NILU Norsk institutt for luftforskning
Norwegian Institute for Air Research

Final report Experimental Study Investigating Risks of selected Amines (ExSIRA)

Task 4: Atmospheric corrosion due to amines

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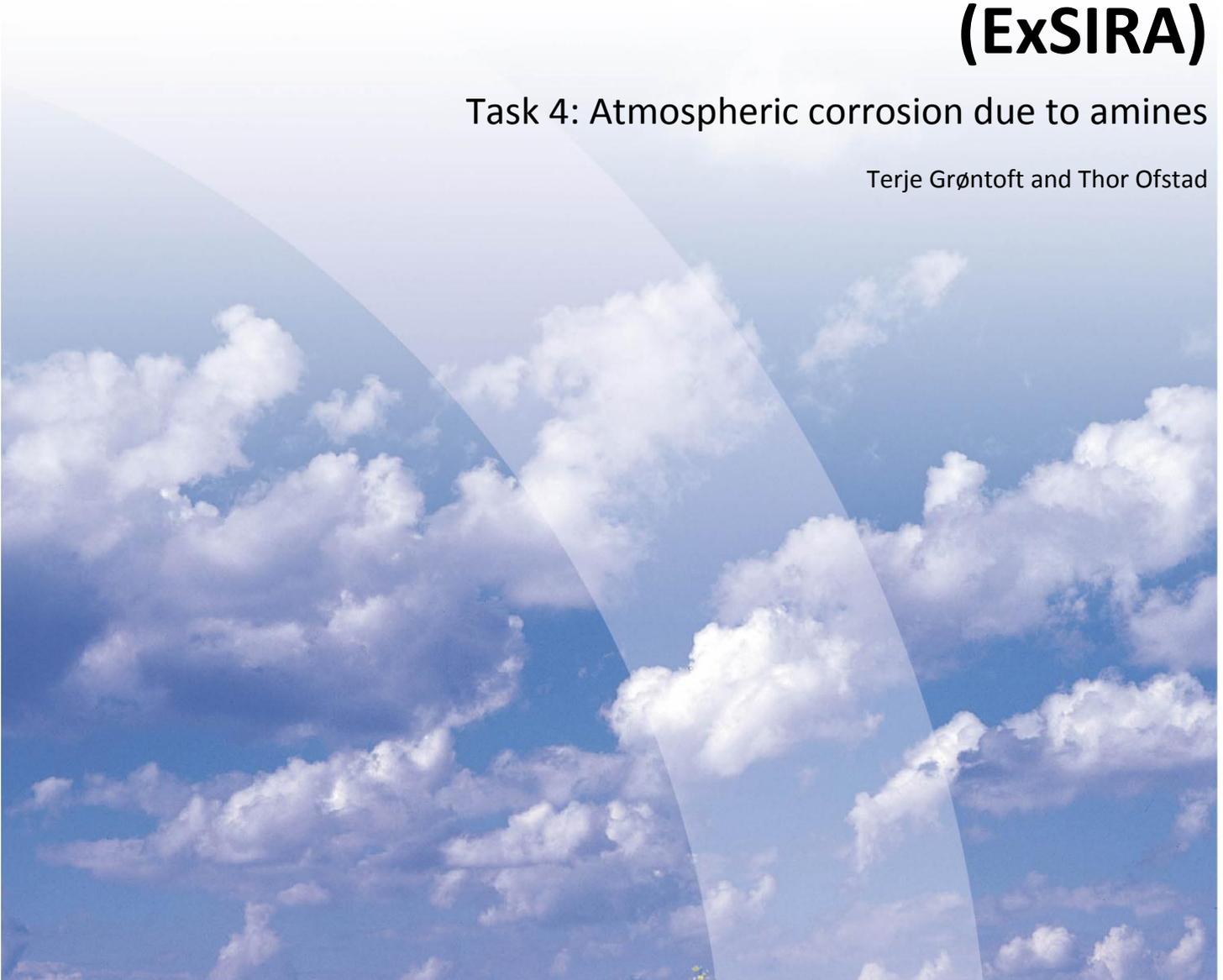
Scientific report

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Summary

The effect of selected amines on the corrosion of carbon steel and copper was investigated in the laboratory and in the field. The steel and copper samples were exposed to loads of the amines in the laboratory, representing estimated 10 years worst case exposure due to emission from a CO_2 capturing plant at the Technology Centre Mongstad (TCM). No effect on the corrosion rate for steel was detected for this dose as compared to blanks. Application of 700 times higher doses of amines in the laboratory was observed to give anodic protection, and thus reduced corrosion, of steel samples, but to dissolve the surface of a copper sample. The anodic protection was due to the formation of an amine surface film that protected the sample from oxidation. The dissolution of copper was probably due to formation of a copper - amine complex at high pH. A slight increase in corrosion was observed for samples that were exposed to the equivalent of 65 years worst case exposure of amines in the field. This may be explained by freezing point depression and increased time of sample surface wetness due to accumulation of the amine solute on the surfaces during the frost season.

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Final report
Experimental Study Investigating Risks of selected Amines
(ExSIRA)

1 Introduction

This report describes the work and results from a study of the possible effect of amine deposition on corrosion of steel and copper. The work was performed as a part of the project:

Amine Emissions during Carbon Capture. Phase II: Experimental Study Investigating Risks of selected Amines (ExSIRA)

Solutions in water of the amines: MEA (Monoethanolamin), DEA (Diethanolamin) and AMP (2-amino-2-methyl-1-propanol), were applied to steel and copper plates of dimensions 15*10*0.1 cm in controlled climate conditions in the laboratory at NILU - Norwegian Institute for Air Research, and positioned for one year outdoor in a field test in the locations of Skøyen-Oslo, Borregaard, Birkenes and Tanananger in Norway, representing an urban background, industrial, rural and coastal station, respectively.

The concentrations of the applied amine solutions were determined based on modelling of the maximum expected deposition of amines due to amine emissions, according to the "design" scenario, from an Aker Clean Carbon (ACC) technology CO_2 capture plant using flue gas from the CHP (Combined Heat and Power plant) (Berglen et al. 2010, pages 26-29). Maximum or higher than maximum doses of amines expected to deposit from the CO_2 capture plant were used. To simulate a more aggressive atmosphere some samples were exposed to SO_2 in the laboratory in addition to the exposure to the amines.

The corrosion of the samples was documented by optical photography of the samples after exposure. The corrosion was determined by the weight loss of the samples after chemical stripping and the elemental composition of the samples was determined by x-ray analysis in a scanning electron microscope (SEM-EDX). The ISO corrosion category for the locations was determined from the measured annual corrosion.

Monthly average values for the amount of the pollutants that are known to affect carbon steel corrosion was measured at the exposure locations in the field by passive sampling of SO_2 and aerosols which were analysed for their content of ions. Approximate values for the annual average temperature and precipitation at the experimental stations were obtained from the nearest climate stations with available data in eKlima (2012), which were located less than 10 km away from experimental field stations.

The effect of the amines on the corrosion was analysed by comparing the corrosion weight gain, or weight loss of the samples after stripping of the

corrosion layer, and elemental content of the corrosion layer, for samples to which an aqueous amine solution or only water had been applied.

The effect of the environment on the corrosion was analysed by single correlation of the measured annual corrosion at the stations with the measured pollutants or climate factors.

2 Project plan

The project was performed according the plan shown in Figure 1.

Year		11												12											
Month		01	02	03	04	05	06	07	08	09	10	11	12	01	02	03	04	05	06	07	08	09	10	11	12
Task 1	Project administration and information							S	St	p	p	p	p	St	p	St	p	p	p	p	S				FR
Task 2	Campaign preparation																								
Task 3	Product study of amines (MEA and AMP), amine degradation products and amine salts as corrosion agents under natural conditions.																								
Task 4	Implementation of field and laboratory tests.					1	1	1	1	1	1	1	1	1	1	1	1								
Task 5	Chemical and gravimetric analysis of corrosion products obtained in laboratory and field tests.																	2	2	2	2	2			
Task 6	Comparison of quantified corrosion rates observed in laboratory and field tests with measured atmospheric pollutant and climate conditions and corrosion levels in ISO standards.																				3	3	3	3	3

St = status meeting presentations; p = progress reporting; FR = Final Report; 1 = Step1 (experiment); 2 = Step 2 (data analysis); 3 =Step 3 (interpretation of data).

Figure 1:   Project plan and timeline.

3 Methodology

3.1 Campaign preparation

The campaign preparation, Task 1, included:

1. The retrieval of data from the ExSIRA amine emission and dispersion studies about the likely amount of amine deposition from the emitting plants.
2. Recalculation to experimental doses to be used in the corrosion field and laboratory tests.
3. The writing of the protocol for the laboratory and field tests.
4. The maintenance and production of needed racks and other equipment to be used in the laboratory and field test.
5. The ordering of analytical monitoring equipment for the laboratory test.
6. The ordering of passive pollution samplers for the field test.
7. The contracting and agreements about procedure of pollution monitoring with local station holders.
8. The selection of material(s) to be exposed, tested for corrosion
9. The selection and preparation (mixing) of the amine solutions to be applied to the material samples.

3.2 Product study

A product study of amines (MEA, DEA and AMP), amine degradation products and possible amine salts as corrosion agents under natural conditions was conducted, in close contact with the other ExSIRA working groups. In the CO_2 sequestration carbamate salts are formed when CO_2 bonds to the amines. These salts are part of a potentially very corrosive inside reformer environment (Botheju, 2006). These salts should remain inside the reformers and it was not possible to get any information about possible release to the atmosphere of these or other inside of plant degradation products from the amines. The starting point for the corrosion studies was the estimation of maximum concentration loads of the amines (MEA, DEA and AMP) deposited to the ground as found from dispersion studies (Berglen et al. 2010). The possible effect of these amines on the corrosion of steel was investigated. A few test were also performed for copper.

3.3 Concentration calculations

As for the other sub projects in ExSIRA it was decided to use MEA (Monoethanolamin), DEA(Diethanolamin) and AMP (2-amino-2-methyl-1-propanol) in ExSIRA corr. The corrosion samples were sprayed or brushed with the amine solutions and in addition control samples were sprayed or brushed with deionized water which was the solvent for the amine solutions.

The concentrations of the applied amine solutions were determined based on modelling of the maximum deposition of amines due to amine emissions according to the "design" scenario from an Aker Clean Carbon (ACC) technology CO_2 capture plant using flue gas from the CHP (Combined Heat and Power plant) (Berglen et al. 2010, pages 26-29). This "worst case scenario" gave the highest concentration among the scenarios available in open sources. The reported maximum deposition of MEA was much higher than for the other amines. This

likely maximum deposition of MEA was used to calculate the doses of amines (MEA, DEA and AMP) to be applied to the material samples in the laboratory and field in ExSIRA corr:

1. Maximum annual MEA deposition to a sample in the field - from emission from the plant.
MEA maximum annual deposition = 1.6 mg/(m^2 year)
Sample size = 10*15 cm * 2 sides = 300 cm^2

MEA maximum annual deposition to sample = 1.6 mg/(m^2 year) * 300 / 10000 = 0.048 mg / year

2. Accelerated exposures in the laboratory representing 10 years:

Exposure time = 1 month
Representing time in the field = 10 years
Application frequency = weekly

Concentration = 10 yearly real deposition / no of applications / volume pr application / mol weight of MEA

Concentration = 10 years * (0.048/1000) g / year $/$ 4 applications $/$ 0.003 l / per application $/$ 61.1 g/mol = **6.5 * 10-4 M**

Field application
Exposure time = 1 year
Representing time in the field = 10 years
Application frequency = second weekly

Concentration = 10 yearly real deposition / no of applications / volume pr application / mol weight of MEA

Concentration = 10 years * (0.048/1000) g / year $/$ 26 applications $/$ 0.003 l / per application $/$ 61.1 g/mol = **1 * 10-4 M**

The maximum annual mean concentration of MEA reported by Berglen et al. (2012) and shown in point 1 above (and Table 1) is very low compared with concentration values known to give observable corrosion for other corrosive pollutant gases (Kucera 2005). Therefore the corrosion studies were started with application of all the three amines at the calculated doses of $6.5 * 10^{-4}$ M and weekly application in the laboratory and two weekly application in the field, which would represent 65 years rather than 10n years deposition in the field. It would then be possible to increase the dose applied in the laboratory if no or little effect was observed in the first set of the laboratory experiments.

The reported maximum concentrations of amines deposited in rain water and the calculated equivalent concentration and dose applied to the field samples and initially to the laboratory samples in ExSIRA corr are shown in Table 1.

