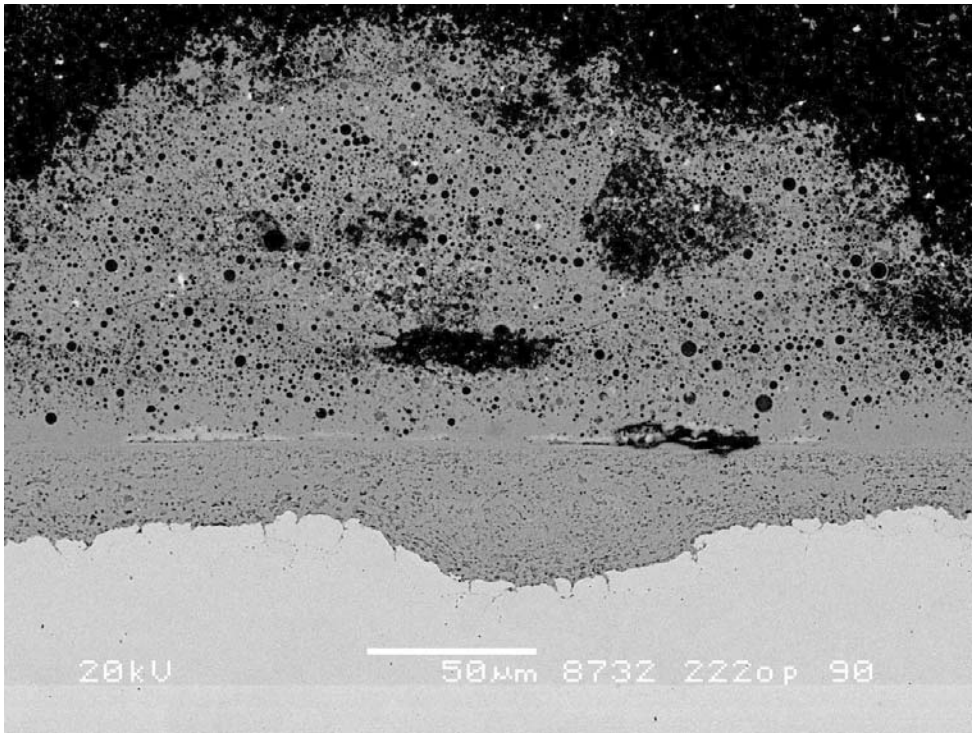
Deposit specimens exposed to 5% switchgrass + coal co-firing at Alliant, Iowa



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1. Introduction

Various deposit probes and tube sections to investigate corrosion have been exposed in the plant at Alliant in Iowa where a combination of switch grass and coal has been used as fuel. Corrosion investigations of tube sections with 100% coal firing have also been undertaken as a reference.

The deposit probes are 10CrMo910 with 2.0-2.5 %Cr and 0.90-1.10 Mo. They have had 540°C metal temperature and varying flue gas temperatures where A=1370°C, B=1100°C and E=750°C. The fuel has been coal with 10% switchgrass. The exposure time was 3 hours.

Photographs of the three specimens are shown in Figure 1. As can be seen, at the higher gas temperature, there is visually a thicker deposit. The deposit probes were exposed in the position A, B and E in Figure 2.

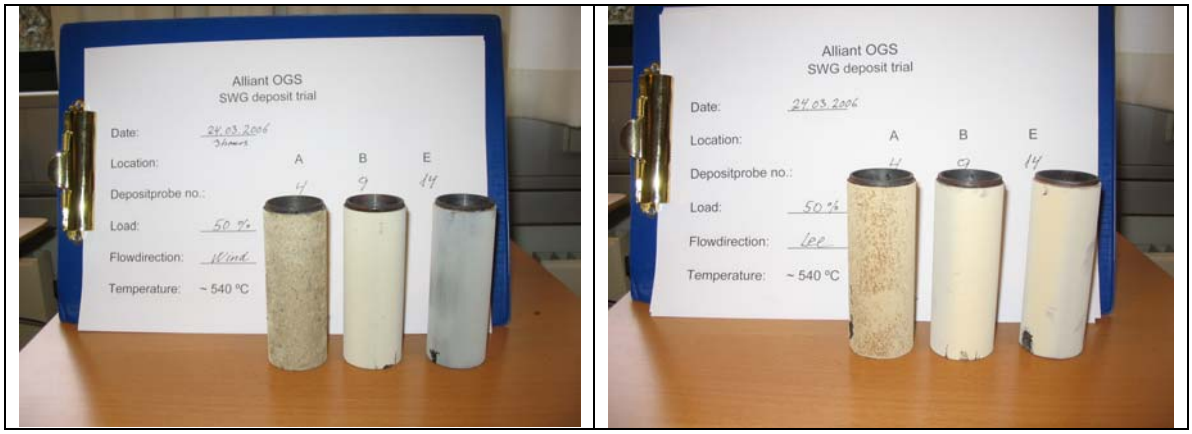


Figure 1: Photographs of deposit probes from windside and leeside.

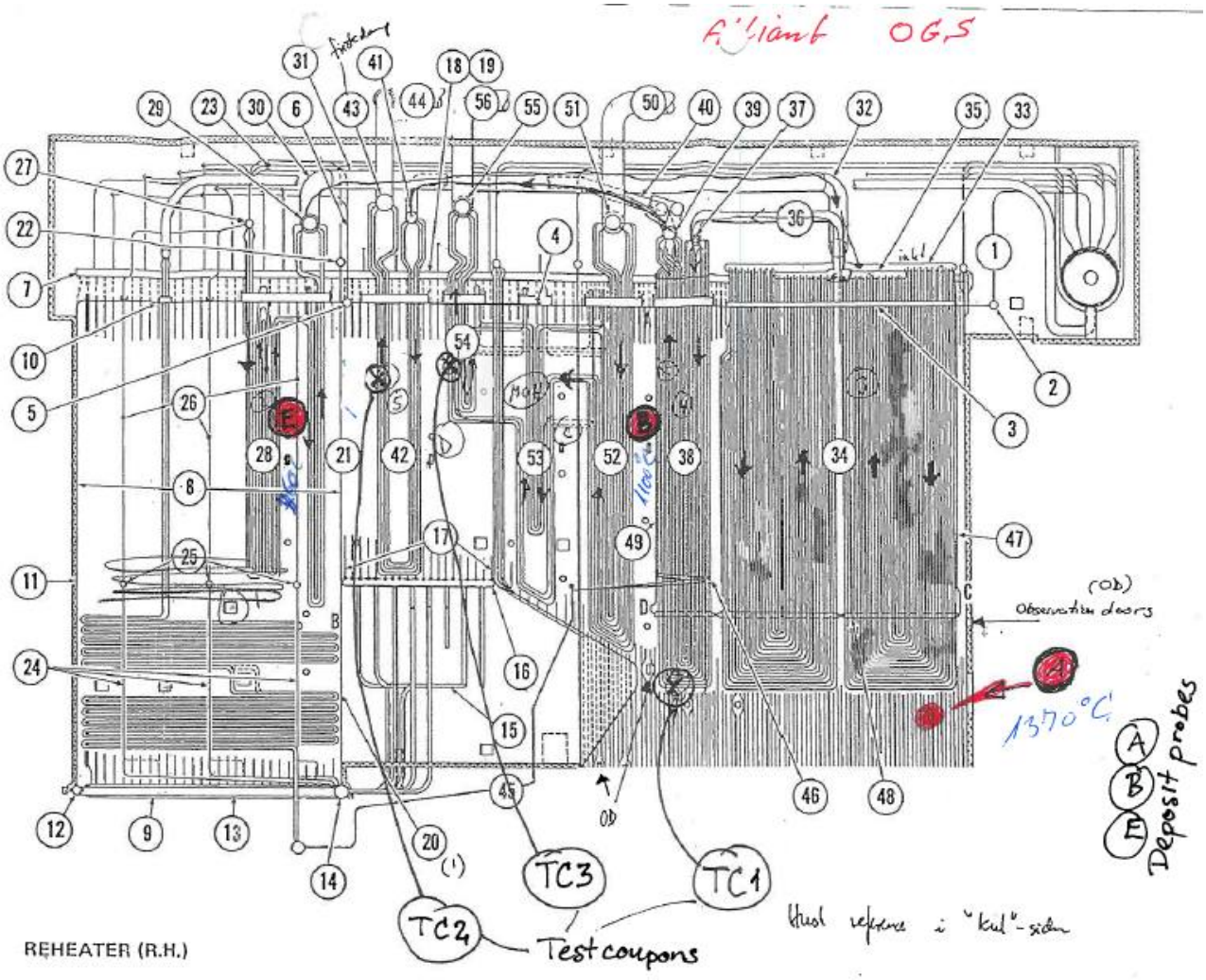


Figure 2: Diagram of location of deposit probes and corrosion sections.

The corrosion sections have been positioned at TC1, TC2, and TC3 as shown in Figure 2. They had been machined before exposure and pre-exposure and post-exposure measurements were undertaken using a profile projector. Residual metal thickness measurements of the specimen exposed to coal were undertaken manually at DTU with a light optical microscope. This gives metal loss due to both corrosion on the fireside and oxidation on the steamside. All specimens have been exposed for 4 months (1675 hrs) during combustion of 95% coal and 5% switchgrass (energy basis) or 100% coal. The alloys investigated are 10CrMo910, 13CrMo44, 347H, 304H

The specifications for the materials investigated are given in Table 1 and the conditions for the exposure are in Table 2.

Table 1: Specifications of alloys investigated.

	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*
347H	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

Table 2: Exposure parameters of specimens investigated

Specimen No.	Material	Location	Analysis position	Fuel	Metal T °C	Gas Temp. °C	Pressure
121	TP347H	TC1	0	5% SWG 95% coal	540°C	1350	200
122	10CrMo910	TC1	0	5% SWG 95% coal	540°C	1350	200
123	13CrMo44	TC1	0	5% SWG 95% coal	540°C	1350	200
124	304H	TC1	0	5% SWG 95% coal	540°C	1350	200
151	TP347H	TC1	180	100% coal	540°C	1350	200
152	10CrMo910	TC1	180	100% coal	540°C	1350	200
153	13CrMo44	TC1	180	100% coal	540°C	1350	200
154	304H	TC1	180	100% coal	540°C	1350	200
221	TP347H	TC2	90, 270	5% SWG 95% coal	540°C	900	200
222	10CrMo910	TC2	90, 270	5% SWG 95% coal	540°C	900	200
223	13CrMo44	TC2	90, 270	5% SWG 95% coal	540°C	900	200
224	304H	TC2	90, 270	5% SWG 95% coal	540°C	900	200
251	TP347H	TC2	90, 270	100% coal	540°C	900	200
253	13CrMo44	TC2	90, 270	100% coal	540°C	900	200
321	10CrMo910	TC3	90, 270	5% SWG 95% coal	540°C	950	50
322	13CrMo44	TC3	90, 270	5% SWG 95% coal	540°C	950	50
323	304H	TC3	90, 270	5% SWG 95% coal	540°C	950	50
324	TP347H	TC3	90, 270	5% SWG 95% coal	540°C	950	50

The specimens were investigated using a JEOL JSM 590 scanning electron microscope with EDS facilities and a backscattered detector. For the deposit specimens, a sample of deposit was removed from the ring, and in addition the ring specimen was cross-sectioned. All specimens were prepared without the use of water as a lubricant.

2. SEM analysis of deposit

The deposit was collected as a powder and in addition, a ring specimen was cross-sectioned. For specimen ES13001 (highest flue gas temperature), analysis was conducted around the whole the specimen. All analyses of specimens are given in the Appendix A. For all the specimens investigated, chlorine was not present within the specimens - however it was noted that a signal for chlorine was present in the mounting material. Table 2 shows the relation between elemental composition of deposit specimens removed from the tube. Elements below 5% are given as minor elements.

Table 3: Deposit composition at the various temperatures.

Specimen	Gas Temp. °C	Major Elements	Minor Elements	Morphology
ES13001	1370	O Ca Fe S Na	Mg Al Si K	Small and large particles
ES13002	1100	O Ca Si Fe Al S	Na Mg P K	Mostly large particles
ES13003	750	O Al Si Ca Fe	Na Mg S K Ti	Mostly large particles

Figure 3 shows the elemental distribution for the probe exposed at the highest flue gas temperature. There are large and smaller silicon, aluminium and calcium particles. Sodium and sulphur is present between these particles. There is also an enrichment of sulphur within the inner chromium rich oxide. No chlorine is present.

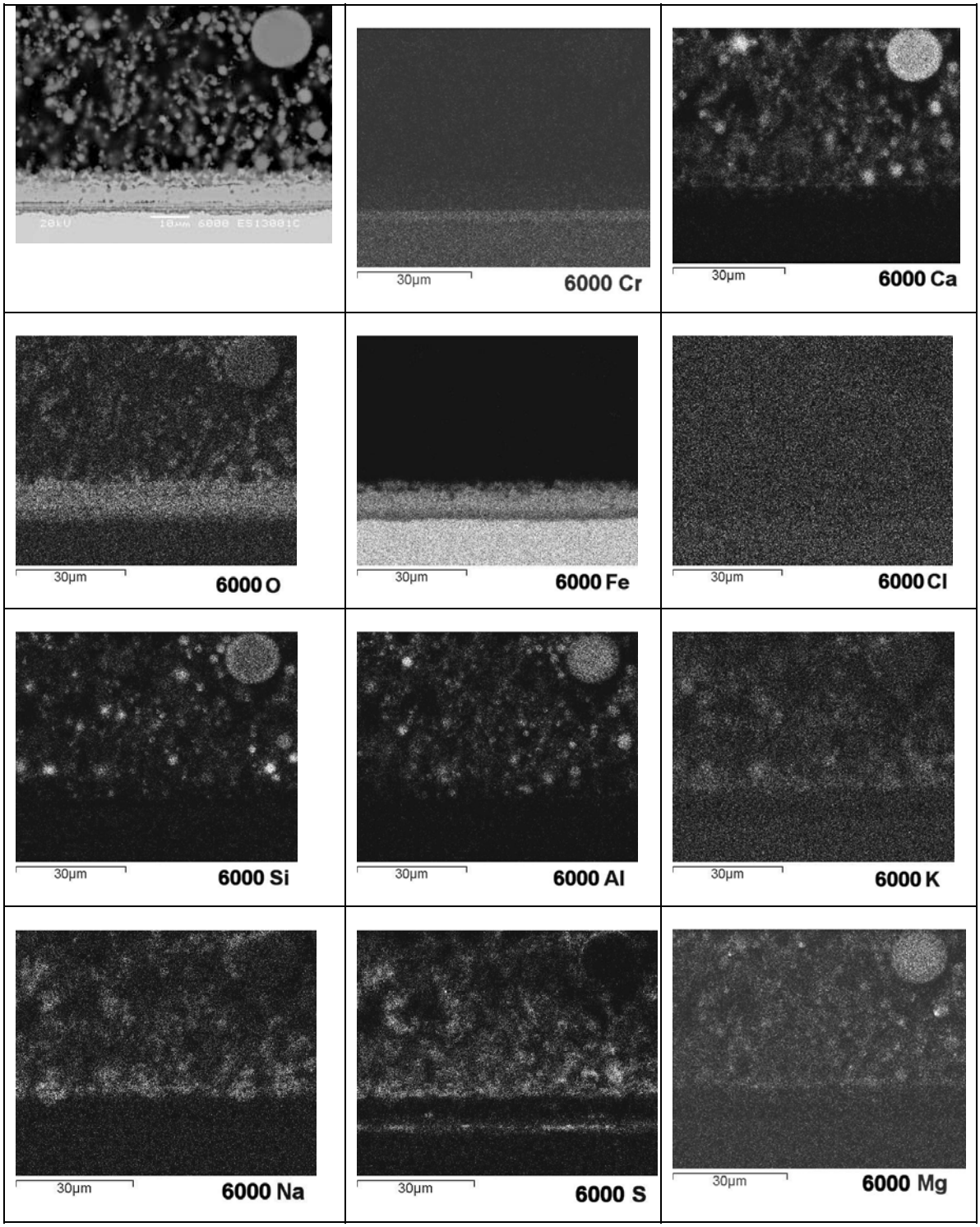


Figure 3: Elemental distribution maps for deposit formation after 3 hours exposure to 10% switch grass + coal at a gas temperature of 1370°C.

3. Analysis of corrosion probes

Pre-exposure and post exposure measurements were undertaken for the corrosion probes, thus the metal loss could be calculated. The corrosion probes were analysed using scanning electron microscopy in the areas around the circumference as detailed in Table 2. These were the areas exposed to the flue gas flow (windward). All analyses are given in the appendices. From SEM micrographs, the oxide was measured and although there is a certain amount of inaccuracy due to possible spallation of the oxide, it is 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 which 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.

3.1. Location TC1

3.1.1. TP347H FG

Figure 4 shows the metal loss thickness for TP347H. According to this diagram, the metal loss in coal firing is similar to that in co-firing with switch grass.

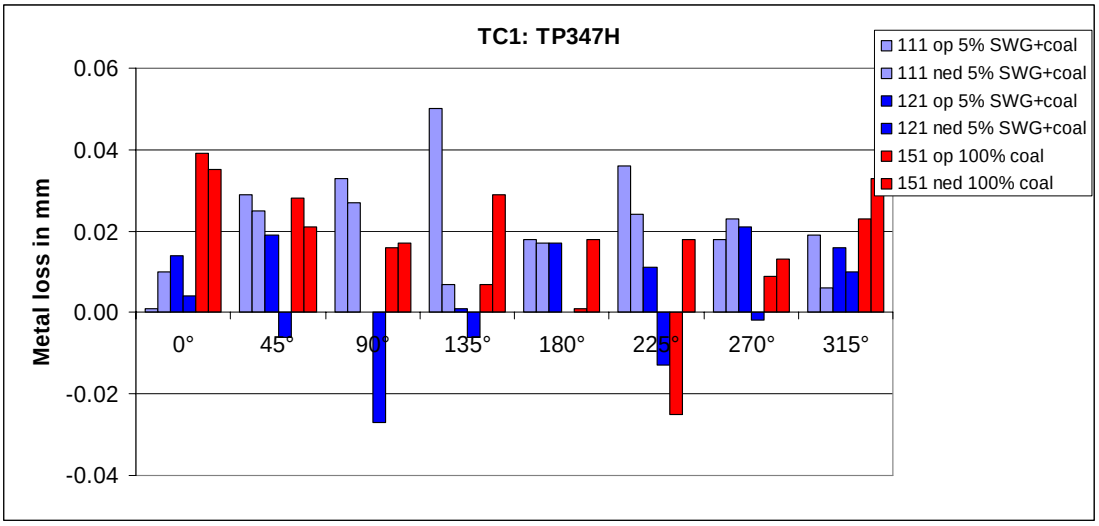
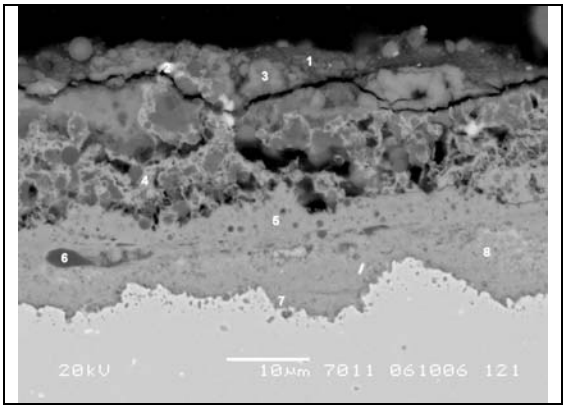


Figure 4: Metal loss measurements for TP347H exposed in TC1

a) 5% Switchgrass, 95% Coal

For the specimen 121 op, the deposit adjacent to the oxide consists of predominantly calcium, oxygen and sulphur, presumably calcium sulphate. In the deposit, aluminium and silicon are also present presumably as particles; barium was also detected (Figure 5). The oxide consisted of an outer oxide of iron oxide and an inner oxide of iron-chromium-nickel oxide. Sulphur was also enriched within this oxide. Iron oxide particles are present within the deposit as threads of oxide. In addition, a trace of chlorine has been detected within the inner oxide. The relevance of this measurement needs to be assessed when comparing with the other specimens.

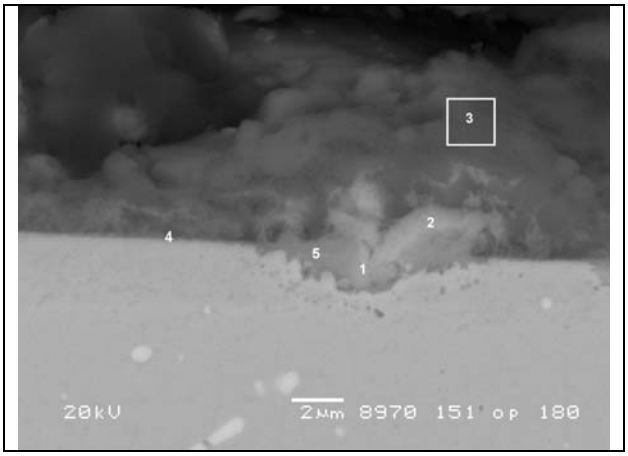


7011	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Mn	Fe	Ni	Ba
1	30	1	1	7	6	1	21		1	23	1			8		
2	17			2	3		15			4				14	1	45
3	27	2	1	5	5		10		1	11		1		39		
4	14			2			3			3		2		74	2	
5	15			1	1							4	1	78		
6	23	1		14	25		2		2		1	15	2	12	2	
7	10				1		6	1				46	4	28	5	
8	9				1		11					37	4	25	13	

Figure 5: SEM-EDS analysis of TP347H in exposed in TC1 to 5%SWG co-firing.

a) 100% Coal

The deposit adjacent to the oxide contains calcium, aluminium, sulphur and oxygen. Iron is also present within the deposit (Figure 6). The oxide formed is very thin and chromium rich, and even the pits are only 2µm thick. Niobium was present in the light grey outer part of the oxide.



8970	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Nb
1	22		2						1		39	4	10	2	21
2	22		4						2		10	2	25	1	34
3	35	1	7	14	5	1	9	0	12	4	1	2	11		
4	7			1	1		4		4	2	12	1	57	11	
5	14				1		2		1	1	54	5	19	3	

Figure 6: SEM-EDS analysis of TP347H exposed in TC1to 100% coal-firing.

3.1.2. 10CrMo910

Figure 7 shows the metal loss thickness for 10CrMo910. According to this diagram, the metal loss in coal firing is similar to that in co-firing with switch grass.

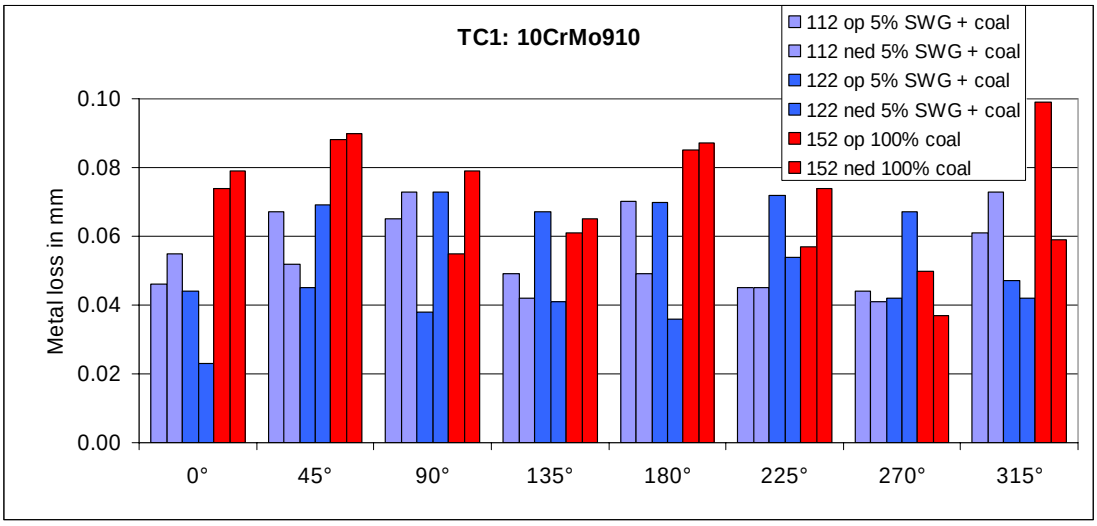
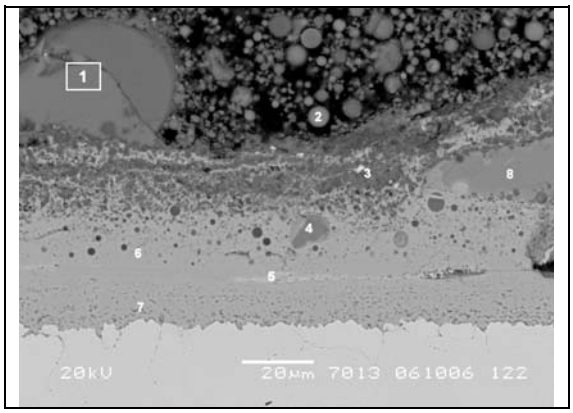


Figure 7: Metal loss measurements for 10CrMo910 exposed in TC1.

a) 5% Switchgrass, 95% Coal

For the specimen 122 op, the outer deposit was rich in titanium. The inner deposit was more calcium and sulphur rich with particles of calcium, silica and aluminium presumably calcium silicate/aluminates (Figure 8). In addition there are many finer particles consisting of silicon and aluminium. Sulphur and oxygen are present throughout the whole of the deposit.



7013	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe
1	24		5	13	10		1		40	1			8
2	20		8	9	5	1	1		44	1			11
3	28	2		3	2		20	17	13				16
4	21		5	9	6	1			38	5			15
5							34						66
6	12						2					1	85
7	12				1		1				4		82
8	19		5	6	6	0			25	1			37

Figure 8: SEM-EDS analysis of 10CrMo910 exposed in TC1tp 5% SWG co-firing .

The inner part of the oxide at the also has a layer of iron sulphide, this seems to be $FeS_{0.9}$ (Mo is not present in this phase).

a) 100% Coal
The deposit consists of a matrix of calcium sulphate with particles containing silicon and aluminium (Figure 9). Barium as barium sulphate is occasionally present in the deposit. The oxide consists of iron oxide and a few particles of iron sulphide (FeS) within the oxide (at the presumed original metal interface). Traces of sulphur are also present at the oxide-metal interface.

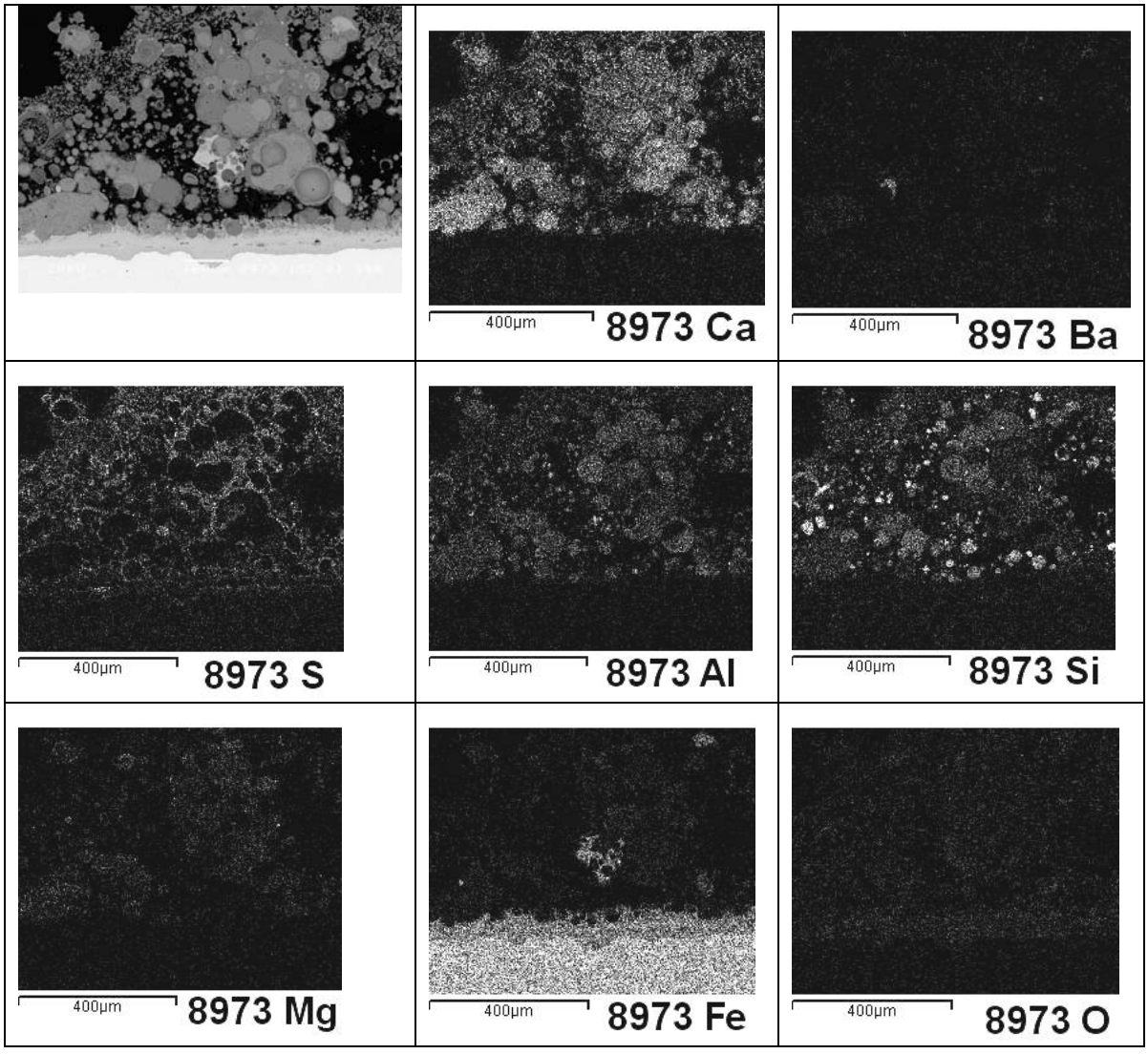


Figure 9: SEM-EDS mapping of deposit present above the oxide for specimen 152op

*3.1.3. **13CrMo44***

Figure 10 shows the metal loss thickness for 13CrMo44. According to this diagram, the metal loss in coal firing is slightly higher than that in co-firing with switch grass.

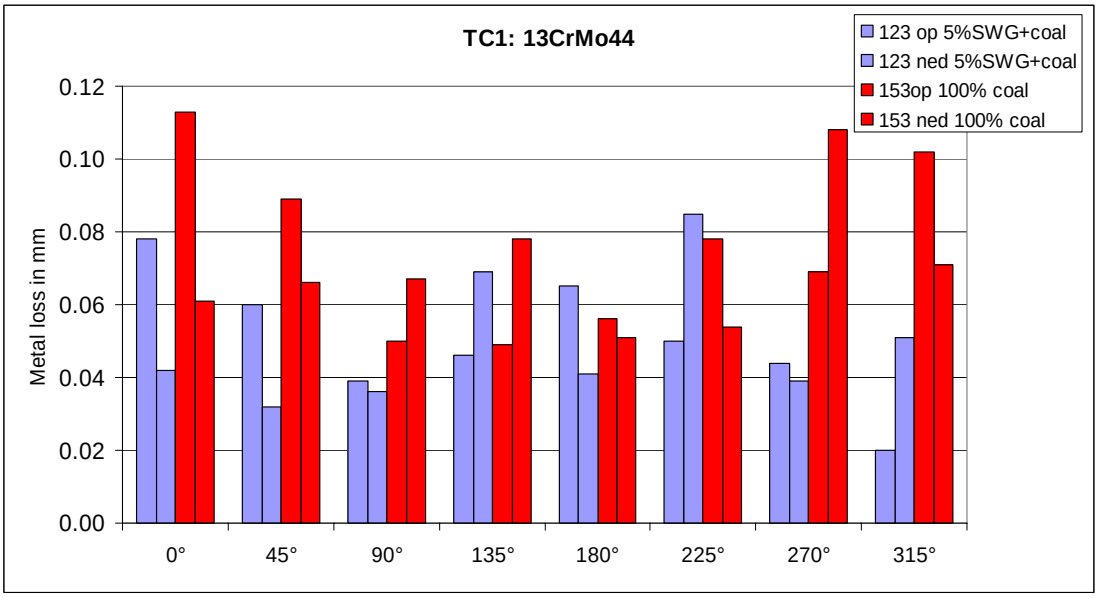
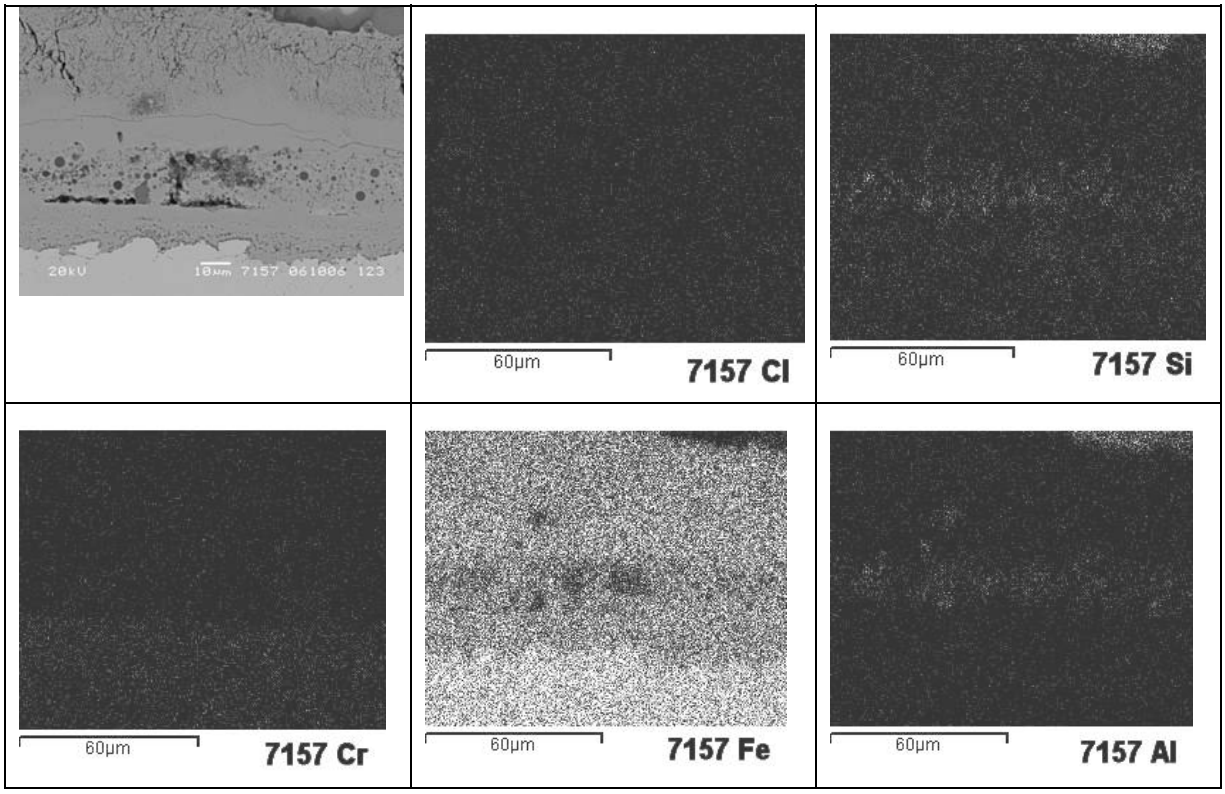


Figure 10: Metal loss measurements for 13CrMo44 exposed in TC1.

a) 5% Switchgrass, 95% Coal

Specimen 123 op has an outer calcium, silicon, aluminium rich deposit. The corrosion products is predominantly iron oxide, however there is both calcium and sulphur detected within the outer oxide (Figure 11).



