finisher), and TC3 (RH) as shown in Figure 1. All the coupons have been machined to provide a level surface prior to installation. Four different alloys were investigated among which two were ferritic (10CrMo910, 13CrMo44) and two were austenitic (TP347H, and 304H) steels. The specifications for the specimens investigated are given in Table 5.

Table 5: Composition of the four steels applied in the corrosion tests.

Material	*C*	*Fe*	*Cr*	*Ni*	*Mn*	*Mo*	*Nb*	*Si*
10CrMo910	0.07-0.15	rest	2.0-2.5		0.40-0.70	0.90-1.0		0.20-0.50
13CrMo44	0.08-0.18	rest	0.70-1.10		0.40-1.00	0.40-0.60		0.10-0.35
TP347H	0.04-0.10	rest	17.0-20.0	9.0-13.0	<2.0		0.8-1.0	<1.00
304H	0.04-0.01	rest	18.0-20.0	8.0-10.5	2.00			0.75

6.1.1 Description of measurements/analysis

After exposure, the corrosion test coupons were removed from the boiler and shipped to the laboratory for metal loss measurements and SEM analysis.

To estimate the metal loss, pre-exposure and post-exposure measurements were undertaken using a profile projector. The profile projector was set to measure the metal thickness of the test coupons at 8 different positions around the metal circumference. For selected coupons the metal loss was both measured in the steam inlet and outlet end of the coupon. For the coal reference coupons, the post-exposure measurements resulted in suspiciously high metal losses (≈0.3-0.5 mm). Therefore, residual metal thickness measurements were undertaken manually with an optical microscope. This gives metal losses due to both corrosion on the fireside and oxidation on the steamside.

In addition, selected test coupons were mounted in epoxy resin and metallographically prepared for SEM investigation. The specimens were investigated using a JEOL JSM 590 scanning electron microscope with EDS facilities and a backscattered detector. The corrosion coupons were analysed in the areas around the circumference as detailed in Table 2, Appendix 1. These areas were located in the windward side (upstream). The SEM-EDS analyses provided the elemental compositions of both the inner deposits as well as the oxides.

From SEM micrographs, the thickness of the oxide was measured and although there is a certain amount of inaccuracy due to possible spallation of the oxide, it has been assumed that little spallation has occurred. Due to machining, the original interface is in many cases apparent. In other cases, the presence of chromium indicates inner oxide, i.e. the oxide present that has replaced the metal. However the low chromium content of 13CrMo44 can also make this assessment difficult. Since the oxide especially for the ferritic steels grew as shallow pits, the thickest oxide has been measured.

6.2 Deposit probes

By use of deposition probes, the effect of co-firing on initial deposition rate and initial deposit chemistry can be evaluated. Probes are to be cooled with water and/or air dependent on the heat load in the measurement positions. The probes are equipped with two exchangeable test rings for deposit collection and a thermocouple ring for metal temperature measurement in three circumferential positions. A control box will adjust the airflow to maintain a constant metal temperature based on the upstream thermocouple temperature registration.

The temperature set point for the probes is to be the same as the steam temperature in the tubes at the same positions. In this case temperature set points were chosen approx. 540°C (1005°F, design temperature) for all locations. Test rings made of 10CrMo910 steel, i.e. common superheater material, were utilized in all tests.

In the superheater pendant area just above the combustion chamber and in the reheater area water and air-cooled probes were used because of flue gas temperature above 900°C (1650°F) so the heat load on the probe was too high.

In the superheater finisher area only air-cooled probe was used as the flue gas temperature was less than 900°C, and therefore the heat input on the probe was less.

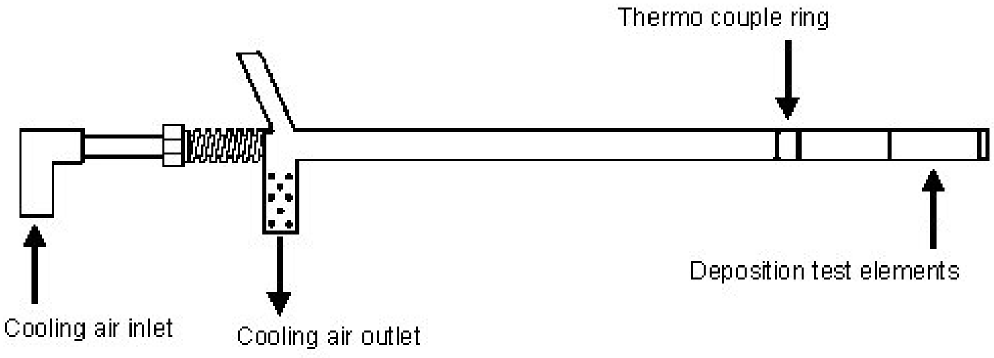

Figure 3: Schematic outline of air-cooled deposit probe.

The positions of the deposition probe measurements have been chosen to be able to evaluate the effect of co-firing on both high-temperature and low-temperature fouling. High-temperature fouling is important, as the increase in potassium from SWG may soften the silicates in this zone. Low-temperature fouling is important, as the Powder River Basin coals have a high tendency to this fouling type, mainly due to the high content of Ca and the potassium from the SWG, which may affect this fouling type. The probe measurements were made in three positions in the eastern part of the boiler: position A – before the Division Panel section (34), position B after the Pendant Platen Section (38) and position E before the Low Temperature Pendant Section (28). The positions can be seen in Figure 2.

6.2.1 Description of measurements/analysis

Deposit probe tests were made parallel to the short-term sampling period at coal base line and co-firing test (see Table 1). The deposit probes were exposed for the last three hours of the five-hour test duration in order to ensure stabilization of boiler conditions. Two supplementary long-term tests each with 24 hours probe exposure were made at normal load for the coal-only-reference and for the co-firing period. Each test included simultaneous measurements in all positions, i.e., three probes.

After exposure, the test rings were dismantled with great care to ensure that no deposit was lost. In the laboratory, the deposited material was carefully removed from the upstream and downstream side respectively, by use of a preformed shape. The weights of the material removed from the upstream and downstream sides were subsequently measured so that the deposition fluxes could be estimated. The collected deposits were subsequently analysed for the elements S, Cl, P, Si, Al, Fe, Ca, Mg, K, Na, Ti and water-soluble Na and K. For selected tests, a part of the deposit was left on the test ring for epoxy impregnation and scanning electron microscope (SEM) analysis.

On the basis of these results combined with the observations, operational measurements, ash analyses, gas measurements, changes in slagging and fouling tendency at co-firing and changing load can be evaluated.

7. Boiler inspections

Before the co-firing period, in between the co firing and the coal alone period and again after the coal alone firing period the boiler was inspected visually and wall thickness measurements were taken of the tubes in the area where the test coupons were built in.

7.1 Boiler inspection no. 1 in January 2006

Before the start of the co-firing test period boiler inspection no. 1 was done in the end of January 2006.

The inspection started in the Reheater area (RH) and in the Superheater Finishing area (SHF) where the test coupons TC3 and TC2 respectively were to be installed.

To get into the boiler, inspection door no. 26 at elevation 290 ft. east boiler was used. To get up to the RH and the SHF tubes a portable ladder was used.

The whole area was visual inspected from the eastside, to the middle and further on to the westside of the boiler.

After finishing inspection in the RH and SHF area, inspection went on in the superheater pendant (SHP) area above the combustion chamber.

Inspection door no. 25 at elevation 290 ft. east boiler was used. To get into the SHP area the RH front pendant (marked as no. 52 in Figure 2) was passed.

7.1.1 Reheater area January 2006

The RH (marked as no. 54 in Figure 2) consists of 165 bundle tubes. Original diameter (OD) and wall thickness (wt) of the tubes in TC3 area were 2.5” x 0.188”.

The RH appeared pretty clean on the lee side. On the lee side of the tubes there was max. 0.01” deposit. On the flue gas wind side up to 2”-4” fouling and slag was observed. The slag “cake” seemed to be easy to break off but close to the tubes the slag was hard and not easy to get off. Between the tubes in the bundle fouling and slag were building up in some places. The fouling and slag colour was yellow/brown.

The coupons TC3.1, TC3.2 and TC3.3 for the RH area were to be welded in approx. 3 ft. from the bottom bend. The tubes cut out in the RH area were measured manually; see Table 6 below for outer diameter (OD) and wall thickness (wt). The tubes look pretty well. No visual corrosion or erosion was observed. Deposit probes were taken.