Table 1: *Reported maximum concentrations of amines deposited in rain water and calculated concentration to be used for application to the metal samples in ExSIRA corr.*

Compound	MEA (Monoethanolamin)	DEA (Diethanolamin)	AMP (2-amino-2-methyl-1-propanol)
Chemical formula	H2N-CH2-CH2-OH (NOC2H7)	HO-CH2-CH2-HN-CH2-CH2-OH (NO2C4H11)	CH3CCH3NH2 CH2OH (NOC4H11)
Atomic weight	61.1	105.16	89.16
MEA maximum short term concentration (8 hrs)	0.1 µg/m^3	0.13 ng/m^3	
MEA maximum annual mean concentration	1.2 ng/m^3	1.6 pg/m^3	
MEA maximum annual deposition	1.6 mg/(m^2 year)	2.1 µg/(m^2 year)	
Max concentration in rain water (weight / l)[1]	0.8 µg/litre.	1.1 ng/litre	
Max concentration in rain water (M) (Scenario: Design-CHP)	1.3 *10-8	1.05*10-11	
Calculated concentrations of amines used in the field exposures and initially in laboratory exposures in ExSIRA corrosion experiments. All the values are based on deposition of MEA			
Experimental cons. in lab (M), weekly application:	6.5 * 10^{-4} M	6.5 * 10^{-4} M	6.5 * 10^{-4} M
Experimental cons. in field (M), two weekly application:	1.0 * 10^{-4} M	1.0 * 10^{-4} M	1.0 * 10^{-4} M

[1] See Berglen et al. 2010

3.4 Corrosion measurements

Measurement of the corrosion of DC 01 steal samples with dimension 15*10*0.1 cm and with the typical reported content elements (minus Fe): C = 0.05 %, Mn = 0.20%, P = 0.01%, S = 0.01%, N = 0.003%, Al = 0.04%, were exposed to the selected amines (MEA, DEA and AMP) in the laboratory and in the field. All of the field steel samples and most of the laboratory steel samples were from a Swedish retailer. Towards the end of the laboratory experiments the Swedish

samples were finished and the last laboratory experiments were performed with DC01 steel samples from a Norwegian retailer. All the samples were degreased before exposure with commercial degreasing agent for metals.

3.4.1   Laboratory test

The laboratory test was performed by exposing steel, and a few copper, samples to the selected amines in two different exposures chambers:

1: The so called "Chalmers chamber" (Figure 2)
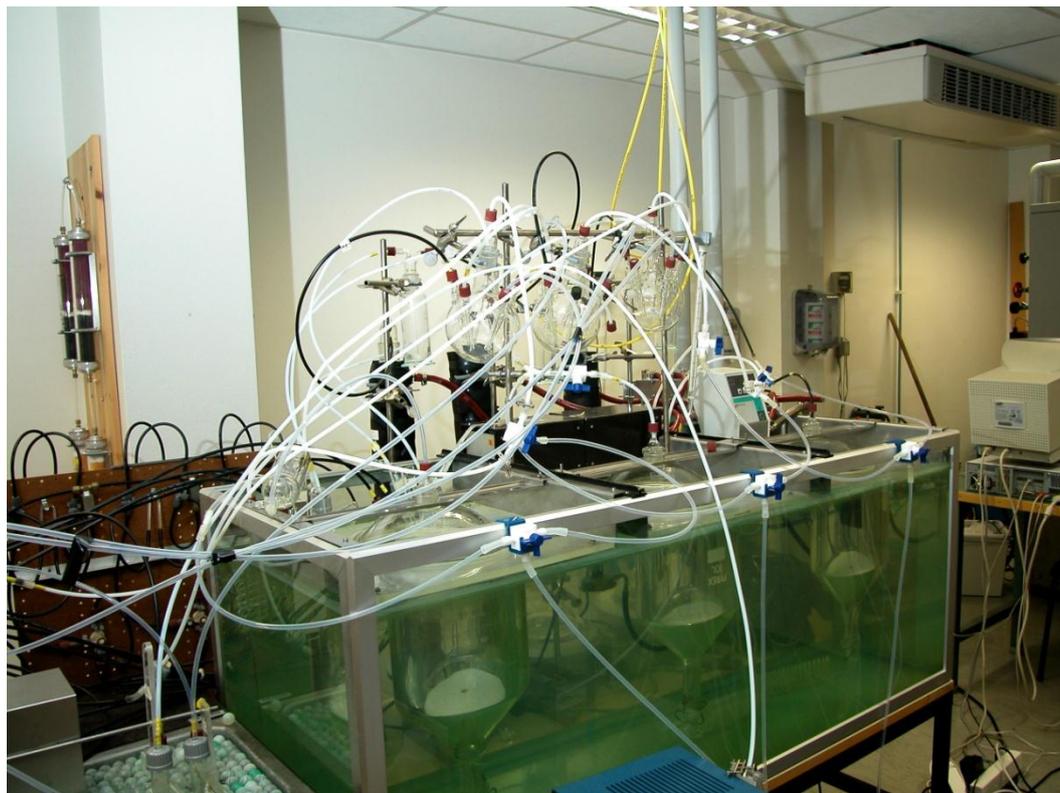
Figure 2:   The Chalmers chamber used to expose samples in controlled air in three smaller chambers immerged in a larger temperature controlled water bath.

which has three separate smaller chambers with a size of ~ 10 l where the samples were exposed to a fixed relative humidity of 90 % at a temperature of 23°C and a laminar air flow of 1.0 l/min, and in addition in three of the experiments to a time averaged concentration of SO_2 of 180 µg m^{-3} emitted from a permeation tube into the air stream.

2: A fog chamber (Figure 3)
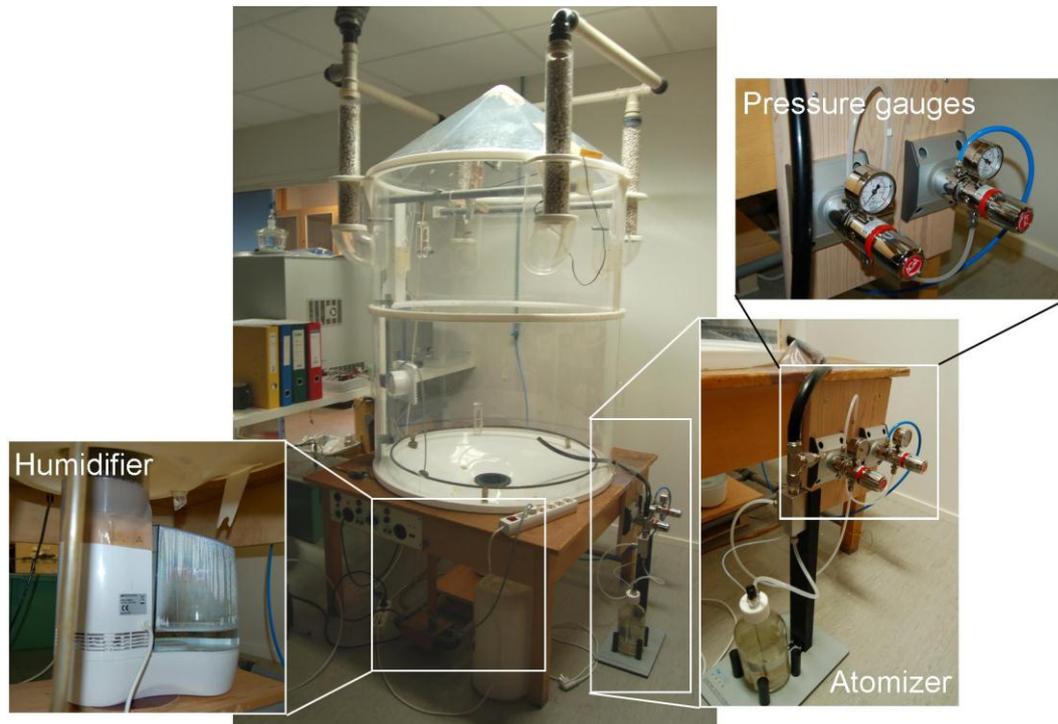
Figure 3:   The fog and aerosol chamber.

where the samples were exposed to a tap water fog emitted from a humidifier giving 100 % RH and a sub micrometer aerosol spray of the amine solution (Karl and López-Aparicio, 2010). An approximate amount of 1 l pr week of the amine solution was atomized into the fog chamber subjecting the wet samples to a fine spray of the amines. A significant amount of the amine aerosol would deposit on the samples. This could be observed as the fine aerosol fog raised towards the samples during its spreading and mixing with the water fog. The exact amount of emitted aerosol spray that deposited on the samples was however not known. Some amount of the aerosol, and probably a larger amount than that deposited on the samples, was deposited on the chamber walls partly after having dissolved in the water fog.

Table 2 gives the data for the eight test periods when exposures of samples were performed in one or more of exposures chambers.

Table 2:   Tests performed in Chalmers chamber.

Experiment no:	Chamber A	Chamber B	Chamber C	Aerosol chamber
1				
Start time		5. Jan 2011. Kl 11.00		5. Jan 2011. Kl 08.00
End time		3. Feb 2011. Kl 12.00		3. Feb 2011. Kl 12.00
Sample material		Swedish DC-01 steel		Swedish DC-01 steel
Number of parallels		3 + sample for chemical analysis = 4		3 + sample for chemical analysis = 4
Applied solution (gas)		Non. Control		Spring water from humidifier and atomizer
Application		Non		-
Sample size				10 * 15 cm
RH (%)		90		100
Time		1 month		1 month
2				
Start time		7. Feb 2011. Kl 09.00	7. Feb 2011. Kl 09.00	7. Feb 2011. Kl 09.00
End time		7.Mar 2011. Kl 0900	7.Mar 2011. Kl 0900	7.Mar 2011. Kl 0900
Sample material		Swedish DC-01 steel	Swedish DC-01 steel	Swedish DC-01 steel
Number of parallels		3	3	3
Applied solution (gas)		DEA solution, $6.5*10^{-4}$ M, applied every week	MEA solution, $6.5*10^{-4}$ M, applied every week	Spring water from humidifier and MEA solution, $6.5*10^{-4}$ M, continuously from atomizer
Application		Spray bottle	Spray bottle	Aerosol spray
Sample size		10 * 15 cm	10 * 15 cm	10 * 15 cm and 5*7.5 cm (1)
RH (%)		90	90	100
Time		1 month	1 month	1 month

Experiment no:	Chamber A	Chamber B	Chamber C	Aerosol chamber
3				
Start time		7.Mars 2011. Kl 0900	7.Mars 2011. Kl 0900	7.Mars 2011. Kl 0900
End time		4.April 2011. Kl 0920	4.April 2011. Kl 0920	4.April 2011. Kl 0920
Sample material		Swedish DC-01 steel	Swedish DC-01 steel	Swedish DC-01 steel
Number of parallels		3	3	3
Applied solution		AMP solution, $6.5*10^{-4}$ M, applied every week	MEA + NH3, $6.5*10^{-4}$ M, solution applied every week	Spring water from humidifier and DEA solution, $6.5*10^{-4}$ M, continuously from atomizer
Application		Spray bottle	Spray bottle	Aerosol spray
Sample size		10 * 15 cm	10 * 15 cm	10 * 15 cm and 5*7.5 cm (1)
RH (%)		90	90	100
Time		1 month	1 month	1 month
4				
Start time		5.April 2011. Kl 1100	5.April 2011. Kl 1100	
End time		13. Juli Kl 0900	13. Juli Kl 0900	
Sample material		Swedish DC-01 steel	Swedish DC-01 steel	
Number of parallels		3	3	
Applied solution		MEA solution, $6.5*10^{-2}$ M, applied every day	Ion rinsed water applied every day	
Application		Spray bottle	Spray bottle	
Sample size		10 * 15 cm	10 * 15 cm	
RH (%)		90	90	
Time		3 months	3 months	
5				
Start time		13. Juli Kl 0900	13. Juli Kl 0900	30. September Kl 1300
End time		15. Oktober 0900	12.Sept kl 0800	31. October Kl 1300
Sample material		New Norwegian DC 01 steel	New Norwegian DC 01 steel	New Norwegian DC 01 steel