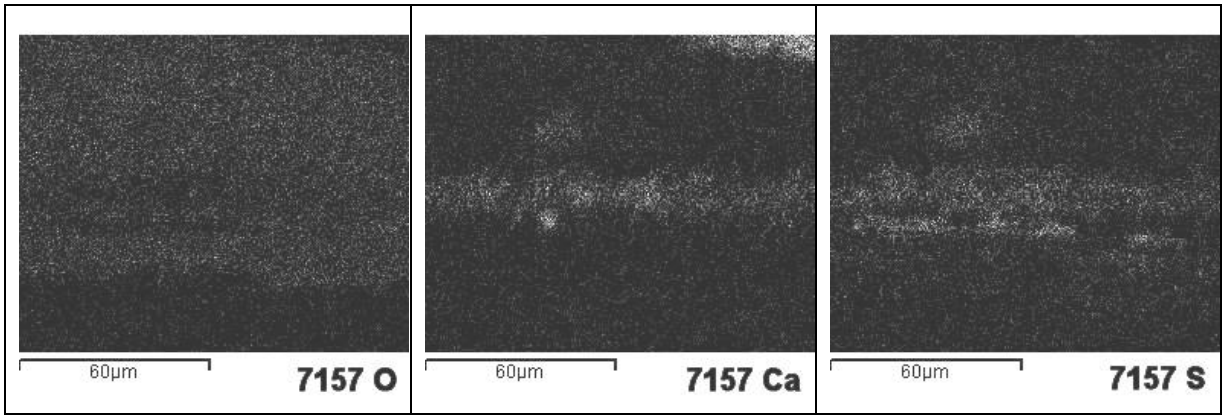
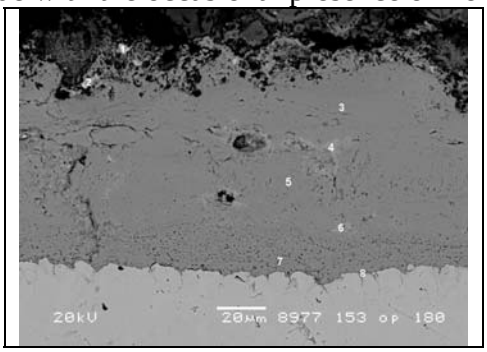


Figure 11: SEM-EDS analysis of 13CrMo44 (123 op) showing elemental distribution.

b) 100% Coal

The deposit and oxide are similar to that observed for 5% switchgrass co-firing. The oxide is mainly iron oxide with the occasional presence of iron sulphide (Figure 12).



8977	O	Si	S	Ca	Cr	Mn	Fe	Ni	Mo	Ba
1	11	0	14	1			16			55
2	14		14	1			17			53
3	12	0	0				88			
4	4	1	23		1		70			
5	10		0		0		90			
6	5	0	18		1		76			
7	9	1	1		3	1	84		1	
8	6	2	2		4	2	82	2	0	

Figure 12: SEM-EDS analysis of 13CrMo44 (153 op) in 100% coal firing

3.1.4. 304H

Figure 13 shows the metal loss thickness for 304H. According to this diagram, the metal loss in coal firing is similar to that in co-firing with switchgrass.

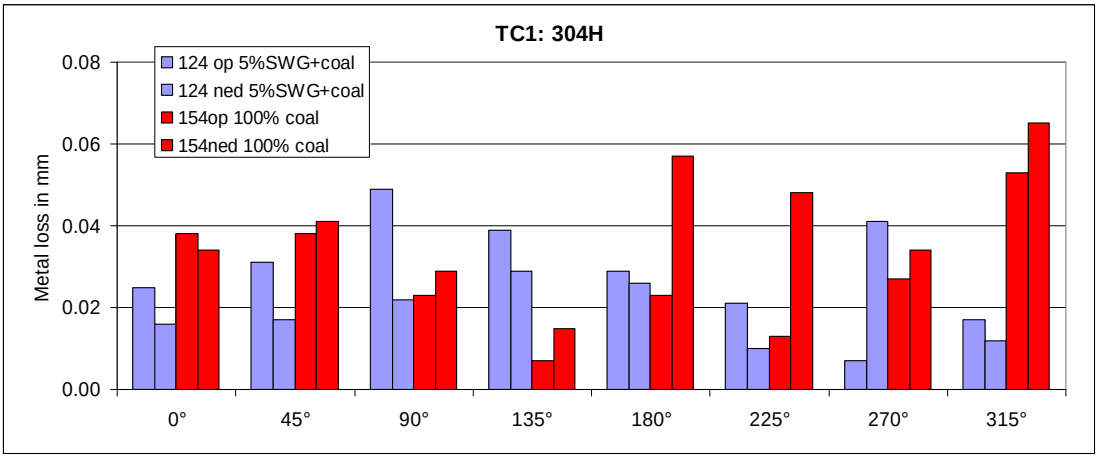
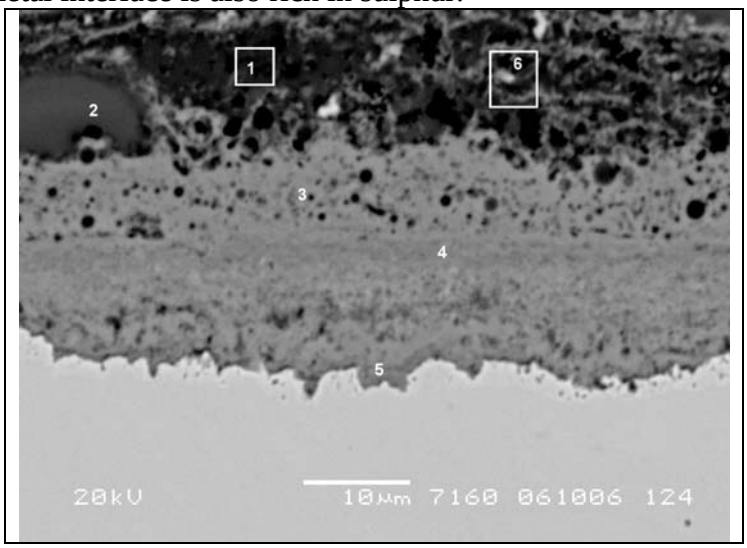


Figure 13: Metal loss measurements for 304H exposed in TC1.

a) 5% Switchgrass, 95% Coal

The outer deposit is calcium sulphate and aluminium silicates. The outer oxide is iron oxide and the inner oxide is iron-chromium oxide (Figure 14). The inner oxide close to the oxide-metal interface is also rich in sulphur.

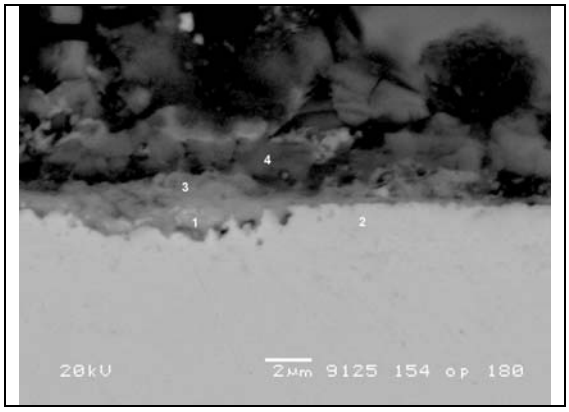


7160	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni
1	31	1	<1	4	4		23	1	29	<1			6	
2	26		6	5	15				39	2			7	
3	16			2	3		<1				1		78	
4	14			1	2	<1	<1				4		78	
5	10				1		14				48	5	22	1
6	27	1		4	4	<1	17	1	20	1			24	2

Figure 14: SEM-EDS analysis of 13CrMo44 (153 op) in 5% SWG- 95% coal firing.

b) 100% Coal

The oxide formed is very thin and consists of a chromium rich oxide. It has a maximum thickness of 2µm (Figure 15)



9125	O	Na	Mg	Al	Si	S	Ca	Ti	Cr	Mn	Fe	Ni
1	10				1	4	0		50	2	28	5
2					0	0	0		11		78	10
3	21			1	1	3	1	11	24	1	37	1
4	28	1	1	6	2	20	23	5	3		9	2

Figure 15: SEM-EDS analysis of 13CrMo44 (153 op) in 100% coal firing

3.1.5 Summary of results for TC1

From the metal loss measurements (Table 4), the austenitic steels have a lower metal loss than the ferritic steels. The worst average is the average of the highest quartile of results. The metal loss for coal firing is marginally higher than that with 5% switch grass after 4 months exposure.

Table 4: Summary of metal loss measurements in mm

TC1	5% SWG+coal		Coal	
	Average	Worst average	Average	Worst Average
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

Figure 16 shows the inner oxide thickness measurements on the fireside.

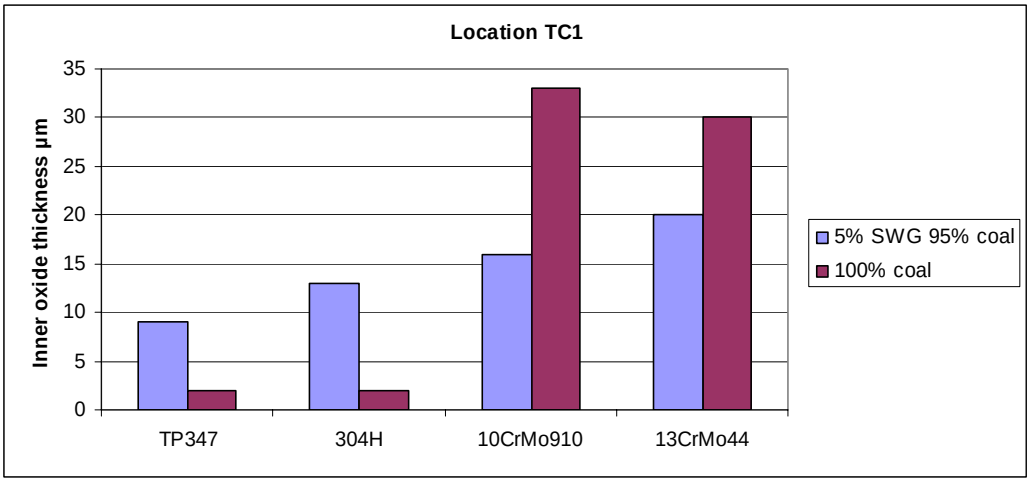


Figure 16: Fireside oxide thickness for specimens located in TC1.

The coal firing oxide thickness is significantly smaller than that for 5% switchgrass mix for the austenitic steels. The opposite trend is shown for ferritic steels.

3.2. Location TC2

3.2.1. TP347H

Metal loss measurements for TP347H are given in Figure 17. The metal loss measurements are very small for all exposures.

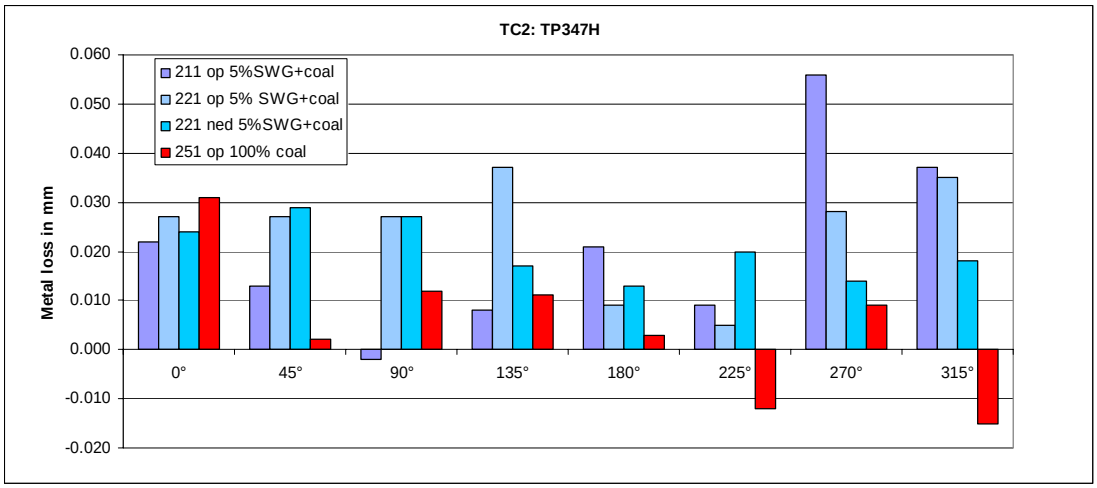
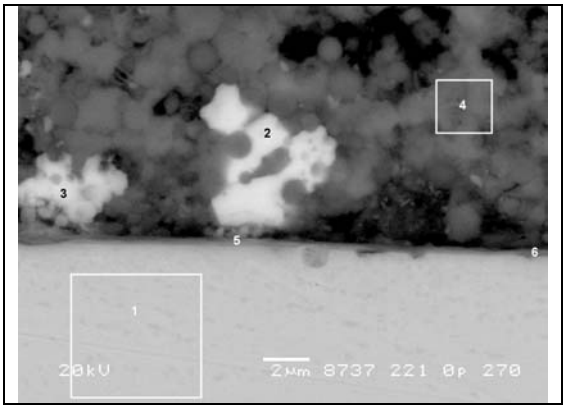


Figure 17: Metal loss measurements for TP347H exposed at location TC2.

a) 5% Switchgrass, 95% coal

The oxide was under a micron thick and was chromium rich. The deposit adjacent to the oxide was predominantly calcium sulphate however there was some potassium sulphate (Figure 18). Particles of barium sulphate were present close to the oxide.

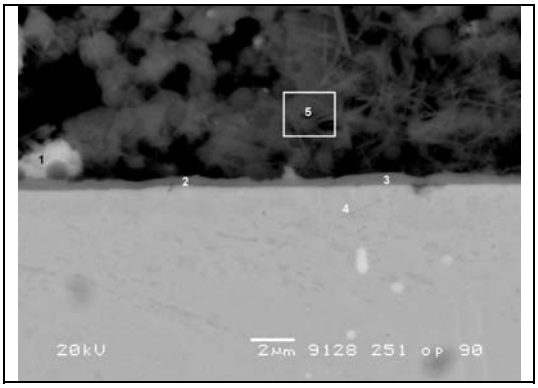


8737	O	Na	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Ba
1									19	2	68	11	
2	14		3	2		17	1	3			2		58
3	17		3	2		17	1	5	3		4		48
4	29	1	6	4	1	24	5	26	1		3		
5	15		2	2		9	1	4	21	3	25	1	18
6	17		3	3		5	1	4	23	3	39	2	

Figure 18: SEM-EDS analysis of TP347H exposed to 5%SWG + coal at TC2.

b) 100% coal

The oxide formed is a thin chromium rich oxide (Figure 19). The alloy below this oxide is chromium depleted. The deposit consists of calcium sulphate with occasional particles of barium sulphate at the oxide-deposit interface.



9128	O	Na	Mg	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Ba
1	16	4	1	2	1		18	0	3	2		2		52
2	19	4	1	2	2	0	5	0	3	39	4	19	1	
3	13	3	1	1	1		2		1	31	3	40	4	
4					1					12	1	71	16	
5	34	5	1	3	3		25	1	25	1		1		

Figure 19: SEM-EDS analysis of TP347H exposed to 100% coal at TC2.

3.2.2. 10CrMo910

Metal loss measurements for 10CrMo910 are given in Figure 20. The results from the coal specimens have not been undertaken.

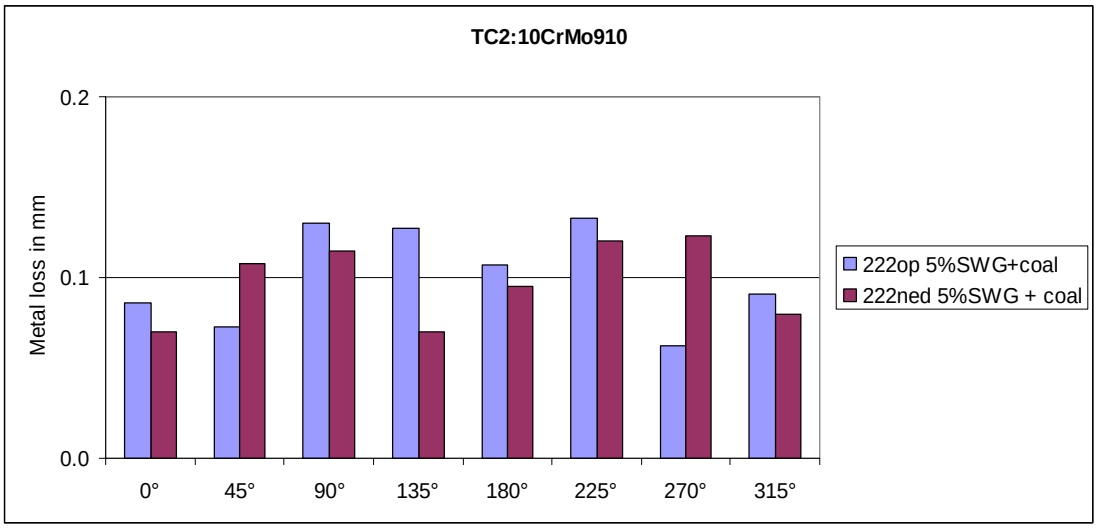
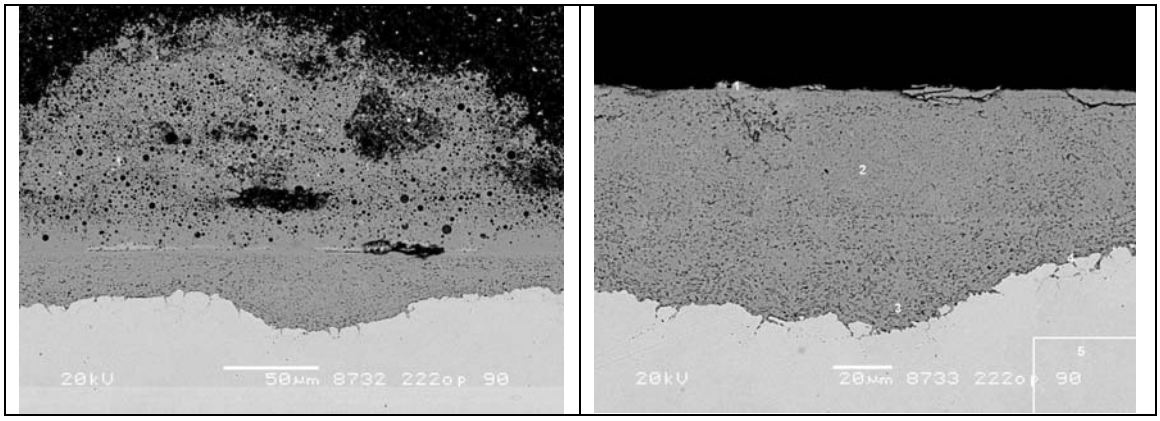


Figure 20: Metal loss measurements for 10CrMo910 exposed at location TC2.

a) 5% Switchgrass, 95% coal

The corrosion product was an outer iron oxide impregnated with silicon and aluminium particles and an inner iron chromium oxide (Figure 21). Iron sulphide (FeS) was present at the original metal interface as a light grey phase on the micrographs. Traces of sulphur were also present within the inner oxide.



8733	O	Si	S	Ca	Cr	Mn	Fe	Ni	Mo
1	9	1	11	1	5	1	72		
2	11	3	4		5	1	77		
3	10	1	1		5	1	80		2
4	7	1	1		5		82	2	2
5		0			2	1	95		1

Figure 21: SEM-EDS analysis of 10CrMo910 at location TC2 exposed to 5%SWG+coal.

3.2.3. 13CrMo44

Metal loss measurements for 13CrMo44 are given in Figure 22. The metal loss measurements are similar.

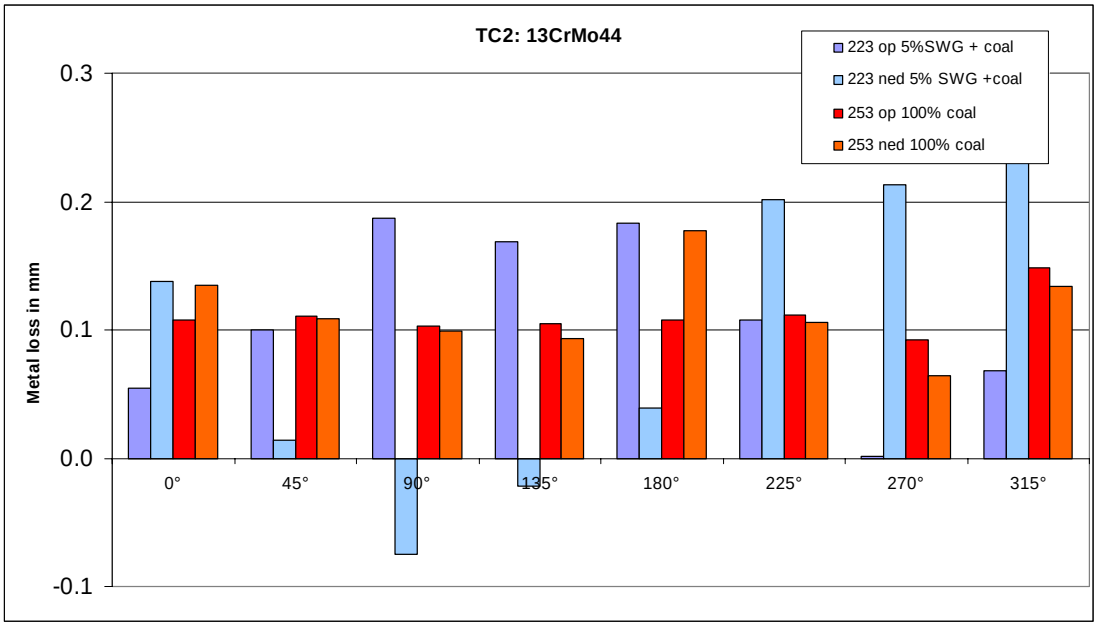


Figure 22: Metal loss measurements for 13CrMo44 exposed at location TC2.

a) 5% Switchgrass, 95% coal

The deposit was primarily calcium sulphate with particles of silicon and aluminium (Figure 23). The oxide was a duplex oxide where the outer part of the oxide contained more deposit components. The original metal surface is shown where there is FeS present.

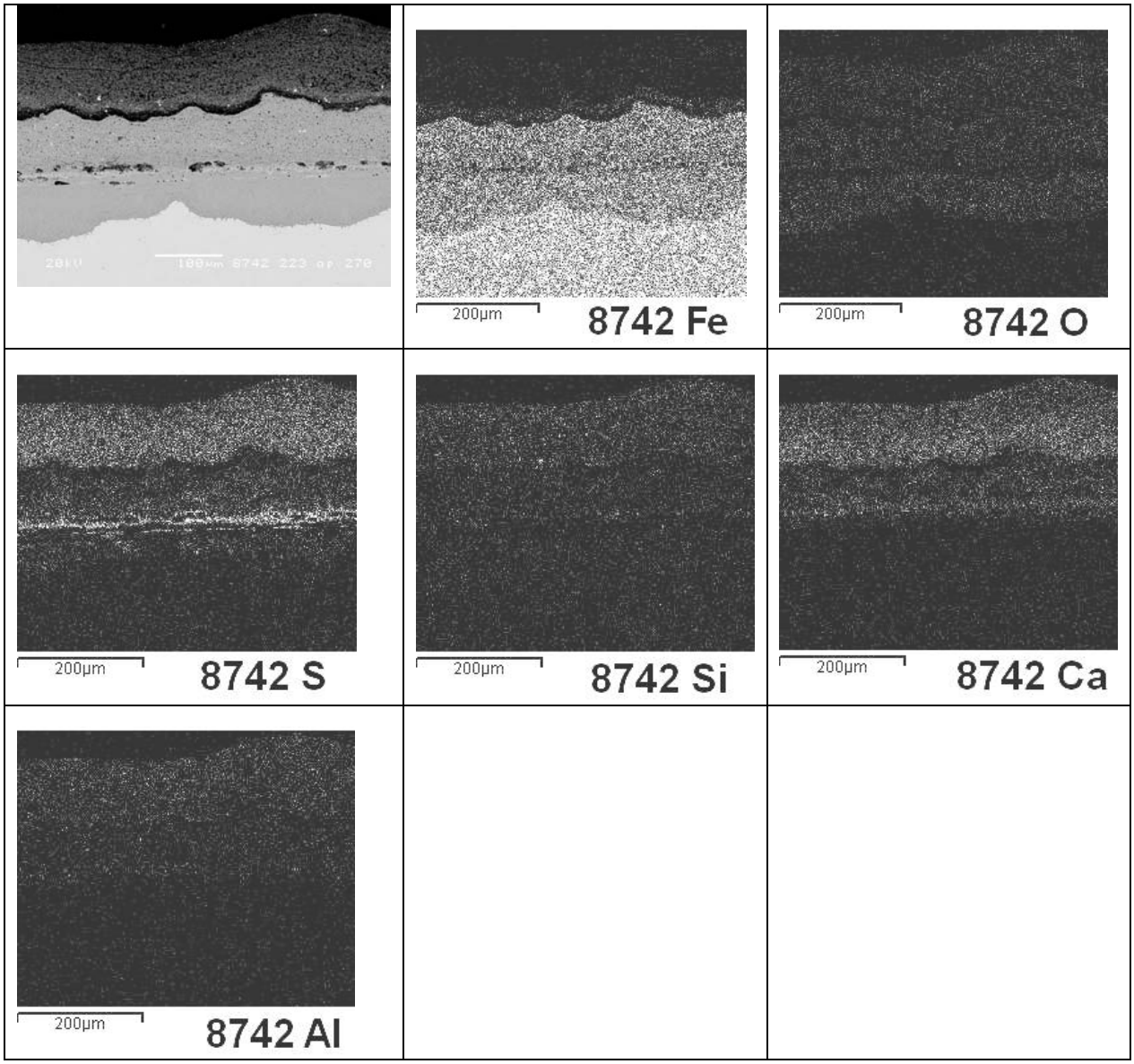
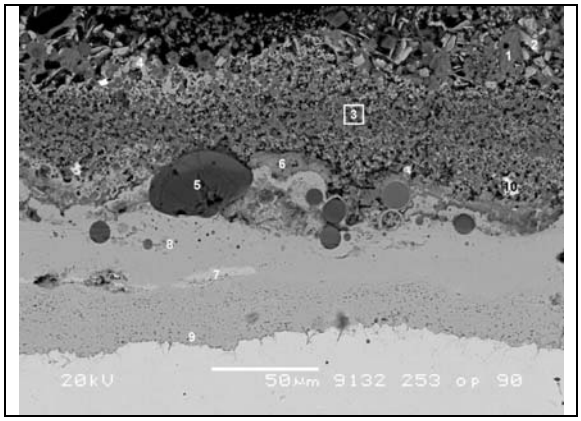


Figure 23: SEM-EDS elemental distribution map for 13CrMo44 in TC2 with 5%SWG+coal.

b) 100% coal

The oxide and deposit is similar to that observed with 5%SWG co-firing. Again barium sulphate was present in small quantities within the deposit. The surface of the original metal surface was difficult to distinguish and it is assumed it is present where FeS is formed and the oxide is more porous (Figure 24). A trace of sulphur is also present within the inner oxide.



9132	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ba
1	24	1	1		0		30		38				7	
2	10	1			0		1		1				85	
3	24	4	1	6	8	1	16	1	15	1			23	
4	15				0		1		0				84	
5	33				66								1	
6	18	4	2	7	3	3	8	1	2	1			52	
7							36						64	
8	12			1	1		1					1	86	
9	11				1		1				2		85	
10	15	1		2	1		15		2				15	49

Figure 24: SEM-EDS analysis of 13CrMo44 exposed to 100% coal at location TC2.

3.2.4. 304H

Metal loss measurements for 304H are given in Figure 25. The results from the coal specimens have not been undertaken.

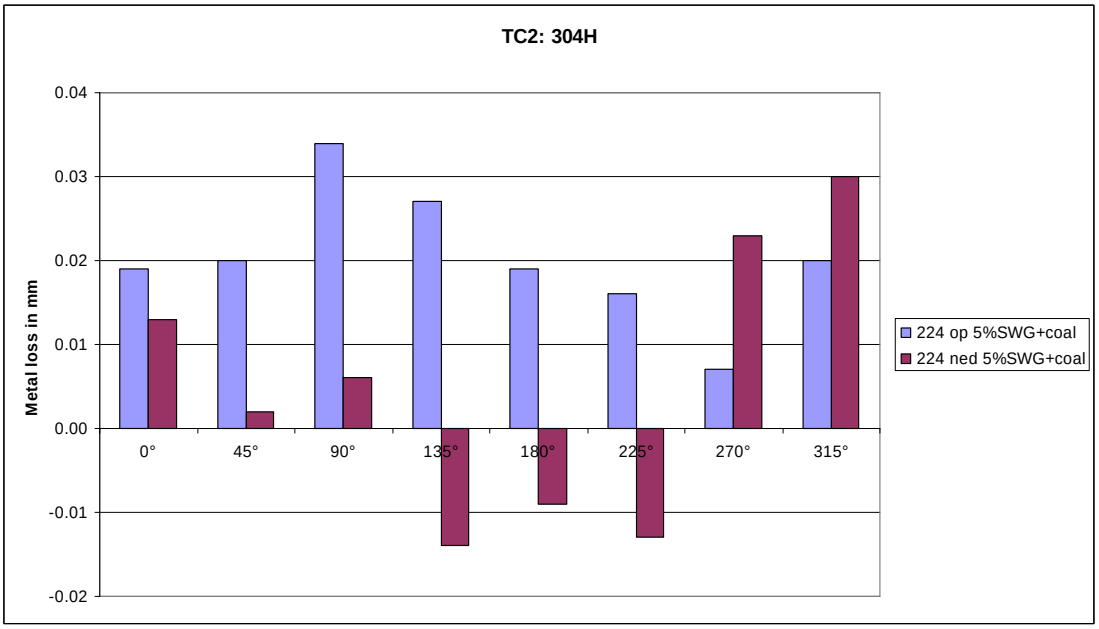
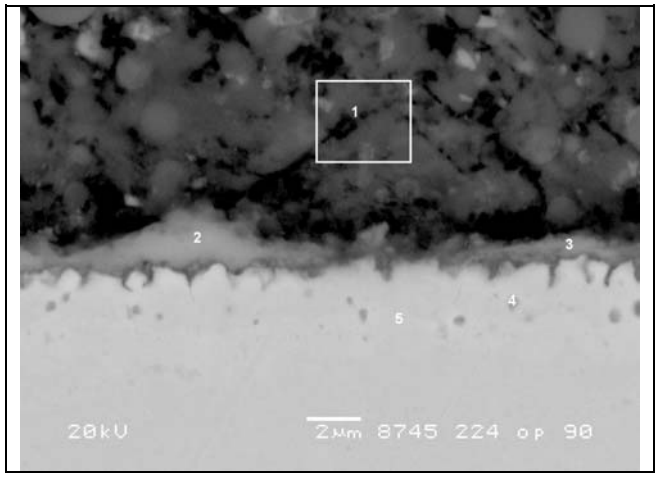


Figure 25: Metal loss measurements for 304H exposed at location TC2.

a) 5% Switchgrass, 95% coal

The oxide formed was a thin chromium rich oxide and the deposit present was calcium sulphate with aluminium and silica particles (Figure 26). Sulphides were formed in the metal close to the metal interface, and significant chromium depletion was also detected.



8745	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Mo
1	29	14	1	5	5	1	26	1	8	1		2		6			
2	14		2		1		11					60	4	8		1	
3	18	4	1	1	3		4		0		1	47	3	18	1		
4							5					5	7	77	6		
5					0					0		8	1	72	17		1

Figure 26: SEM-EDS analysis of 304H exposed at to 5%SWG+coal firing at location TC2.