Table 6: Dimensions of tubes cut out in RH area.

Tubes cut out in RH area	Pos. TC3.1 east bundle no. 5	Pos. TC3.2 middle bundle no. 83	Pos. TC3.3 west bundle no. 161
OD [inch]	2.51	2.50	2.50
wt wind side [inch]	0.181	0.173	0.173
wt lee side [inch]	0.181	0.177	0.181

7.1.2 Superheater Finishing area January 2006

The SHF (marked as no. 42 in Figure 2) consists of 165 panel bundle tubes. Original diameter (OD) and wall thickness (wt) of the tubes in the TC2 area was 1.88” x 0.2”.

On the flue gas inlet side of the SHF some fouling and slag were building up (up to 4” cakes). On the flue gas outlet side of the SHF less than 0,01” deposit was observed.

Between the centre tubes in the panel bundle up to 2 ft. cakes were built up all over the tubes surface in the flue gas inlet direction. Fouling and slag were also built up like a firm surface in between the individual tubes all over in the panel bundle.

No tube corrosion or erosion was observed in the SHF area. Slag cakes could be broken off but close to the tubes it was not possible. The slag was very hard. Fouling and slag probes from the SHF tubes were taken out 3’ ft above the ground level in the duct. The colour of the fouling and slag was yellow/brown.

The coupons TC2.1, TC2.2 and TC2.3 for the RH area were to be welded in approx. 1 ft. from the roof. The tubes cut out in the SHF area were measured (see Table 7 below). The tubes look pretty well. No corrosion or erosion was detected. Deposit probes were taken.

Table 7: Dimensions of tubes cut out in SHF area.

Tubes cut out in SHF area	Pos. TC2.1 east bundle no. 5	Pos. TC2.2 middle bundle no. 83	Pos. TC2.3 west bundle no. 161
OD [inch]	1.88	1.88	1.88
wt wind side [inch]	0.228	0.224	0.228
wt lee side [inch]	0.220	0.220	0.224

7.1.3 Superheater Pendant area January 2006

SHP (marked as no. 38 in Figure 2) consists of 41 panel bundle tubes. Original diameter (OD) and wall thickness (wt) of the tubes in the TC1 area was 2.13” x 0.3”.

During the inspection in the area it was observed that the fouling and slag on the bundle tubes was porous and easy to remove. The bundle tube no. 5 cut out looked pretty well. No erosion or corrosion was seen. In fact the area at bundle tube no. 20 and 37 looked the same. Two of the tubes cut out in the SHP area were measured (see Table 8 below).

Table 8: Dimensions of tubes cut out in SHP area.

Tubes cut out in SH Pendant area	Pos. TC1.1 east bundle no. 5	Pos. TC1.2 middle bundle no. 20	Pos. TC1.3 west bundle no. 37
OD [inch]	2.13	2.13	No measuring done
wt wind side [inch]	0.331	0.335	No measuring done
wt lee side [inch]	0.339	0.339	No measuring done

7.2 Boiler inspection no. 2 in May 2006

In the middle of May 2006, after 4 months co-firing test period boiler inspection no. 2 was conducted.

Inspection started in the Reheater area (RH) where the test coupons TC3 were installed, and in the Superheater Finishing area (SHF) where the test coupons TC2 were installed.

To get into the boiler, inspection door no. 26 at elevation 290 ft. east boiler was used.

The whole area was visual inspected from the eastside, to the middle and further on to the westside of the boiler.

After finishing the inspection in the RH and SHF area inspection went on in the Superheater Pendant (SHP) area where TC1 were built in.

Inspection door 25 at elevation 290 ft. east boiler was used. To get into the SHP area RH front pendant (marked as no. 52 in Figure 2) was passed.

7.2.1 Reheater area May 2006

The RH wind side looked “dusty”. On the lee side of the bundle tubes there be max. 0.01” deposit. On the flue gas flow side in between the bundle tubes fouling and slag were built up. The slag cake seemed to be easy to break off but close to the tubes the slag was hard and not easy to get off. The fouling and slag colour was yellow/brown.

At the positions of the TC3.1 (east) and TC3.3 (west) in the wind side of the coupons up to 3” fouling and slag were built up. On the lee side light deposit layer was observed. At the TC3.2 (middle) in the wind side of the coupon up to 8” fouling and slag were built up. Fouling and slag thickness was measured up to 5”.

Fouling and slag sample near the RH coupon TC3.2 located in the centre of the duct were taken. Colour of fouling and slag was yellow/brown.

In the TC3 RH areas no tube corrosion or erosion was visually observed. Existing tube ends in RH area were measured (see Table 9).

Table 9: Existing tube dimensions in RH area, May 2006.

Existing tube in RH area	Pos. TC3.1 east bundle no. 5	Pos. TC3.2 middle bundle no. 83	Pos. TC3.3 west bundle no. 161
OD [inch]	2.50	2.50	2.50
wt wind side [inch]	0.173	0.173	0.177
wt lee side [inch]	0.173	0.173	0.177

7.2.2 Superheater Finishing area May 2006

On the flue gas inlet side of the SHF slag are building up (up to 6” cakes). It seems to be more fouling and slag building up in the eastern side than in the western side of the SHF inlet duct area. On the flue gas outlet lee side of the SHF less than 0,01” deposit are manually measured.

Between the centre tubes in the panel bundle up to 2 ft. cakes were built up all over the tubes surface in the flue gas inlet direction. Fouling and slag were also built up like a surface in between the individual tubes all over in the panel bundle.

In the TC2 SHF area no tube corrosion or erosion were visually observed.

Slag cakes could be broken off but close to the tubes it was not possible. Slag and fouling samples from the SHF tube inlet were taken out 3 ft above the ground level in the centre of the duct. Colour of the slag and fouling was yellow/brown.

The coupons TC2.1, TC2.2 and TC2.3 in the SHF were cut out.
In the wind side of the coupons up to 3” slag were built up between the tubes in the bundle. On the lee side light deposit layer was obtained. Some small areas on the coupons were shelling.

Existing tube ends in SHF area were measured (see table Table 10).

Table 10: Existing tube dimensions in SHF area, May 2006.

Existing tube in SHF area	Pos. TC2.1 east bundle no. 5	Pos. TC2.2 middle bundle no. 83	Pos. TC2.3 west bundle no. 161
OD [inch]	1.89	1.89	1.89
wt wind side [inch]	0.224	0.224	0.232
wt lee side [inch]	0.228	0.220	0.232

7.2.3 Superheater Pendant area May 2006

Inspection in the TC1.1, TC1.2 and TC1.3 areas was done. Some of the fouling and slag on the bundle tubes was porous and easy to remove. Other was hard like concrete. One fouling and slag sample was taken from the bundle number 5 in SHP.

Existing tube ends in SHP area were measured (see table Table 11).

Table 11: Existing tube dimensions in SHP area, May 2006.

Existing tube in SHP area	Pos. TC1.1 east bundle no. 5	Pos. TC1.2 middle bundle no. 20	Pos. TC1.3 west bundle no. 37
OD [inch]	2.12	2.12	2.11
wt wind side [inch]	0.331	0.331	0.335
wt lee side [inch]	0.335	0.335	0.327

7.3 Boiler inspection no. 3 in September 2006

In the end of September 2006, after 4 months coal-alone test period boiler inspection no. 3 was conducted.

Inspection started in the Reheater area (RH) where the test coupons TC3 were installed, and in the Superheater Finishing area (SHF) where the test coupons TC2 were installed.

Entering the boiler, inspection door no. 26 at elevation 290 ft. east boiler was used.

The whole area was visual inspected from the eastside, to the middle and further on to the westside of the boiler.

After finishing inspection in the RH and SHF area inspection went on in the SHP area where TC1 were built in.

Inspection in SHP area was done from outside boiler through inspection doors and openings.

In general the boiler ducts and bundle in RH and SHF area seemed to be less mucky than in May 2006.

7.3.1 Reheat area September 2006

On the lee side of the bundle tubes there be max. 0.01” deposit. On the flue gas wind side in between the bundle tubes fouling and slag were built up. The slag cakes seemed to be easy to break off but close to the tubes the slag was hard and not easy to get off. The fouling and slag colour is yellow/brown.