Experiment no:	Chamber A	Chamber B	Chamber C	Aerosol chamber
		+ Swedish DC-01 steel (previous batch)	+ Swedish DC-01 steel (previous batch)	+ Swedish DC-01 steel (previous batch)
Number of parallels		3 (+ 1 Swedish steel)	3 (+ 1 Swedish steel)	4 (+ 1 Swedish steel)
Applied solution		APM solution, $6.5*10-2M$, applied every day	Ion rinsed water applied every day	Spring water from humidifier and AMP solution, $6.5*10^{-4}$ M, continuously from atomizer
Application		Spray bottle	Spray bottle	Aerosol spray
Sample size		10 * 15 cm	10 * 15 cm	10 * 15 cm
RH (%)		90	90	100
Time		3 months	3 months	1 month
6				
Start time	15. Nov 0830	17. Nov 1205		
End time	16. Jan 1030	17. Feb 1000		
Sample material	Norwegian DC 01 steel + Cu sample	Norwegian DC 01 steel + Cu sample		
Number of parallels	3 steel + 1 Cu sample	3 steel + 1 Cu sample		
Applied solution	SO_2 gas (ca 180 ppb) flow = 1 l / min.	DEA solution, $6.5*10^{-2}$M, applied every day		
Application	Permeation tube	Spray bottle		
Sample size	10 * 15 cm	10 * 15 cm		
RH (%)	90	90		
Time	2 months	3 months		
7				
Start time	16. Jan1030			
End time	16. Mar 1000			
Sample material	Norwegian DC 01 steel + Cu sample			
Number of parallels	3 steel + 1 Cu			

Experiment no:	Chamber A	Chamber B	Chamber C	Aerosol chamber
Applied solution	SO₂ gas (ca 180 ppb) flow = 1 l / min + MEA, 6.5*10⁻⁴ M, sprayed on Mon/Wed/Fri			
Application	Permeation tube			
Sample size	10 * 15 cm			
RH (%)	90			
Time	2 months			
8				
Start time	24. Apr 1500			
End time	25. Jun 1200			
Sample material	Norwegian DC 01 steel + Cu sample			
Number of parallels	3 steel + 1 Cu			
Applied solution	SO₂ gas (ca 180 ppb) flow = 1 l / min + Ion rinsed water - sprayed on Mon/Wed/Fri			
Application	Permeation tube			
Sample size	10 * 15 cm			
RH (%)	90			
Time	2 months			

In the Chalmers chamber exposure test no. 1 to 3 were run in the laboratory with weekly application (spraying) of the amine with a concentration of $6.5 \cdot 10^{-4}$ M. Experiments no. 4 to 6 were then performed with daily application (spraying) of the amine with a concentration of $6.5 \cdot 10^{-2}$ M. Lastly in experiments no. 6 to 8 SO₂ at approximately 180 μg m⁻³ was added to the inflowing air and the samples were sprayed with the amine with the concentration of $6.5 \cdot 10^{-4}$ M or ion rinsed water (experiments no. 7 and 8) three times a week, on Monday, Wednesday and Friday.

In experiment no 6, 7 and 8 one Copper sample was added with the steal samples.

In experiments 1 to 3 and 5 samples were also exposed in the fog chamber.

3.4.2 Field tests

Steel samples were mounted 1st May 2011 at four Norwegian stations; Skøyen (urban), Borregaard (industrial), Birkenes (rural), and Svanvik (coastal), to be exposed outdoors for one year (Figure 4 and Figure 5). The samples were mounted at 45 degrees and shielded from rain to avoid off washing of the applied amine solution by rain water (Figure 5).
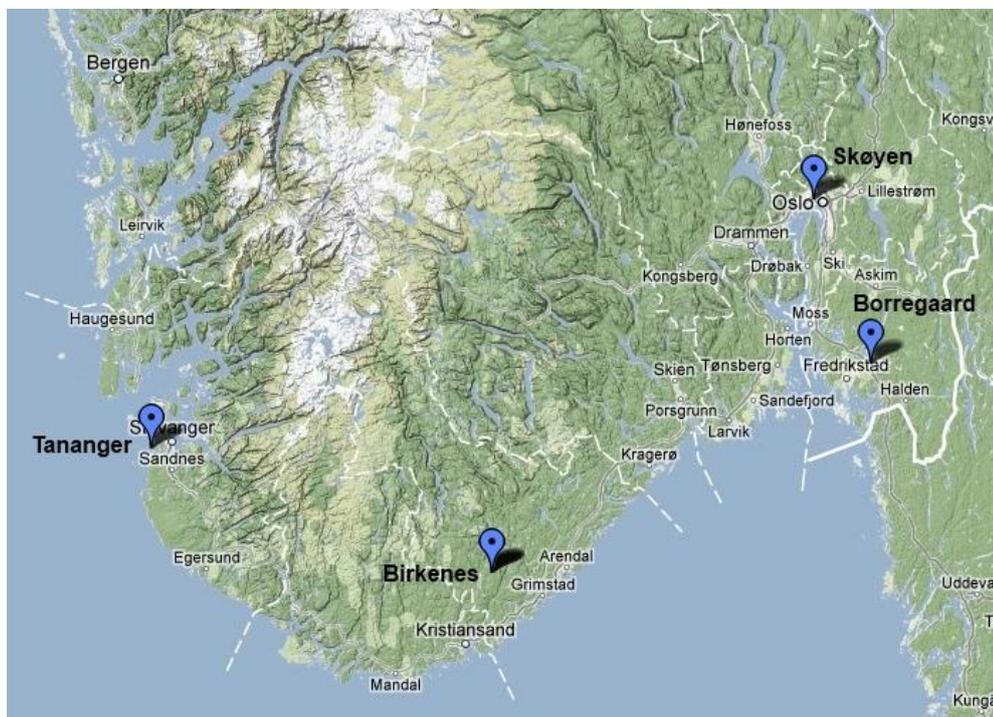

Figure 4:   The location of the measurement stations.
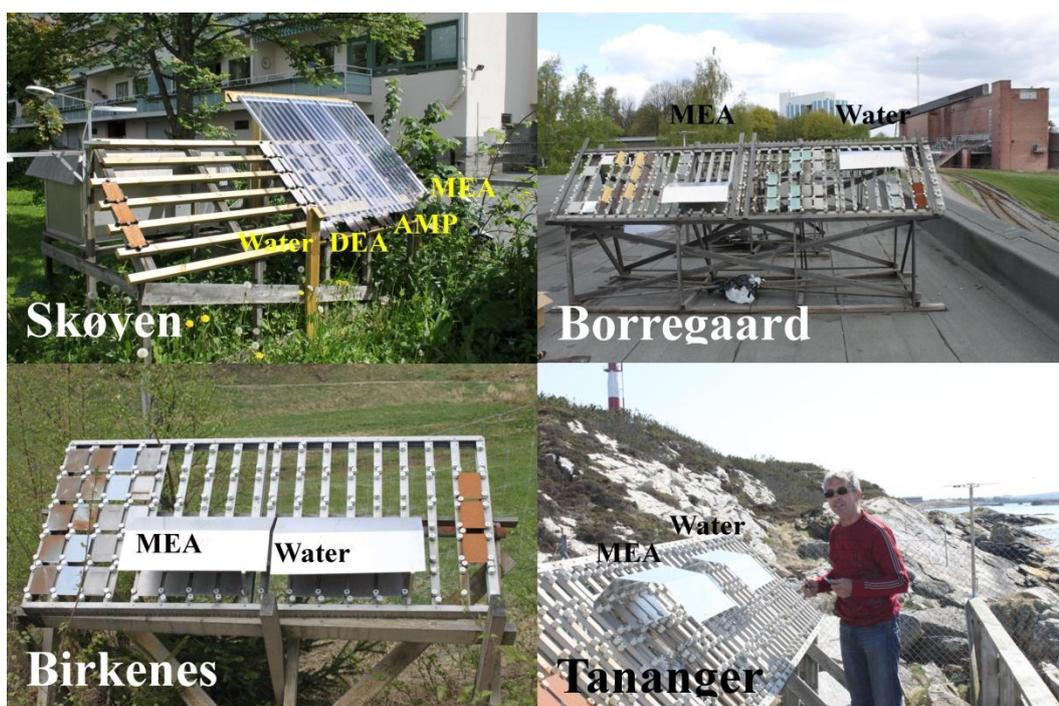

*Figure 5:   The mounted samples at the measurement stations.*

The amine solution and ion rinsed water, used for the control samples, were sprayed or brushed (only Birkenes) on both sides (over and under) of the two different similar sets of samples every fourteen days at all stations.

At Skøyen four sets of four times three samples were sprayed with MEA, DEA, AMP and ion rinsed water respectively. For every set, and thus applied solution, three adjoining samples were exposed from the start for 3 months, three for six months, three for 9 months and the remaining three samples were then demounted after 12 months. At the three other stations MEA was applied to one set of 4 samples whereas ion rinsed water was applied to the other set of four samples, and all the samples were exposed for 12 months and then removed.

For every set of samples, and applied solution, one sample was assigned for possible later analysis by analytical techniques. The other samples were assigned for measurement of weight loss of the steel by stripping of the corrosion layer after exposure.

3.5   Passive sampling of pollutants

Monthly passive sampling was performed to measure and estimate the mass concentration in air of sulphur dioxide, SO_2, and the anionic and cationic composition and pH of deposited aerosol at the four stations. The SO_2 sampling was performed with passive samplers of the IVL batch type produced at NILU (Rosenberg et al. 2009, Ferm 1991). The sampler (Figure 6) is cylindrical box with a diameter of 2.5 cm and a height of 1 cm which represents the diffusion length from the top net to the filter in the bottom, which is impregnated with an alkali.

Figure 6:   Passive SO₂ sampler.

The SO_2 concentration is calculated from the amount of sulphate collected on the filter, which is determined by ion chromatography, from the geometry of the sampler and from the diffusion coefficient of SO_2. The SO_2 samplers were mounted under a shield as seen in Figure 7.
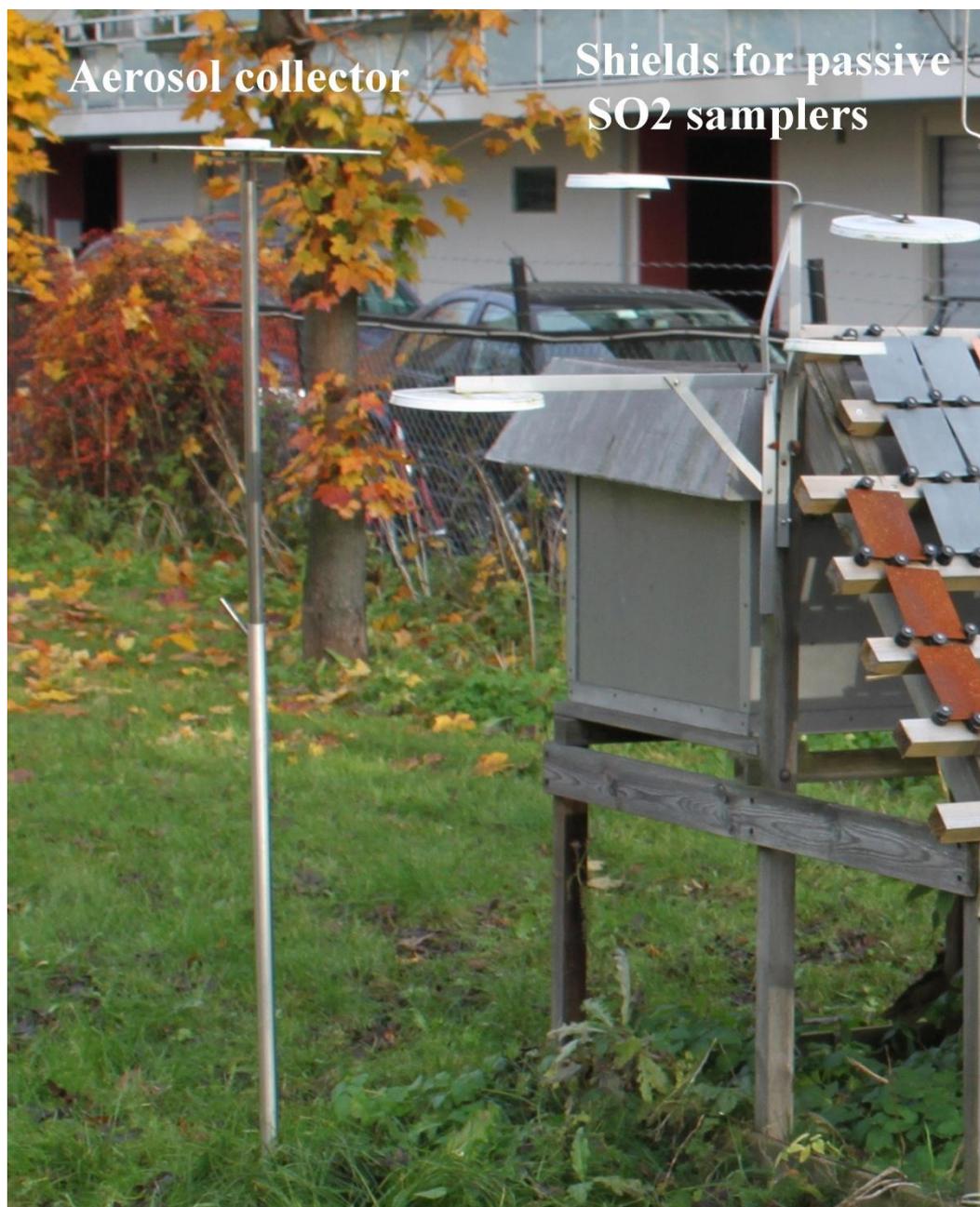
Figure 7: The aerosol holder and the shields for the passive gas sampling of SO_2 at the Skøyen station.