3.2.5 Summary of results for TC2

There was no difference in either deposit composition or oxide morphology for specimens exposed in 5% switch grass + coal or 100% coal. The deposit consisted of calcium sulphate with alumina and silica deposits. Barium sulphate is present within the deposit close to the surface of the oxide. For the ferritic steels, the oxide was duplex with an outer iron oxide with deposit particles incorporated into it. Iron sulphide was present at the inner-oxide outer-oxide interface. The inner oxide was a chromium enriched iron oxide. The oxide grew as shallow pits resulting in variable oxide thickness. For the austenitic steels, there was a thin chromium rich oxide present.

A summary of metal loss results is given in Table 5.

Table 5: Summary of metal loss measurements in mm

TC2	5% SWG+coal		Coal	
	Average	Worst average	Average	Worst Average
13CrMo44	0.09-0.11	0.19-0.22	0.11	0.13-0.16
10CrMo910	0.10	0.12-0.13	No results	No results
TP347H	0.02	0.03-0.05	0.01	0.02-
304H	0.01-0.02	0.03	No results	No results

The thickness of inner oxides is shown in Figure 27. Here the oxide thickness is similar for TP347H in both fuel conditions and is lower for 13CrMo44 for 100% coal. Although the metal loss measurements are higher, they reflect the same trend where 13CrMo44 has the greatest metal loss and the austenitic steels have the lowest metal loss.

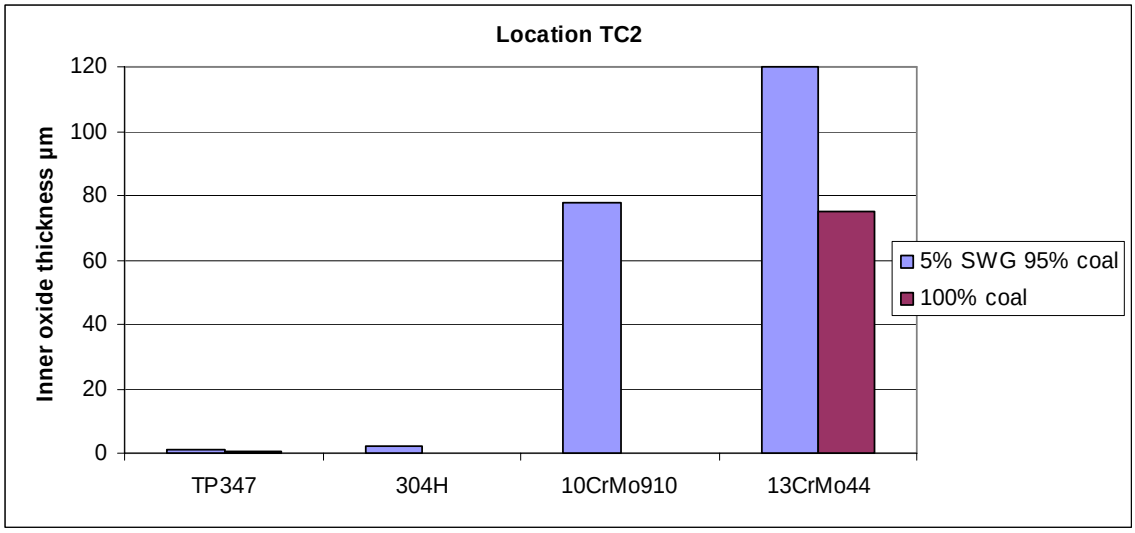


Figure 27: Inner fireside oxide thickness for specimens at location TC2.

3.3. Location TC3

3.3.1. TP347H

Metal loss measurements for TP347H are given in Figure 28. The results from the coal specimens have not been undertaken yet.

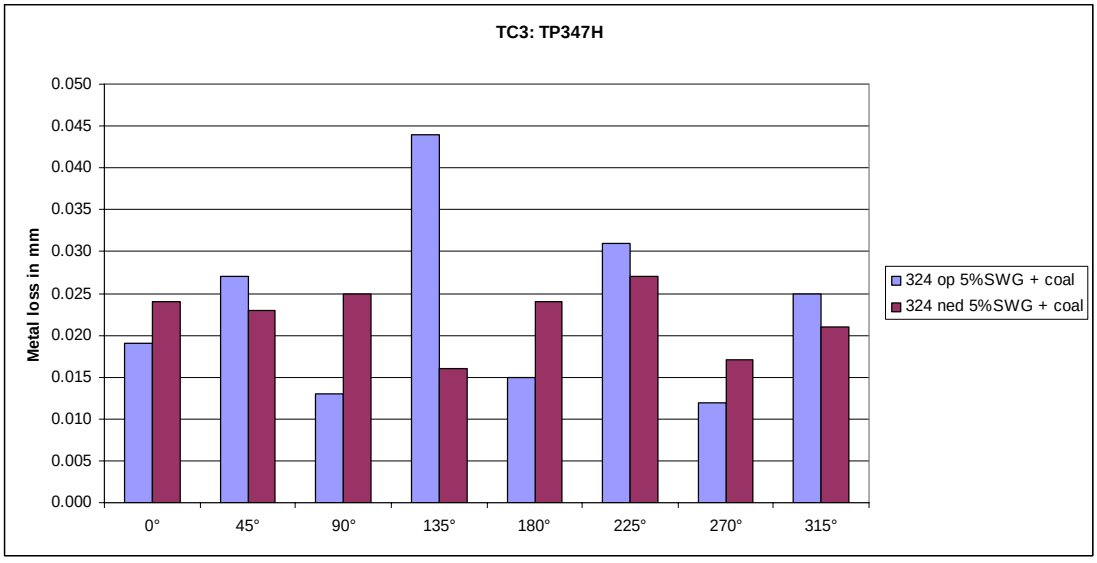
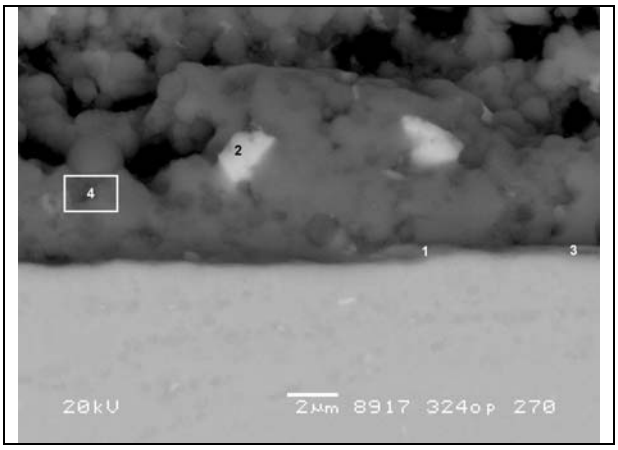


Figure 28: Metal loss measurements for 347H exposed at location TC3.

a) 5% Switchgrass, 95% coal

The deposit consists of calcium sulphate with silica and alumina particles (Figure 29). Close to the oxide, barium sulphate is present. The oxide was chromium rich and less than 1µm thick.



8917	O	Na	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Ba
1	16		1	1		5	1	4	25	3	40	4	
2	22		2			20		7			1		48
3	10			1	1	3		3	19	4	56	4	
4	36	1	6	4		22	1	25	2		2		

Figure 29: SEM-EDS analysis of 347H exposed at to 5%SWG+coal firing at location TC3.

3.3.2. 10CrMo910

Metal loss measurements for 10CrMo910 are given in Figure 30. The results from the coal specimens have not been undertaken yet.

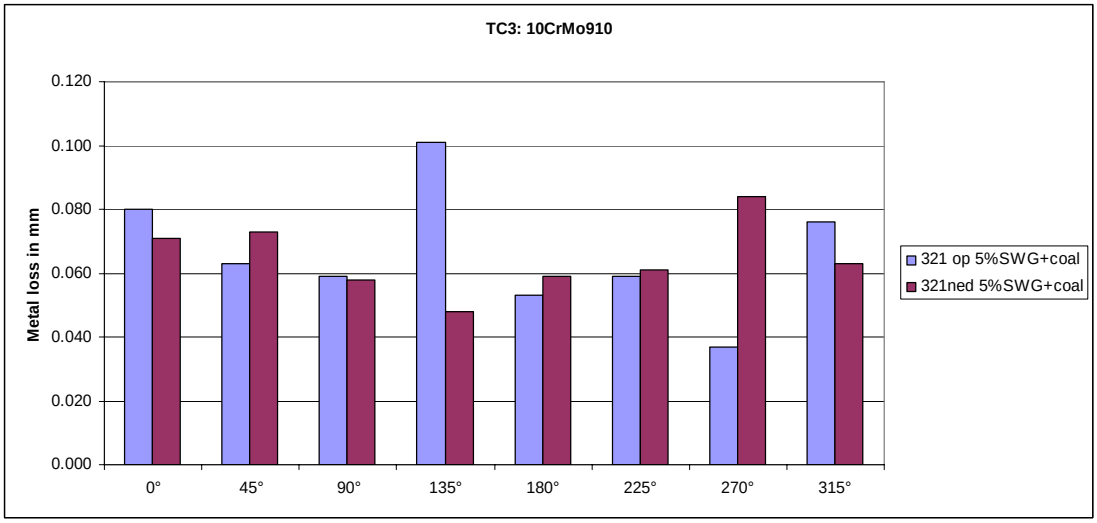


Figure 30: Metal loss measurements for 10CrMo910 exposed at location TC3.

5% Switchgrass, 95% coal

The outer deposit is calcium sulphate with silica and alumina particles. The oxide consists of an outer layer of iron oxide where silica and alumina particles are incorporated (Figure 31). The inner oxide is a chromium-iron oxide and iron sulphide is present between the two oxides at the original metal surface.

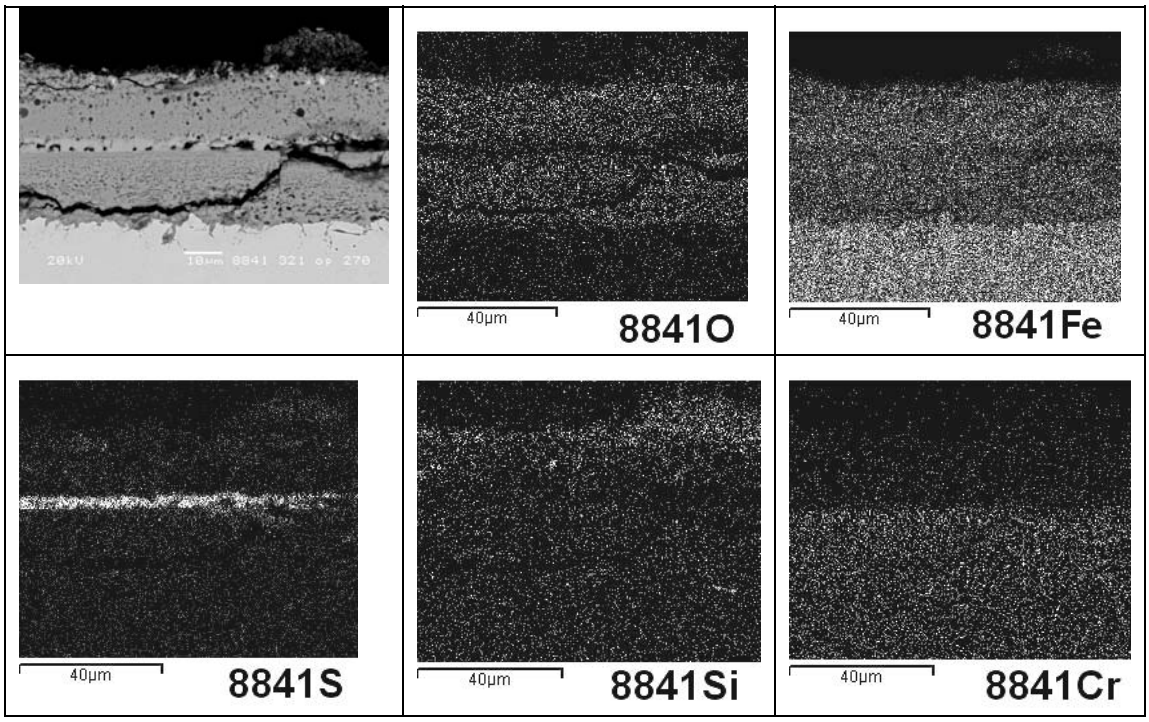


Figure 31: SEM-EDS elemental maps for 10CrMo910 at TC3 location.

3.3.3. 13CrMo44

Metal loss measurements for 13CrMo44 are given in Figure 32. The results from the coal specimens have not been undertaken yet.

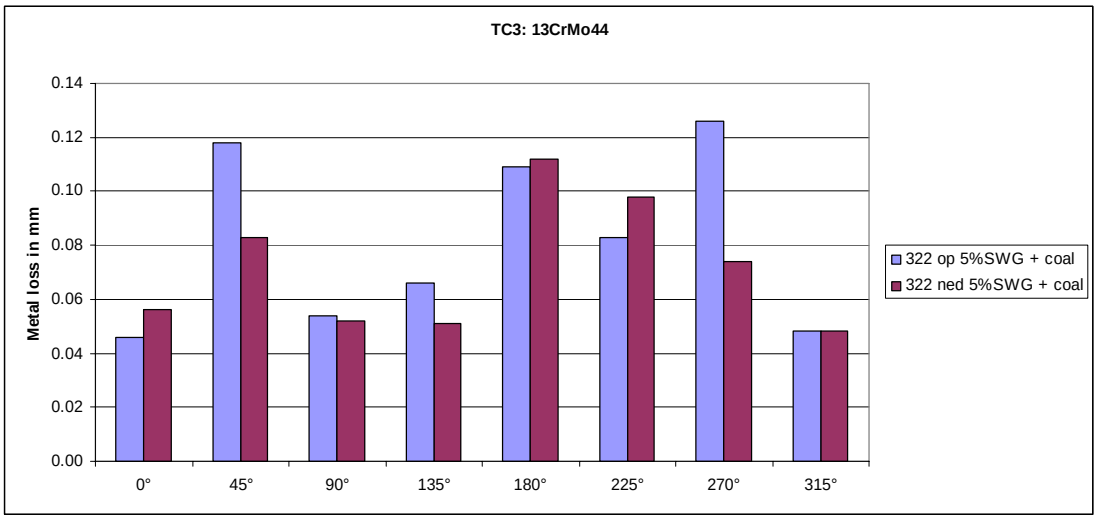
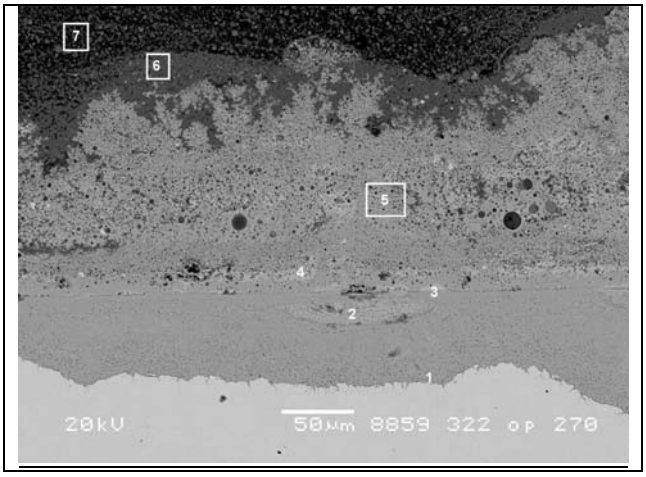


Figure 32: Metal loss measurements for 13CrMo44 exposed at location TC3.

a) <u>5% Switchgrass, 95% coal</u>

The deposit consists of calcium sulphate with alumina and silica particles (Figure 33). The outer oxide consisted of iron oxide and with some of the elements from the deposit. At the inner oxide-outer oxide interface, iron sulphide is present. The inner oxide is predominantly chromium enriched iron oxide with a traces of sulphur.



8859	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe
1	12				1		1				2	1	83
2	6				1		22				2	1	68
3							38						62
4				1	1	0	36		1				61
5	13		1	3	3		6	0	4				71
6	26	2	2	6	6	1	21	1	28	1			4
7	27	2	3	9	9	1	17	2	25	1			3

Figure 33: SEM-EDS analysis of 13CrMo44 exposed to 5%SWG+coal firing at location TC3.

3.3.4. 304H

Metal loss measurements for 304H are given in Figure 34. The results from the coal specimens have not been undertaken yet.

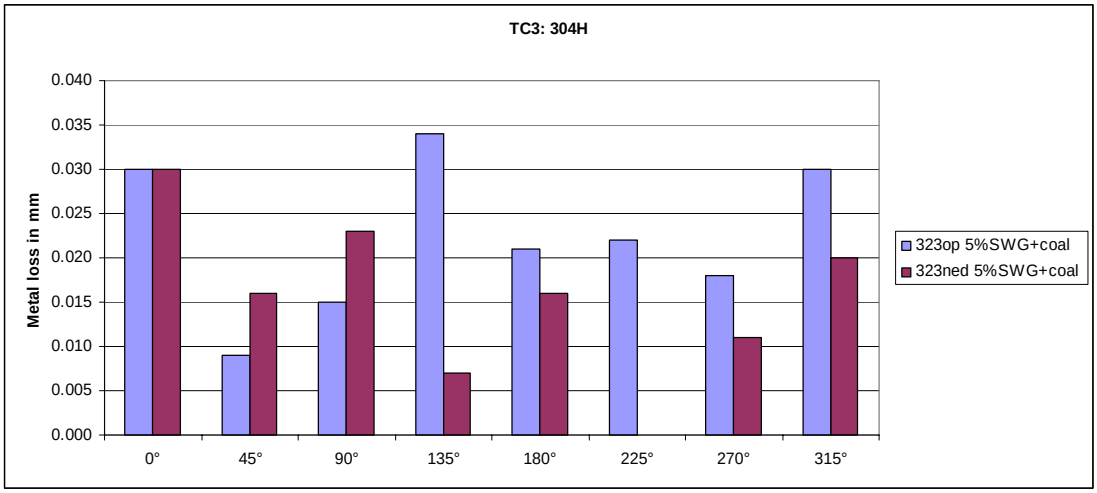
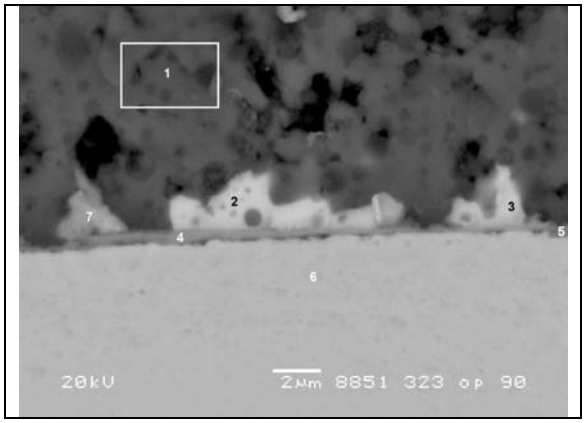


Figure 34: Metal loss measurements for 304H exposed at location TC3.

a) <u>5% Switchgrass, 95% coal</u>

The deposit consists of calcium sulphate with contributions from aluminium and silicon (Figure 35). Barium sulphate is present on the surface of the oxide. The oxide is a thin chromium enriched iron oxide with some manganese.



8851	O	Na	Mg	Al	Si	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Cu	Ba
1	27	1	1	4	4	27	3	32	1	1		1			
2	13	1		3	2	17	1	3		1		2			57
3	16	1		3	3	18	1	8		6		4		1	40
4	11			1	2	6		1		29	7	30	2		11
5	15		1	2	2	9		7		32	5	26	3		
6					0			0		19	1	70	9		
7	13			2	1	31		5		16		4	9	19	

Figure 35: SEM-EDS analysis of 304H exposed at to 5%SWG+coal firing at location TC3.

3.3.5 Summary of results for TC3

Similar to the other areas, the deposit consists of a matrix of calcium sulphate with particles of silica and aluminium. Barium sulphate was often present within the deposit and at the surface of the oxide. The oxide for the austenitic steels was a thin chromium rich iron oxide. The oxide for the ferritic steels consisted of two layers, an outer iron oxide in which elements from the deposit were present, and an inner chromium enriched oxide. Iron sulphide is often observed at the inner oxide-outer oxide interface.

The metal loss is higher for the ferritic steels than the austenitic steels (Table 6). The metal loss data for coal firing is marginally higher than with co-firing.

Table 6: Summary of metal loss data for TC3

TC3	5% SWG+coal		Coal	
	Average	Worst average	Average	Worst Average
13CrMo44	0.07-0.08	0.11-0.12	No results	No results
10CrMo910	0.06-0.07	0.08-0.09	0.09	0.11
TP347H	0.02	0.03-0.04	No results	No results
304H	0.02	0.03	0.01	0.05

As shown in Figure 36, the oxide thickness increases with decrease in chromium content as would be expected.

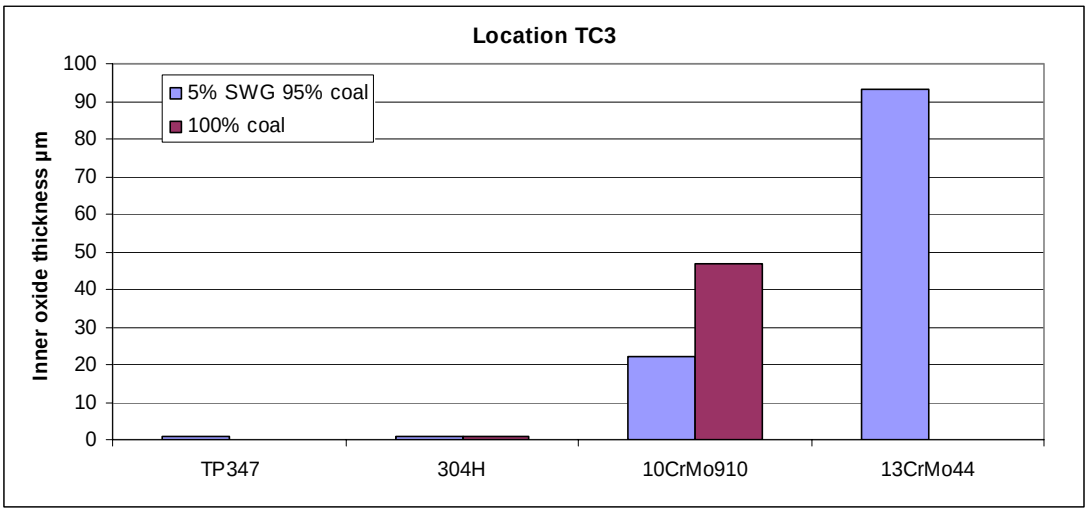


Figure 36: Inner fireside oxide thickness for specimens on TC3.

4. Discussion

Deposit analysis does not show the presence of chlorine. Based on the analyses undertaken, it must be concluded that there is no chlorine present in the deposits or corrosion products and this has reacted according to the equations below:

$$2KCl + Al_2O_3 + 6SiO_2 + H_2O \rightarrow K_2O \cdot Al_2O_3 \cdot 6SiO_2 + 2HCl(g)$$
$$2KCl + SO_2 + H_2O + ½O_2 \rightarrow K_2SO_4 + 2HCl(g)$$

These results substantiate the calculations based on bulk ash composition of the coal and switchgrass[1]. Thus the risk of chlorine corrosion due to co-firing with switchgrass is unlikely, however this does not remove the threat of sulphur corrosion. The deposit contains calcium sulphate and alumina silicates; however there are also small amounts of both potassium and sodium present. There is no significant difference between the deposit composition at 100% coal firing and 5% switchgrass co-firing with coal. The demonstration project at Studstrup with a lower sulphur Columbian type coal[2] showed that increase in straw fraction from 0% to 10% to 20% increased the amount of potassium sulphate within the deposit resulting in increased sulphate corrosion with 20% co-firing. The Powder River Basin coal used is high in calcium resulting in calcium sulphate within the deposit. Increase in switchgrass content should result in increase in potassium sulphate content. A marginal increase can be seen occasionally in the deposit from 2% to 5% potassium in the deposit.

This increase in potassium sulphate within the deposit can result in a $CaSO_4$-K_2SO_4 eutectic melt (Figure 37).

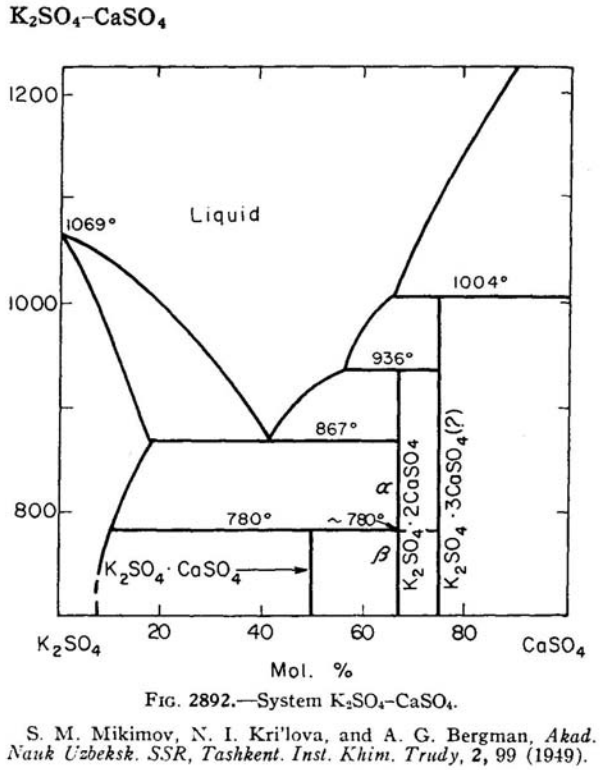


FIG. 2892.—System K_2SO_4–$CaSO_4$.

S. M. Mikimov, N. I. Kri'lova, and A. G. Bergman, *Akad. Nauk Uzbeksk. SSR, Tashkent. Inst. Khim. Trudy*, **2**, 99 (1949).

Figure 37: Phase diagram of calcium sulphate and potassium sulphate.

Where there is a thin deposit, such a eutectic could be present close to the oxide where the flue gas temperature is high. For 5% switchgrass firing at the TC1 position, one analysis of corrosion products adjacent the oxide reveals the presence of deposits rich in calcium and potassium and iron together - perhaps an iron alkali (Ca,K) sulphate. In addition there is the presence of iron calcium oxide which indicates that the calcium and potassium sulphates attack the outer iron oxide. The flue gas temperature in this case was 1350°C which will result in a high heat flux. The presence of barium sulphate does not make matters worse as $BaSO_4$-$CaSO_4$-K_2SO_4 has a eutectic melt at 867°C.

For both types of fuel sulphidation and oxidation has occurred according to the following reactions.. For the ferritic steels, FeS is present at the original metal interface which indicates that this is formed in the initial stages.

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

It is difficult to assess the kinetics of corrosion when there is only data for one exposure time. Long term exposures from Studstrup have also indicated that 10% co-firing results in sulphidation[3].Based on oxide thickness measurements, the corrosion rate is low for the austenitic steels. It must be noted that oxide thickness for the austenitic steels was very low such that a duplex oxide was only formed for the 5%SWG co-firing specimens. It is suggested that the machining process in the other exposures has caused cold deformation to result in improved chromium transport at the surface and therefore formation of a protective chromium oxide layer. The influence of machining on steam oxidation results has been reported previously[4]. The ferritic steels reveal a higher corrosion rate as would be expected due to their lower

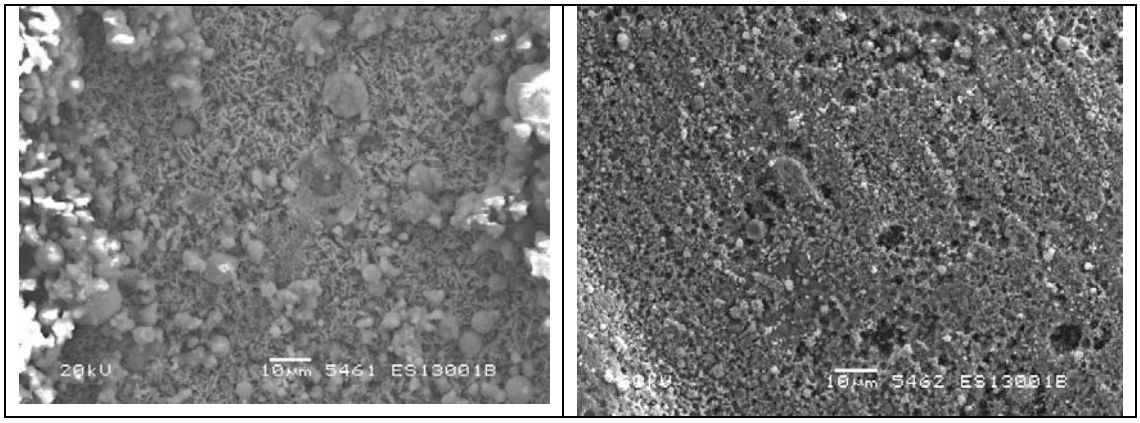
content of chromium. The oxide thickness for the ferritic steels spans from 30µm in TC1 to 90-120 in TC2 and TC3. At TC1, there is a higher flue gas temperature of 1350°C compared with the lower flue gas temperature of 900-950°C for TC2 and TC3. Analysis of deposits shows that there is a lower concentration of soluble K and Na species condensed on probes exposed at the higher flue gas temperatures[1]. At the high flue gas temperatures such species as alkali sulphates are stable in the gas phase, and with a decrease in flue gas temperatures, these species will then condense on metallic surfaces. This could be a reason for the thicker corrosion product at lower flue gas temperatures.

References:

1. J. Knudsen et al, Proceedings Snowbird Conference 2006
2. M. Montgomery and OH Larsen "Field test corrosion experiments in Denmark with biomass fuels Part 2: Co-firing of straw and coal" Materials and Corrosion 53 pp185-194 (2002).
3. R.B. Frandsen et al"Field test corrosion experiences when co-firing straw and coal: Ten year status within Elsam" Proceedings of International conference in New Zealand Feb. 2006.
4. M. Montgomery, OH Larsen, SA Jensen, O. Biede "Field investigation of steamside oxidation for TP347H" Materials Science Forum vols 461-464 pp1007-1014, (2004).

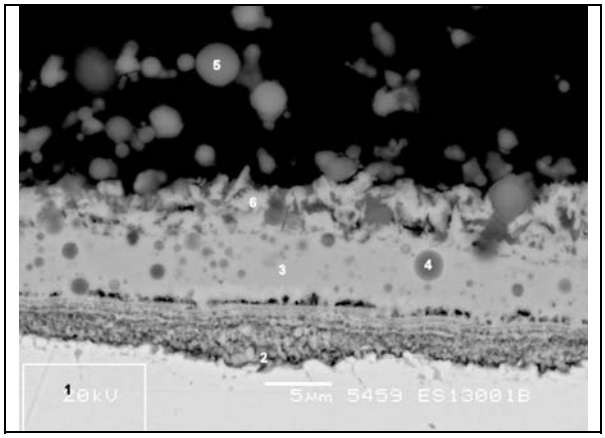
Appendices

ES13001- Probe 4 from Alliant OGS Iowa -3 hr exposure: metal temperature 540°C, Flue gas temperature 1300°C.