In the TC3 RH areas no tube corrosion and erosion was visually observed.

One welding between an existing tube and a test coupon done at the erection of coupons in May 2006 appeared to be bad. A hole in the welding in the end of TC3.5 had caused damage to this end of the coupon (tube no. 351) and steam trail was seen. In the second row one tube was damaged locally. The test coupons in the RH area were cut out.

In the RH area at the wind side of coupons TC3.4, TC3.5 and TC3.6 up to 2” fouling and slag were built up. On the lee side light deposit layer was obtained.

Tube wall thickness was measured (see Table 12 below). The measurement was done approx. at the same location as in May 2006 at boiler inspection no. 2.

Table 12: Existing tube dimensions in RH area, Sep. 2006.

Existing tube in RH area	Pos. TC3.4 east bundle no. 5	Pos. TC3.5 middle bundle no. 83	Pos. TC3.6 west bundle no. 161
OD [inch]	2.50	2.50	2.50
wt wind side [inch]	0.181	0.177	0.185
wt lee side [inch]	0.177	0.173	0.177

7.3.2 Superheater Finishing area September 2006

On the SHF flue gas inlet side fouling and slag were built up (up to 6” cakes). Slag seemed to build up alike in the SHF inlet duct area. On the SHF flue gas lee side less than 0,01” deposit occurred.

Between the centre tubes in the panel bundle up to 1.5 ft. cakes were built up all over the tubes surface in the flue gas wind direction. Slag and fouling were also built up like a firm surface in between the individual tubes in the panel bundle.

In the TC2 SHF areas no tube corrosion or erosion were visually observed. The test coupons in SHF area were cut out. In the wind side of coupons TC2.4, TC2.5 and TC2.6 up to 1” fouling and slag was built up. In the lee side light deposit was obtained.

Tube wall thickness was measured (see Table 13 below). The measurement was done approx. the same location as in May 2006 at boiler inspection no. 2.

Table 13: Existing tube dimensions in SHF area, Sep. 2006.

Existing tube in SHF area	Pos. TC2.4 east bundle no. 5	Pos. TC2.5 middle bundle no. 83	Pos. TC2.6 west bundle no. 161
OD [inch]	1.89	1.89	1.89
wt wind side [inch]	0.228	0.228	0.232
wt lee side [inch]	0.228	0.220	0.232

7.3.3 Superheater Pendant area September 2006

Due to some de-slagging performed before the inspection minor amounts of fouling and deposit on the coupons were seen. Some deposits were seen on the lee side in between the tubes in the bundles.

The coupons TC1.4, TC1.5 and TC1.6 were cut out. Tube wall thickness was measured on existing boiler tube at coupon end (see Table 14 below). The measurement was done approx. the same location as in May 2006 at boiler inspection no. 2. The measurements though are uncertain because the test coupons where cut out very close to the erection weld (no space for exact measure).

Table 14: Existing tube dimensions in SHP area, Sep. 2006.

Existing tube in SHP area	Pos. TC1.4 east bundle no. 5	Pos. TC1.5 middle bundle no. 20	Pos. TC1.6 west bundle no. 37
OD [inch]	2.12	2.12	2.12
wt wind side [inch]	0.328	0.328	0.325
wt lee side [inch]	0.333	0.328	0.328

7.4 Resume

The boiler was inspected three times. Before co-firing, in between co-firing and coal-only and after the coal-only test periods.

The inspections were done in the areas where the test coupons were mounted. The Superheater Pendant (SHP) above the combustion chamber, the Superheater Finishing (SHF) and Reheater (RH) Finishing areas were inspected visually across the boiler. Outer diameter and wall thickness measureishing areas were inspected visually across the boiler. Outer diameter and wall thickness measurements were conducted.

In the SHP areas fouling and slag was built up in between the bundle tubes. Some fouling or slag was porous other hard like concrete. There were no differences to be seen at the three inspections.

In general the lee side of all SHF and RH areas was pretty clean at all the inspections. Fouling and deposit layer were less than 0.01”.

At the wind side in SHF panel bundles and in between the tubes fouling and slag were built up. Slag formations up to 1.5 -2 ft. were seen at all three inspections.

In the RH area fouling in the wind side and in between the panel bundles were 2-4” at all three inspections.

In general no visually sign of corrosion or erosion in the inspected areas was seen and no significant differences were observed between the inspections before co-firing, in between co-firing and coal-only and after the coal-only test periods.

8. Test burn Data collection

During each co-firing test according to Table 1, samples of coal, SWG, bottom ash and fly ash were collected and analyzed. Similar during each coal-only test, samples of coal, bottom ash and fly ash were collected and analyzed. The analysis are reported in Report PO# LTB-296-025 by CONSOL Energy.

During the co-firing period the feed rate, bale weight and moisture content of the SWG were recorded on a daily basis. Furthermore the OGS EtaPRO data system has been used to collect a wide range of operational data.

9. Results

9.1 Corrosion tests

This section summarizes the main results and conclusions from the corrosion investigation. For further details, Appendix 1 can be consulted.

Metal loss measurements

The results of the metal loss measurements for the corrosion coupons are shown in Figure 4, Figure 5 and Figure 6. The flue gas temperature has been approximately 1350, 900, and 950°C at position TC1, TC2, and TC3 respectively. The metal temperature (steam temperature) has been 540°C for the corrosion coupons at all positions.

Generally, it appears from Figure 4, Figure 5 and Figure 6 that similar metal losses are experienced during SWG co-firing and 100% coal firing taking the experimental uncertainty into consideration. Thus, there is no evidence of increased corrosion rates during 5 %-wt. SWG co-firing.

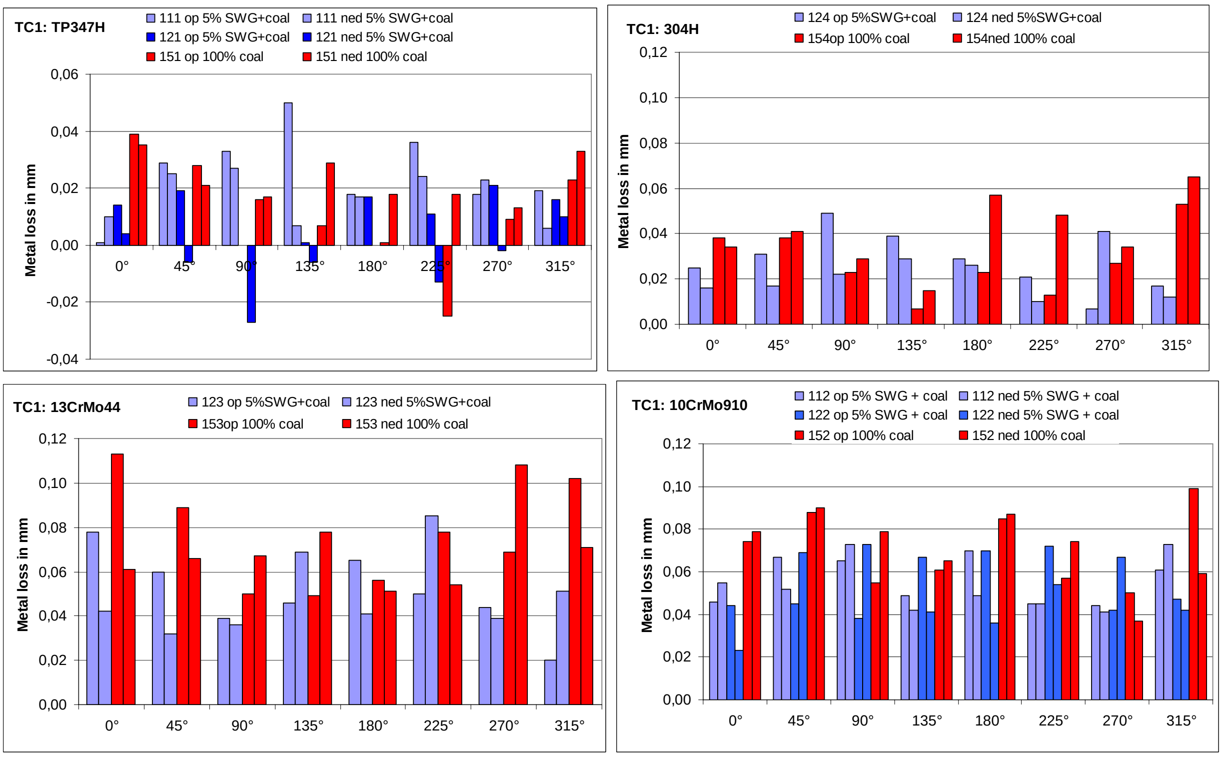

Figure 4: Metal losses determined for corrosion coupons in position TC1.