The anionic and cationic composition of aerosol was measured by passive sampling on a glycerol impregnated Teflon filter with a diameter of 12.5 cm, subsequent washing in deionised water and analysis by ion chromatography. The aerosol sampling gave values for Cl, NO_3-N, SO_4-S, Na, NH_4-N, K, Mg and Ca. The pH was measured in the washing water with a glass electrode. The filter was fastened horizontally sheltered from rain on the smaller lower plate in the filter

holder shown in Figure 7. One prepared aerosol filter was stored in the lab in its plastic package during one month as a blank and analysed with the same procedure as for the exposed samples.

Climate data, precipitation and temperature, were collected from the eKlima pages of the Norwegian meteorological institute for the closest stations to the ExSIRA corrosion stations (Table 3).

Table 3:   Stations where meteorological data were collected.

ExSIRA corrosion station	Meteorological station	Approximate distance between stations (km)
Skøyen	Oslo-Blindern	3.5
Birkenes	Senumstad (Birkenes)	5
Borregaard	Sarpsborg, Glensgt. 15.	7
Tananger	Sola	9

3.6   Analysis of corrosion crusts

The steel plates were weighed before exposure and weighed again after exposure, before and after stripping with Clark's solution (100 parts HCl, 2 parts Sb_2O_3 and 5 parts $SnCl_2$). The total weight gain and the weight loss of the steel due to corrosion was measured as the difference in weight from before exposure to after exposure and stripping.

Some of the corrosion layer was scraped off the samples before stripping. This powdered corrosion was subjected to analysis with scanning electron microscopy with element analysis (SEM-EDAX) to identify the elements in the corrosion products an possible inclusion of nitrogen from the amines..

4   Results

4.1   Corrosion measurements

4.1.1   Laboratory measurements

Table 4 shows the exposure conditions and results from the corrosion measurements for the samples exposed in the laboratory.

Table 4: Results for steel and copper samples exposed to amines in the laboratory. The sample notation for the experiments performed in the fog / aerosol chamber are in bold italic. The results from stripping of one non exposed steel sample "blank" is in italics.

Chalmers chamber						Corroded		Stripped	
Sample	Steel type S=Swedish N=Norwegian	No. of samples. Weight increase / weight loss	Concentration of applied amine(M) and SO_2(ppb)	Exposure time / months	Application frequency of amine / H_2O	Weight increase (g)	st.dev	Weight loss (g)	st.dev
1B No application	DC01 S	3/3	0	1	Weekly	0.008	0.0017	0.065	0.0046
2B DEA	DC01 S	3/2	$6.5*10^{-4}$	1	Weekly	0.0007	0.0025	0.095	0.0007
3B AMP	DC01 S	3/2	$6.5*10^{-4}$	1	Weekly	0.02	0.03		
2C MEA	DC01 S	3/2	$6.5*10^{-4}$	1	Weekly	0.0003	0.00058	0.1	0.0014
3C MEA + NH3	DC01 S	3/2	$6.5*10^{-4}$	1	Weekly	0	0		
1D H₂O	*DC01 S*	*4/3*		*1*	*Continuous*	*0.043*	*0.009*	*0.14*	*0.07*
2D MEA	*DC01 S*	*3/2*	*$6.5*10^{-4}$*	*1*	*Continuous*	*0.004*	*0.0015*	*0.20*	*0.030*
3D DEA	*DC01 S*	*3/2*	*$6.5*10^{-4}$*	*1*	*Continuous*	*0.005*	*0.0026*		
5D AMP	*DC01 N*	*4/4*	*$6.5*10^{-2}$*	*1*	*Continuous*	*0.012*	*0.008*	*0.18*	*0.056*
5D AMP	*DC01 S*	*1/0*	*$6.5*10^{-2}$*	*1*	*Continuous*	*0*	*0*		
6A SO₂ No application	DC01 N	3/3	180 ppb	2		0.4	0.18	0.7	0.28
7A SO₂ + MEA	DC01 N	3/2	180 ppb + $6.5*10^{-4}$	2	Mo, We, Fr	0.6	0.29	1.5	0.46
8A SO₂ + H₂O	DC01 N	3/2	180 ppb	2	Mo, We, Fr	0.8	0.37	1.39	0.045
			Increased amine load						
4C H₂O	DC01 S	3/2		3.3	Daily	0.028	0.0017	0.20	0.005
4B MEA	DC01 S	3/2	$6.5*10^{-2}$	3.3	Daily	0.012	0.002	0.03	0.004
5C H₂O	DC01 N	3/0		1.5	Daily	0.057	0.018		
5C H₂O	DC01 S	1/0		1.5	Daily	0			
5B AMP	DC01 N	3/0	$6.5*10^{-2}$	3	Daily	-0.0003	0.0043		
5B AMP	DC01 S	1/0	$6.5*10^{-2}$	3	Daily	0			
6B DEA	DC01 N	3/0	$6.5*10^{-2}$	3	Daily	-0.010	0.004		
Blank	*DC01 N*	*0/1*						*0.12*	*0.05*
	Copper								
6A SO₂ No application	Copper	1/0	180 ppb	2		-0.0047			
6B SO₂ + DEA	Copper	1/0	180 ppb + $6.5*10^{-2}$	3	Daily	-0.107			
7A SO₂ + MEA	Copper	1/0	180 ppb + $6.5*10^{-4}$	2	Mo, We,Fr	0.0166			
8A SO₂ + H₂O	Copper	1/0	180 ppb	2	Mo, We,Fr	0.04720			

Figure 8 shows the weight increase after exposure and the weight loss after stripping for the steel samples exposed in the laboratory, except those that were exposed in an SO₂ atmosphere which are shown in Figure 9.
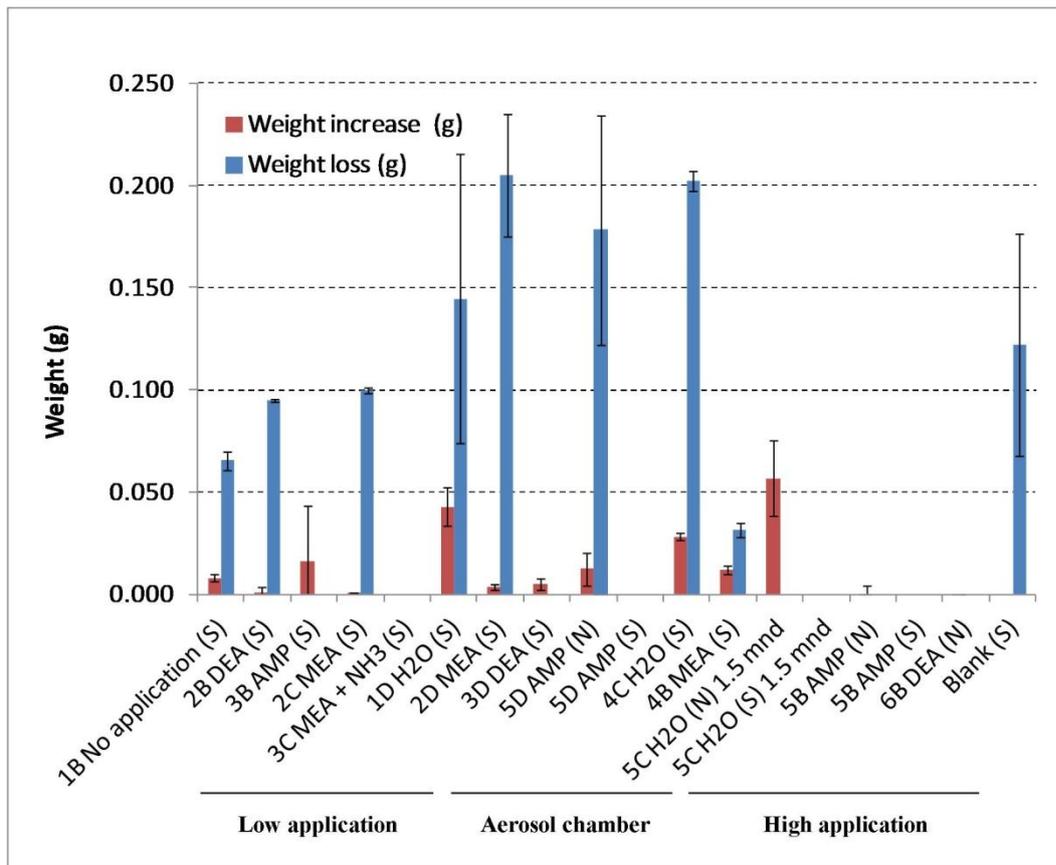
Figure 8:   *Weight increase after exposure and the weight loss after stripping for the steel samples exposed in the laboratory, except those exposed to an SO₂ containing atmosphere. The experiments are divided between those with application of low and high application (increased concentration and / or frequency of application) of amines and those run in the aerosol chamber with continuous application. The blank shows the loss of steel due to the stripping.(S) = DC01 steel bought in Sweden. (N) = DC01 steel bought in Norway. All the experiments were run for 3 months except 5C H₂O (N) which was run for 1.5 months.*
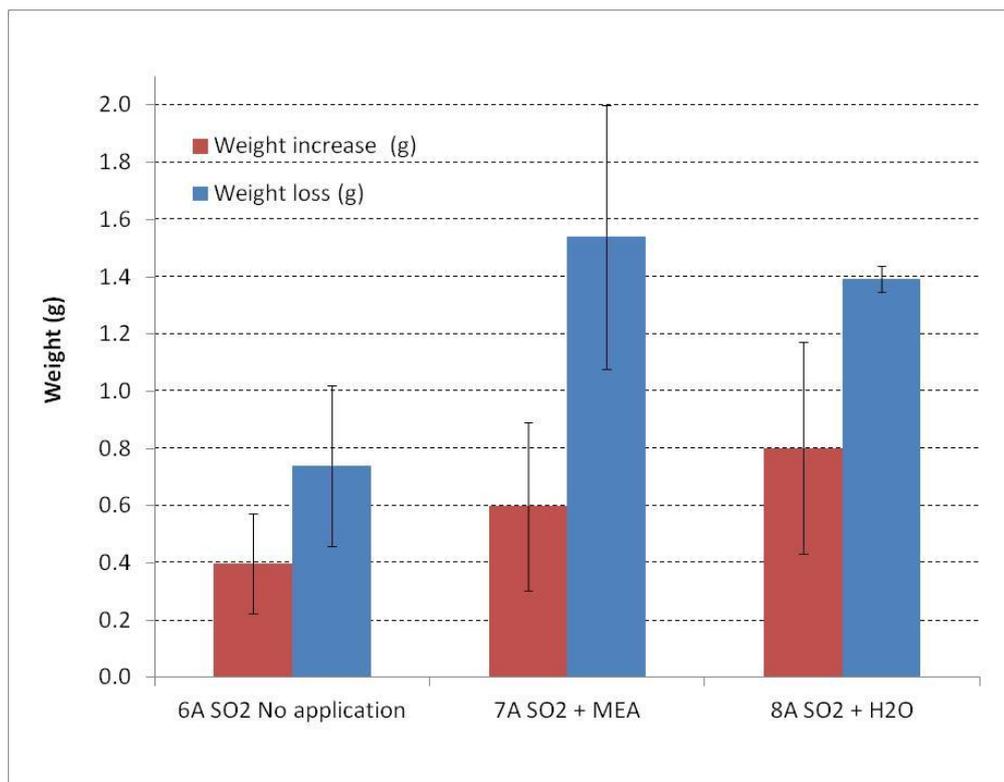
Figure 9:   *Weight increase after exposure and the weight loss after stripping for the steel samples exposed in the laboratory to an SO_2 containing atmosphere. The error bars show one standard deviation.*