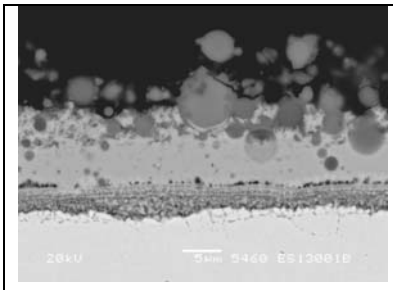
ES13001	O	Al	Si	Na	Mg	Al	Si	S	K	Ca	Ti	Mn	Fe
5461	21			8	2	3	3	11	2	12	1	1	36
5462	12	1	1					1		1		1	83

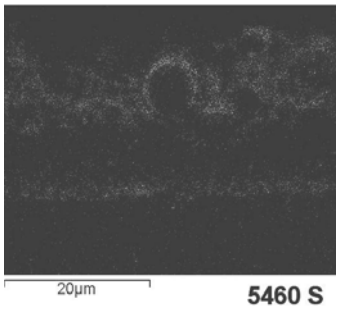
Cross-section of deposit:

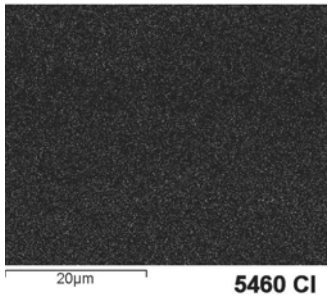


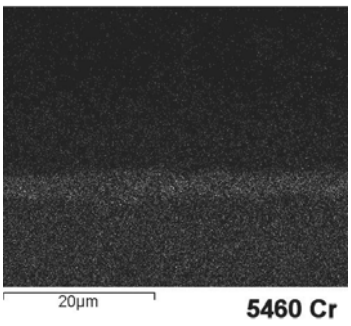
5459	O	Na	Mg	Al	Si	S	Cl	K	Ca	Ti	Cr	Mn	Fe	Mo
1					0						3	1	96	1
2	6				1	7					6	1	79	
3	13				0	0			0		0		86	
4	16		2	11	11	0		0	4	0		1	54	
5	31	2	4	6	20	2	1	0	26	4			4	
6	15	2		1	0	2		0	1				78	

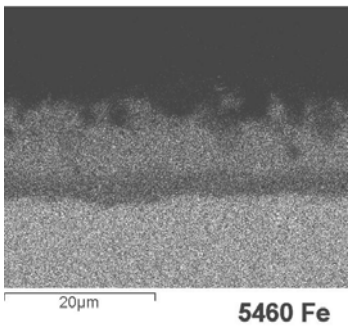
Appendix A: Analyses of deposit probes

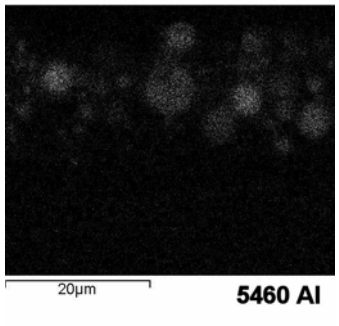


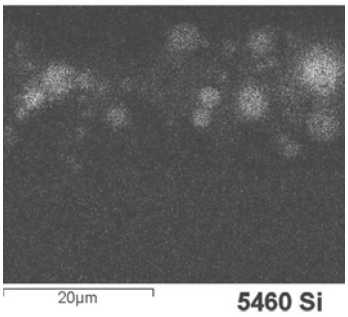




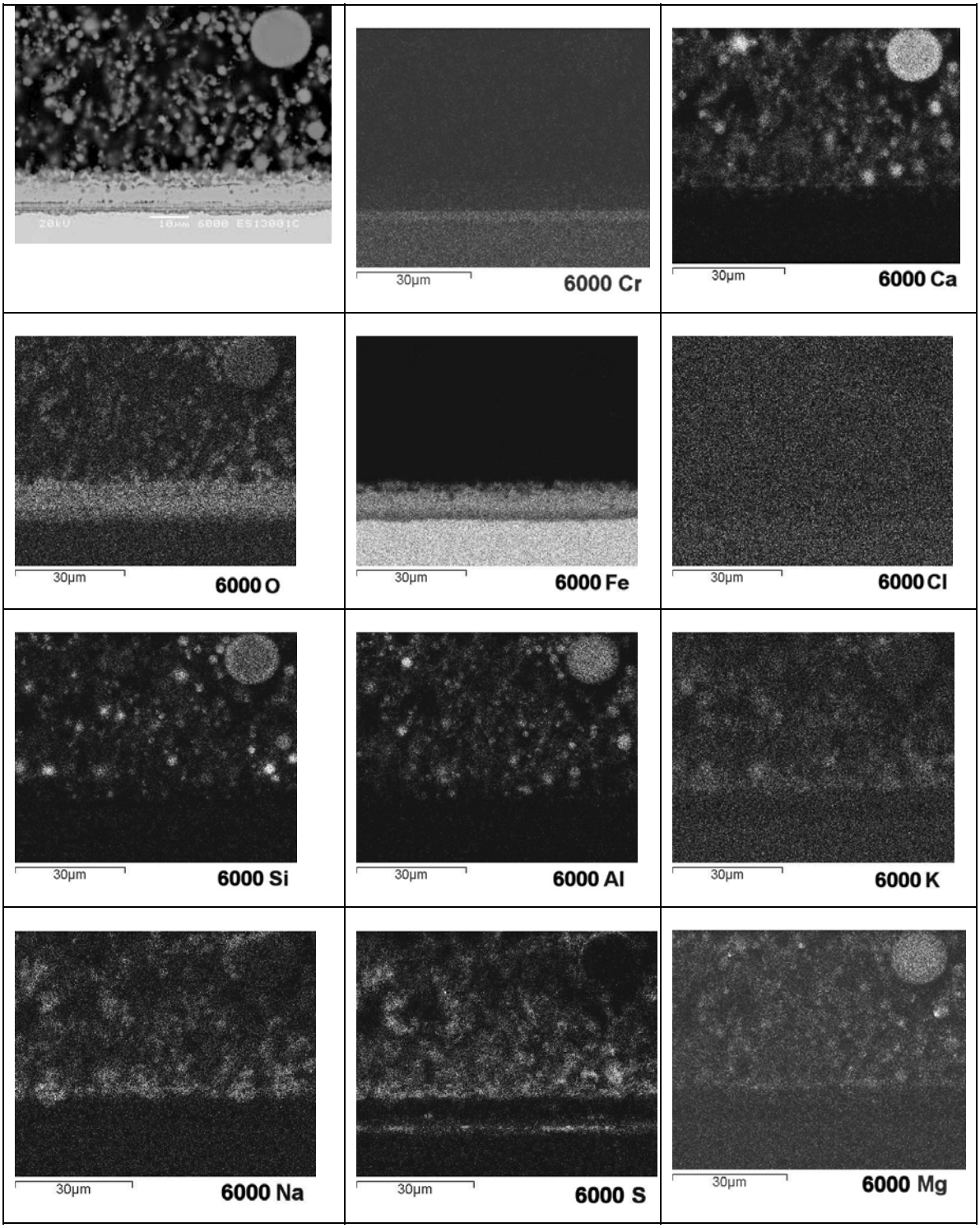




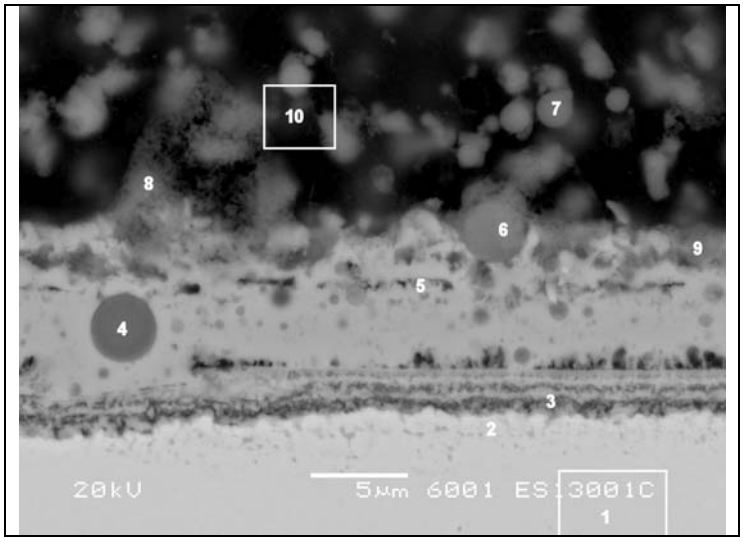




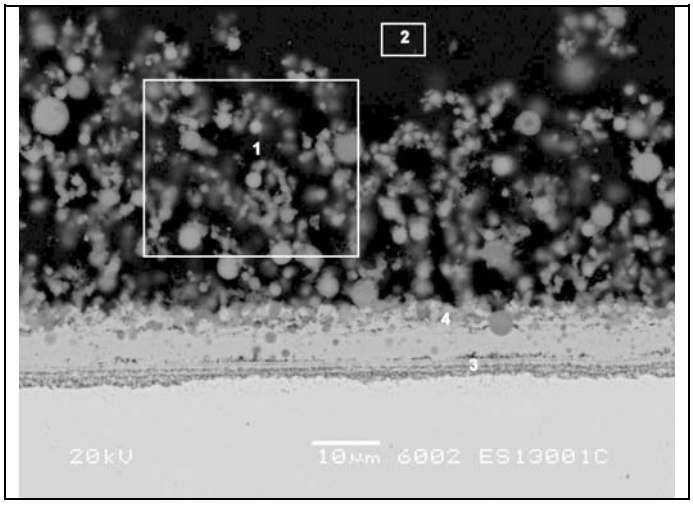
Appendix A: Analyses of deposit probes



Appendix A: Analyses of deposit probes

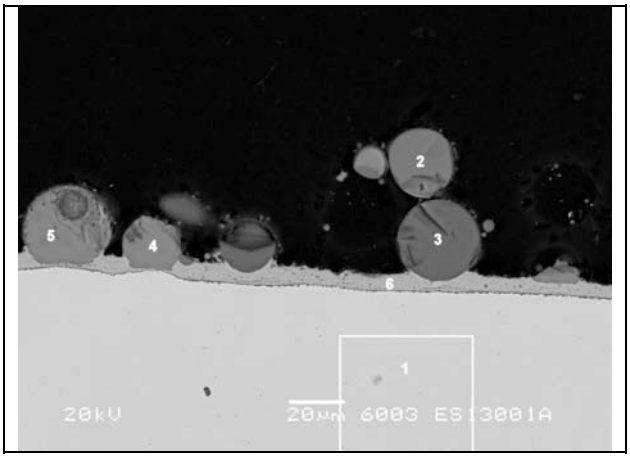


6001	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	Mo
1					0							3	96	1
2					0		3					2	95	
3	6				1		4			0		8	81	
4	22	1	3	3	26				1	22	2		21	
5	9				0		1			1			88	
6	24	2	4	5	15		4		1	34	3		10	
7	34	4	3	13	16		8	1	2	17	1		3	
8	25	6	1	4	4	1	20	1	2	25			11	
9	24	4	1	4	2		14		1	14			36	
10	29	7	2	7	8	1	17	2	5	18	1		4	
11	4									0		2	94	

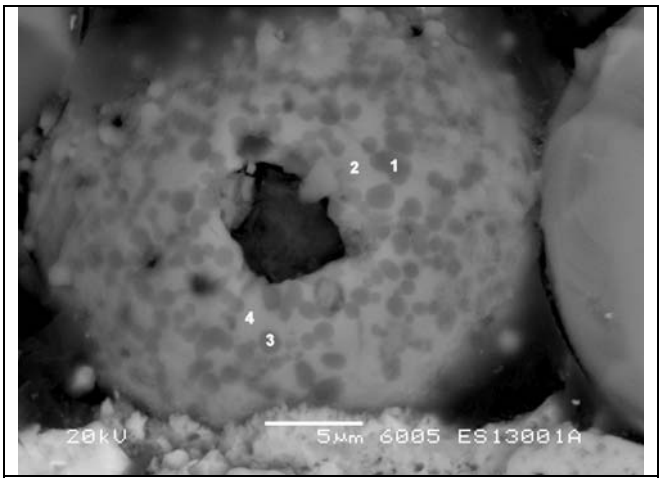


6002	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe
1	29	5	2	7	8	1	13	2	3	22	1		6
2	66				4		4	16		5			5
3	6				1		4					9	80
4	10	2		1	1		2		0	3			81

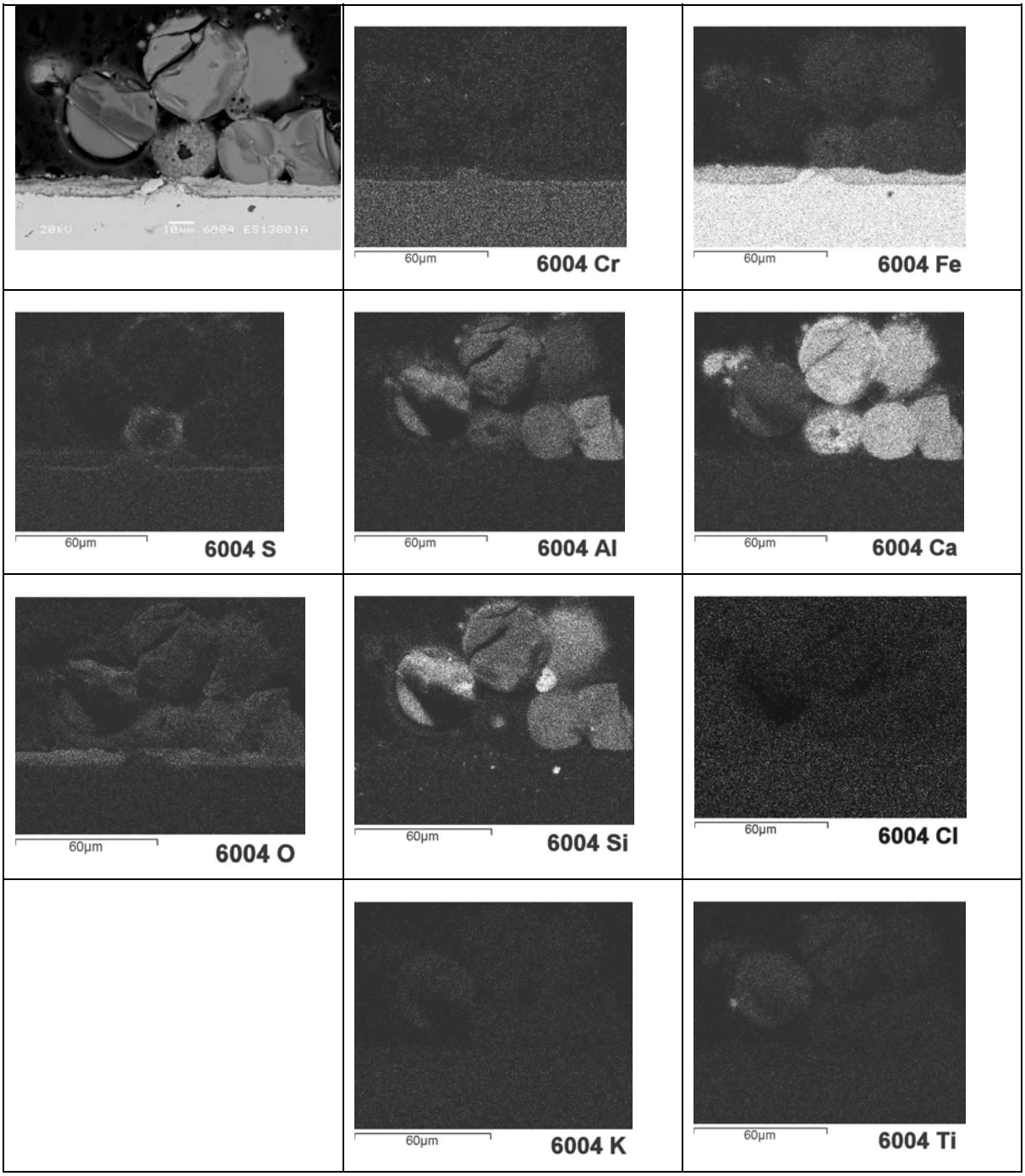
Appendix A: Analyses of deposit probes



6003	O	Na	Mg	Al	Si	K	Ca	Ti	Cr	Mn	Fe	Mo
1					0				2	1	95	1
2	24	1	4	11	20		33	2			6	
3	29	4	2	18	27	1	14	1			3	
4	22		4	16	1		47	1			10	
5	22		5	16	2		46	1			8	
6	13								0		87	

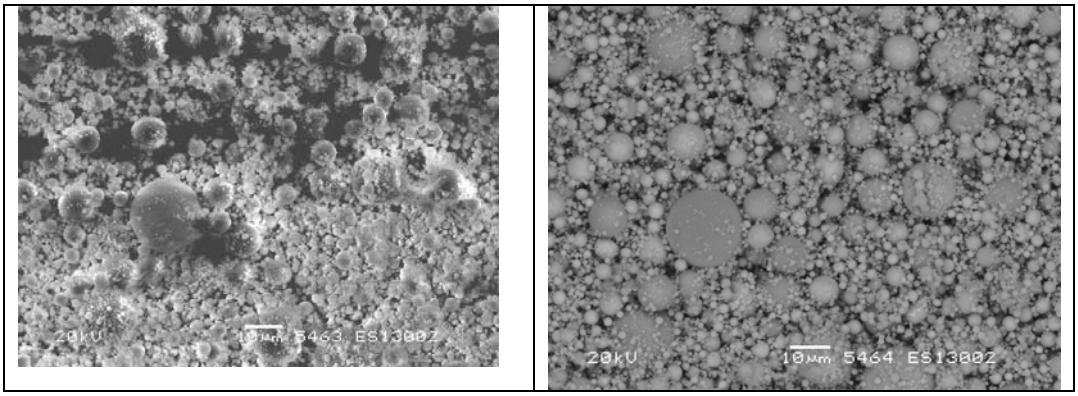


6005	O	Mg	Al	Si	S	Ca	Ti	Fe
1	29	32	5	0		23	1	10
2	27	7	4	0	1	55		6
3	26	32	4		0	28	0	9
4	22	11	10	1		36	1	19
5	12	1			1	3		83


60µm
6004 Cr
60µm
6004 Fe
60µm
6004 S
60µm
6004 Al
60µm
6004 Ca
60µm
6004 O
60µm
6004 Si
60µm
6004 Cl
60µm
6004 K
60µm
6004 Ti

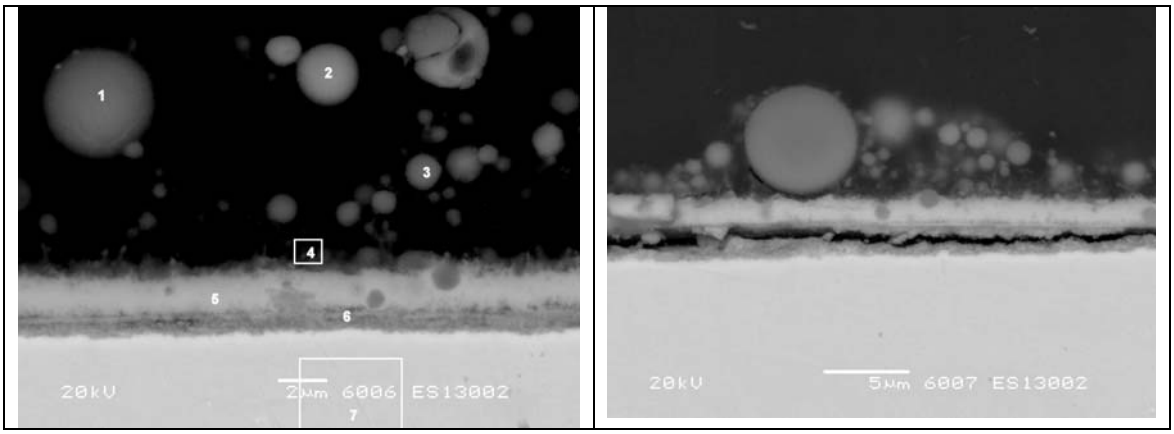
ES13002- Probe 9 from Alliant OGS Iowa -3 hr exposure: metal temperature 540°C, Flue gas temperature 1000°C.

Analysis of deposit:



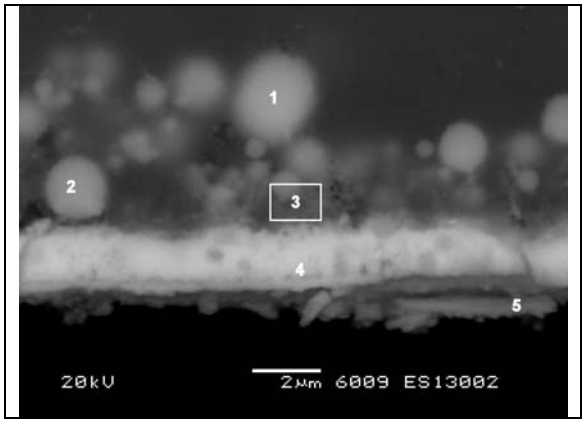
	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe
5463	30	3	3	8	12	1	5	2	30	1	5
5464	30	3	3	8	11	1	5	1	32	1	5

Analysis of cross-section:

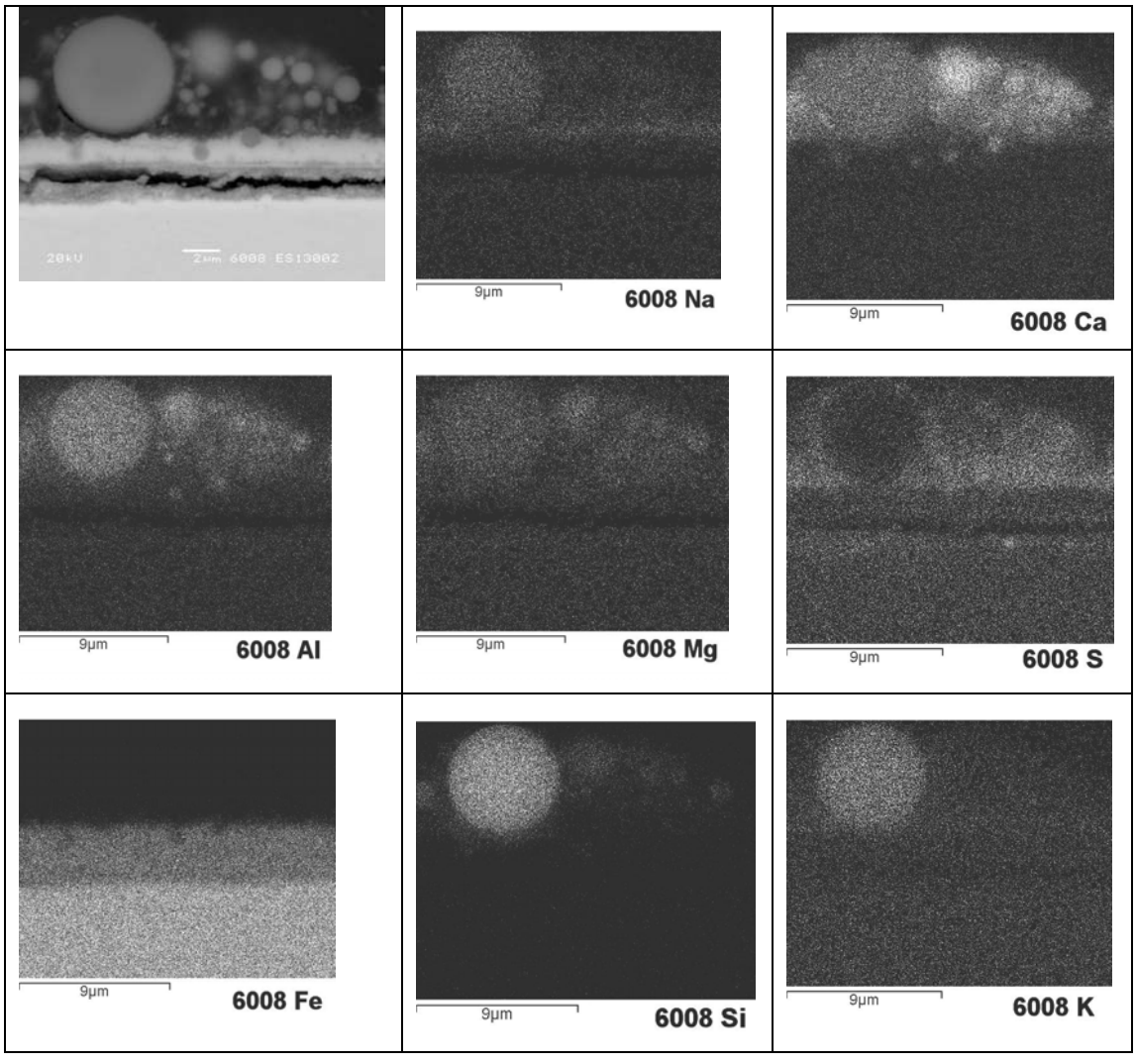


6006	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe
1	31	3	3	15	22				0	19	3		3
2	28		4	7	5	1	3	0		35	5		11
3	35	3	5	4	20	1	3	1	1	21	1		5
4	17	8	1	1	2		6	1	2	4			57
5	14						0			0		1	84
6	9				1		2			0		5	83
7					1		0					2	97

Appendix A: Analyses of deposit probes

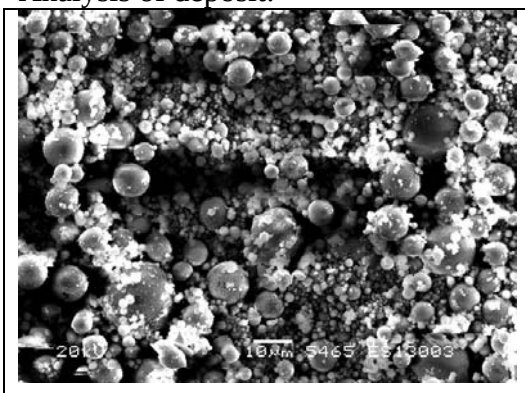


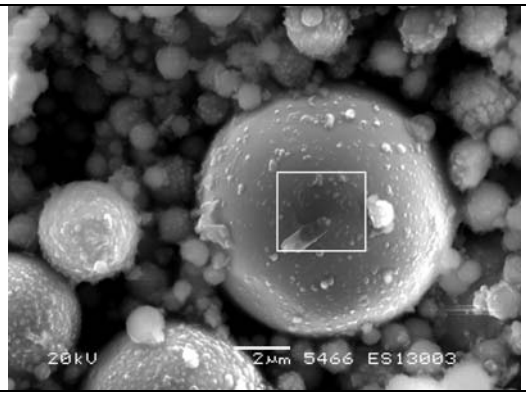
6009	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	Mo
1	31	1	5	7	14	1	1	0		34	1		5	
2	31	2	3	8	8	1	5	0	1	23	1		17	
3	22	8	3	5	5	1	8	1	2	14	1		31	
4	12				1		1			0		2	85	
5	2									0		5	90	3



ES13002- Probe 14 from Alliant OGS Iowa -3 hr exposure: metal temperature 540°C, Flue gas temperature 750°C.

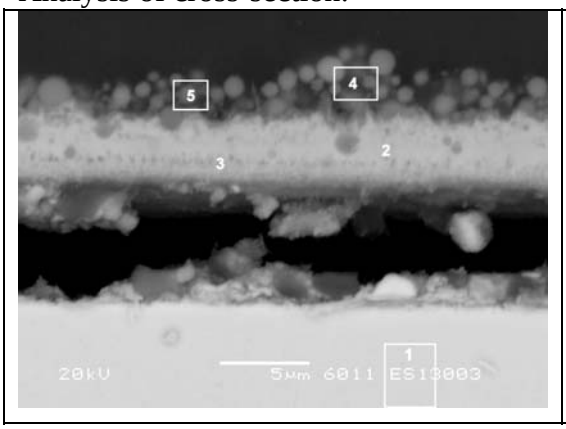
Analysis of deposit:

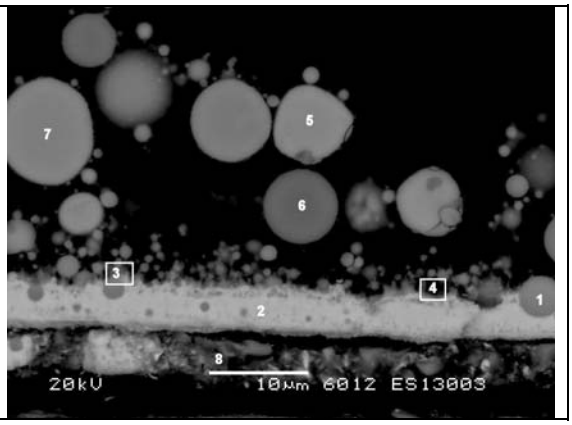




	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe
5465	29	2	3	9	13	1	3	1	31	2	6
Area 2	30	3	3	9	13	1	3	1	30	1	6
5466	26	1	5	5	22		0		35	1	4

Analysis of cross-section:

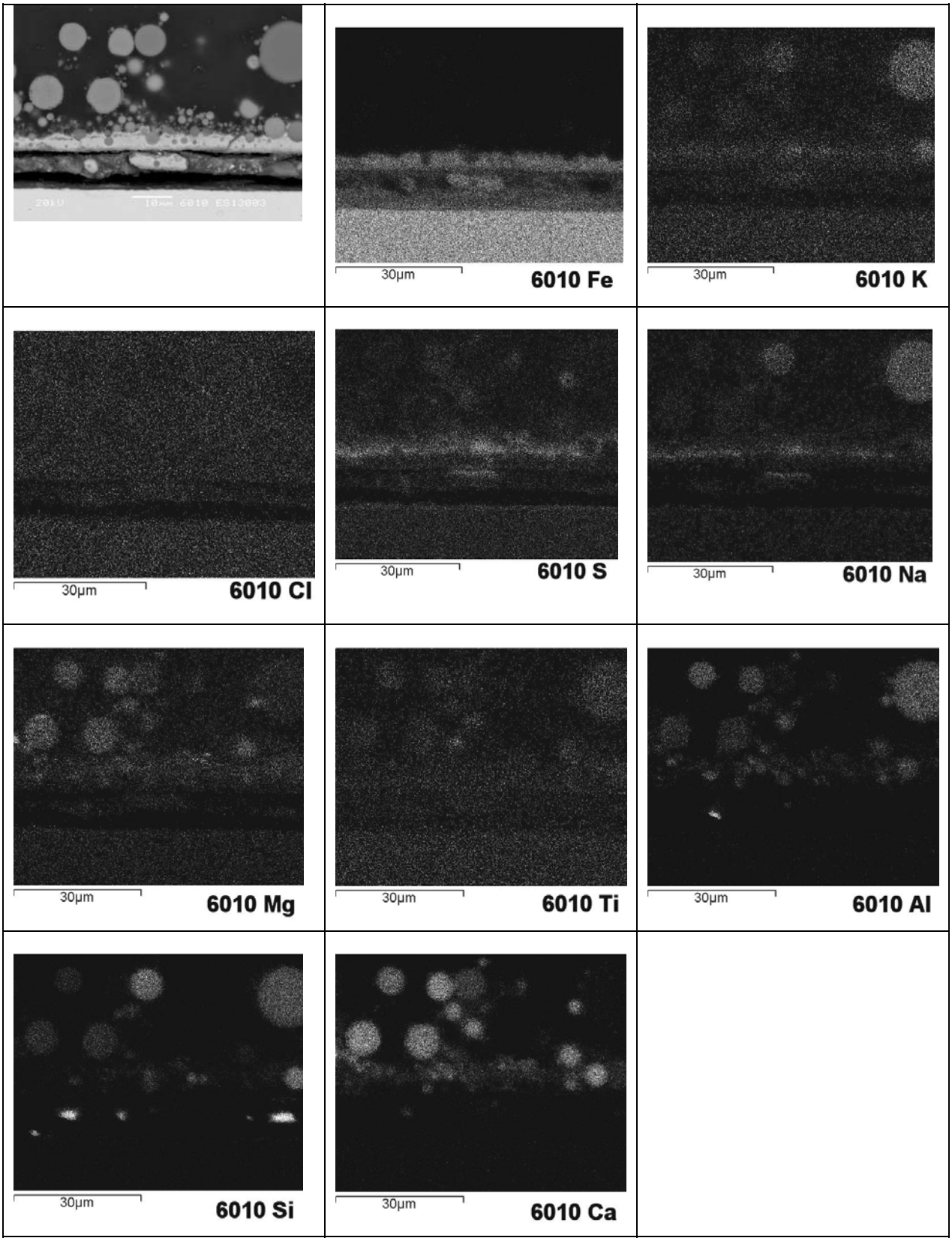




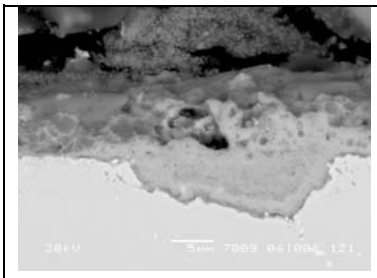
6011	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Mn	Fe
1					0		0					2		97
2	14						1			1		0	1	84
3	12				1		1			1		3		82
4	25	4	4	9	7	2	9	1	1	24	2			11
5	26	5	2	8	7	1	11	2	1	18	1			17

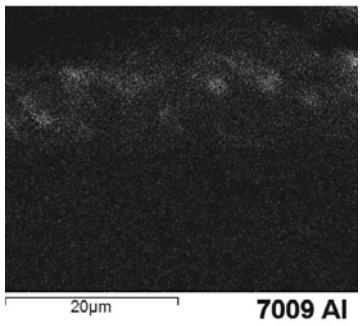
6012	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	Sn
1	23		5	18	2	1	1			37	0		13	
2	13						0			1		0	86	
3	26	3	3	7	3	1	8	1	1	22	4		22	
4	22	11	2	6	4		12	1	2	10			30	
5	21		2	12	5	1	1			47	2		10	
6	32	6	1	2	49				5	3			2	
7	25		4	17	6	1				39	1		7	0
8	3				13		2					4	78	

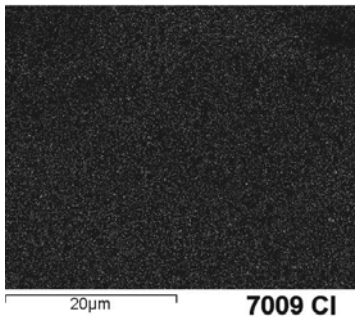
Appendix A: Analyses of deposit probes

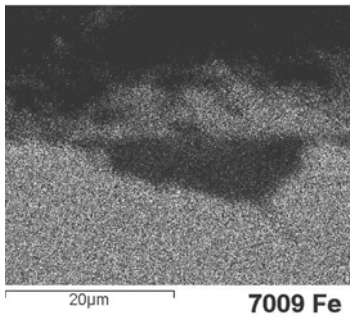


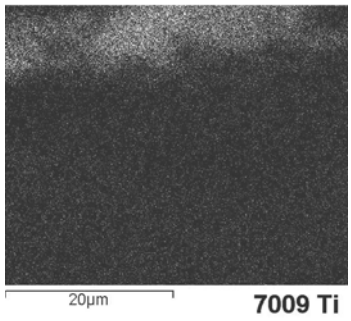
Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C, 2880hs exposure:
Tube 121: TP347H FG