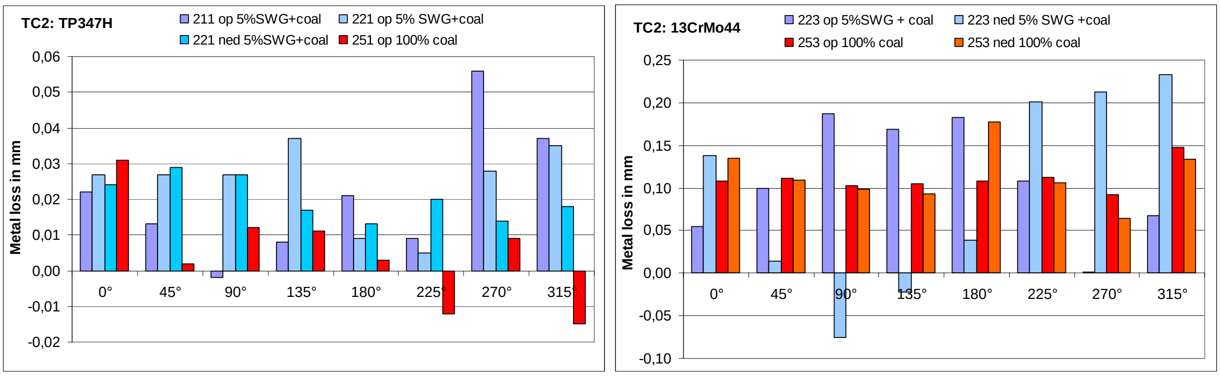

Figure 5: Metal losses determined for corrosion coupons in position TC2.

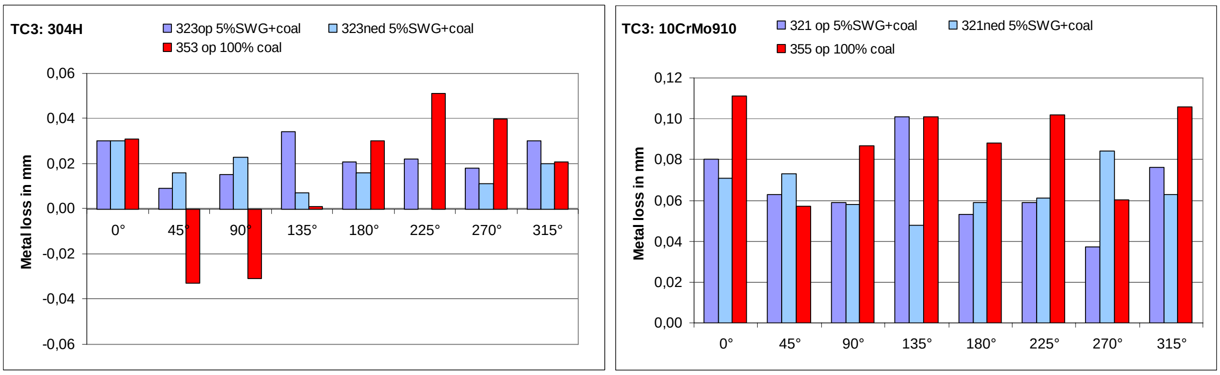

Figure 6: Metal losses determined for corrosion coupons in position TC3.

It is also seen in Figure 4, Figure 5 and Figure 6 that the measured metal losses are relatively similar at both ends of the test coupons, i.e. specimens denoted “op” (steam inlet) and “ned” (steam outlet).

Based on the multiple samples and measurement points, the average metal loss has been computed for each material in each boiler position TC1-TC3. This is presented in Table 15. Because negative losses are measured for some of the materials, the average value may not be the best basis for comparison. Therefore, the average of the highest quartile of results, named the “worst average” is introduced.

Table 15: Summary of metal loss data (in mm) for test coupons exposed for approximately 4 months.

Position	*Material*	*5% SWG co-firing*		*Coal*	
		Average	Worst average	Average	Worst Average
TC1:	13CrMo44	0.05	0.07-0.08	0.07-0.08	0.09-0.11
	10CrMo910	0.05-0.06	0.07	0.07	0.09
	TP347H	-0.01-0.03	0.01-0.04	0.01-0.02	0.03
	304H	0.02-0.03	0.03-0.04	0.03-0.04	0.05-0.06
TC2:	13CrMo44	0.09-0.11	0.19-0.22	0.11	0.13-0.16
	10CrMo910	0.10	0.12-0.13	n.d.	n.d.
	TP347H	0.02	0.03-0.05	0.01	0.02
	304H	0.01-0.02	0.03	n.d.	n.d.
TC3:	13CrMo44	0.07-0.08	0.11-0.12	n.d.	n.d.
	10CrMo910	0.06-0.07	0.08-0.09	0.09	0.11
	TP347H	0.02	0.03-0.04	n.d.	n.d.
	304H	0.02	0.03	0.01	0.05

It is clearly seen in Table 15 that the two ferritic steels show consistently higher metal losses than the two austenitic steels. Even though the worst average is considered, no greater metal loss than 0.05 mm i.e. 0.15 mm/year has been observed for the austenitic steels in the co-firing case. For the ferritic materials, metal losses of up to 0.22 mm, i.e. 0.66 mm/year are measured during co-firing. The corrosion rates measured for the austenitic materials are fully within the acceptable range whereas for the ferritic materials they are higher than acceptable.

With respect to the position in the boiler, Table 15 indicates that for the ferritic steels, the highest metal losses are observed in position TC2, the superheater finishing region. For the austenitic materials no distinctive influence on position can be observed. TC2 is the position with the lowest flue gas temperature. The influence of position will be further discussed below.

SEM-EDS analysis

In the following, SEM images of selected test specimens exposed in position TC1 and TC2 are shown. In Appendix 1, all of the SEM-EDS analysis results are shown.

SEM images of TP347H (the better material) and 13CrMo44 (the poorer material) steels at position TC1 for SWG co-firing and coal reference tests are shown in Figure 7 and Figure 8. It is clearly seen that a thinner oxide (2-10 μm) is formed for the TP347H than the 13CrMo44 steel (20-40 μm).

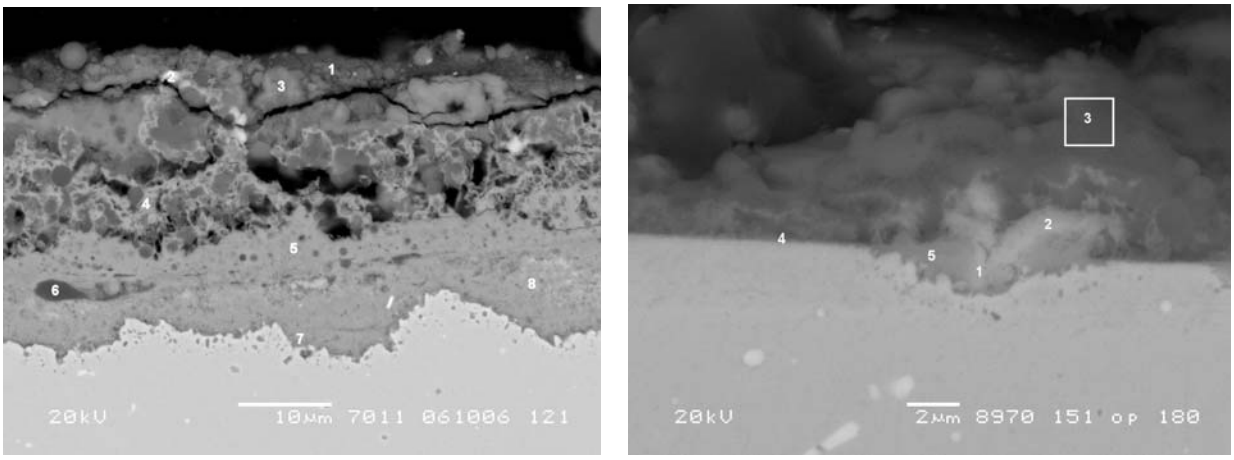

Figure 7: SEM images of inner oxide layer for test specimen of TP347H located in position TC1. Left: SWG Co-firing. Right: 100% Coal.