Figure 10 shows the weight gain of the steel samples that were exposed to the high amine loads (Table 4, Figure 8) as a function of the duration of the exposure, with two data points during the exposure time for most of the samples. The figure also shows the weight loss after stripping for the samples from two of the experiments.
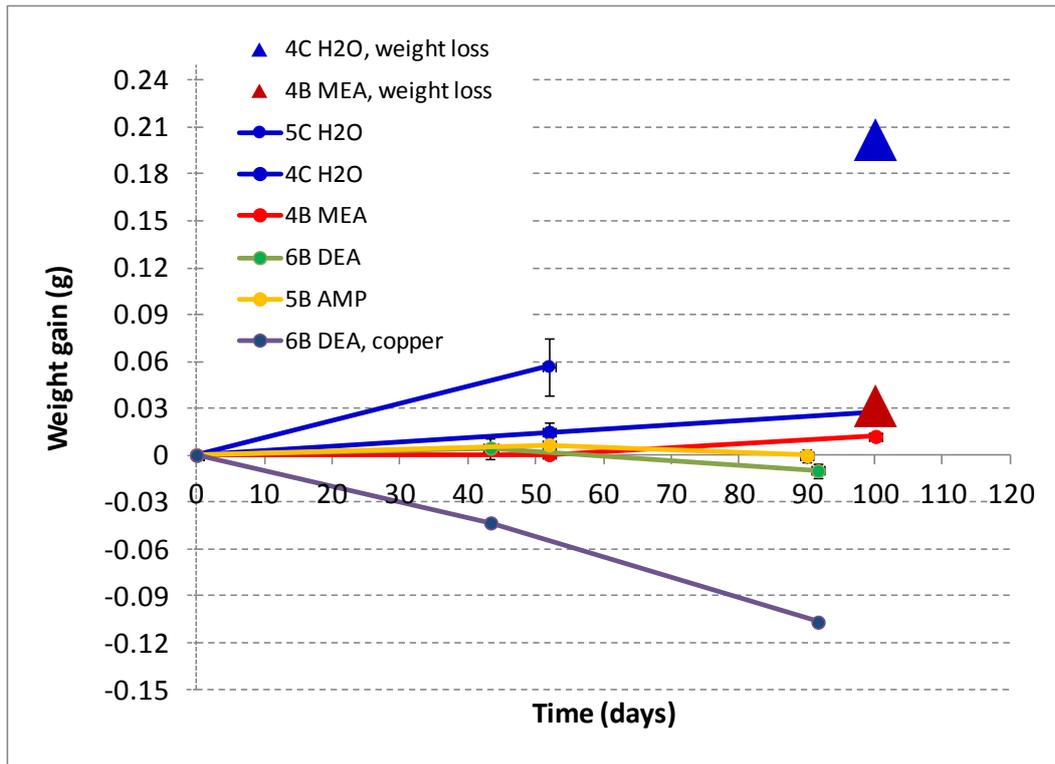
Figure 10 *Weight gain, and weight loss for two of the experiments, for experiments run with the higher loads of applied amines to the steel samples, and one copper sample.*