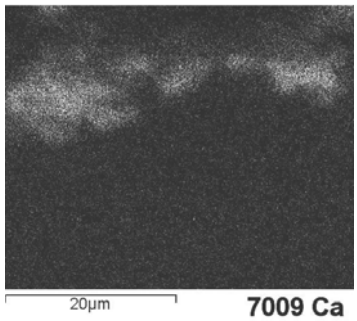


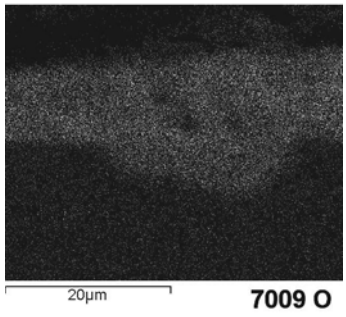


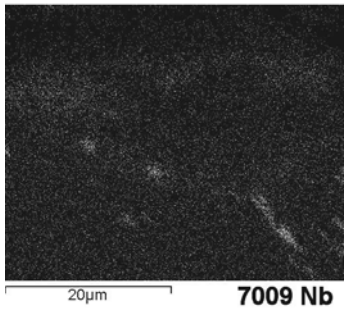


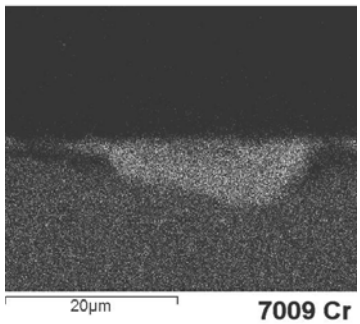


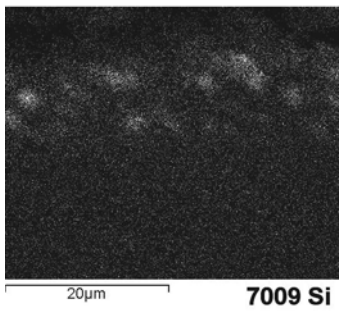


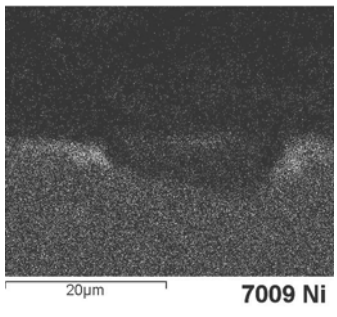


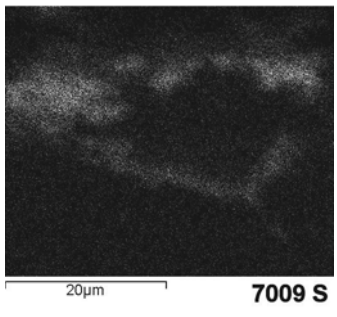


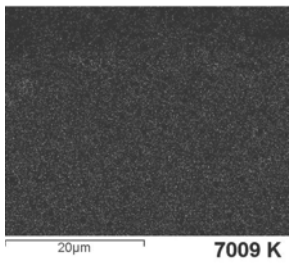




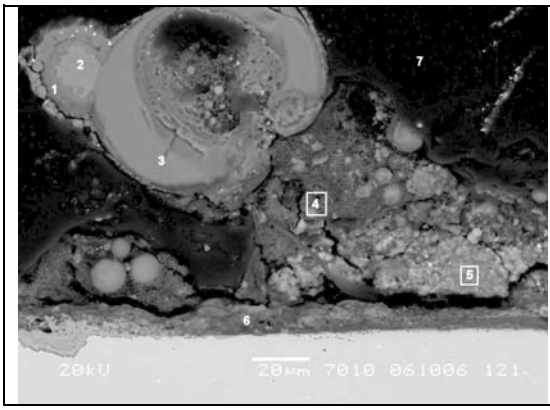


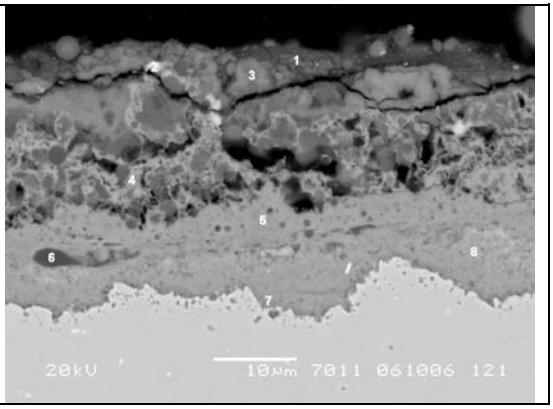






Appendix B: Specimens from TC1 location



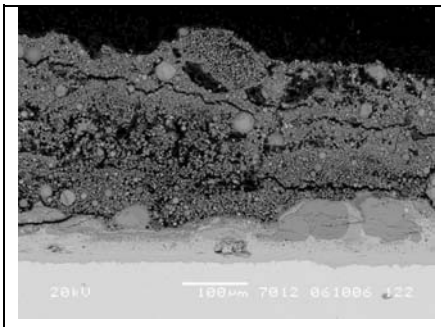


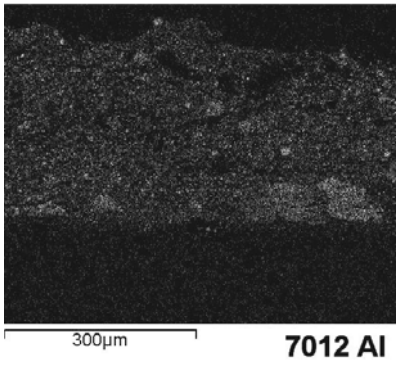
7010	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe
1	25	1	9	11	10		5		1	17	2		19
2	21		4	8	6					47	1		12
3	26	1	4	6	27					27	2		7
4	18			3	3		3	2		11	54		7
5	33	1		3	2	0	20		0	24	1	1	16
6	36	1		3	4		22		1	26	1	1	6
7	51							49					

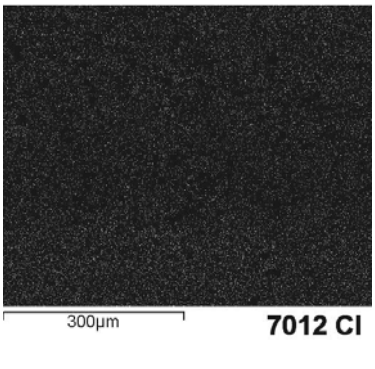
7011	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Mn	Fe	Ni	Ba
1	30	1	1	7	6	1	21		1	23	1			8		
2	17			2	3		15			4				14	1	45
3	27	2	1	5	5		10		1	11		1		39		
4	14			2			3			3		2		74	2	
5	15			1	1							4	1	78		
6	23	1		14	25		2		2		1	15	2	12	2	
7	10				1		6	1				46	4	28	5	
8	9				1		11					37	4	25	13	

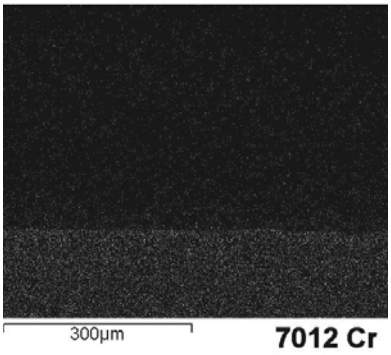
Appendix B: Specimens from TC1 location

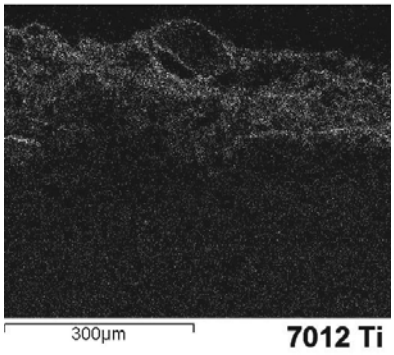
Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C, 2880hs exposure:
Tube 122: 10CrMo910

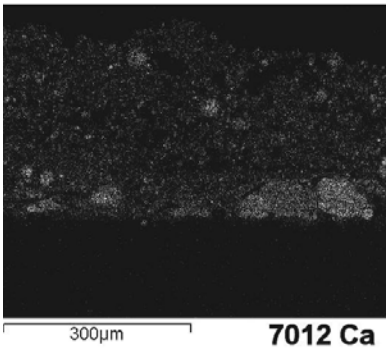


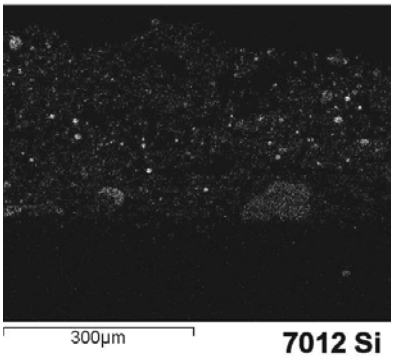


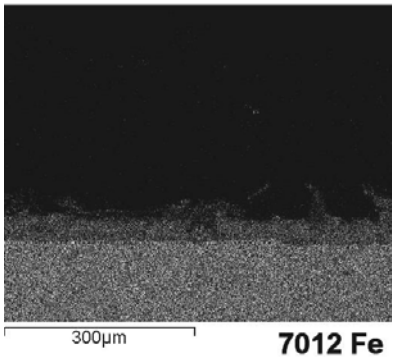


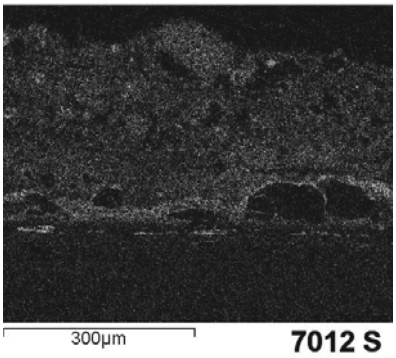


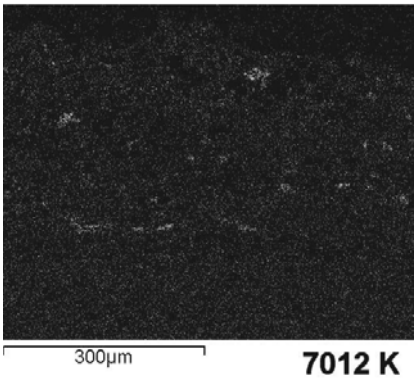




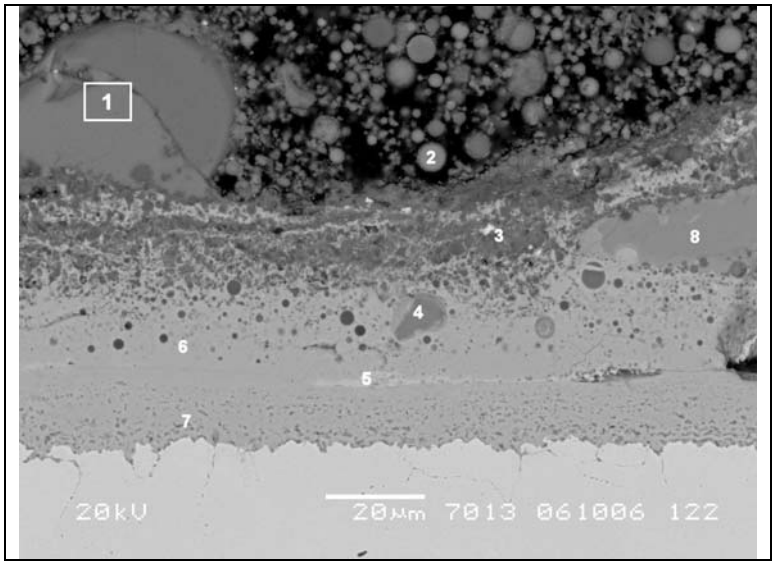






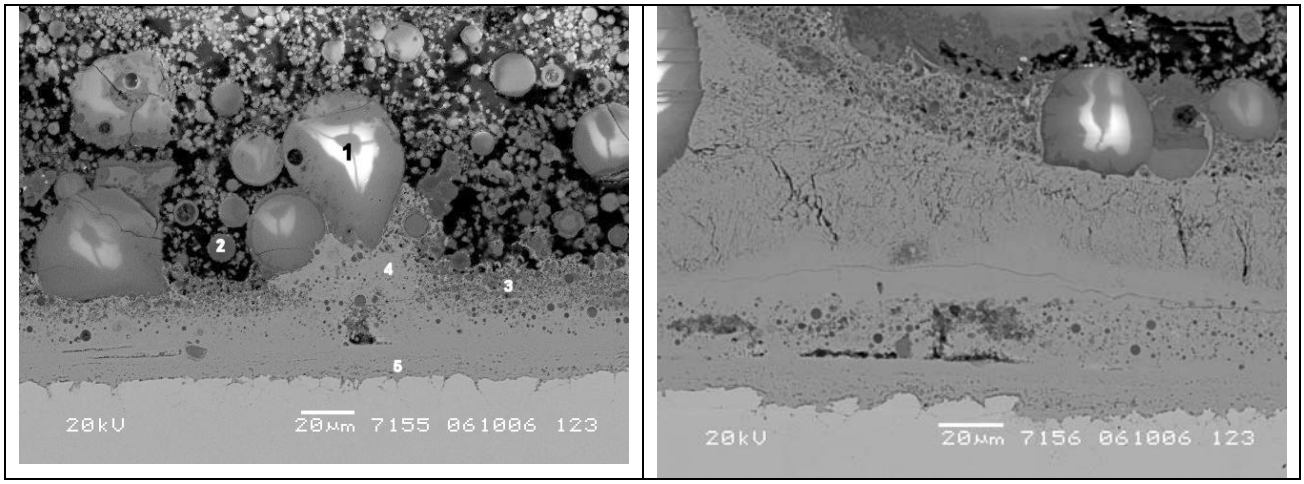


Appendix B: Specimens from TC1 location

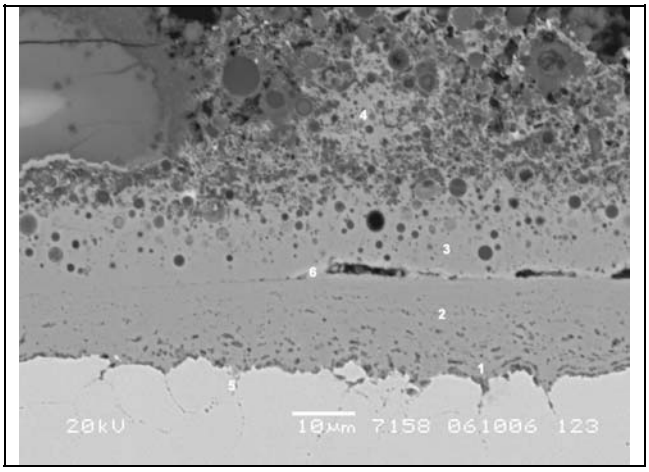


7013	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe
1	24		5	13	10		1		40	1			8
2	20		8	9	5	1	1		44	1			11
3	28	2		3	2		20	17	13				16
4	21		5	9	6	1			38	5			15
5							34						66
6	12						2					1	85
7	12				1		1				4		82
8	19		5	6	6	0			25	1			37

Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C, 2880hs exposure:
Tube 123: 13CrMo44

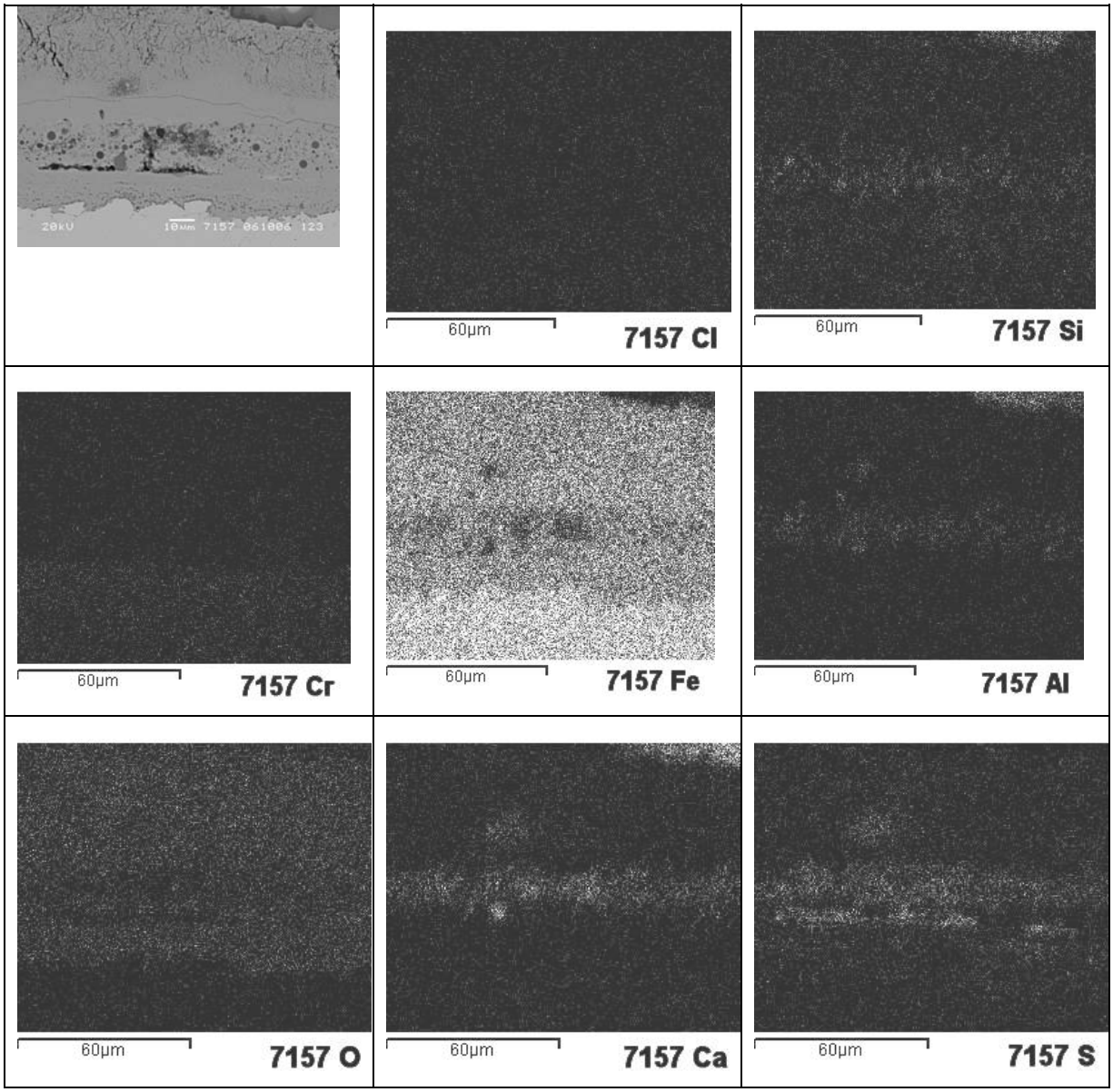


7155	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Mn	Fe	Ba
1	35		4	15	4	4				32	2			4	
2	47	1	2	4	7		17	1		19				3	
3	21		1		1		9		5	6			1	54	1
4	18			8	7	1	4			3	1			59	
5	9				1		8			1		1	1	81	

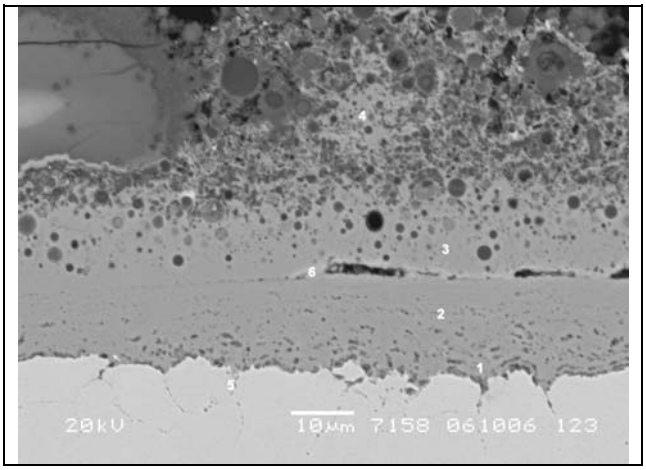


7158	O	Al	Si	P	S	Ca	Ti	Cr	Mn	Fe	Ni
1	12		1		1			2	1	83	
2	12		1		4			2	1	80	
3	12		0		1	1		0	1	85	
4	14	3	2	1	0	0	0			80	
5			1		1			2		94	1
6	3				29					68	

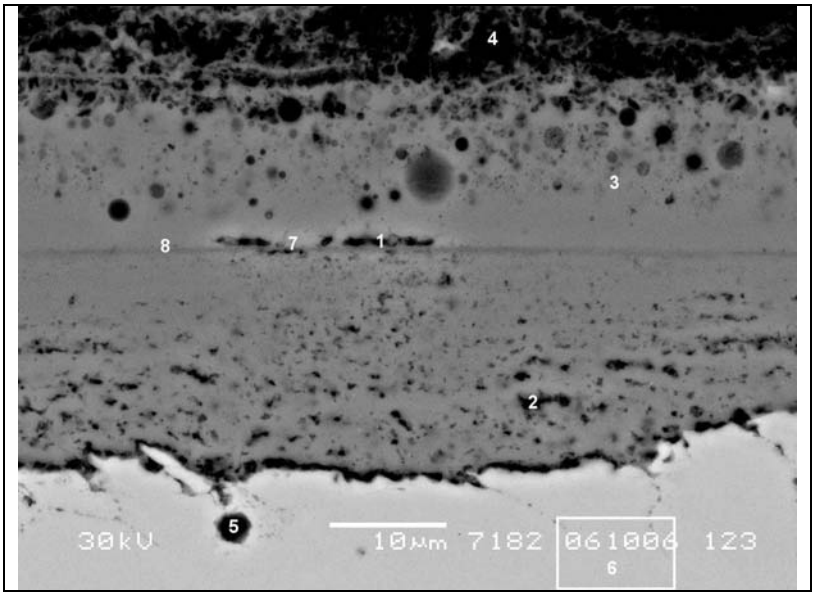
Appendix B: Specimens from TC1 location



Appendix B: Specimens from TC1 location

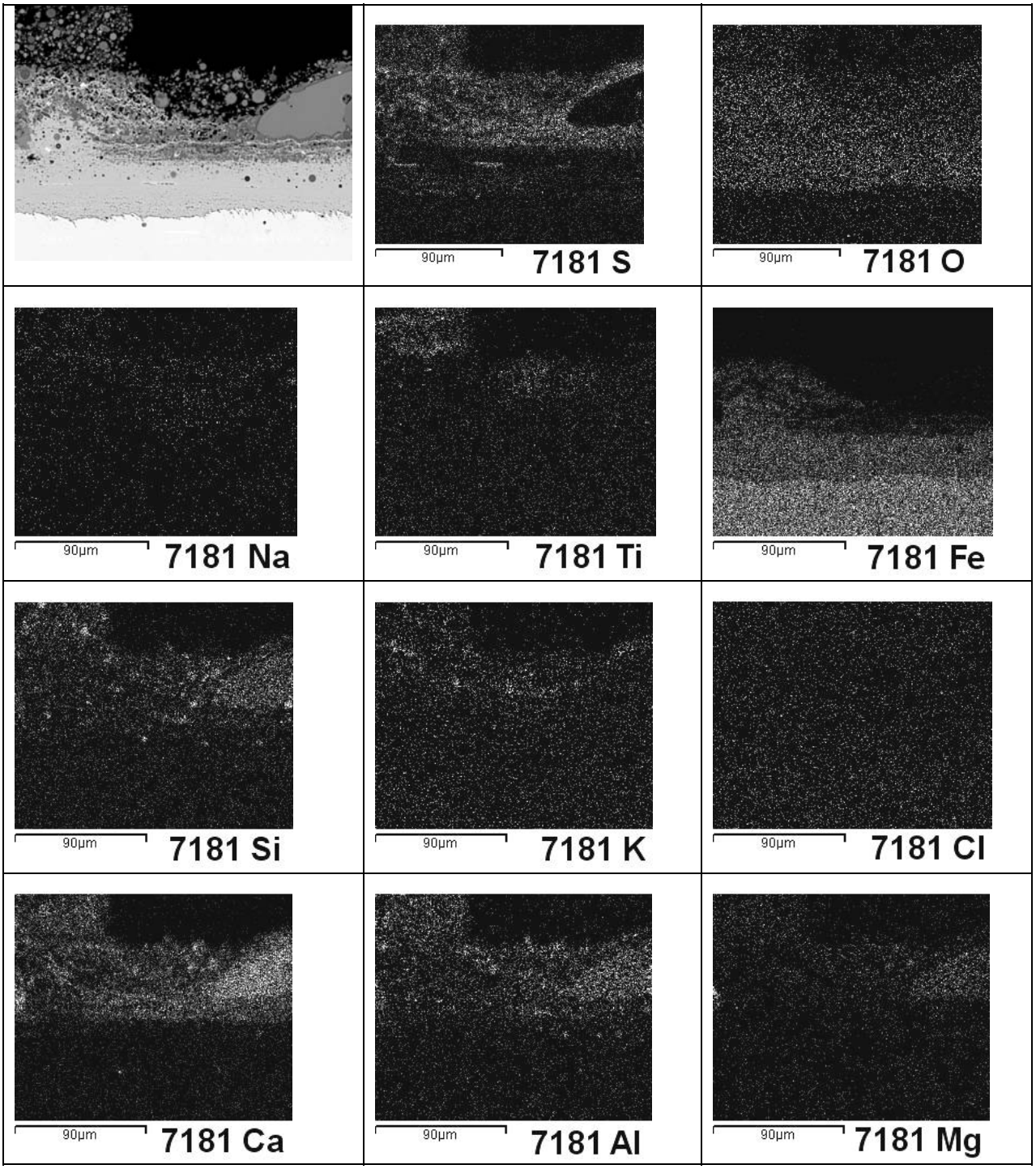


7158	O	Al	Si	P	S	Ca	Ti	Cr	Mn	Fe	Ni
1	12		1		1			2	1	83	
2	12		1		4			2	1	80	
3	12		0		1	1		0	1	85	
4	14	3	2	1	0	0	0			80	
5			1		1			2		94	1
6	3				29					68	

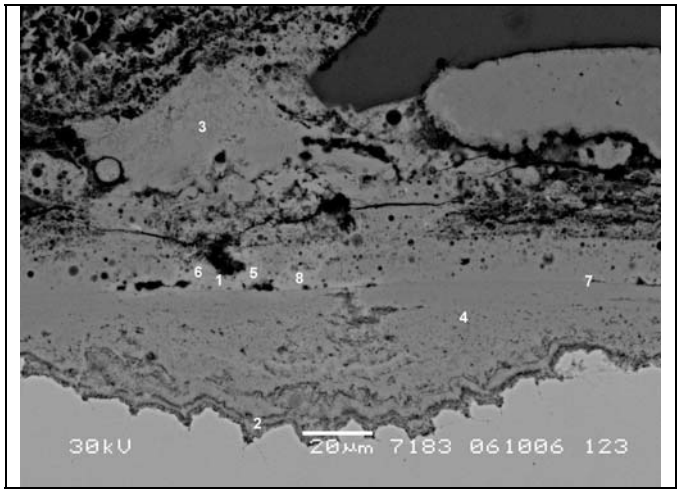


7182	O	Mg	Al	Si	S	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Mo
1	4			1	13		0			1	1	81		
2	8			2	3				0	3	1	82		
3	13			1	1		1				1	84		
4	24	1	2	2	19	0	22					31		
5			1		13		12	1		1	1	72	1	
6				1						1	1	97		0
7	5			0	22		0			1	1	71		
8	12			1	1		0			1	1	84		

Appendix B: Specimens from TC1 location

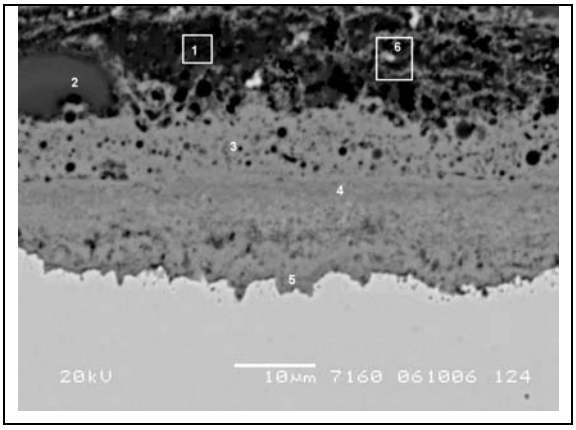


Appendix B: Specimens from TC1 location

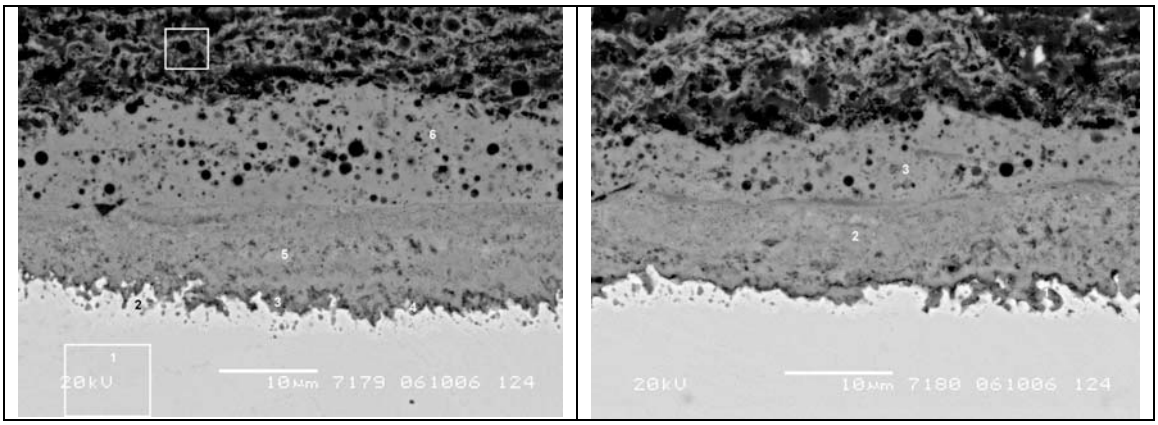


7183	O	Al	Si	S	Ca	Cr	Mn	Fe
1				35	0	0		64
2	8		2	13		4	1	73
3	12	1	2	3	3			79
4	10		1	4		3	1	81
5	1		1	34	1			63
6	5	1	1	23	1		1	69
7	13			4	0	1	1	82
8	4			26				70

Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C, 2880hs exposure:
Tube 124: Super 304H 0 punktet



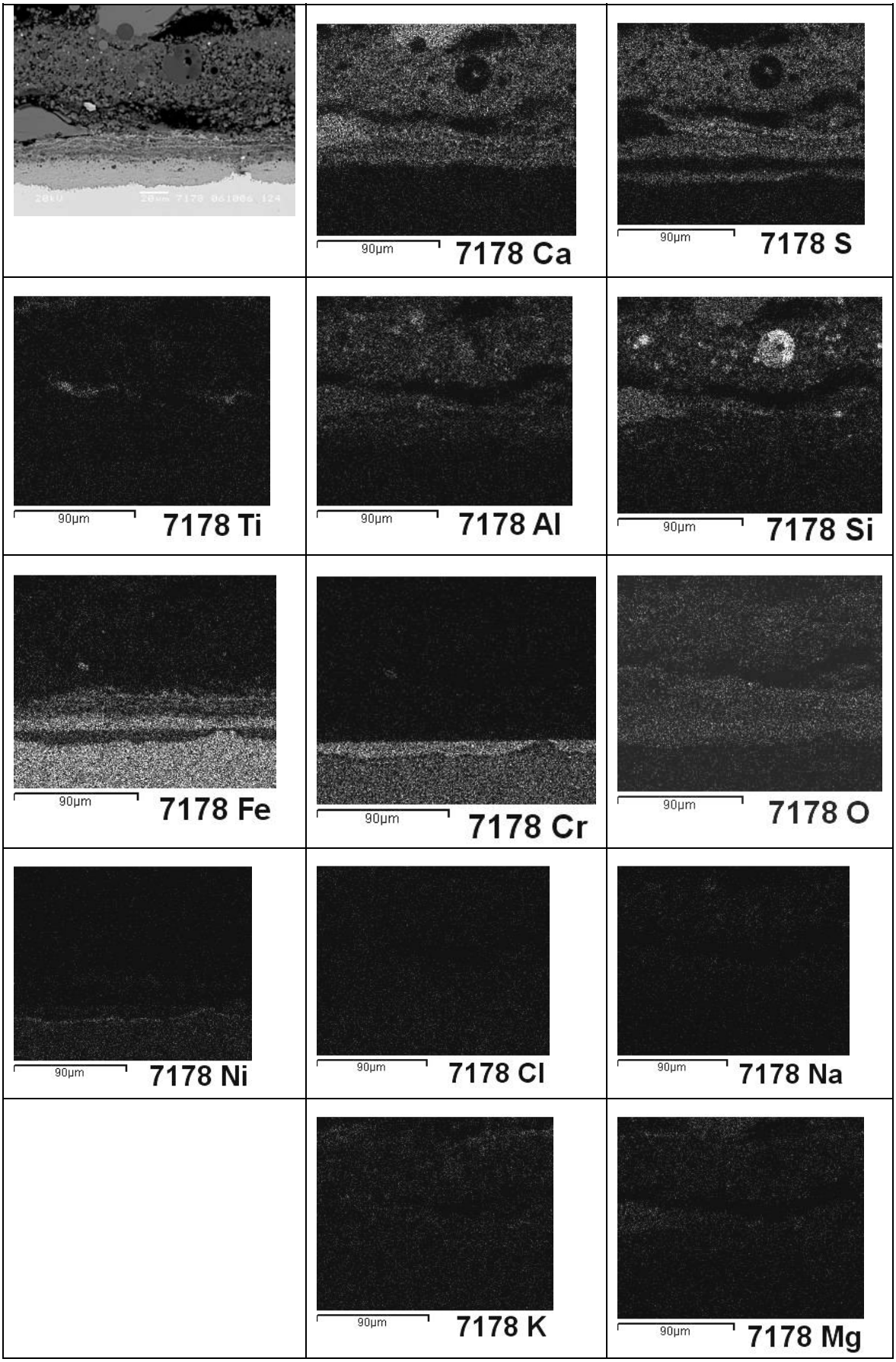
7160	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni
1	31	1	0	4	4		23	1	29	0			6	
2	26		6	5	15				39	2			7	
3	16			2	3		0				1		78	
4	14			1	2	0	0				4		78	
5	10				1		14				48	5	22	1
6	27	1		4	4	0	17	1	20	1			24	2



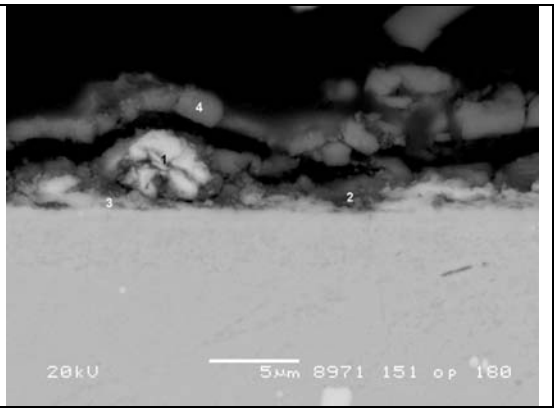
7179	O	Mg	Al	Si	S	K	Ca	Ti	V	Cr	Mn	Fe	Ni
1				0						19	3	69	8
2				1	2					12	1	53	32
3	8			1	8					40	4	31	7
4	6			1	11					34	3	34	11
5	9			1	12				0	43	3	29	3
6	15		1	1	0					1		81	
7	25	1	4	3	17	1	19	0				27	2