For both the co-firing and coal-firing cases (TP347H), the deposits adjacent to the oxide are mainly composed of Ca, Fe, O, and S (CaSO4 + FeO + $FeSO_4$) as well as minor amounts of Al and Si (Al-silicates). No chlorine and only small amounts of potassium (1-2%) are observed within the deposit for the co-firing case. The TP347H oxide consists of an outer layer of Fe-oxide and an inner of Fe-Cr-Ni-oxide. Sulfur was also found within the inner oxide. This indicates that sulfur take actively part in the corrosion mechanism.

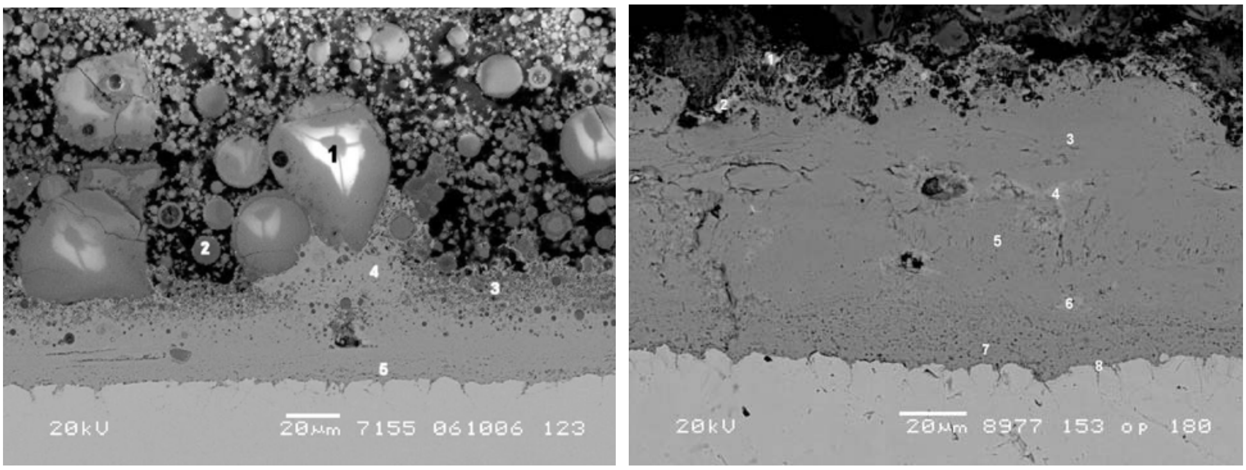

Figure 8: SEM images of inner oxide layer for test specimen of 13CrMo44 located in position TC1. Left: SWG Co-firing. Right: Coal reference.

For the 13CrMo44 co-firing specimen (Figure 8, left), particles rich in Mg-Ca-Al-Si are seen in the inner deposit. The oxide consist mainly of Fe-oxide but also some Ca and S. At the deposit-oxide interface (spot #3), minor amounts of potassium is also detected, i.e. mixed sulfates of K and Ca. No chlorine is detected. In the coal case, the oxide is similarly composed of Fe-oxide and smaller amounts of S.

SEM micrographs of TP347H and 13CrMo44 test coupons exposed in position TC2 are shown in Figure 9 and Figure 10. As in the TC1 position, a very thin oxide (approx. 1 μm) are observed for the TP347H specimens and significantly thicker oxides (50-100 μm) for the 13CrMo44 specimens.

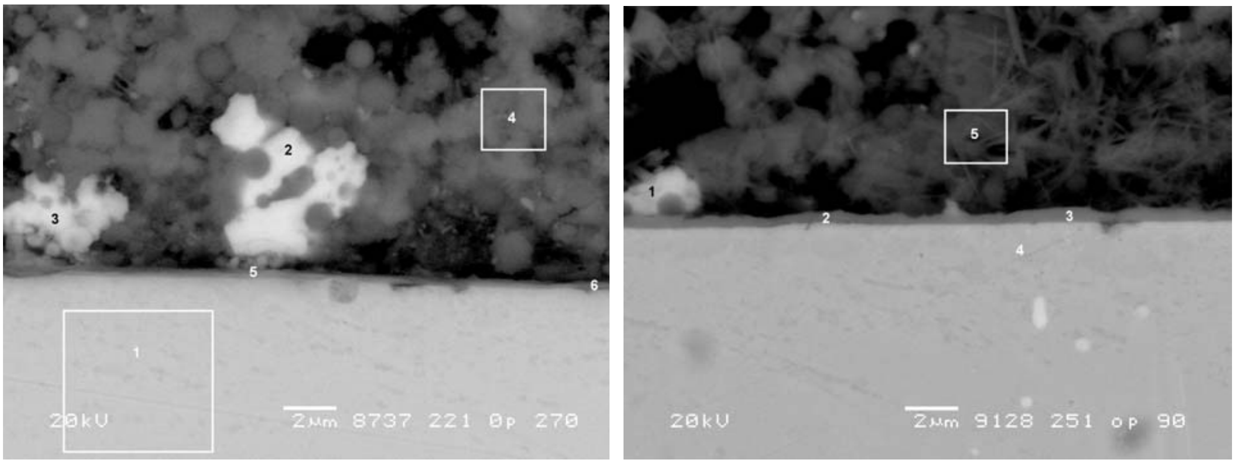

Figure 9: SEM images of inner oxide layer for test specimen of TP347H located in position TC2. Left: SWG Co-firing. Right: 100% Coal.

Figure 9, left indicates that the inner deposit of the TP347H co-firing specimen is mainly composed of $CaSO_4$ and Al-silicates. Also 1-5% of K is found together with Ca and S. The bright white particles (spot #2 and #3) that are seen in the SEM image consist of nearly pure $BaSO_4$. The oxide is thin and rich in Cr. No chlorine is detected in the deposit or oxide. The deposit composition and texture of the coal reference specimen appear much similar. However for the coal specimen, the K content of the inner deposit is lower, but instead Na is detected together with Ca and S. The oxide is similarly thin and rich in Cr.

The inner deposit of the 13CrMo44 co-firing specimen (Figure 10, left) contains primarily $CaSO_4$. The outer oxide layer contains elements from the deposit, Ca, S and Al whereas the inner oxide is mainly Fe-oxide and sulfur. The dark colored line that is seen dividing the oxide is composed of FeS and indicates the original metal surface. No chlorine is observed. In general, the inner deposit and oxide of the specimen from the coal reference test (Figure 10, right) are similar. Sulfur is also found within the inner oxide.

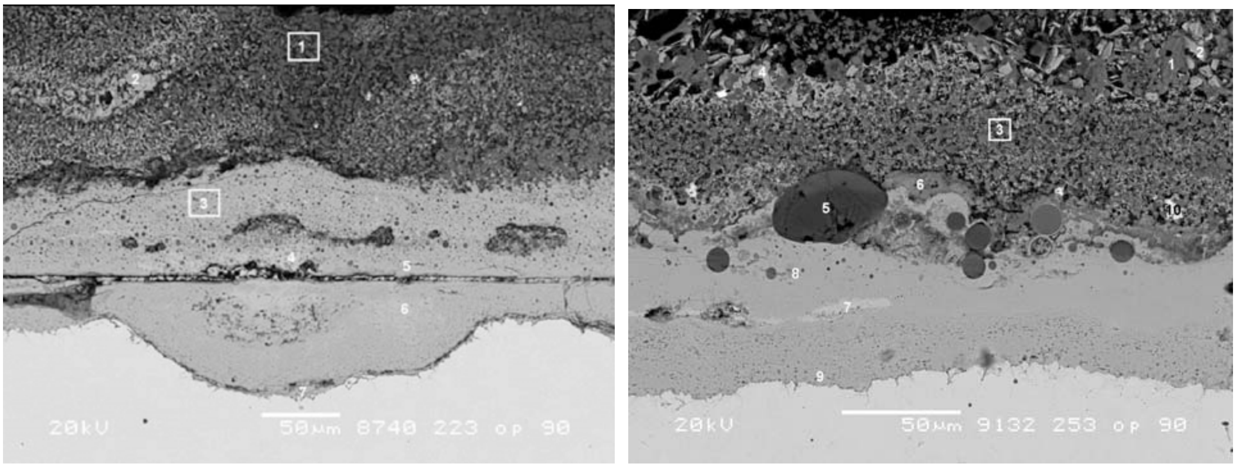

Figure 10: SEM images of inner oxide layer for test specimen of 13CrMo44 located in position TC2. Left: SWG Co-firing. Right: 100% Coal.