Figure 11 to Figure 13 show the samples 1D H_2O (A) and 2D MEA (B), 4C H_2O (A) and 4B MEA (B), and 5C H_2O (A), 6B DEA (B), 5B AMP (C), respectively, with the intact corrosion layer after 1 to 3 months exposure (Table 4), except Figure 13 A1 and Figure 13 C1 which shows the samples after 24 hours exposure.
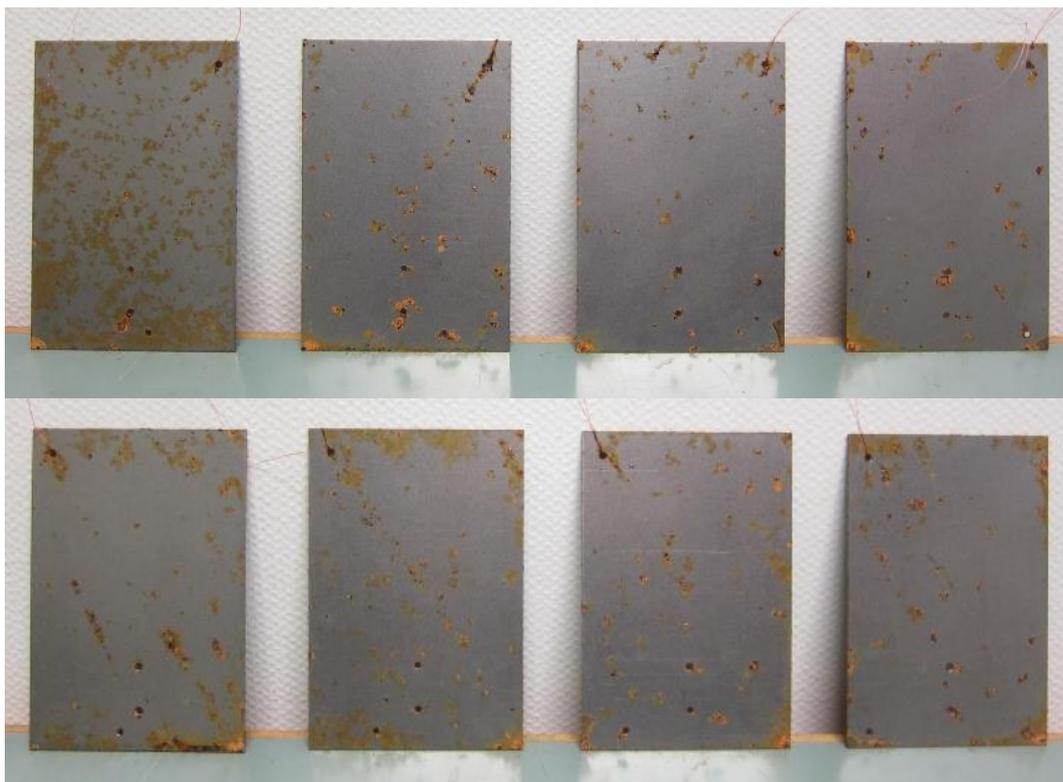
Figure 11A: Samples 1D H$_2$O after exposure (Swedish DC01 steel, three samples, both sides).
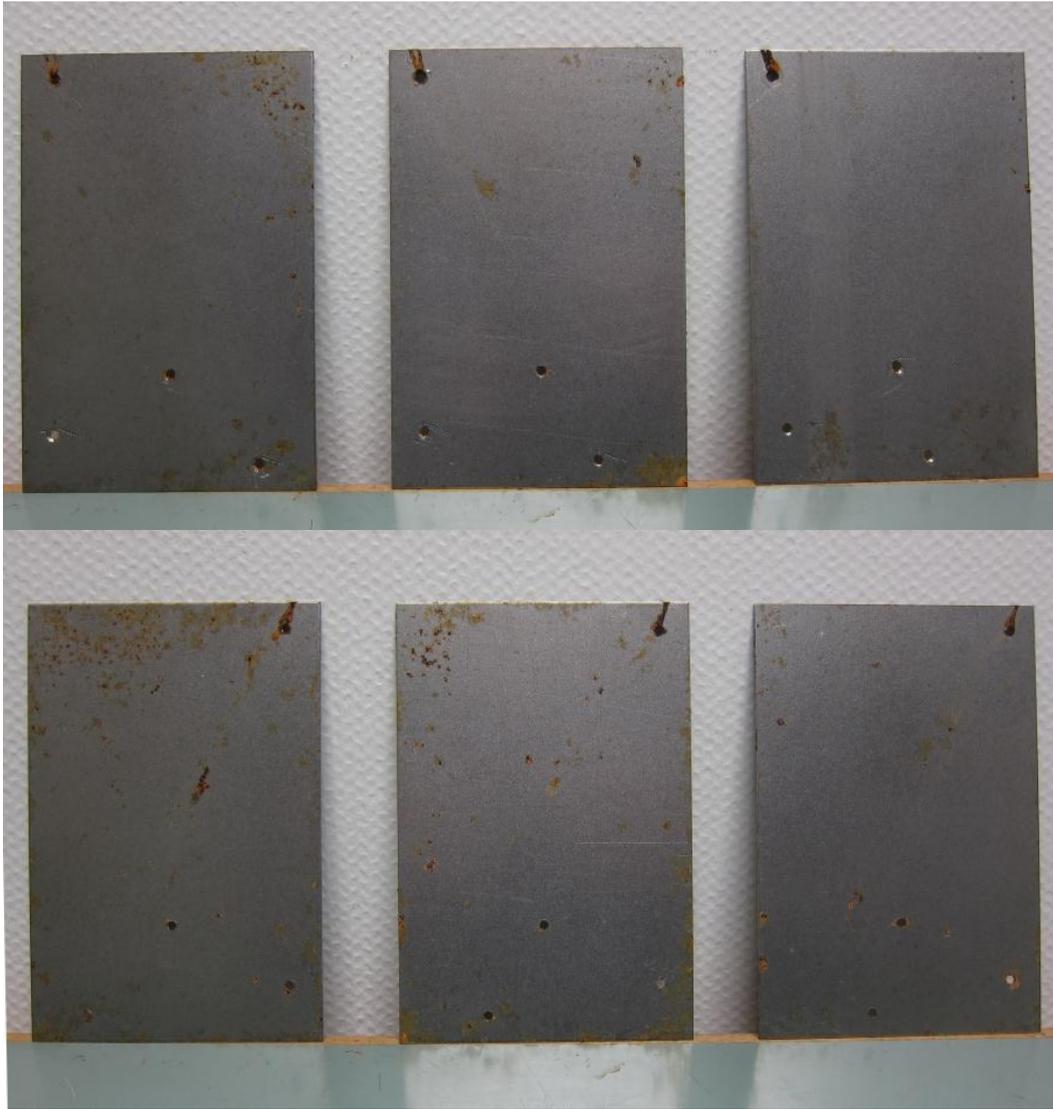
Figure 11B: Samples 2D MEA after exposure (Swedish DC01 steel, three samples, both sides).
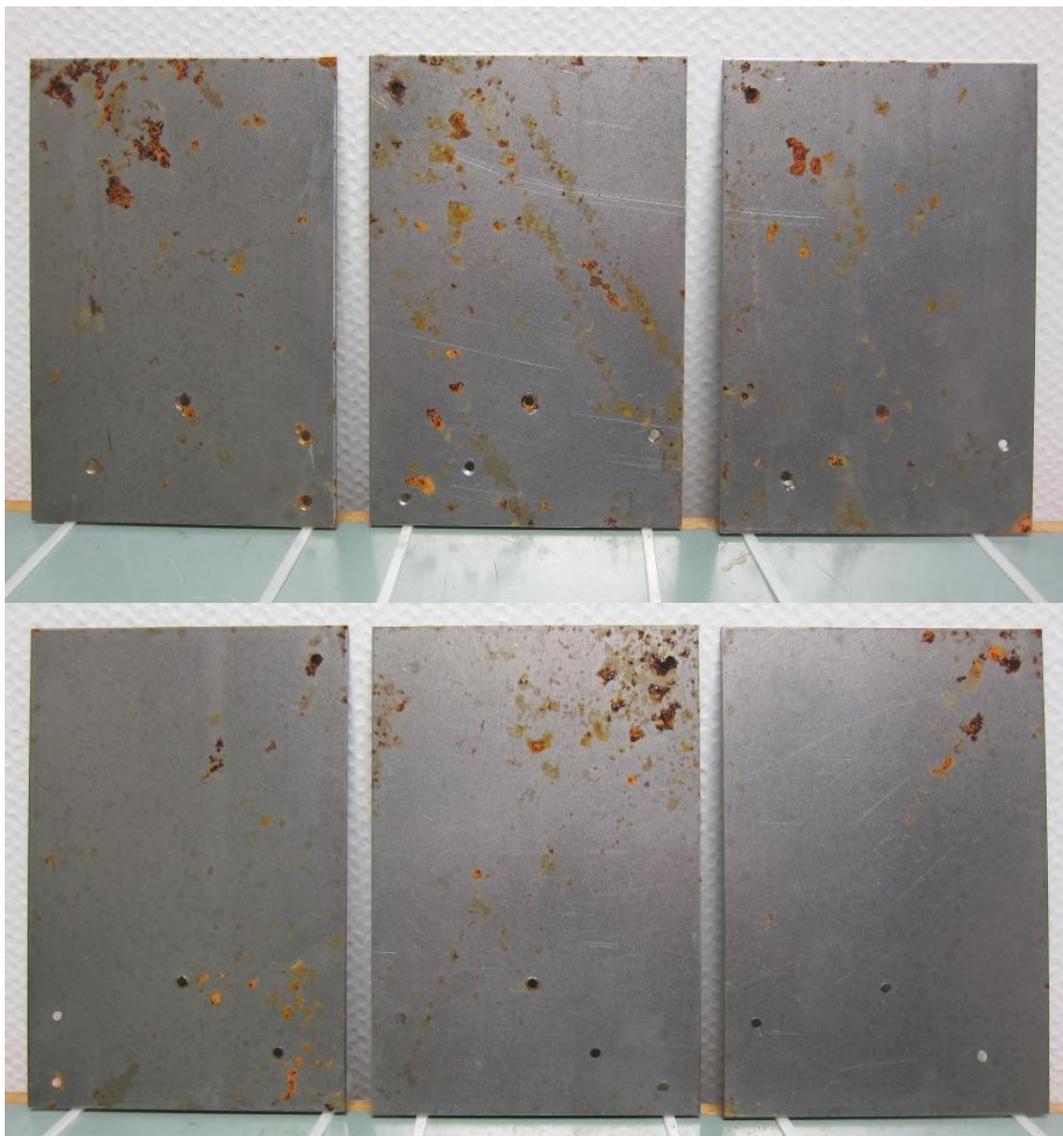
Figure 12A: Samples 4C H₂O after exposure (Swedish DC01 steel, three samples, both sides).
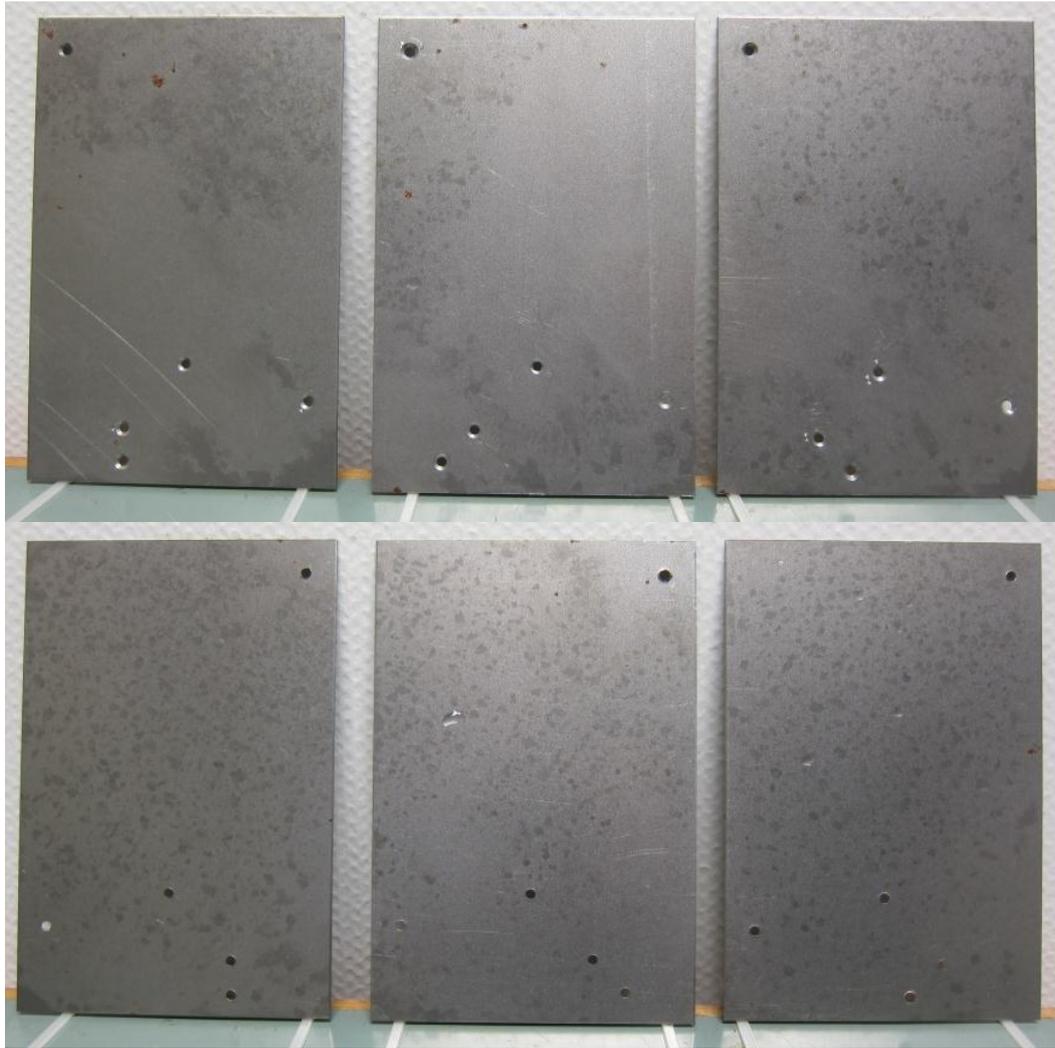
Figure 12B: Samples 4B MEA after exposure (Swedish DC01 steel, three samples, both sides).
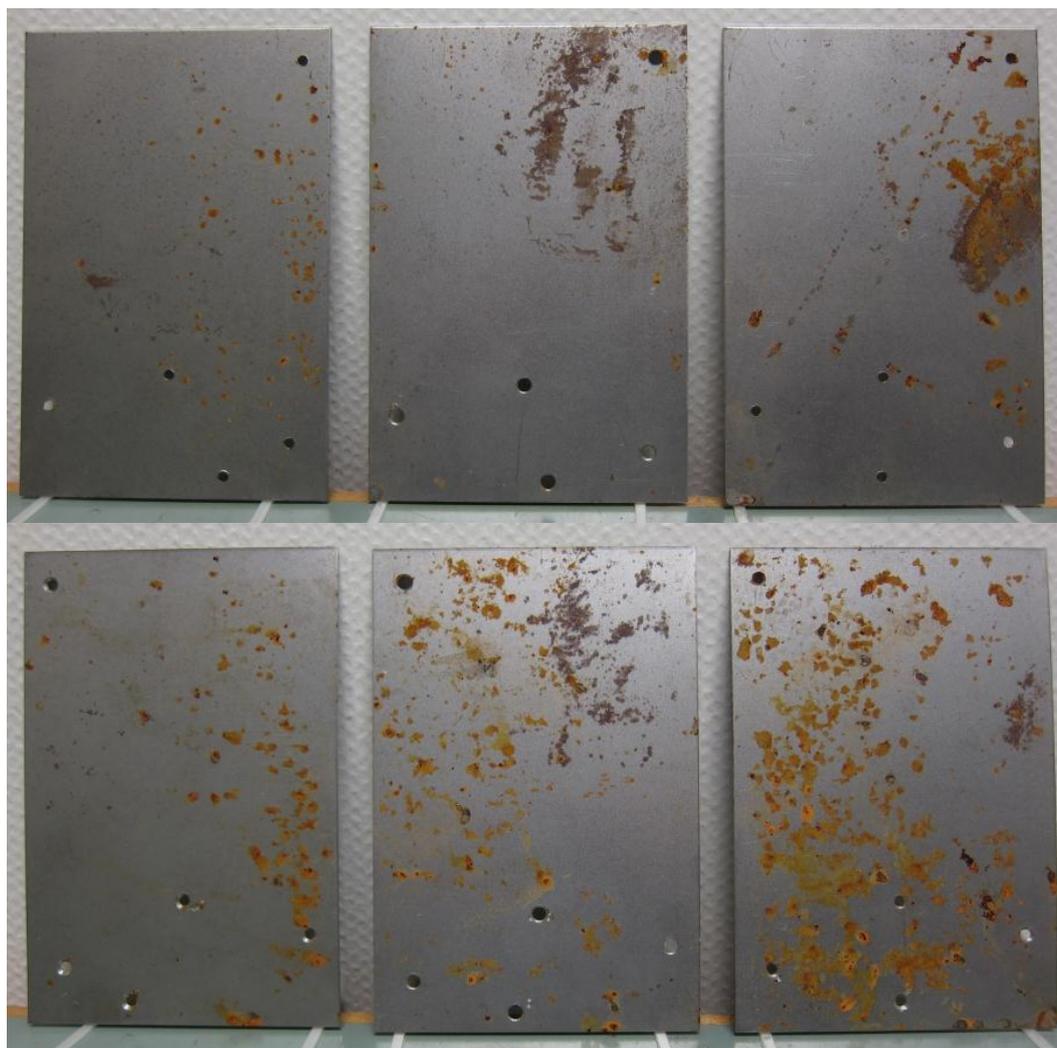
Figure 13A1: Samples 5C H₂O after 24 hours exposure (Norwegian DC01 steel, three samples, both sides. – Different batch of samples than Figure 13A2).
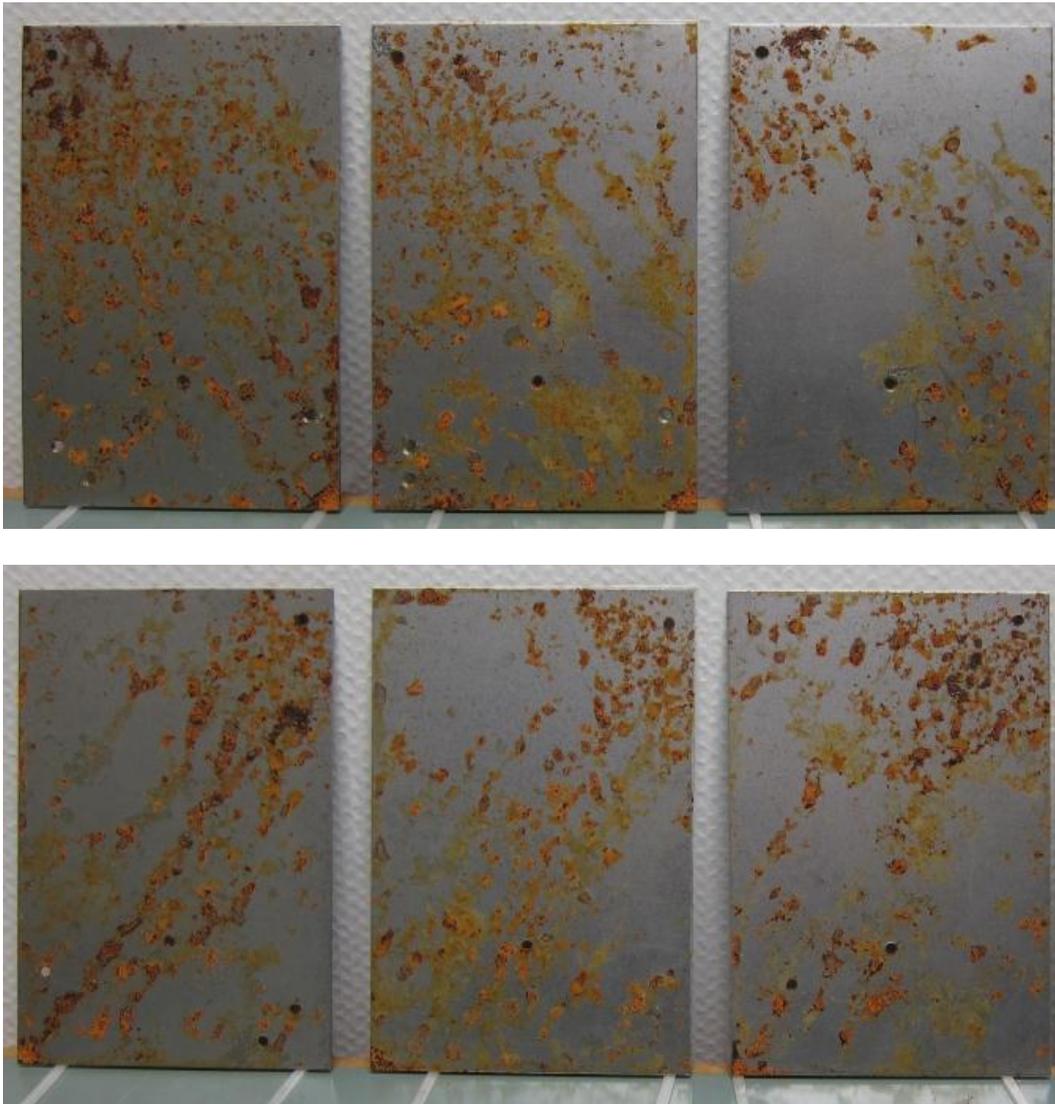
Figure 13A2: Samples 5C H$_2$O after 1.5 months exposure (Norwegian DC01 steel, three samples, both sides. – Different batch of samples than Figure 13A1).
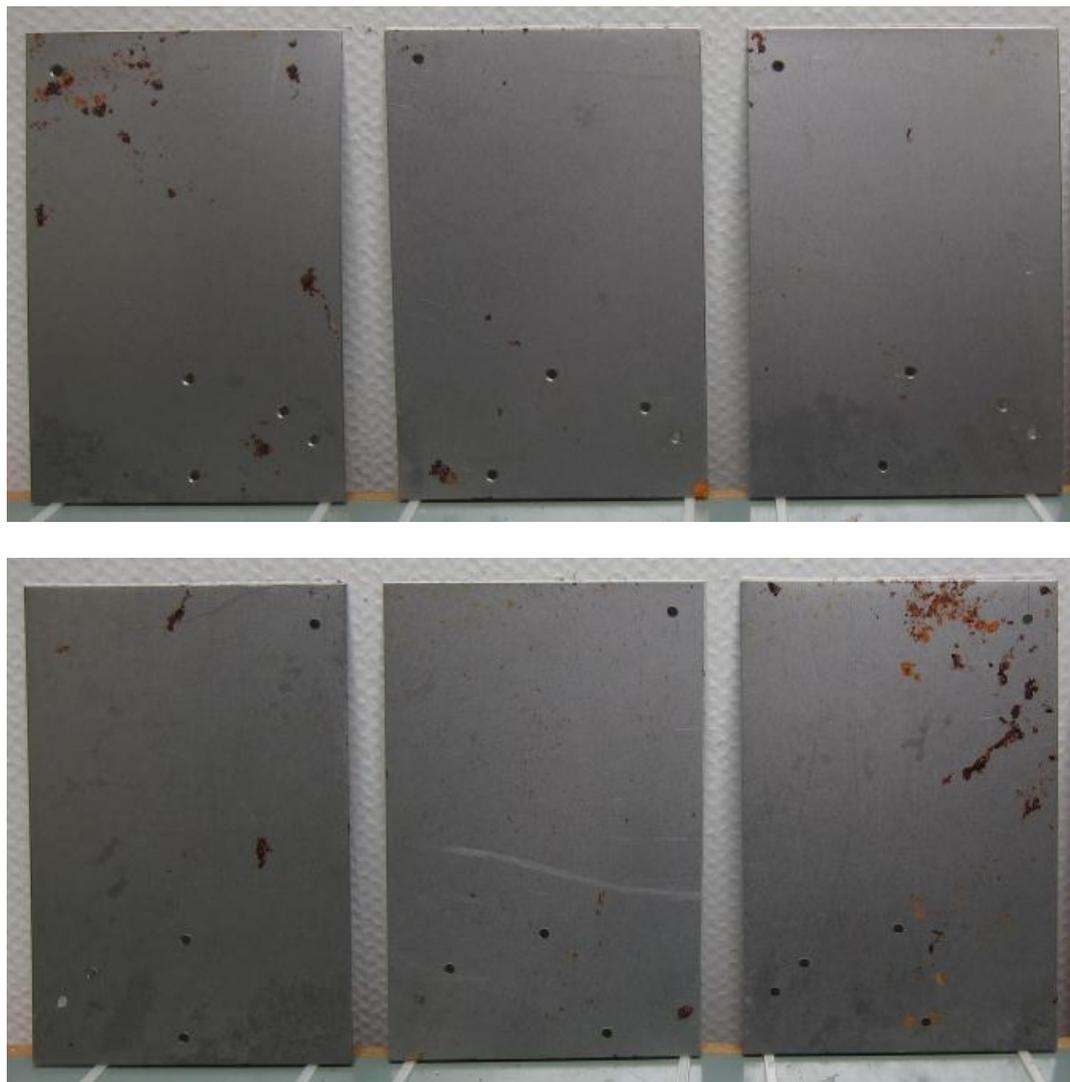
Figure 13B: *Samples 6B DEA after exposure (Norwegian DC01 steel, three samples, both sides).*
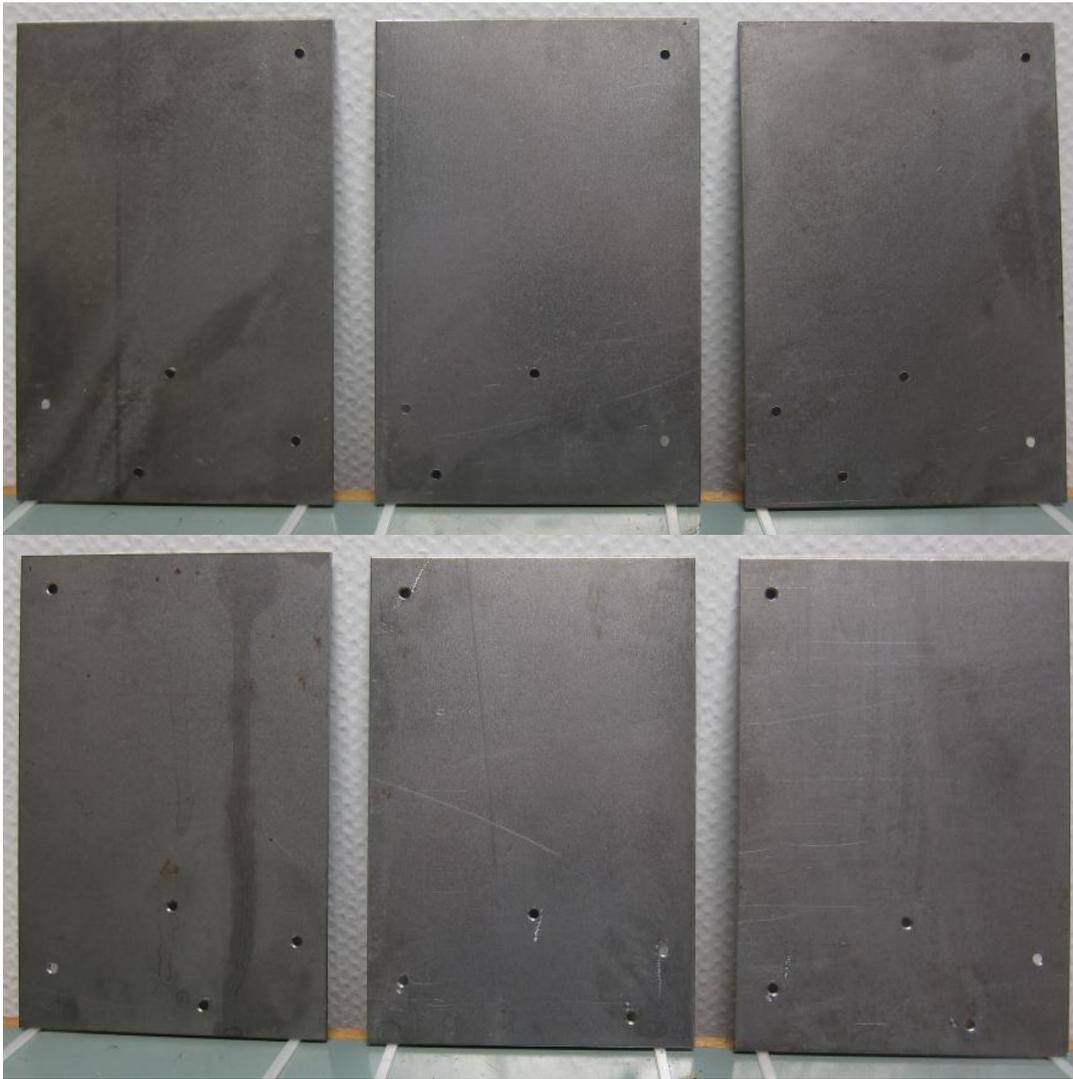
Figure 13C1: Samples 5B AMP after 24 hours exposure (Norwegian DC01 steel, three samples, both sides).
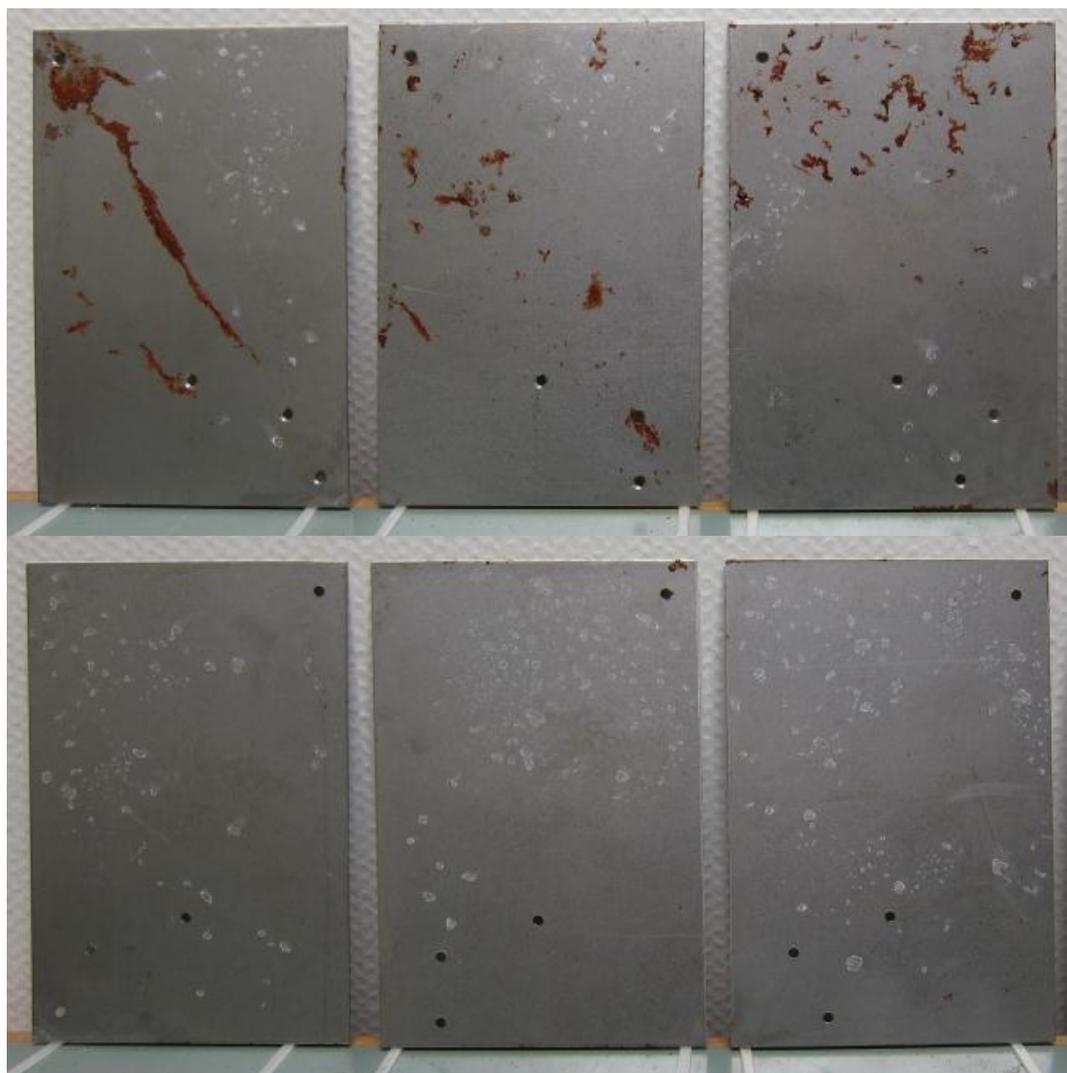
Figure 13C2: Samples 5B AMP after 3 months exposure (Norwegian DC01 steel, three samples, both sides).