7180	O	Al	Si	P	S	Ti	Cr	Mn	Fe	Ni
1	7		1		8		29	3	37	17
2	10		1		9		44	3	28	6
3	14	1	0	0	0	0	2		78	3

Appendix B: Specimens from TC1 location

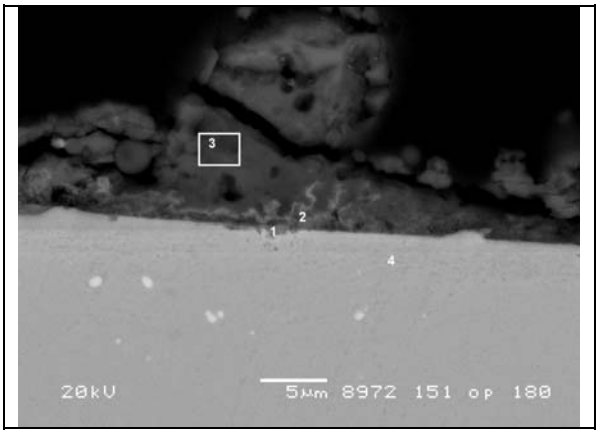


Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C,
2880hours exposure in coal
Tube 151 op 180°: TP347H FG



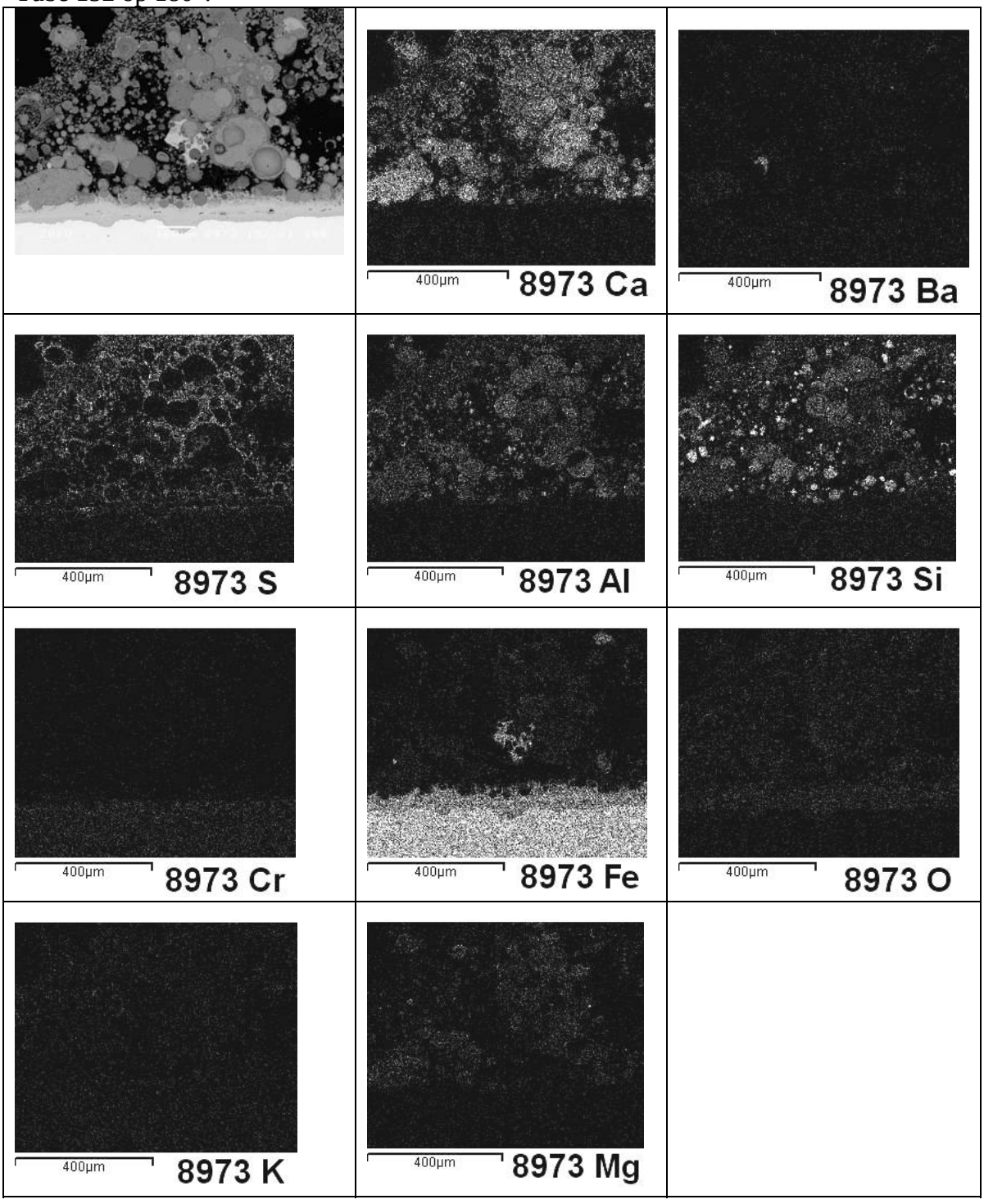
8970	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Nb
1	22		2						1		39	4	10	2	21
2	22		4						2		10	2	25	1	34
3	35	1	7	14	5	1	9	0	12	4	1	2	11		
4	7			1	1		4		4	2	12	1	57	11	
5	14				1		2		1	1	54	5	19	3	

8971	O	Mg	Al	Si	S	Ca	Ti	Cr	Fe	Ni
1	2			1	1	1	1	12	73	9
2	26	1	1	1	15	16	10	6	22	3
3	7			1	3	2	3	14	64	6
4	33		0	1	24	31	6	1	5	

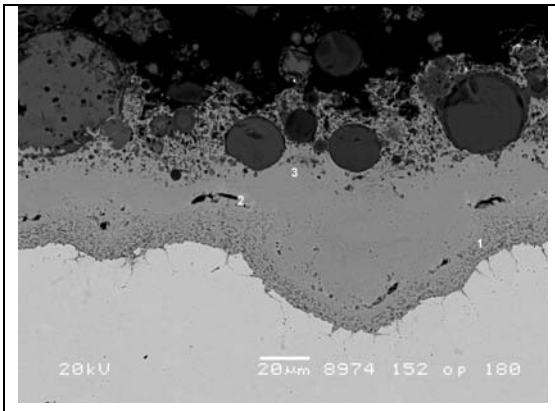


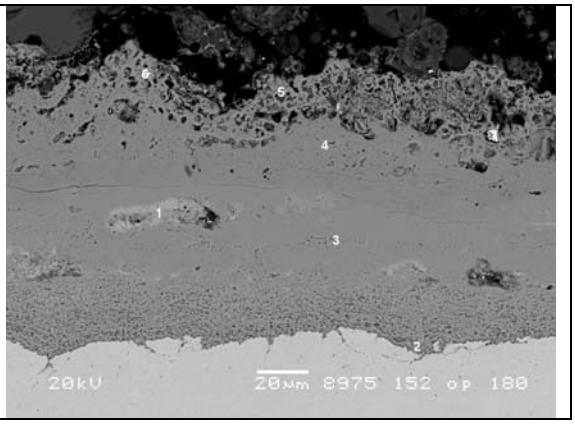
8972	O	Na	Mg	Al	Si	S	Ca	Ti	Cr	Mn	Fe	Ni	Nb
1	11			1	2	6	2	1	37	9	28	3	
2	25		1	1	1	13	15	15	4		25		
3	32	1	9	13	5	13	16	4		1	7		
4					1				19	1	69	10	0

Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C,
2880hours exposure in coal, 10CrMo910
Tube 152 op 180°:



Appendix B: Specimens from TC1 location

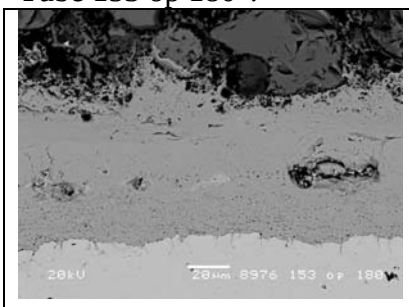


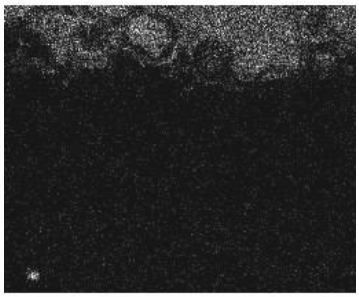


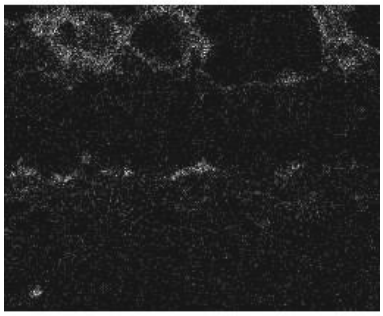
8974	O	Si	S	Ca	Cr	Mn	Fe	Mo
1	11	1	0		5	1	80	2
2	9	0	6	0	3	1	80	
3	11	0	1		1	1	86	1

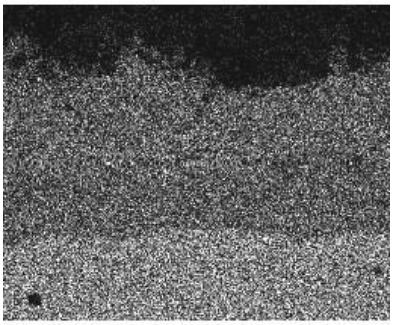
8975	O	Mg	Si	S	Cl	K	Ca	Cr	Mn	Fe	Mo	Ag
1	2		1	28				1		68		
2	10		1					4	1	80	3	
3	11		0	0				1		88	1	
4	14		1	1						85	0	
5	10	1	1	3		0	2			82	0	
6	7		1	1						84	1	6
7	6	2	2	2	1		1			48		39

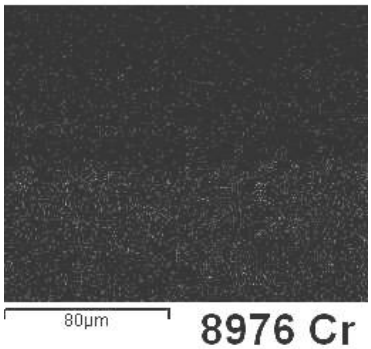
Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C,
2880 hours exposure in coal, 13CrMo44
Tube 153 op 180°:

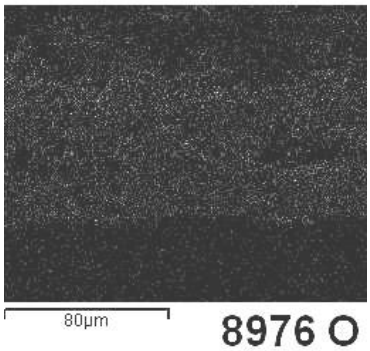


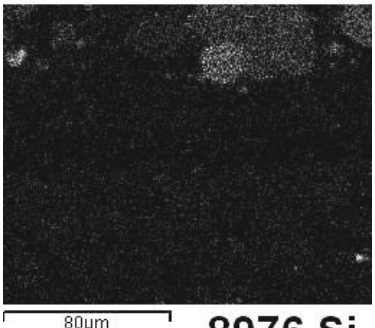


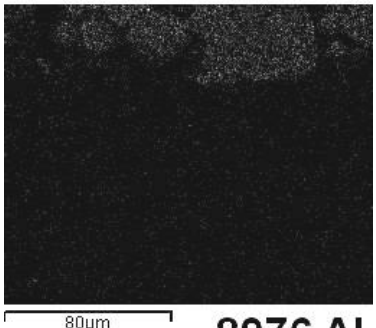




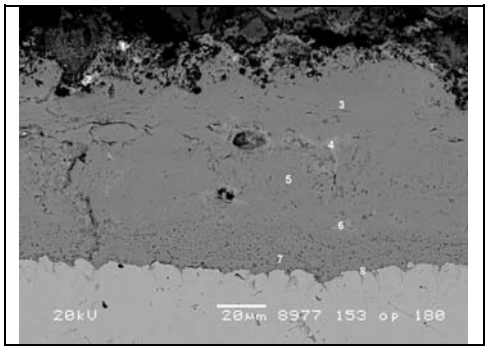




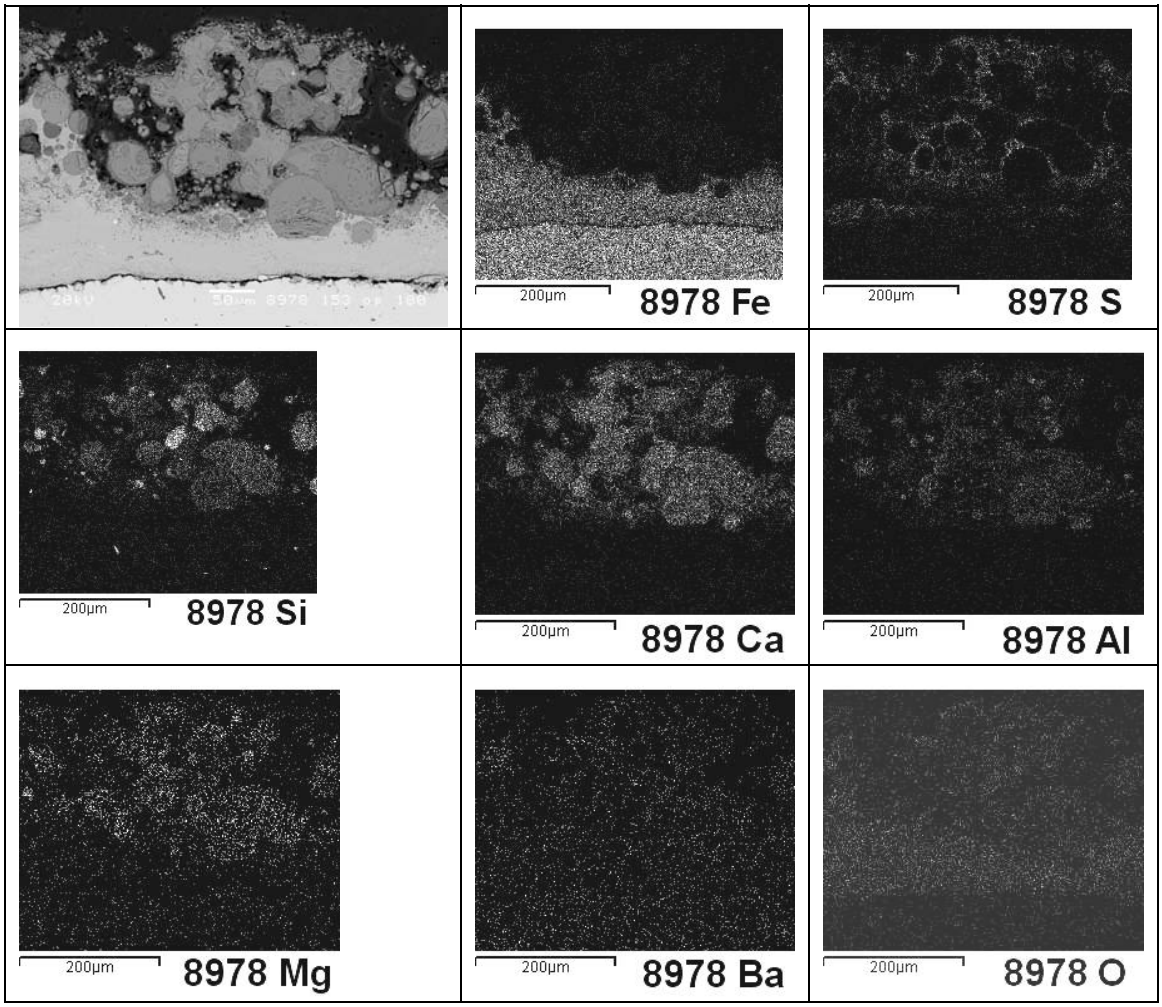




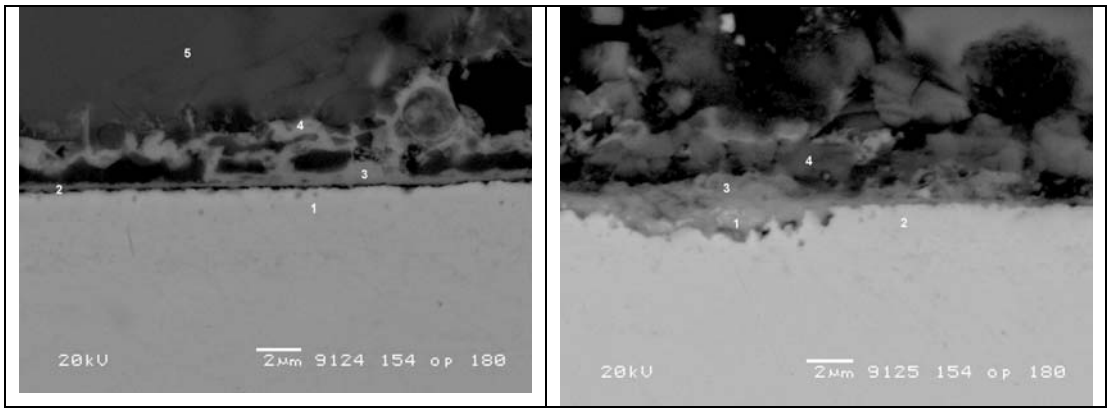
Appendix B: Specimens from TC1 location



8977	O	Si	S	Ca	Cr	Mn	Fe	Ni	Mo	Ba
1	11	0	14	1			16			55
2	14		14	1			17			53
3	12	0	0				88			
4	4	1	23		1		70			
5	10		0		0		90			
6	5	0	18		1		76			
7	9	1	1		3	1	84		1	
8	6	2	2		4	2	82	2	0	

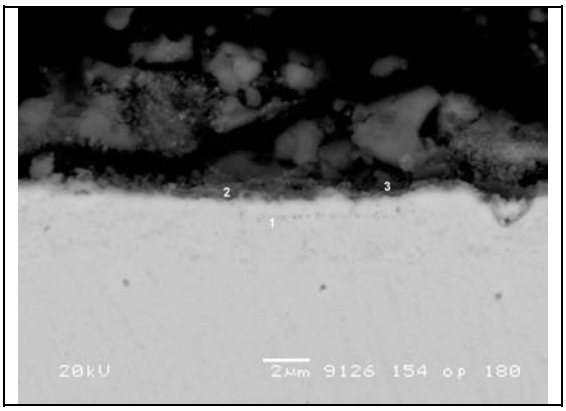


Specimens positioned at TC1: Flue gas T 1350°C, steam T 540°C,
2880 hours exposure in coal, Super 304H
Tube 154 op 180°:



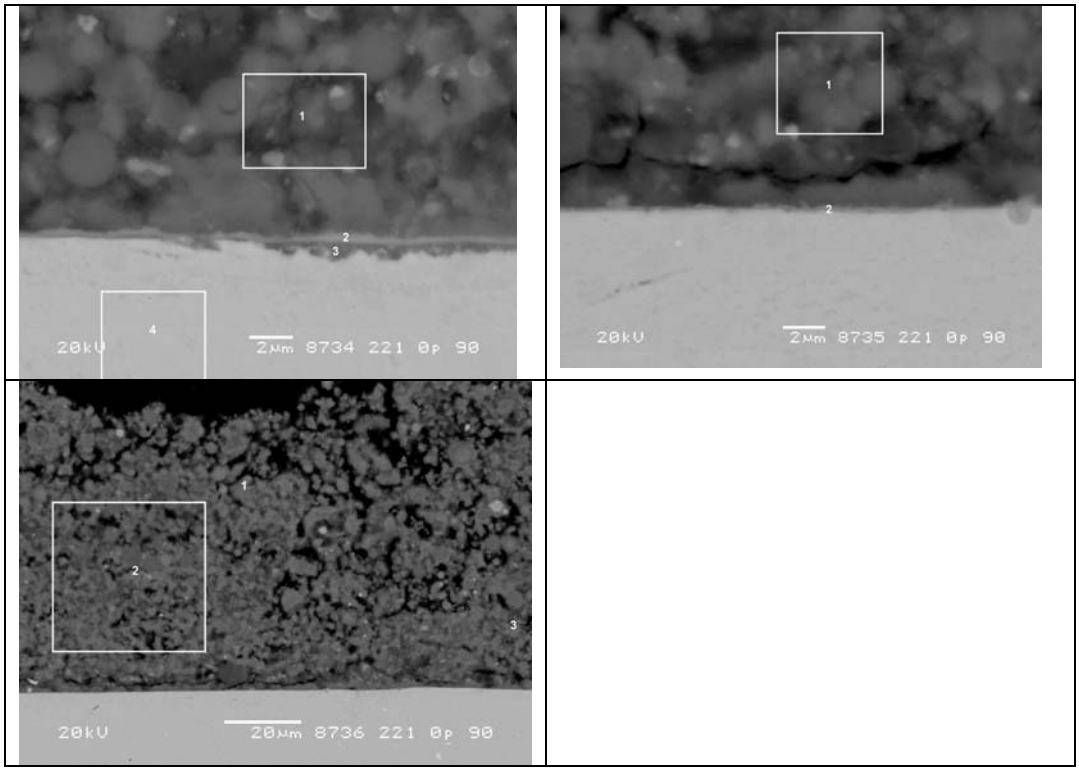
9124	O	Mg	Al	Si	S	Ca	Ti	Cr	Mn	Fe	Ni
1				1				9	0	81	8
2	11			1	7	6		28	4	41	2
3	10			1	2	1		23	4	56	3
4	16		3	2	6	7		1	1	62	2
5	23	6	13	12		39	1			7	

9125	O	Na	Mg	Al	Si	S	Ca	Ti	Cr	Mn	Fe	Ni
1	10				1	4	0		50	2	28	5
2					0	0	0		11		78	10
3	21			1	1	3	1	11	24	1	37	1
4	28	1	1	6	2	20	23	5	3		9	2



9126	O	Na	Mg	Al	Si	S	Ca	Ti	Cr	Mn	Fe	Ni
1					0	1	0		12	2	74	11
2	12		0	1	1	3	2	5	29	4	38	3
3	17	2	1	1	2	11	10	4	20	2	29	2

Specimens positioned at TC2: Flue gas T 900°C, steam T 540°C, 2880hs exposure:
Tube 221: TP347H.
90°



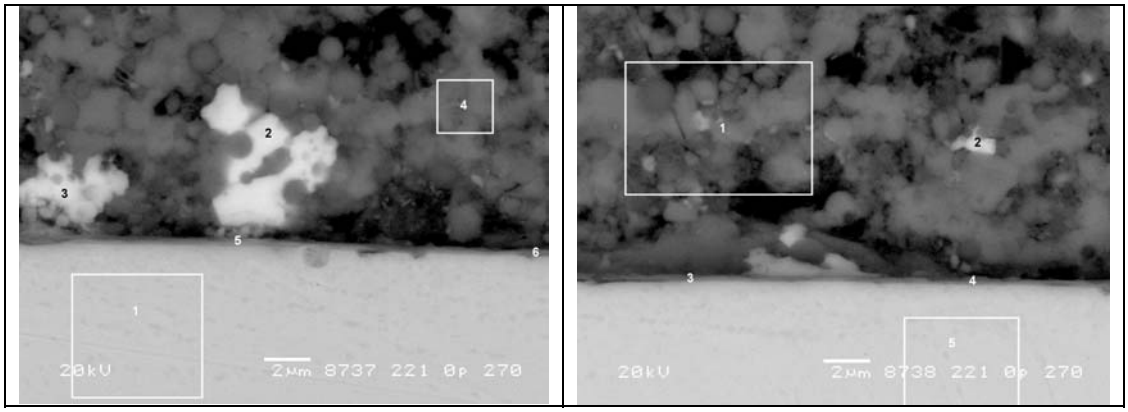
8734a	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni
1	28	1	3	7	7	1	21	3	19	1			9	
2	17		2	2	1	1	9		7		39	4	15	2
3	11		2		1		7	1	2		27	2	39	8
4					1						18	3	69	10

8735	O	Na	Mg	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni
1	26	2	4	11	14	1	17	2	13	1		8	
2	14		2		1		8		6	26	5	37	2

8736	O	Na	Mg	Al	Si	P	S	K	Ca	Fe
1	29		2	6	6	2	25		27	4
2	33	1	3	6	8		21	1	21	5
3	29		4	5	7		27	2	23	4

221 op 270°

Appendix C: Specimens from TC2 location

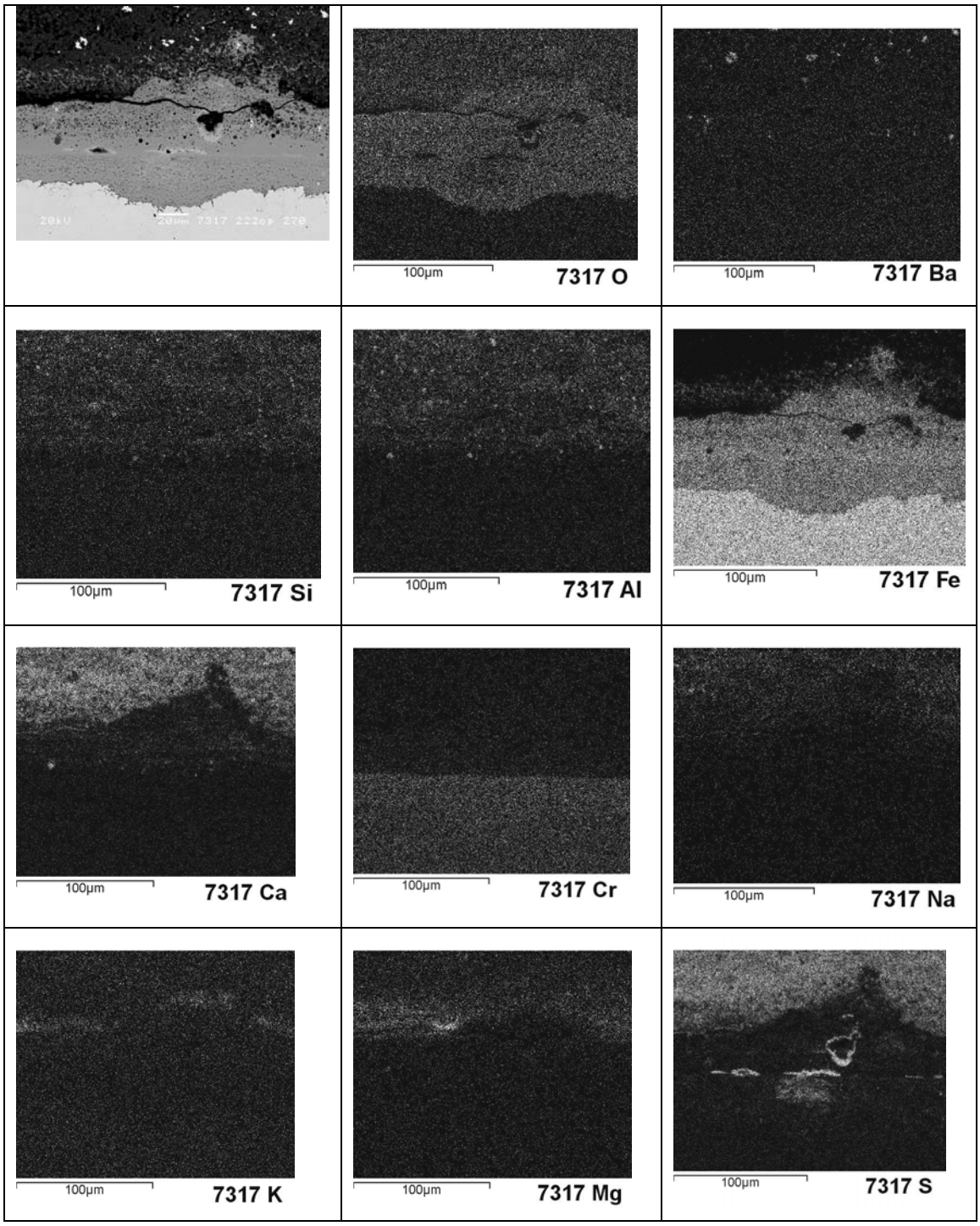


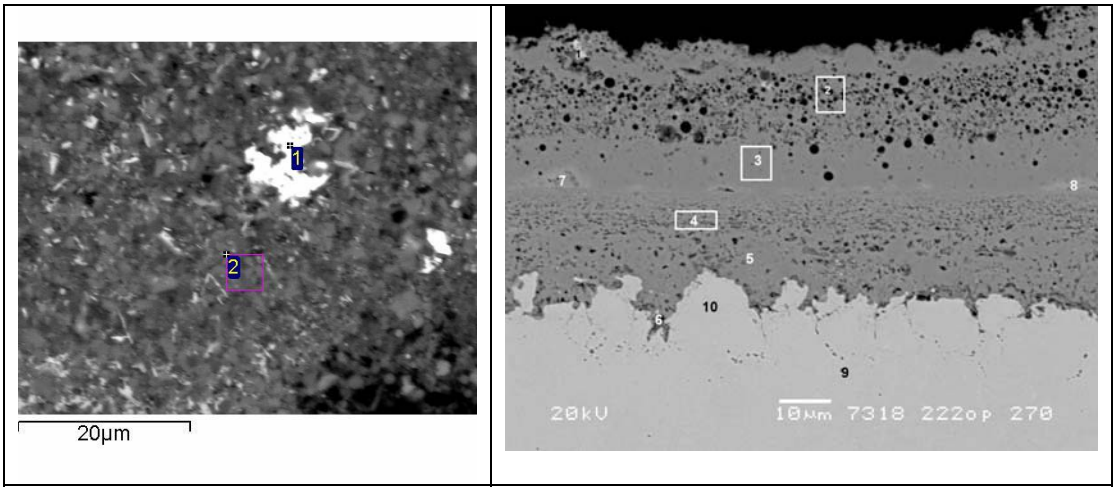
8737	O	Na	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Ba
1									19	2	68	11	
2	14		3	2		17	1	3			2		58
3	17		3	2		17	1	5	3		4		48
4	29	1	6	4	1	24	5	26	1		3		
5	15		2	2		9	1	4	21	3	25	1	18
6	17		3	3		5	1	4	23	3	39	2	

8738	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Nb	Ba
1	27	2	1	6	5	1	23	2	26	1	1		5			
2	26	1		4	4		20	1	13				2			29
3	19	1		2	2	1	9	0	9		20	3	32	2		
4	14			2	2	1	6	1	5		20	4	42	3		
5					0						18	2	68	11	1	

Specimens positioned at TC2: Flue gas T 900°C, steam T 540°C, 2880hs exposure: Tube 222 op: 10CrMo910.