In conclusion, the SEM investigation reveals that the inner deposit and oxide composition and morphology are relatively similar between the SWG co-firing and the coal specimens. In all investigated specimens sulfur is enriched in the inner deposits and oxides. Sulfur originates mainly from the coal. No chlorine and only minor amounts of potassium are present in the inner deposit of the co-firing specimens.

On the basis of all the SEM micrographs investigated, the thickness of the fireside oxide-layer has been measured for each steel and position, which is shown in Figure 11.

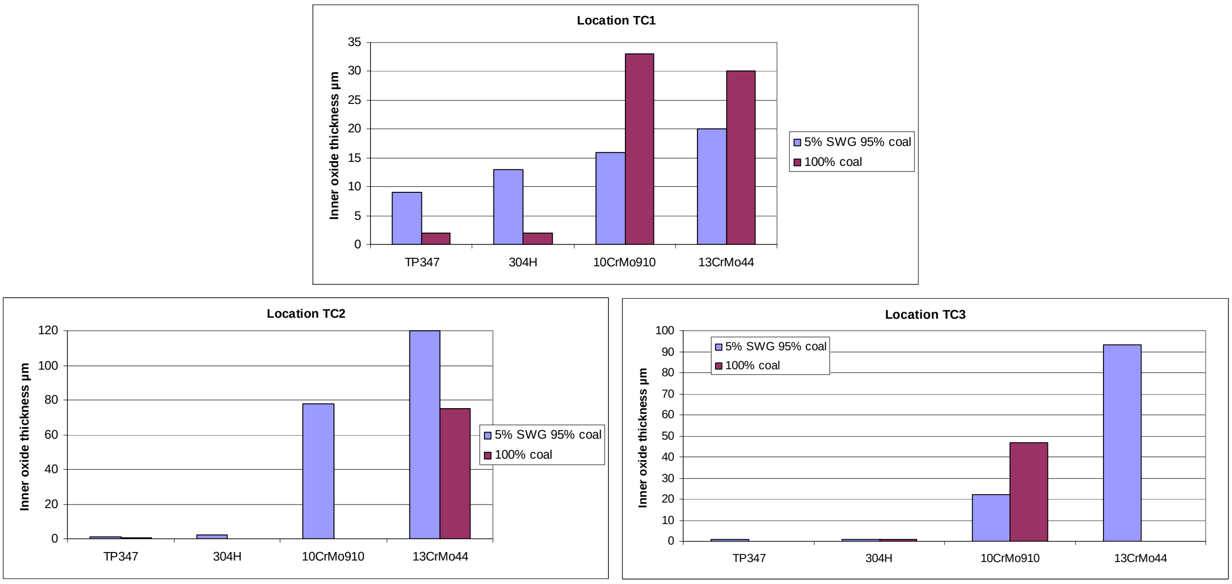

Figure 11: Thickness of inner fireside oxide for specimens at position TC1-TC3.

It is seen in Figure 11 that the oxide is much thicker for the ferritic than the austenitic materials. This is consistent with the higher metal losses measured for the ferritic steels as shown in Figure 4, Figure 5 and Figure 6 and Table 15. This is furthermore in agreement with the expectations as the thickness of the oxide typically increases with decreasing Cr content, i.e. 0.7-2.5 % for the ferritic and 17-20 % for the austenitic steels. It is also seen in Figure 11 that the oxide thickness for the ferritic steels spans from

30 µm in position TC1 to 90-120 µm in positions TC2 and TC3. This indicates higher corrosion rates at the latter positions although the flue gas temperature is much higher at position TC1 (1350°C) compared to that of TC2 and TC3 (900-950°C). This may be caused by the in general higher concentrations of soluble K and Na salts (primarily sulfates) in the deposits at positions TC2 and TC3. At position TC1, the relatively high flue gas temperature prevents condensation of alkali sulphates to a large extent. The oxide thickness for the austenitic materials is low at all positions.

None of the SEM analyses reveal the presence of chlorine in the deposits or in the corrosion products. This indicates that the alkali chlorides (mainly KCl) volatilized from the SWG have reacted with the aluminum-silicates and sulfur constituents of the coals as illustrated by the reactions:

$$2KCl + Al_2O_3 + 6SiO_2 + H_2O \rightarrow K_2O \cdot Al_2O_3 \cdot 6SiO_2 + 2HCl(g)$$
$$2KCl + SO_2 + H_2O + \tfrac{1}{2}O_2 \rightarrow K_2SO_4 + 2HCl(g)$$

Thus, it can be concluded that the risk of chlorine-induced corrosion due to co-firing with up to 5 %-weight SWG is remote.

Co-firing with high alkali biomasses such as SWG may also increase the threat of sulfur melt corrosion because of formation of eutectics. In the $CaSO_4$-K_2SO_4 system, the phase diagram (Figure 37, Appendix 1) reveals that melting can occur down to 867°C at a molar ratio of K_2SO_4 to $CaSO_4$ of 1.5. Based on the inputs of Ca and K with the coal and SWG it has been estimated that the K_2O/CaO molar ratio of the bulk ash has been approximately 0.01-0.03 during the SWG tests. Thus on bulk basis, the potassium input with SWG is far too low to result in eutectic melt formation. However, locally where the deposit is thin, such a eutectic could be present close to the oxide where the flue gas temperature is high. For instances it was observed in a single analysis of a SWG co-firing specimen (10CrMo910 at TC1) that the corrosion products adjacent the oxide was rich in calcium, potassium, iron and sulfur together. This could indicate that a melt of mixed calcium and potassium sulphates had attacked the outer iron oxide. However, because of the low potassium to calcium content this corrosion mechanism is unlikely to play a significant role in the overall corrosion phenomena.

For both the SWG co-firing and coal reference tests sulphidation and oxidation have occurred according to the following reactions:

$$4M + 3O_2 \rightarrow 2M_2O_3$$
$$2M + S_2 \rightarrow 2MS$$

For the ferritic steels, FeS is present at the original metal interface, which indicates that this is formed in the initial stages. Long-term exposures of corrosion coupons at the Danish Studstrup Power Station have also indicated that 10% straw co-firing results in sulphidation. However, it is difficult to assess the kinetics of corrosion when there is only data for one exposure time.

Altogether the corrosion investigation indicates that sulphidation and oxidation are the dominating corrosion mechanisms during both 100% coal firing and SWG co-firing. Little (if any) influence is related to SWG co-firing.

9.2 Deposit tests

By co-firing SWG, the deposition behavior may be affected because of the much higher content of water-soluble alkali elements, mainly potassium, in SWG compared to that of coal. Potassium associated in water-soluble compounds, i.e., salts, is easily volatilized in the burner zone and may subsequently form low-melting deposits on heat transfer surfaces. However, during co-firing with coal the potassium that has been volatilized from the SWG may to a high extent be transformed into high-melting Al-silicates by interaction with the mineral constituents of coal. For this reason, the stoichiometry between the Al, Si, and alkali elements is important in determining the impact of SWG co-firing on deposition.

During each co-firing test, samples of coal and SWG were collected and analyzed. On the basis of fuel analyses (CONSOL Energy, Report PO# LTB-296-025), the changes in the molar ratios of the key ash-forming elements have been estimated as shown in Table 16. It is seen in Table 16 that the SWG share during the co-firing tests has been in the range of 3-5 %-wt. (dry matter) of the total fuel input. This has resulted in an increase of the total alkali input of 5-13% compared to coal firing alone. Additionally, it appears that the increase in alkali input has not affected the Al/(K+Na) and Si/(K+Na) ratios significantly compared to coal firing alone. For all of the conducted tests, there is a vast excess of Al and Si to facilitate complete incorporation of the alkali constituents into alumina-silicates. Table 16 further indicates that in all of the co-firing tests, the Cl/(K+Na) and 2S/(K+Na) molar ratios are significantly below and above unity, respectively. This indicates that in the case that the alkali contents of SWG is not completely incorporated into Al-silicates, the remnants will most likely be present as sulfates instead of the more corrosive chlorides.