Figure 14 shows the results for all the exposed copper samples.
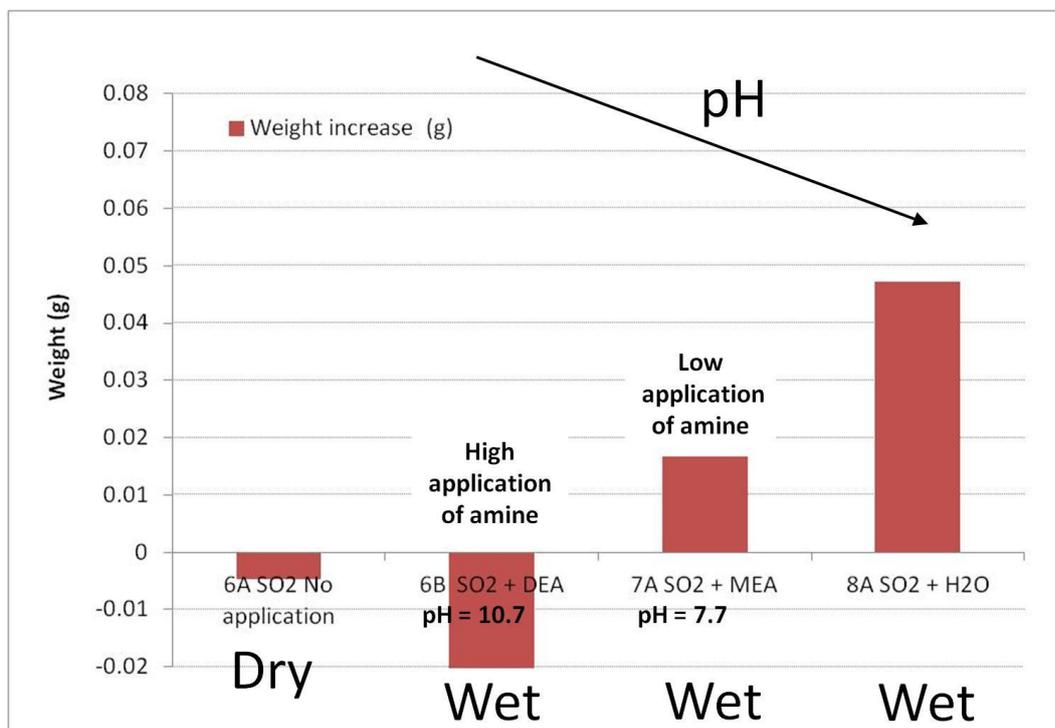
Figure 14   *Weight gain of copper samples after dry exposure, after exposure to high and low doses of amines (DEA and MEA respectively) and exposure to ion rinsed water.*

Table 5 shows results from pH measurements of the applied amines with the low concentration (0.00065 M) and additionally of DEA with the high concentration (0.065 M) before application to a copper plate and of the off running solution from the copper plate.