270°

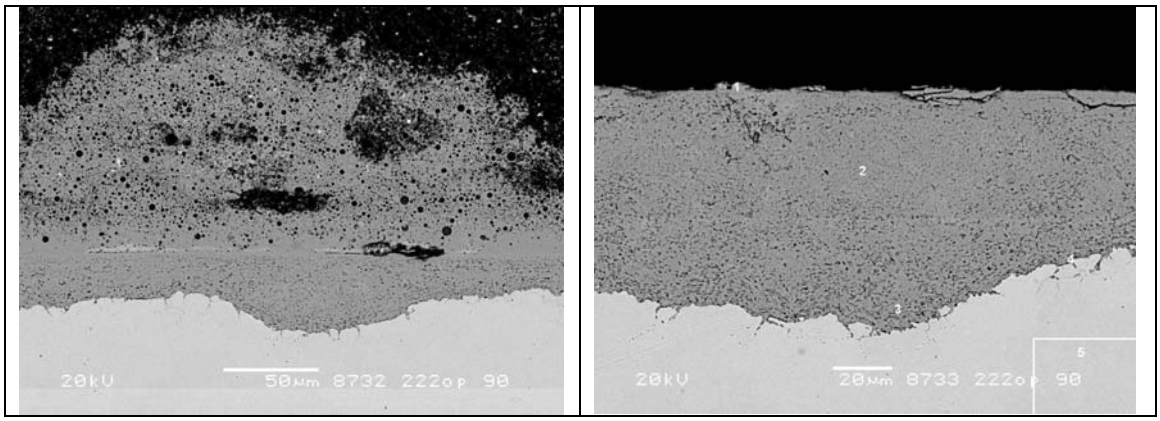




222 op	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe	Ba
1	14	1	1	2	2	0	16	1	2		5	57
2	29	5	2	4	4	0	23	1	23	0	7	

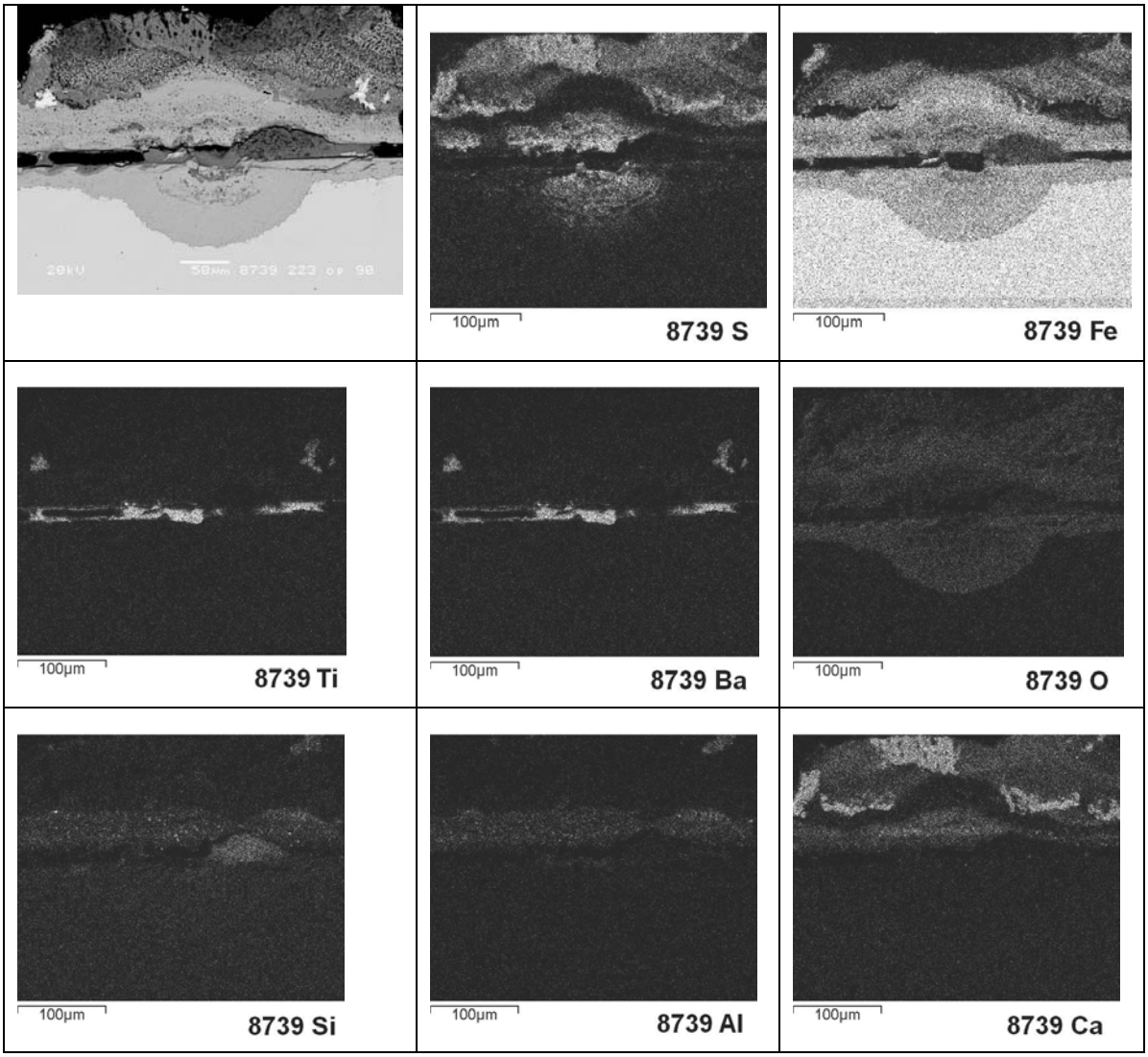
7318	O	Na	Mg	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Cu	Mo	Ba
1	12			2	2	0	13	1	1			17		1		51
2	14	1		2	2	0	1	0	2			77				
3	11				0		2			0	1	86				
4	11				1		1			5	1	81				
5	11				1					4	1	80			3	
6	7		2		1		3			5	1	81	1			
7	6				0		22		0	1		70				
8	8				1		10		0	4	1	75				
9					0		9			7	3	80		1		
10					0					2	1	96			1	

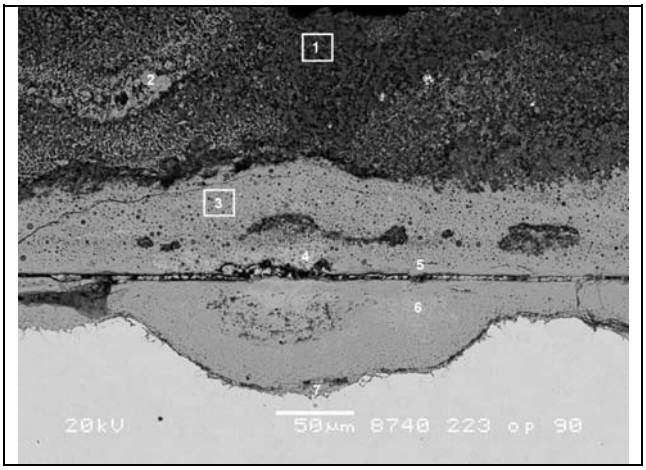
90°



8733	O	Si	S	Ca	Cr	Mn	Fe	Ni	Mo
1	9	1	11	1	5	1	72		
2	11	3	4		5	1	77		
3	10	1	1		5	1	80		2
4	7	1	1		5		82	2	2
5		0			2	1	95		1

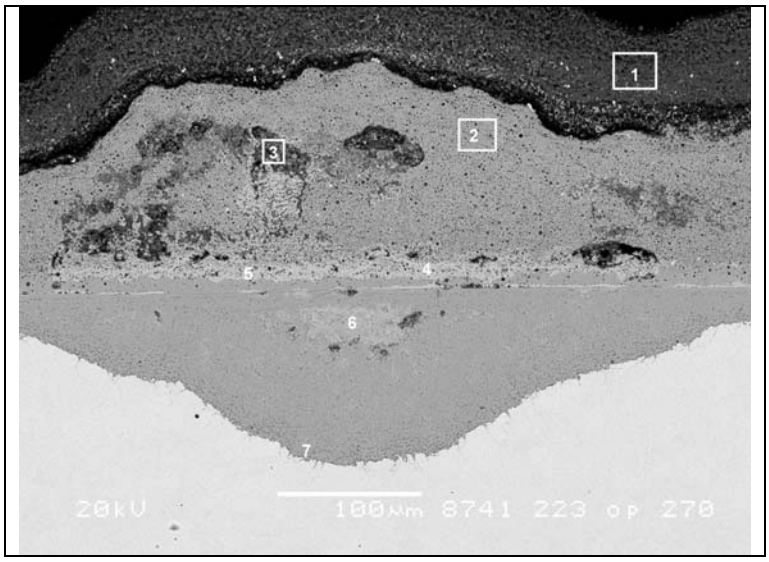
Specimens positioned at TC2: Flue gas T 900°C, steam T 540°C, 2880 hs exposure:
Tube 223 op: 13CrMo44.
90°





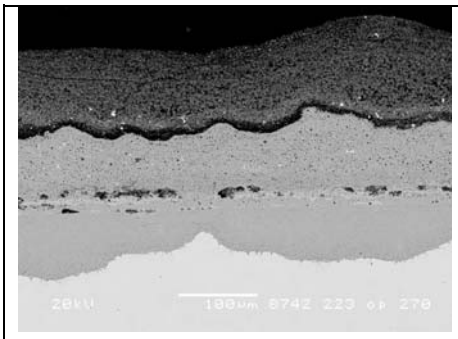
8740	O	Na	Mg	Al	Si	S	Ca	Ti	Cr	Mn	Fe	Mo
1	30	18	1			33	13				6	
2	16				0	0	0				84	0
3	13		1	3	3	5	4			1	71	0
4	3		1	2	1	32	4	0			57	
5	12			1	0	1	1				85	0
6	8				1	14			2	1	74	
7	12				1	2			2		81	1

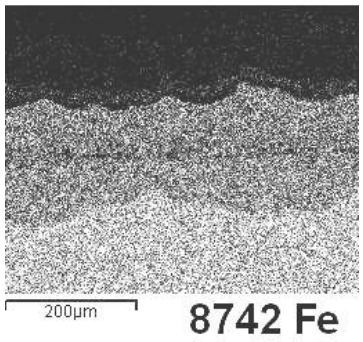
223 op 270°

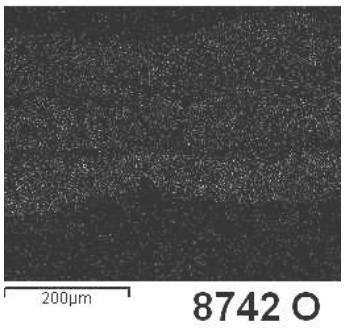


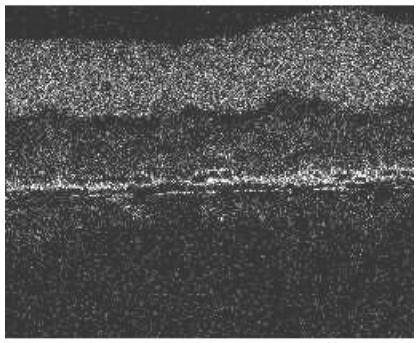
8741	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Mo
1	28	3	3	6	6	1	21	2	24	1			5	
2	12		1	2	2	0	6	0	4				73	
3	10	1	1	2	4		14	0	9				58	
4	3			1	1		33		3				59	
5				1	1		35		1				61	
6	8				2		13				3	1	74	
7	12				1						2	1	80	3

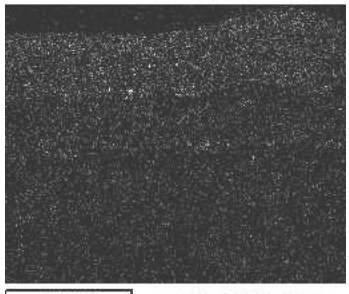
Appendix C: Specimens from TC2 location

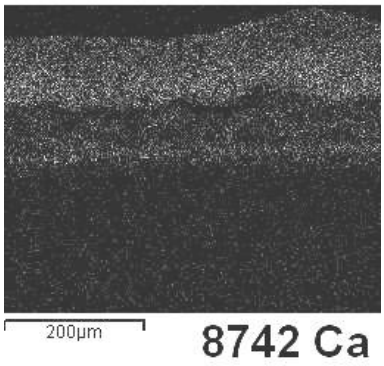


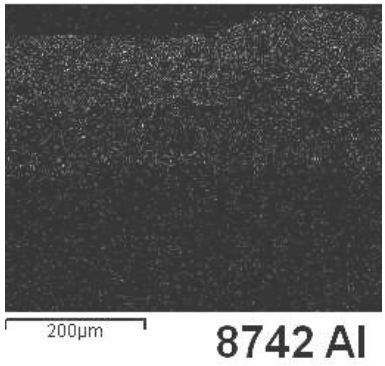






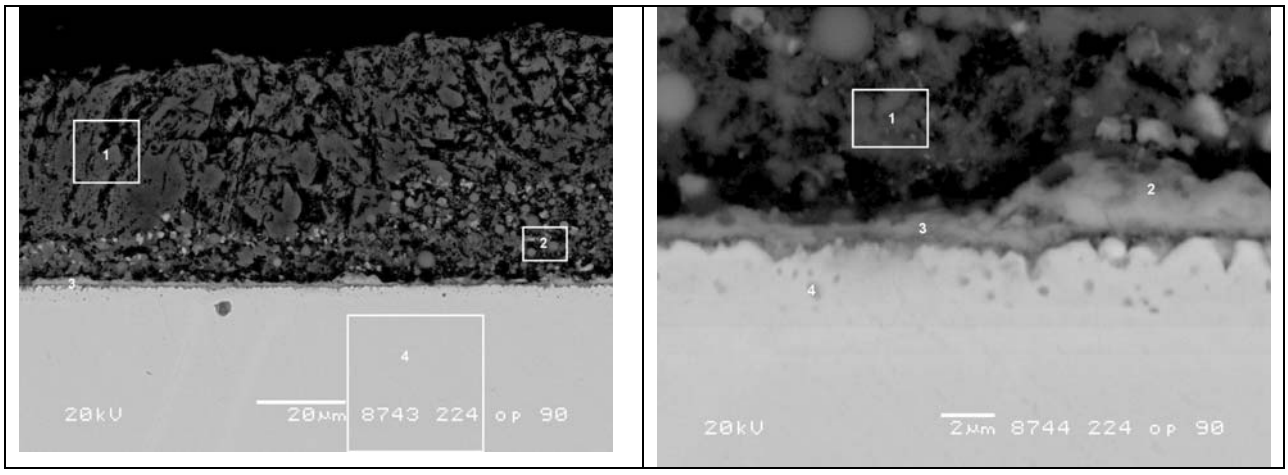






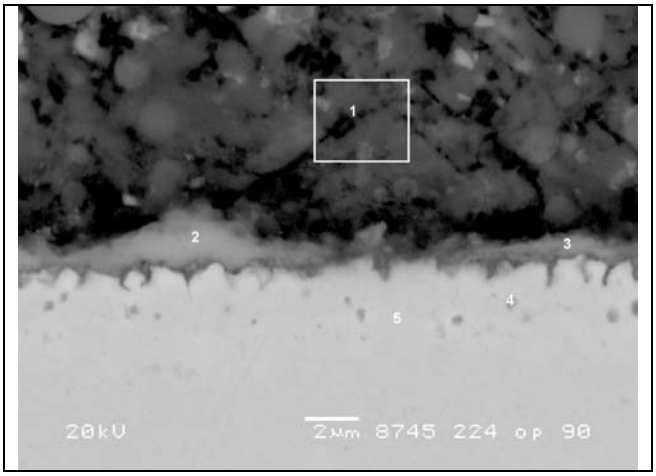
Specimens positioned at TC2: Flue gas T 900°C, steam T 540°C, 2880 hs exposure:
Tube 224 op: Super 304H.

90°



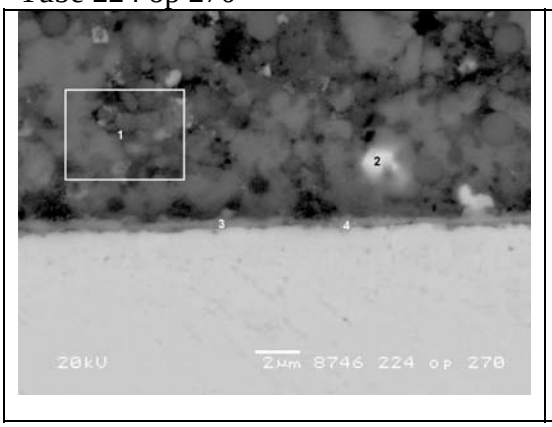
8743	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	V	Cr	Mn	Fe	Ni
1	34	20	1				32	1	10					2	
2	29	12	1	10	12	1	19	2	6	1		2		5	
3	15		2		2	1	4				1	54	5	15	1
4					1							19	2	67	10

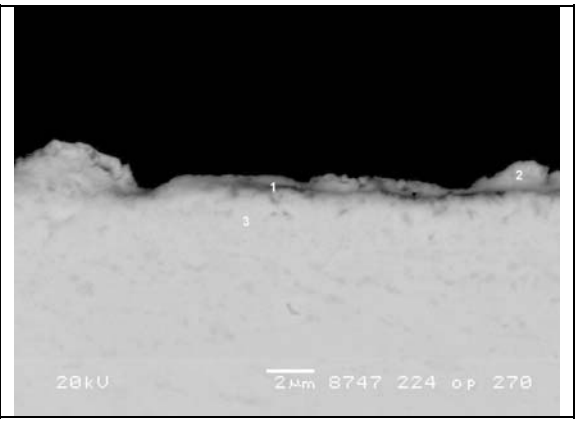
8744	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni
1	28	14	1	7	8		23	2	5	1	6		4	
2	18	1	1	1	1	1	3		1		67	2	5	
3	17	2	2	1	3		3				42	5	25	2
4					0		7				7	12	65	10



8745	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Mo
1	29	14	1	5	5	1	26	1	8	1		2		6			
2	14		2		1		11					60	4	8		1	
3	18	4	1	1	3		4		0		1	47	3	18	1		
4							5					5	7	77	6		
5					0					0		8	1	72	17		1

Tube 224 op 270°

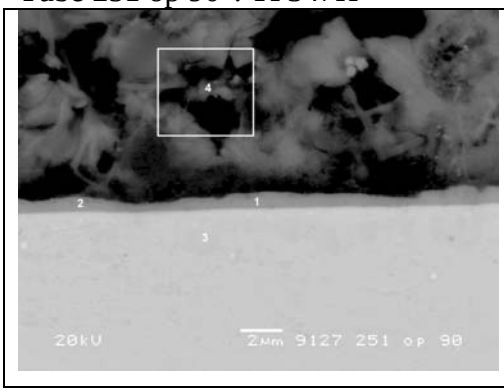


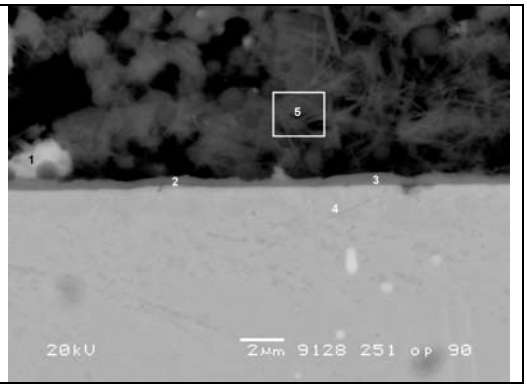


8746	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Ba
1	30	6	1	5	4	1	24	2	22	1	3		2		
2	16	1	1	2	2		22	1	10				2		46
3	20	1	1	1	2	1	8		6		37	3	19	1	
4	13	1	1	3	3	1	4	0	3	1	30	8	28	3	

8747	Si	Cr	Fe	Ni	Mo
1	1	11	81	6	1
2	1	10	82	6	0
3	1	13	78	8	0

Specimens positioned at TC2: Flue gas T 900°C, steam T 540°C, 200 bar
2880 hours exposure in coal,
Tube 251 op 90°: TP347H

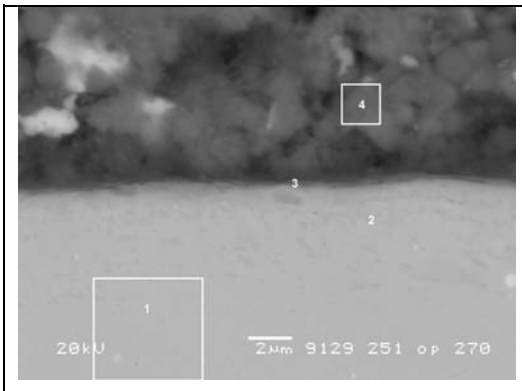


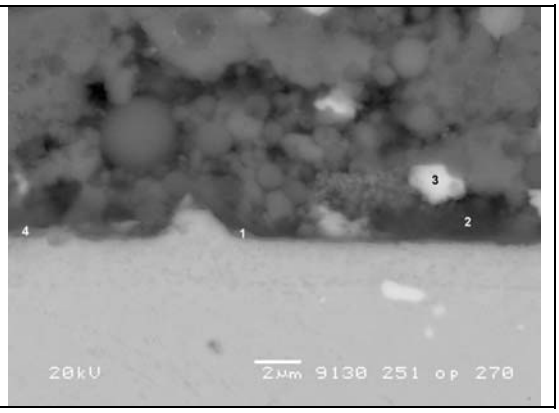


9127	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	V	Cr	Mn	Fe	Ni
1	18	3	1	1	1	1	3		1			51	6	13	
2	13	2	1	1	1	1	2	0	1		1	44	5	27	2
3					0				0			8	1	84	8
4	33	7	2	4	3		26	2	20	1		1		2	

9128	O	Na	Mg	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Ba
1	16	4	1	2	1		18	0	3	2		2		52
2	19	4	1	2	2	0	5	0	3	39	4	19	1	
3	13	3	1	1	1		2		1	31	3	40	4	
4					1					12	1	71	16	
5	34	5	1	3	3		25	1	25	1		1		

270°

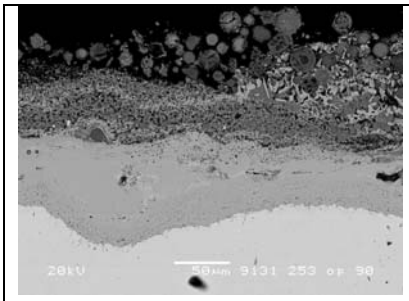


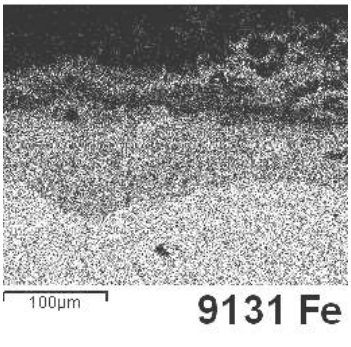


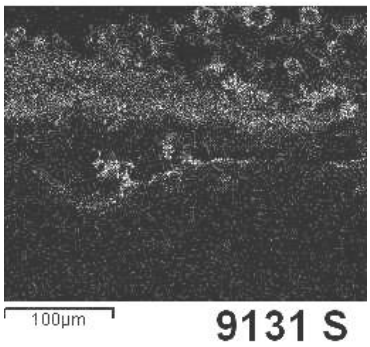
9129	O	Na	Mg	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Nb
1					0					19	2	68	10	
2					1					15		68	16	0
3	17	3	1	4	2	1	6	0	3	21	3	36	2	
4	34	4	1	3	3		25	1	24	1		3		

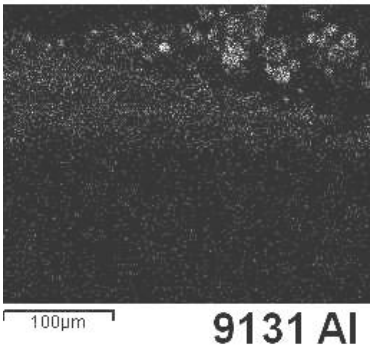
9130	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Ba
1	16	3	1	2	2	1	4		3	3	29	5	30	2	
2	17	3	2	2	2		16	1	12	22	10	1	13		
3	13	2	1	2	2		17	1	6		2		3		51
4	4				1		1		1		10	1	79	4	

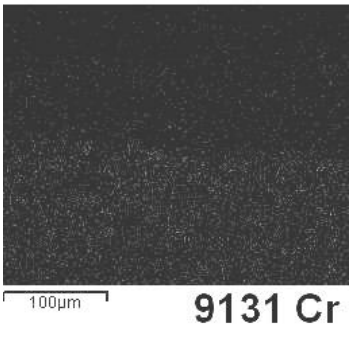
Specimens positioned at TC2: Flue gas T 900°C, steam T 540°C, 200 bar
2880 hours exposure in coal, 13CrMo44
Tube 253 op 90°:

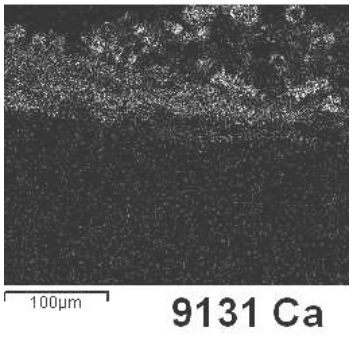


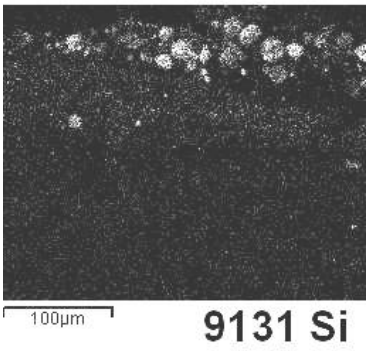


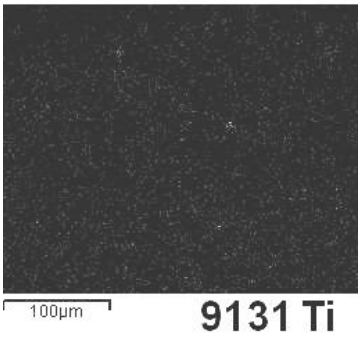




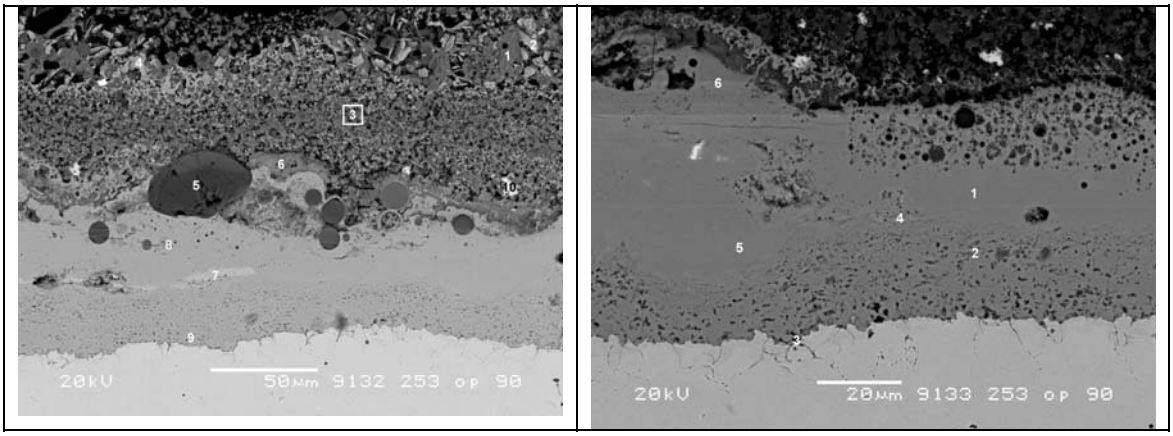








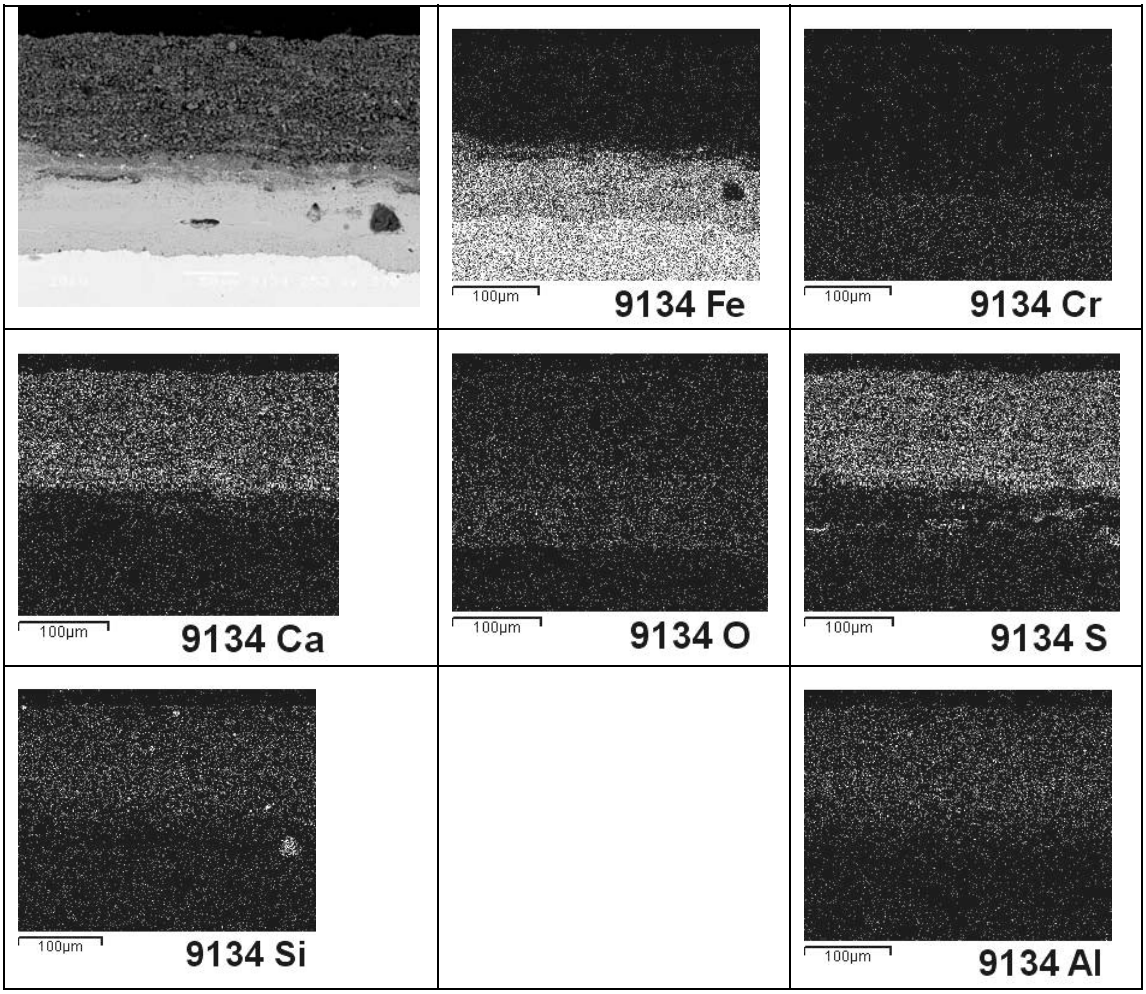
Appendix C: Specimens from TC2 location

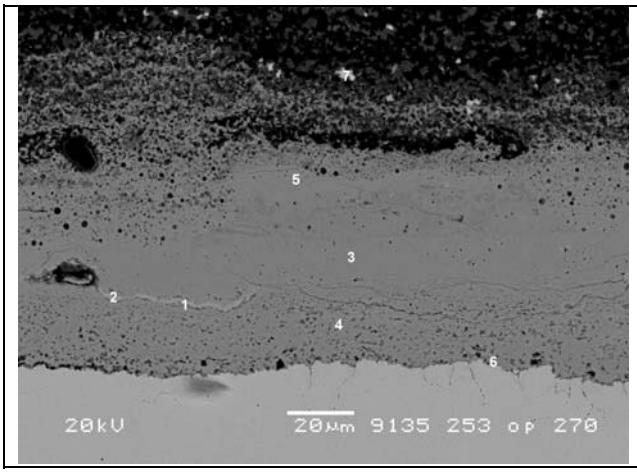


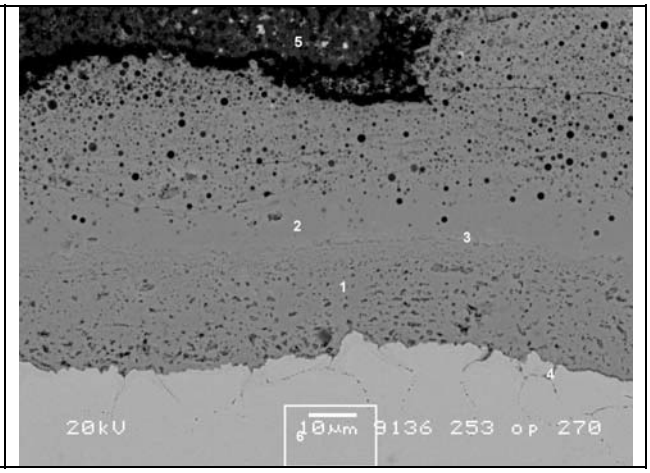
9132	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ba
1	24	1	1		0		30		38				7	
2	10	1			0		1		1				85	
3	24	4	1	6	8	1	16	1	15	1			23	
4	15				0		1		0				84	
5	33				66								1	
6	18	4	2	7	3	3	8	1	2	1			52	
7							36						64	
8	12			1	1		1					1	86	
9	11				1		1				2		85	
10	15	1		2	1		15		2				15	49

9133	O	Na	Al	Si	S	Ca	Cr	Mn	Fe
1	11							1	88
2	11			2	1		3	1	82
3	5	1		1	1		3	1	88
4	10		0	1	6		2	1	80
5	11			0	2	0	4	1	82
6	15		1	1	1	0			81

270°


100µm
9134 Fe
100µm
9134 Cr
100µm
9134 Ca
100µm
9134 O
100µm
9134 S
100µm
9134 Si
100µm
9134 Al

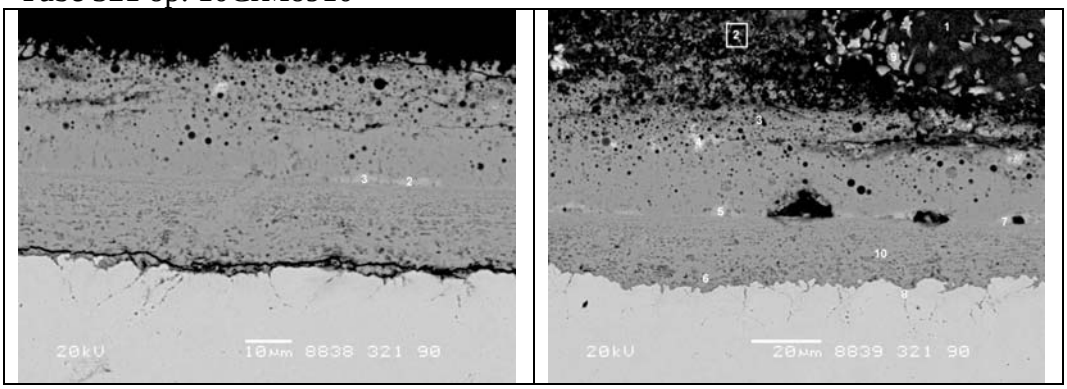




9135	O	Na	Mg	Al	Si	S	K	Ca	Cr	Mn	Fe	Mo	Ba
1	2				1	29			1	1	66		
2	6					22			0		72		
3	10										90		
4	11				1				2	1	83	1	
5	12										88		
6	11				2	1			2		84		
7	14	2	1	2	2	19	1	6			2		52