Thus, based on the change in bulk ash composition no significant change in the deposition behavior or fouling tendency is expected during SWG co-firing by up to 5%-weight.

Table 16: Influence of SWG co-firing on bulk ash composition (CONSOL Energy, PO# LTB-296-025).

Test	*SWG share (%-wt., dry)*	*Increase in K+Na (%)*	*Al/(K+Na)*	*Si/(K+Na)*	*Cl/(K+Na)*	*2S/(K+Na)*
Pure coal (average)	0	-	3.9	6.0	0.01	3.6
Pure SWG (average)	100	-	0.26	6.1	0.18	0.26
Co-firing:						
Test 1	3.1	6.3	4.3	8.0	0.038	4.6
Test 2	5.1	13.3	3.2	5.8	0.038	3.3
Test 3	3.0	6.2	3.9	6.8	0.013	3.3
Test 4	4.6	12	3.3	5.5	0.022	3.1
Test 5	3.3	5.0	3.7	5.0	0.018	2.7

In general, the deposit probe measurements confirm that the deposit composition and the deposition behavior are only marginally influenced by SWG co-firing. On the other hand, the change of boiler load from 100 to 50% has a great impact on the deposition behavior.

In Figure 12, pictures of deposits obtained during SWG co-firing at 100 and 50% boiler load, respectively, are shown. The big deposit pieces, which are seen in front of test ring A (left picture) are recovered from the outer deposit layer (upstream side). These pieces detached during probe retraction. It is evident from Figure 12 that most material is deposited in position A followed by B and E. It is also clear that more material is deposited during the test at 100% load despite the fact that the SWG share is lower during this test.

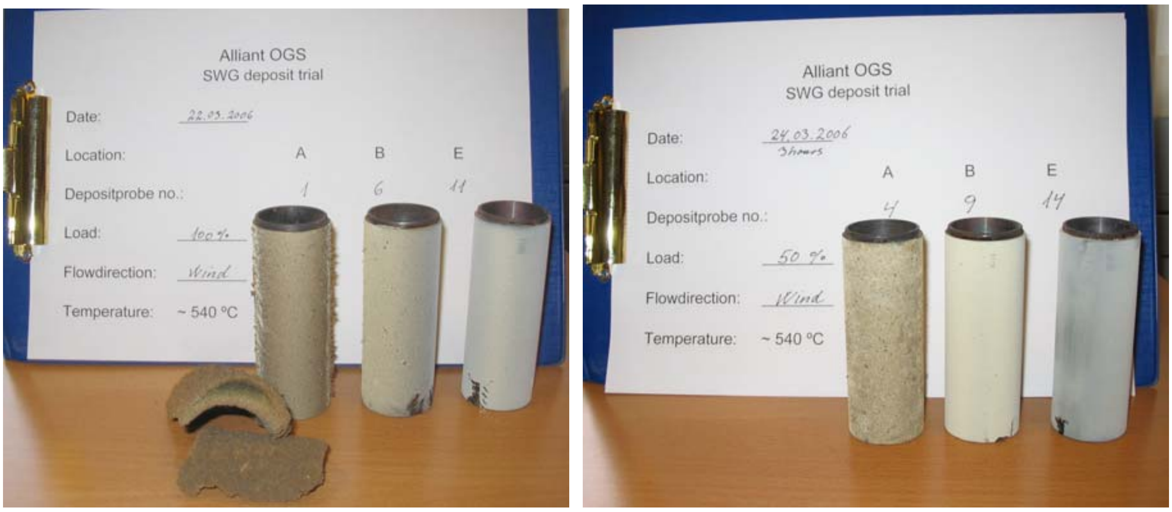

Figure 12: Deposit test rings after 3 hours' exposure. Left: Co-firing Test 1 - 100% load. Right: Co-firing Test 2 – 50% load.

Estimates of the deposition fluxes (upstream side) at positions A, B, and E can be derived from the deposit probe measurements, which are shown in Figure 13. As some of the deposited material was lost from the probe during retraction in most of the tests, the estimated values only provide an order of magnitude estimate. At position A, the deposition flux is very high (1-10 kg/m^2/h) during full load but decreases substantially (10-20 g/m^2/h), as the load is reduced. In position B, the deposition flux is much lower than at A at full load, but at 50% load the difference is less pronounced. In position E, the deposition flux is lower (0.5-6 g/m^2/h) than at the other two positions. It is expected that locations further downstream are experiencing lower deposition fluxes, because the flue gas temperature is lower (≈750 °C at pos. E contra ≈1370 °C at pos. A) and thereby the fly ashes have lower tendency to stick. Figure 13 furthermore reveals that SWG co-firing has no detectable influence on the deposition fluxes.

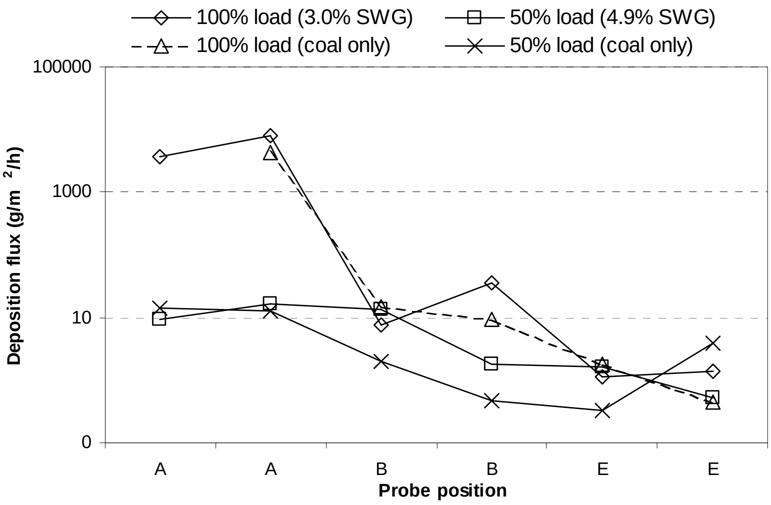

Figure 13: Measured deposition flux (upstream side) as a function of probe position.

The deposition flux at the downstream side of the deposit probe has been estimated to be in the range of 0.5-20 g/m^2/h. The influence of probe location and boiler load is less distinct. Again, no noticeable effect of the SWG share is observed. The deposition flux at the downstream side is expected to be much lower because it is shielded from impacting particles.

As described in section 6.2.1, chemical analyses have been performed on the deposit samples. In most of the tests, the material collected at position E was too low to allow full chemical analysis. In Figure 13, the elemental composition of the deposits collected at positions A and B during co-firing and 100% coal-firing is shown. The chlorine content is not shown in the diagrams, as it was very low (<0.1 %-wt.) and typically below the detection limit at all probe locations (A, B, and E) and for all SWG shares. The low chlorine content of the deposits indicates that the risk of chlorine-induced corrosion at the SWG share applied in these tests is low. Likewise, the concentration of low-melting alkali chlorides in the deposits is too low to affect the general melting behavior of the deposits.