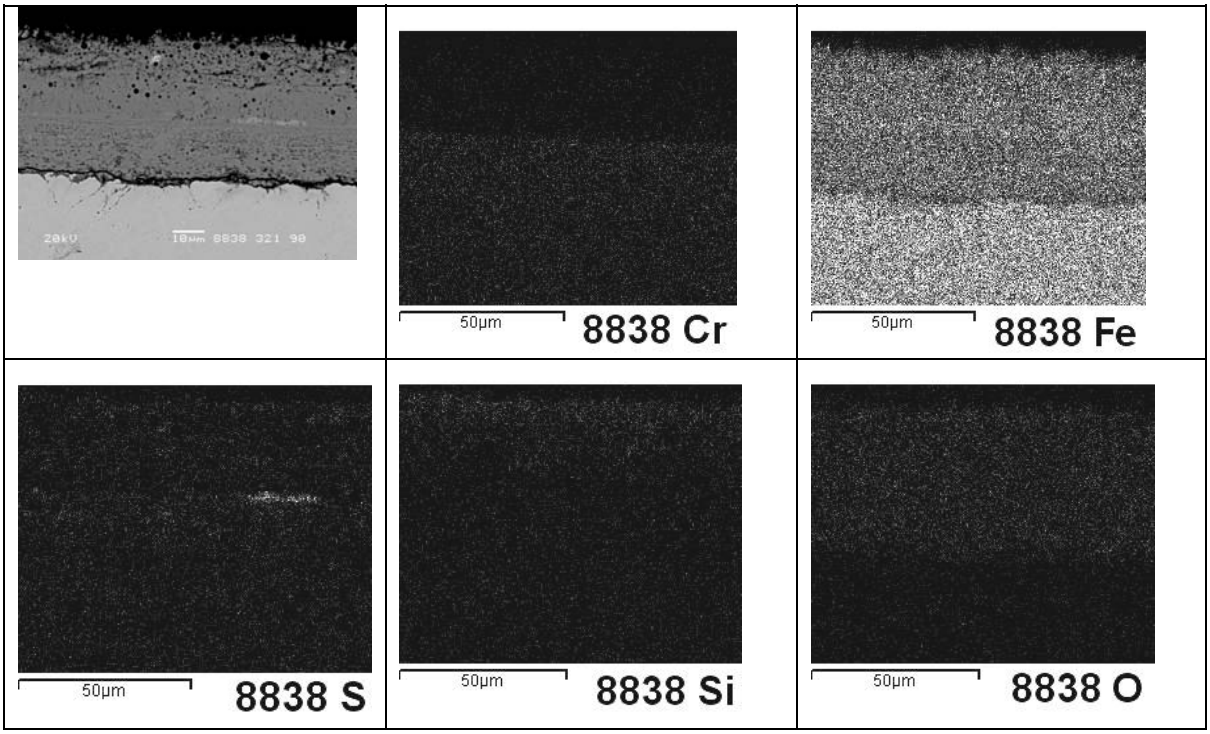
9136	O	Na	Mg	Al	Si	S	K	Ca	Cr	Mn	Fe	Mo
1	11				2	1			3	1	83	
2	11					1					88	
3	8				1	11		1	2	1	77	
4	6				1	2			3	1	87	
5	23	1	0	2	2	27	1	35			8	
6					1				1	1	96	1

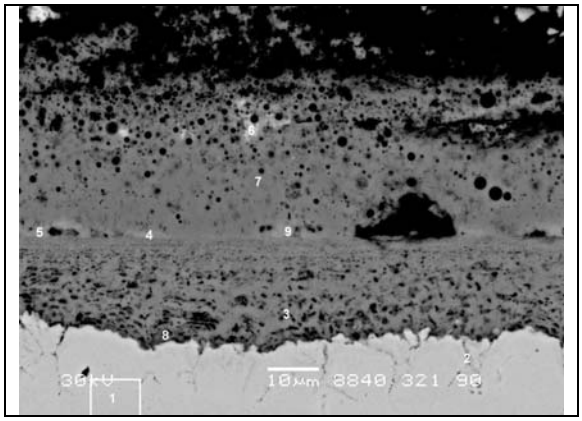
Specimens positioned at TC3: Flue gas T 950°C, steam T 540°C, 50 bar reheater
95% coal - 5% switch grass, 2880 hs exposure:
Tube 321 op: 10CrMo910



8838	O	Si	S	Cr	Mn	Fe
2	10	1	4	6	1	78
3	10	1	4	7	1	77

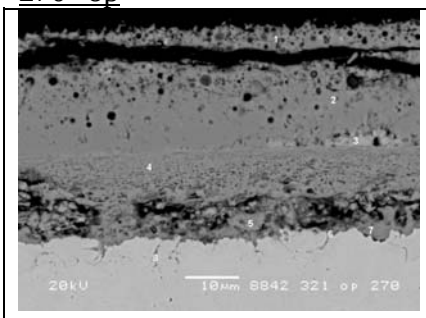
8839	O	Na	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Mo	Ba
1	28		2						69			1			
2	23	2	5	4	1	12	1	14	1			38			
3	17	1	5	5	1	1	1	2	1			68			
4	11		1	1		13	0	0				21			52
5	1					31				1		66			
6	11			1		0				5	1	81		2	
7	8			1		10		0		6	1	73			
8				0		1				3		96			
9	11			0		0			3	3		82	1		
10	12			0		0				5		79		3	

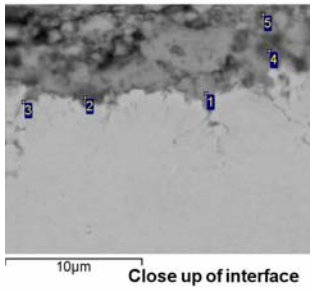




8840	O	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Cu	Mo	Ba
1					0				2	1	96			1	
2			0		2				4	1	92	1			
3	11		1		1				5	1	82				
4	7		0		12		0		3	1	77				
5	8		0		10		0		4	1	77				
6	13	1	1		9	0	1				48		1		26
7	11		0	0	1		1	0	0	1	86				
8	10		1		1				6	1	82				
9	2				24				1	1	72				

270° op

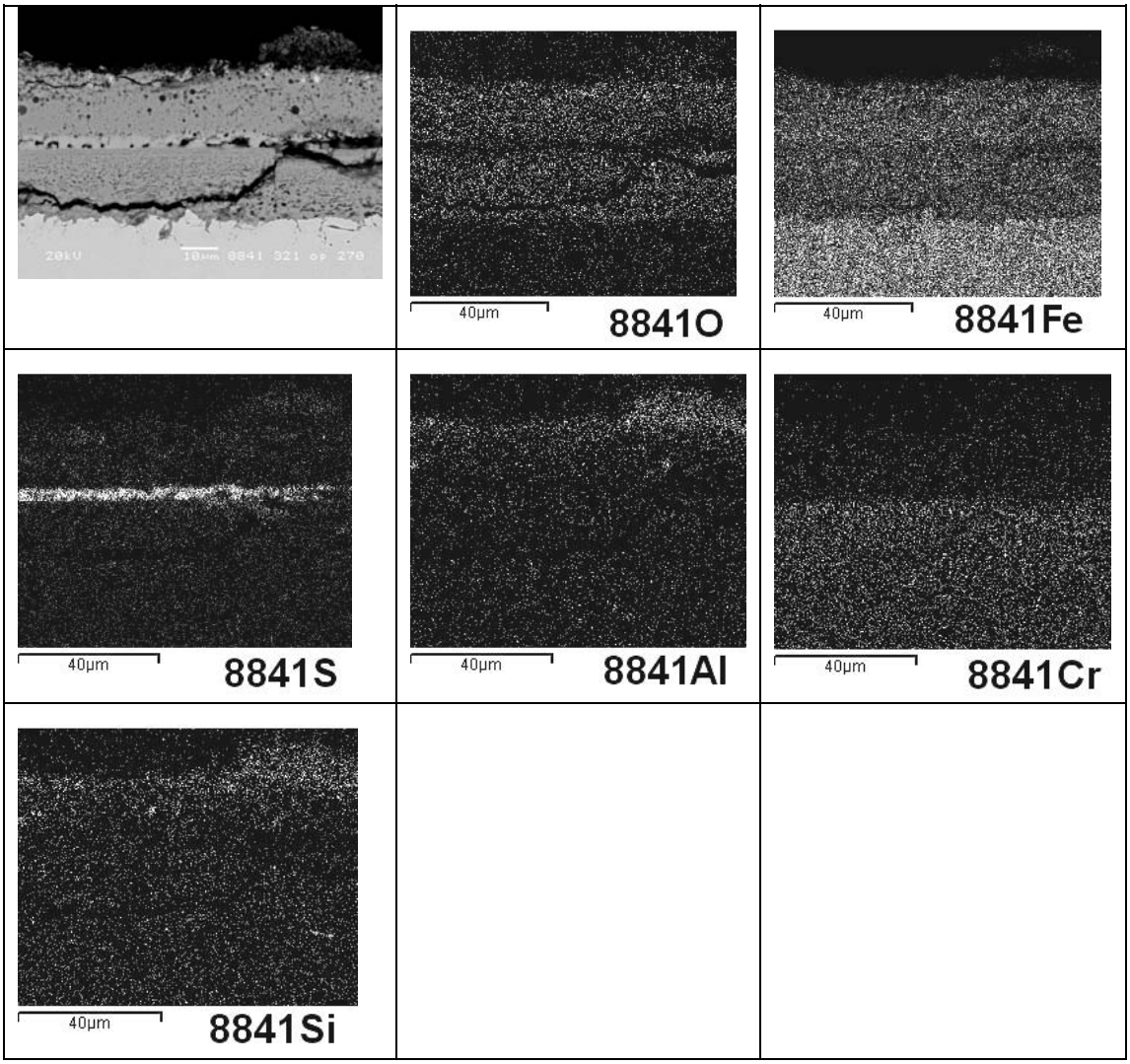




8842	O	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Cu	Mo
1	18	1	3	3	0	1	0	1	9			63	1	
2	11		0			1		0		0	1	86		
3						36				1		63		
4	9			1		3				6	1	81		
5	13			1		0				4	1	78		3
6	9			1		1				6	1	78		4
7	12			1		1				5	1	81		
8	3		0	1		0				9	2	83		2

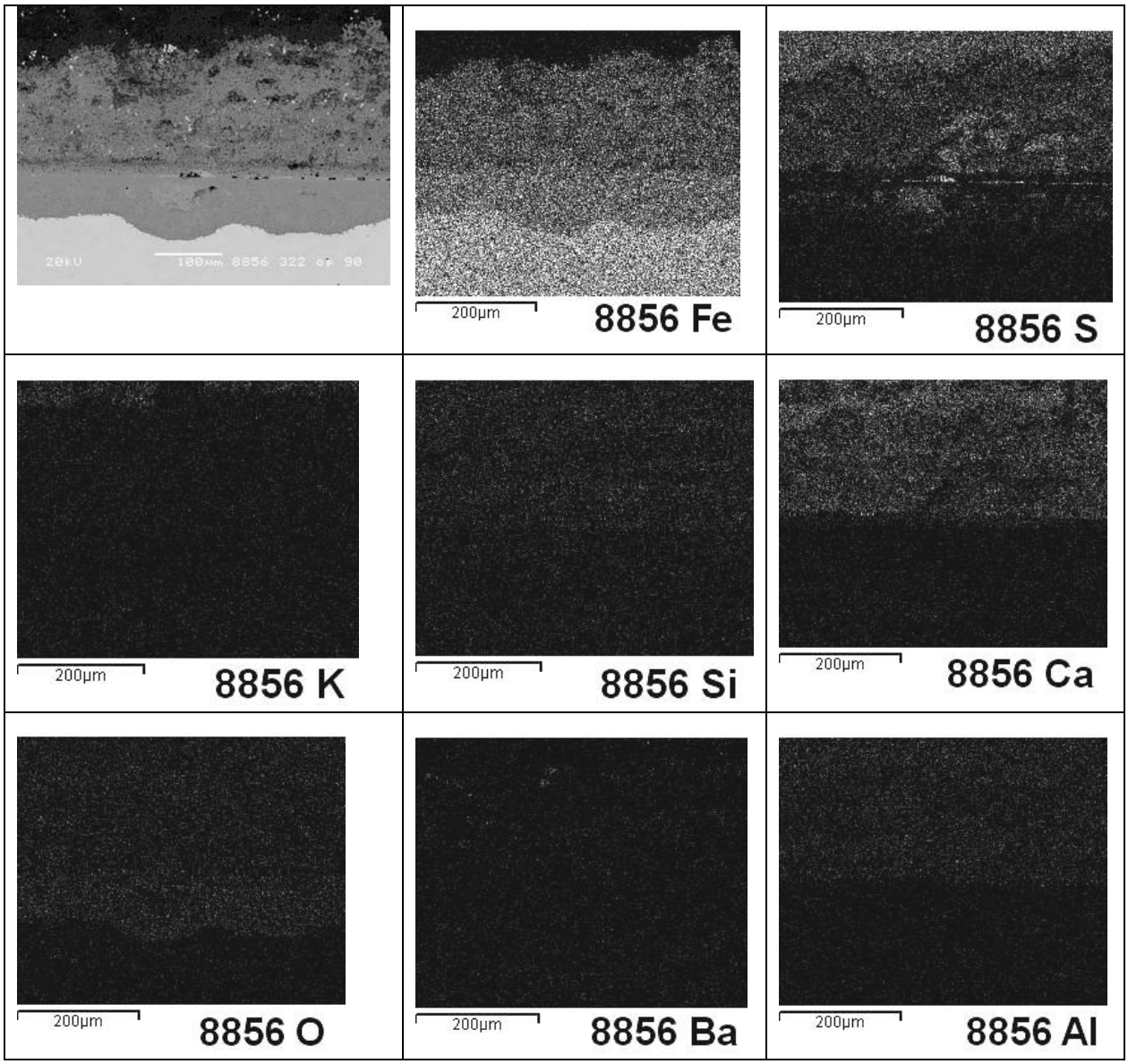
8842 interface	O	Na	Si	S	Cr	Mn	Fe	Ni	Mo
1	11		1	1	4	1	82		
2	6	1	1	1	4	1	84	1	1
3	4		1	1	4	1	88	1	
4	14	2	1	3	4	1	74		0
5	8	1	1	1	4		84		

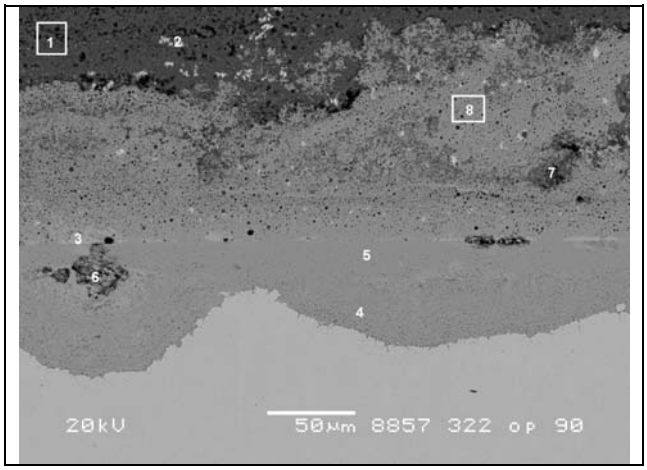
270°


40µm
8841O
40µm
8841Fe
40µm
8841S
40µm
8841Al
40µm
8841Cr
40µm
8841Si

Appendix D: Specimens from TC3 location

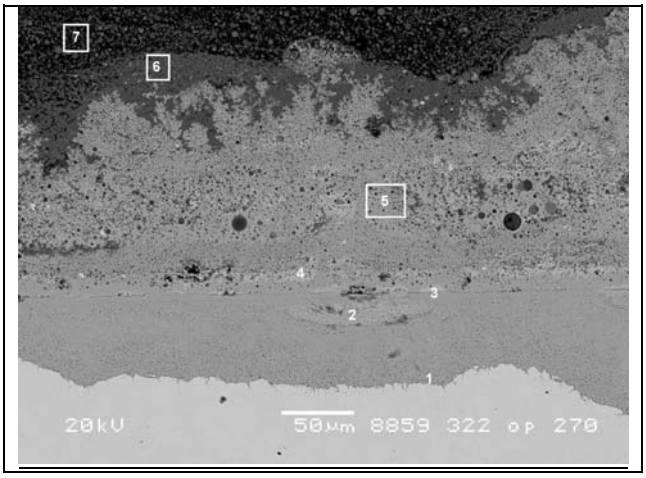
Specimens positioned at TC3: Flue gas T 950°C, steam T 540°C, 50 bar reheater
95% coal - 5% switch grass, 2880 hs exposure:
Tube 322 op: 90° 13CrMo44





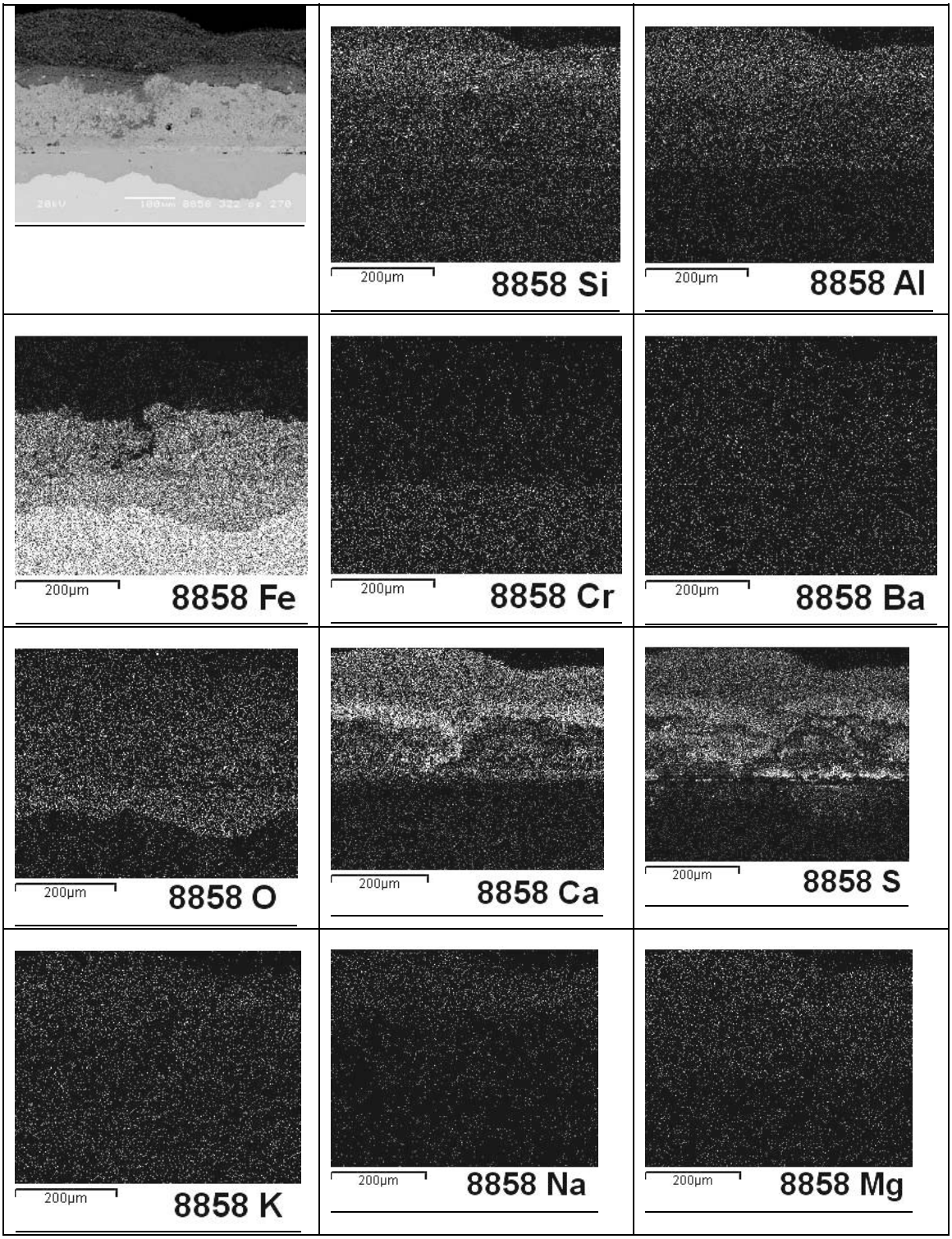
8857	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe	Mo	Ba
1	28	3	1	4	4	1	25	1	27	0			4		
2	13		1	3	2		18	1	3				2		58
3	3						29						68		
4	12				1		0				2		83	1	
5	11				1		1				1	1	84	1	
6	10	3			2		17				4	2	62	0	
7	15		2	9	9	1	8	2	28	1			26		
8	12		1	3	2		9	0	10	0			63	0	

322 op 270

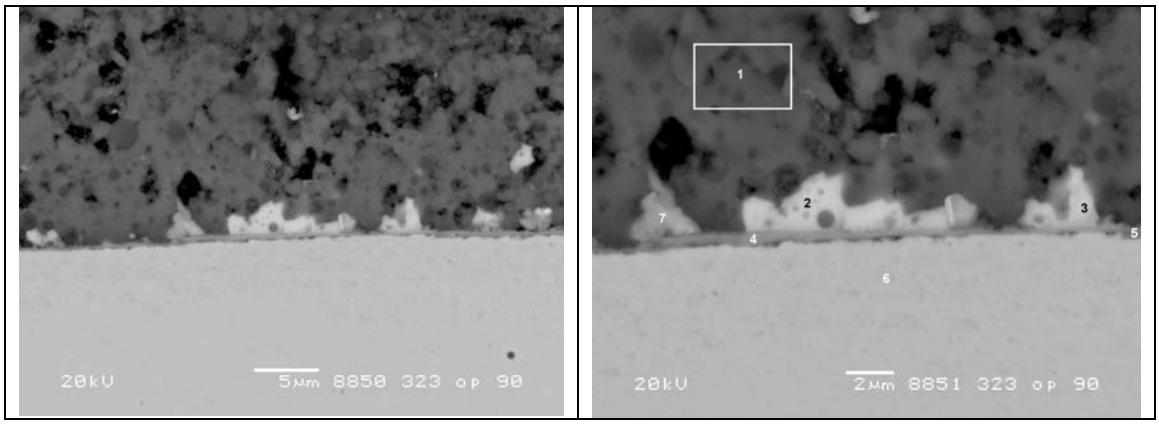


8859	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Mn	Fe
1	12				1		1				2	1	83
2	6				1		22				2	1	68
3							38						62
4				1	1	0	36		1				61
5	13		1	3	3		6	0	4				71
6	26	2	2	6	6	1	21	1	28	1			4
7	27	2	3	9	9	1	17	2	25	1			3

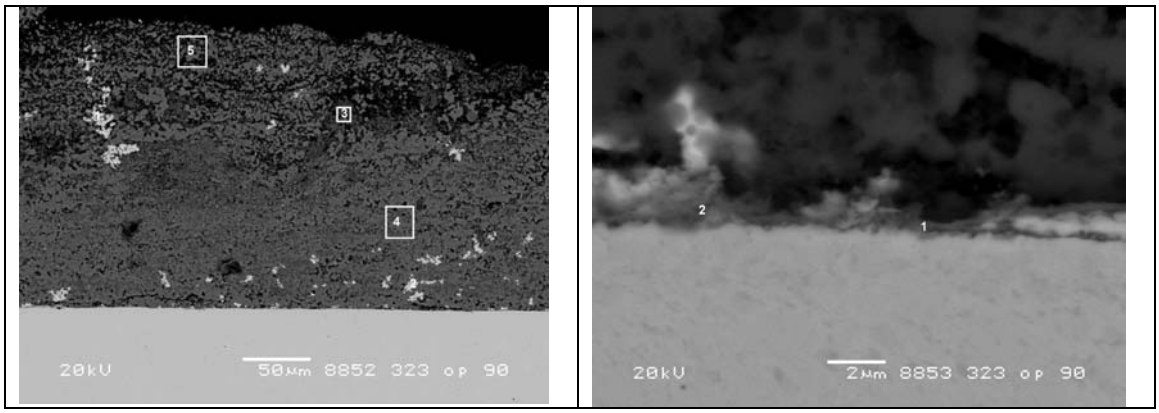
Appendix D: Specimens from TC3 location



Specimens positioned at TC3: Flue gas T 950°C, steam T 540°C, 50 bar reheater
95% coal - 5% switch grass, 2880 hs exposure:
Tube 323 op: 90° Super 304H



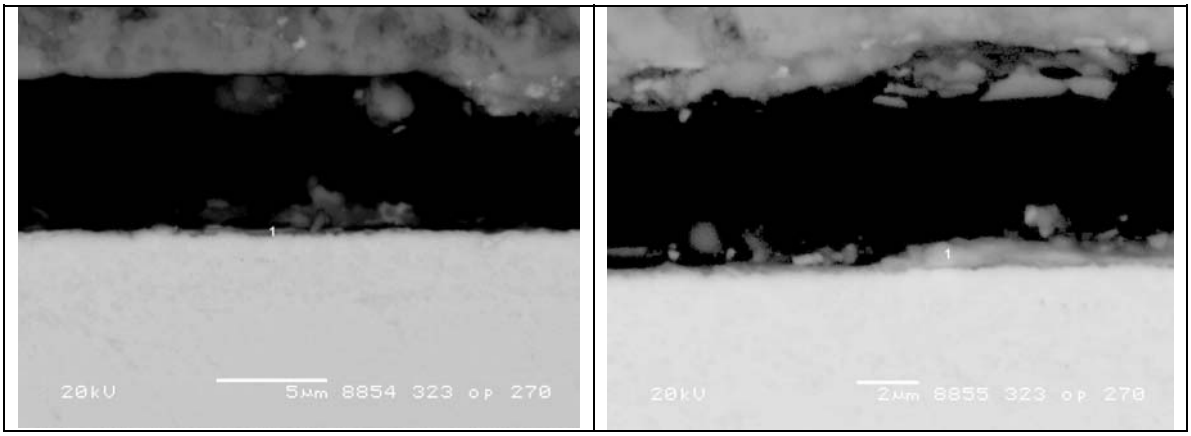
8851	O	Na	Mg	Al	Si	S	K	Ca	Ti	Cr	Mn	Fe	Ni	Cu	Ba
1	27	1	1	4	4	27	3	32	1	1		1			
2	13	1		3	2	17	1	3		1		2			57
3	16	1		3	3	18	1	8		6		4		1	40
4	11			1	2	6		1		29	7	30	2		11
5	15		1	2	2	9		7		32	5	26	3		
6					0			0		19	1	70	9		
7	13			2	1	31		5		16		4	9	19	



8852	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe	Ba
1	16			3	3		17	1	4		1	55
2	16	1		3	3	1	18	1	4			55
3	34	3	6	6	7		22	17	2	1	2	
4	30	3	2	4	4	1	26	4	23	1	2	
5	30	2	2	6	7	1	23	4	20	1	3	

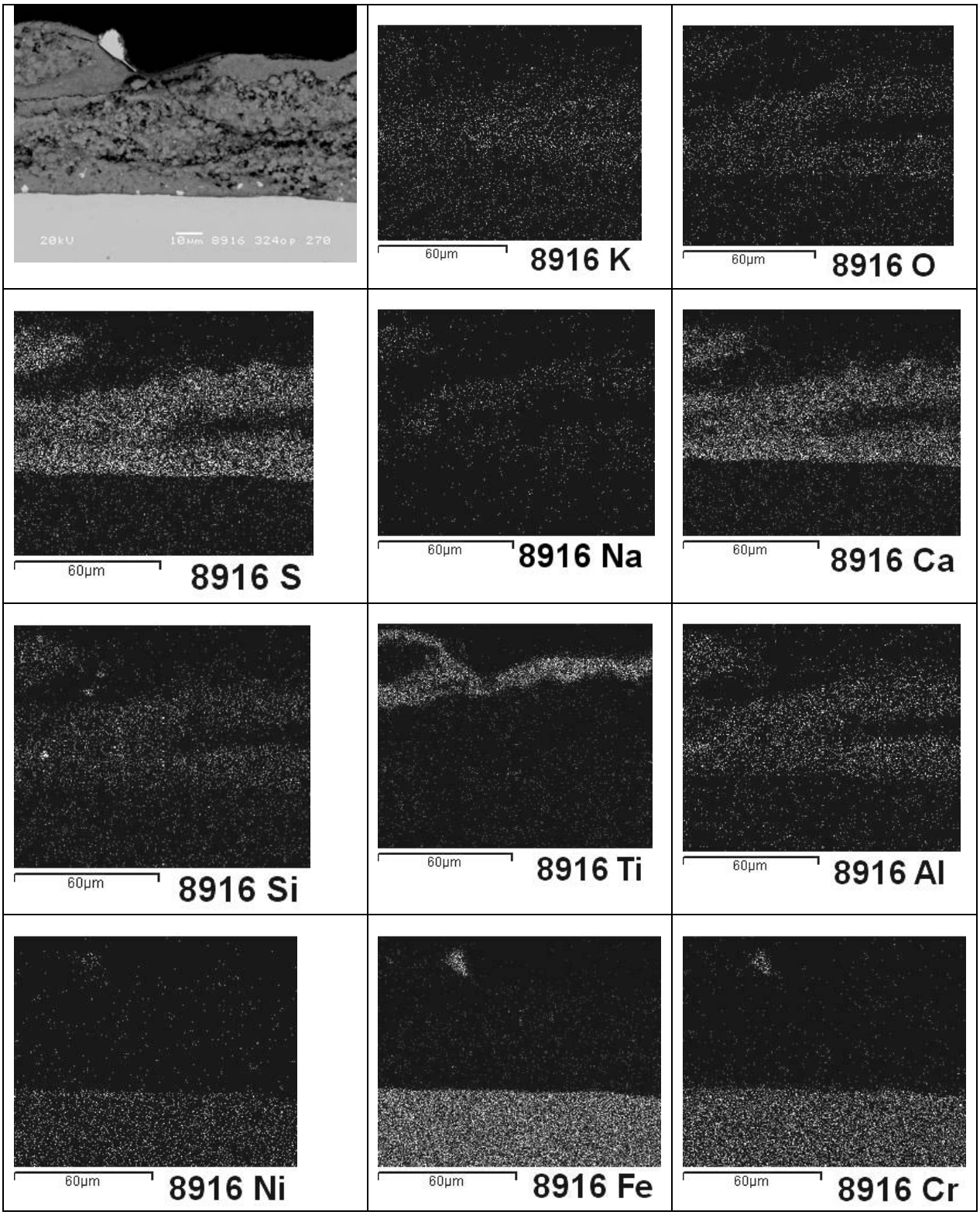
8853	O	Na	Mg	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Ba
1	15	1	1	1	1	1	7		6	32	5	28	3	
2	12	1	1		2		6	0	1	21	2	38	3	12

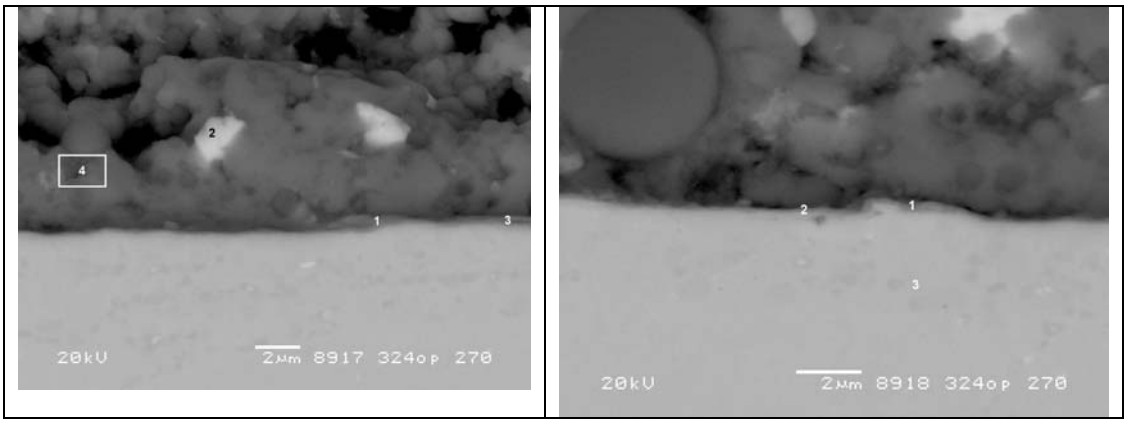
270°



	O	Na	Mg	Al	Si	P	S	Ca	Ti	Cr	Mn	Fe	Ni
8854 1	11	1	1		1	1	4	5		37	6	30	3
8855 1	12			4	1	0	3	2	0	27	8	40	3

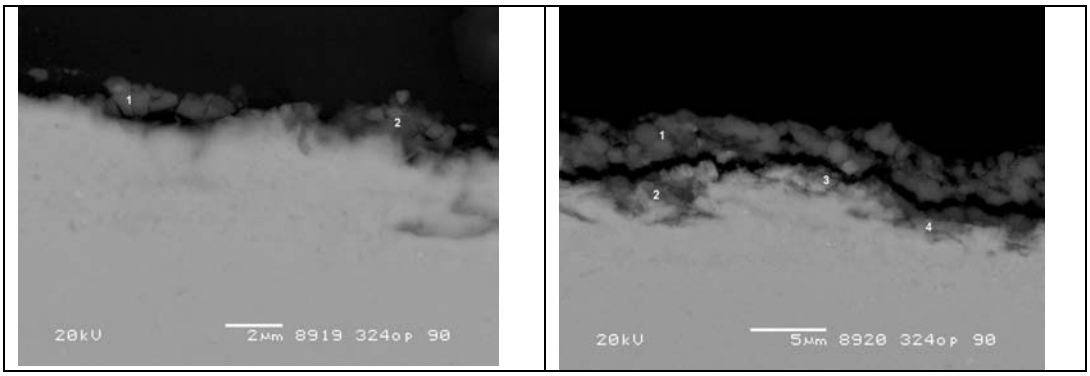
Specimens positioned at TC3: Flue gas T 950°C, steam T 540°C, 50 bar reheater
95% coal - 5% switch grass, 2880 hs exposure:
Tube 324 op: 90° TP347H





8917	O	Na	Al	Si	P	S	K	Ca	Cr	Mn	Fe	Ni	Ba
1	16		1	1		5	1	4	25	3	40	4	
2	22		2			20		7			1		48
3	10			1	1	3		3	19	4	56	4	
4	36	1	6	4		22	1	25	2		2		

8918	O	Al	Si	S	Ca	Ti	Cr	Mn	Fe	Ni
1	15		2	8	6	2	22	4	38	3
2	7	1	2	3	3		13	1	61	9
3							15		76	10



8919	O	Na	S	Ca	Cr	Mn	Fe
1	15				58	6	22
2	27	2	16	18	17		20

8920	O	Na	Al	Si	S	K	Ca	Ti	Cr	Mn	Fe	Ni
1	16	1	4	5	29	2	39		1		2	
2	27	1	6	7	18	2	19		10		10	
3	24	1	2	2	14	1	14	1	27	3	9	
4	12		3	2	12	1	13		20	2	35	2