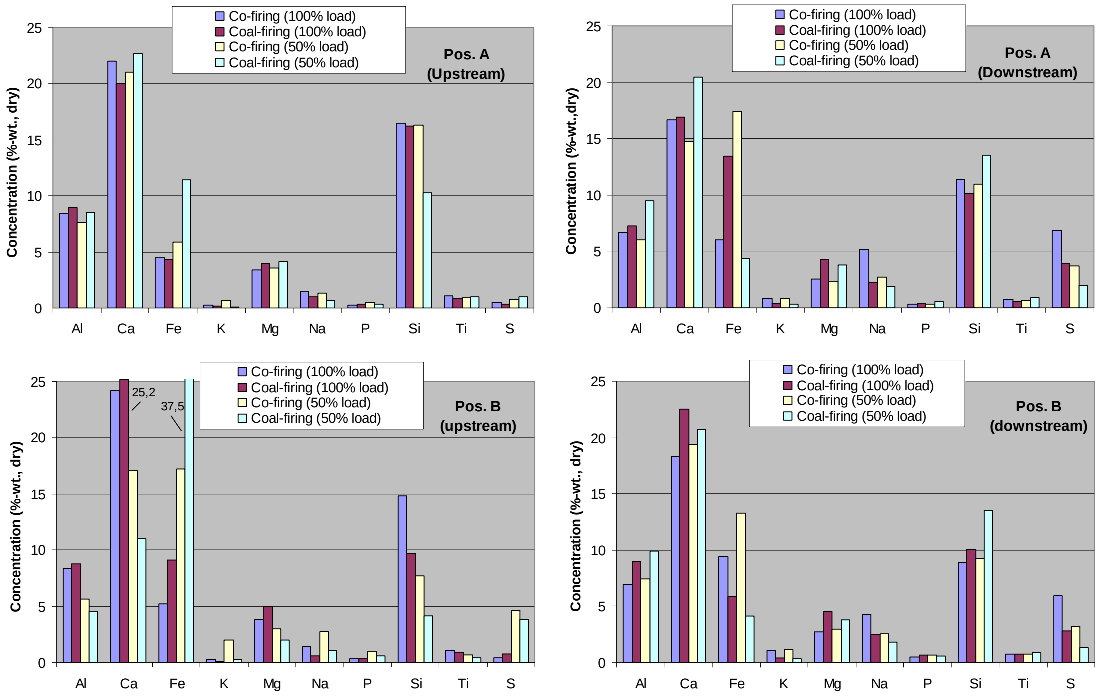

Figure 14: Elemental composition of deposit samples obtained during SWG co-firing and coal reference tests.

Generally, Figure 14 shows that the deposits collected during co-firing and 100% coal-firing as well as at 100 and 50% load (corresponding to 3.0 and 4.9 %-wt. SWG share, respectively) have very similar composition. The increase in potassium content caused by the increased SWG share is insignificant. Comparison of the upstream and downstream side of the deposits reveals that the downstream side contains higher levels of sodium and sulfur, i.e., sodium sulfate. This is as expected as the leeward side will be richer in flame-volatilized species and leaner in elements contained in entrained ash particles (non-volatile elements). The high iron content observed in some of the samples is most likely related to contamination of the deposit sample with iron from the metal test ring. This may artificially lower the concentration of the other elements.

The concentration of water-soluble alkali (K+Na) in the deposits is varying between 0.1 and 6.7 %-wt. In Figure 15, left and right, the concentration of water-soluble K+Na in the deposits collected on the upstream and downstream side, respectively, is shown as a function of the applied SWG share. 0 %-wt. share SWG represents the coal reference tests.

It appears from Figure 15 that there is no clear correlation between the SWG share and the concentration of water-soluble alkali in the deposits. This is probably related to the fact that even small variations in the alkali concentration of the coals causes greater change in the K and Na inputs than co-firing of up to 5 %-wt. SWG. In addition, as the SWG share was increased by decreasing the boiler load, the flue gas temperature will decrease at each probe position as well. This suggests that flame-volatilized species may condense further upstream at reduced boiler load, which is in agreement with the results in Figure 15.

On the upstream side, it is seen that the concentration of water-soluble alkali is very low for all tests at probe position A. For probe positions B and E, the concentration of soluble alkali is in most cases significantly higher. At probe position E, the concentration of soluble alkali appears to be higher for the co-firing tests than the coal reference tests.

For the downstream side, Figure 15 (right) indicates that there are small amounts of water-soluble alkali present in the deposits collected at all locations. This is probably related to the fact that the downstream side, to a higher extent, is composed of flame-volatilized material. The concentration of soluble alkali on the downstream side does not appear to increase with increasing SWG share.

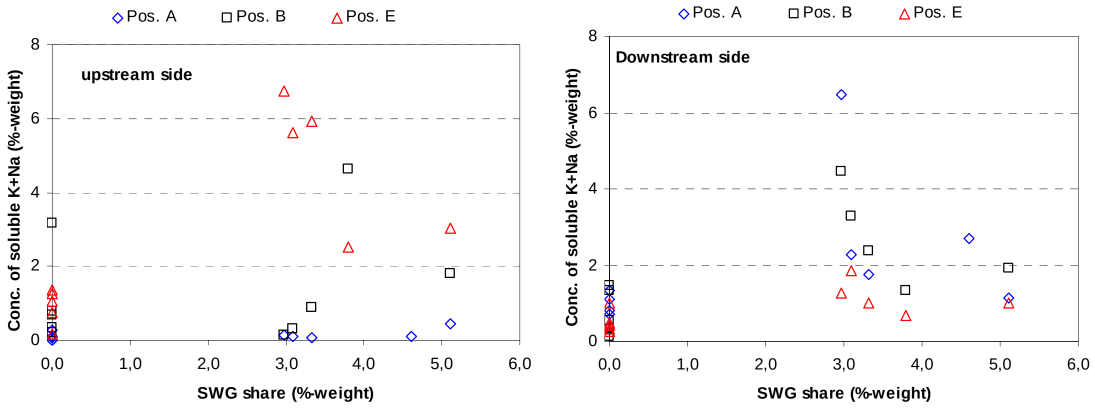

Figure 15: Concentration of soluble K+Na (%-wt.) in deposit from the upstream and downstream sides.

Altogether, the deposition probe measurements revealed that neither the deposit chemistry nor the deposition behavior was significantly affected by co-firing of up to 5 %-weight SWG.

9.3 Ash characteristics

In Table 17, the elemental composition of fly ash samples obtained during co-firing and coal-reference tests are shown. In general, there is very little difference in the fly ash characteristics between the reference and co-firing tests. Similarly no significant influence of boiler load (and SWG share) is observed. The potassium content is slightly higher in the fly ashes obtained during SWG co-firing due to the increased potassium input with SWG. However, the concentration of soluble potassium remains low although increasing marginally. The chlorine concentration is very low in all the fly ash samples. The concentration of sulfur, sodium and water-soluble sodium are somewhat higher in the fly ashes generated during co-firing. As the sodium and sulfur contents of SWG are relatively low, these differences are presumably related to variations in the sodium and sulfur contents of the coals fired in the two testing periods.

It also appears from Table 17 that the fly ash composition resembles the composition of the deposits collected from the upstream side in position A and B (Figure 14).

Table 17: Influence of SWG co-firing on fly ash composition (%-weight, dry).

Test	*Na(aq)*	*K(aq)*	*Si*	*Al*	*Fe*	*Ca*	*Mg*	*Na*	*K*	*S*	*Cl*
Co-firing:											
Test 1 – 100% load	0.97	0.09	15.4	8.7	4.3	20.5	3.6	3.0	0.44	1.37	0.002
Test 2 – 50% load	0.93	0.12	15.2	8.4	4.0	21.2	3.6	2.9	0.44	1.43	0.002
Coal-reference:											
Test 1,2– 100% load	0.35	0.04	15.8	8.9	3.7	19.7	3.9	1.9	0.32	0.86	0.001
Test 3 – 50% load	0.30	0.03	15.6	9.1	3.6	20.0	3.8	1.8	0.30	0.90	0.001

In conclusion, co-firing SWG in the applied amounts does not considerably affect the elemental composition of fly ash.

10. Conclusions

Corrosion and deposit investigations have been conducted during a long-term test burn period with 1675 hours of co-firing switchgrass to the coal-fired boiler at OGS. As a reference similar investigations have been made during a period of firing coal only.

According to inspections on site, in general no visually sign of corrosion or erosion in the inspected areas was seen and no significant differences were observed between the inspections before co-firing, in between co-firing and coal-only and after the coal-only test periods.

In all investigated specimens from the test coupons sulfur is enriched in the inner deposits and oxides. Sulfur originates mainly from the coal. No chlorine and only minor amounts of potassium are present in the inner deposit of the co-firing specimens. It can be concluded that the risk of chlorine-induced corrosion due to co-firing with up to 5 %-weight SWG is remote.

Altogether the corrosion investigation indicates that sulphidation and oxidation are the dominating corrosion mechanisms during both 100% coal firing and SWG co-firing. Little (if any) influence is related to SWG co-firing.

The deposition probe measurements revealed that neither the deposit chemistry nor the deposition behavior was significantly affected by co-firing of up to 5 %-weight SWG.

Furthermore it is concluded that co-firing SWG in the applied amounts does not considerably affect the elemental composition of fly ash.