Table 5:   *pH in amine solutions.*

Sample	Concentration (M)	pH
DEA off running from copper (and some from steal)	0.065	9.27
Pure DEA	0.065	10.73
Pure DEA	0.00065	8.18
Pure MEA	0.00065	7.77
Pure AMP	0.00065	9.63

Figure 15 shows the dissolved copper in the off running DEA solution of high concentration.

Figure 15:   Dissolved copper in DEA solution of high concentration having run off a copper sample.

Figure 16 shows the copper samples after exposure.
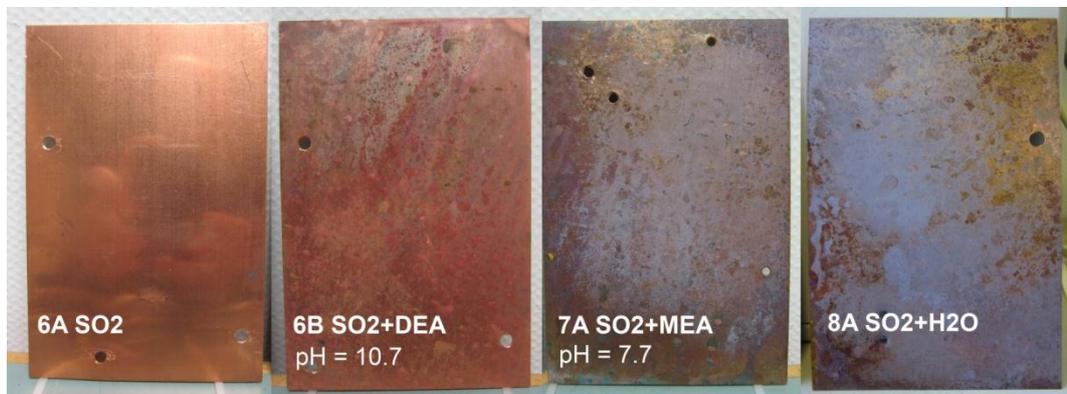
Figure 16.   Copper samples after exposure to dry air (6A), SO$_2$ and amines (6B and C) and SO$_2$ and H$_2$O.

4.1.2   Field measurements

Table 6 shows the results from the corrosion measurements of the samples exposed in the field.

Table 6: Results from the corrosion measurements of the samples exposed in the field.

Exposure solution:		Ion rinsed H2O		DEA		AMP		MEA	
Station	**Exposure time (months)**	**Weight loss (g)**	**stdev**	**Weight loss (g)**	**stdev**	**Weight loss (g)**	**stdev**	**Weight loss (g)**	**stdev**
Skøyen	3	0.12	0.05	0.094	0.007	0.103666667	0.008	0.131	0.006
Skøyen	6	0.187	0.006	0.18	0.01	0.182666667	0.004	0.19	0.03
Skøyen	9	0.378	0.005	0.412	0.006	0.426666667	0.033	0.48	0.01
Skøyen	12	0.77	0.03	0.79		0.7845	0.021	0.75	0.04
Borregaard	12	13.295	0.5					14.0	0.2
Birkenes	12	1.556	0.03					1.57	0.05
Tananger	12	18	2					20	1
		Weight gain (g)	**stdev**	**Weight gain (g)**	**stdev**	**Weight gain (g)**	**stdev**	**Weight gain (g)**	**stdev**
Skøyen	6	0.11	0.01	0.109	0.012	0.11	0.01	0.2	0.1
Skøyen	9	0.221	0.002	0.253	0.006	0.25	0.02	0.292	0.007
Skøyen	12	0.56		0.57	0.02	0.58	0.03	0.56	0.02
Borregaard	12	-1.2	0.9					-1.9	0.3
Birkenes	12	0.85	0.01					0.82	0.02
Tananger	12	8	2					7	1

Figure 17 and Figure 18 show the results the samples exposed in the field. Figure 17 shows the weight gain with the intact corrosion layer after the 12 months exposure at the four stations. Figure 18 shows the weight loss after stripping of the corrosion layer.
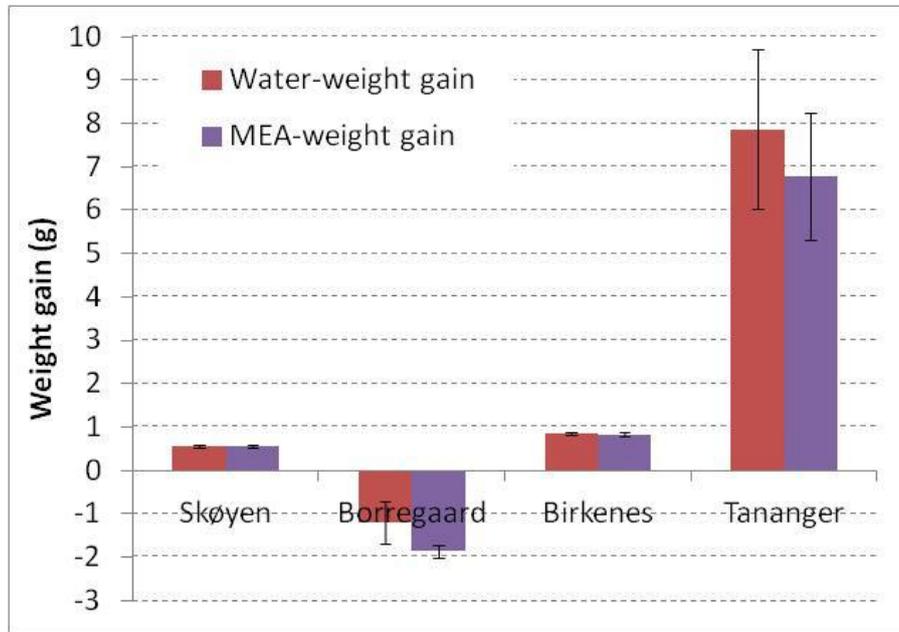
Figure 17: *Weight gain of the field samples with the intact corrosion layer after 12 months exposure. The error bars show the standard deviation or three samples.*
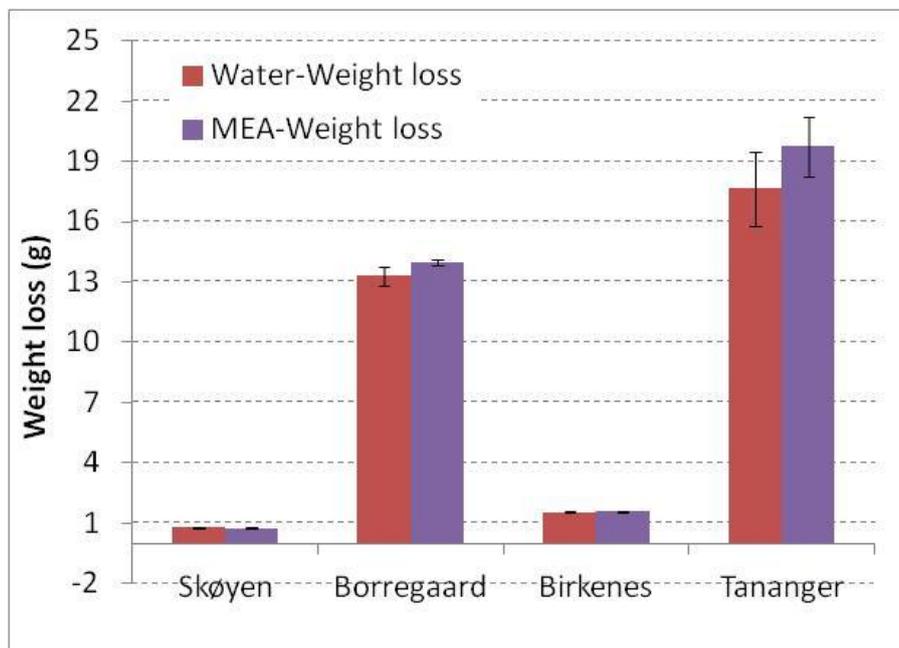
Figure 18: *Weight loss after stripping of the corrosion layer after 12 months exposure. The error bars show the standard deviation or three samples.*

Figure 19 shows the weight loss after stripping of the corrosion layer of the samples exposed at the Skøyen station for three, six, nine and 12 months.
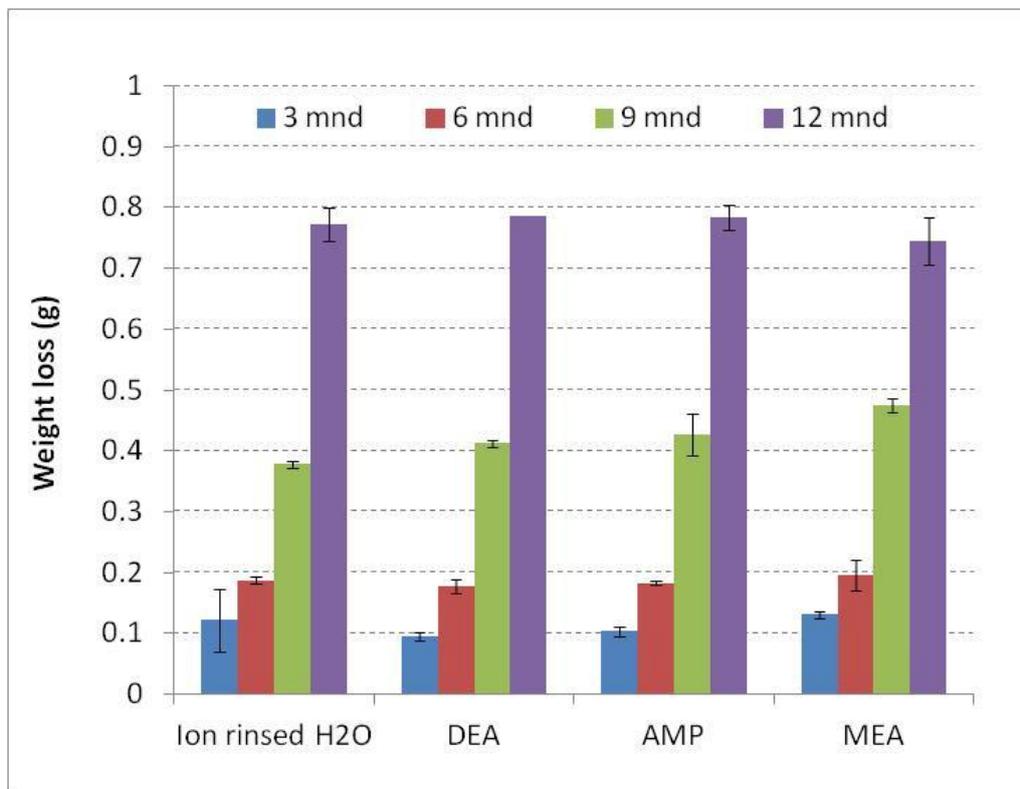
Figure 19: Weight loss after stripping of the corrosion layer of the samples exposed at the Skøyen station for three, six, nine and 12 months. The error bars show the standard deviation or two samples.

Figure 20 and Figure 21 show the upper and under side, respectively, of the samples exposed to ion rinsed water and the amines after three months exposure at the Skøyen station.

Figure 22 and Figure 23 show the upper and under side, respectively, of the samples exposed to ion rinsed water and the amines after 12 months exposure at the Skøyen station.
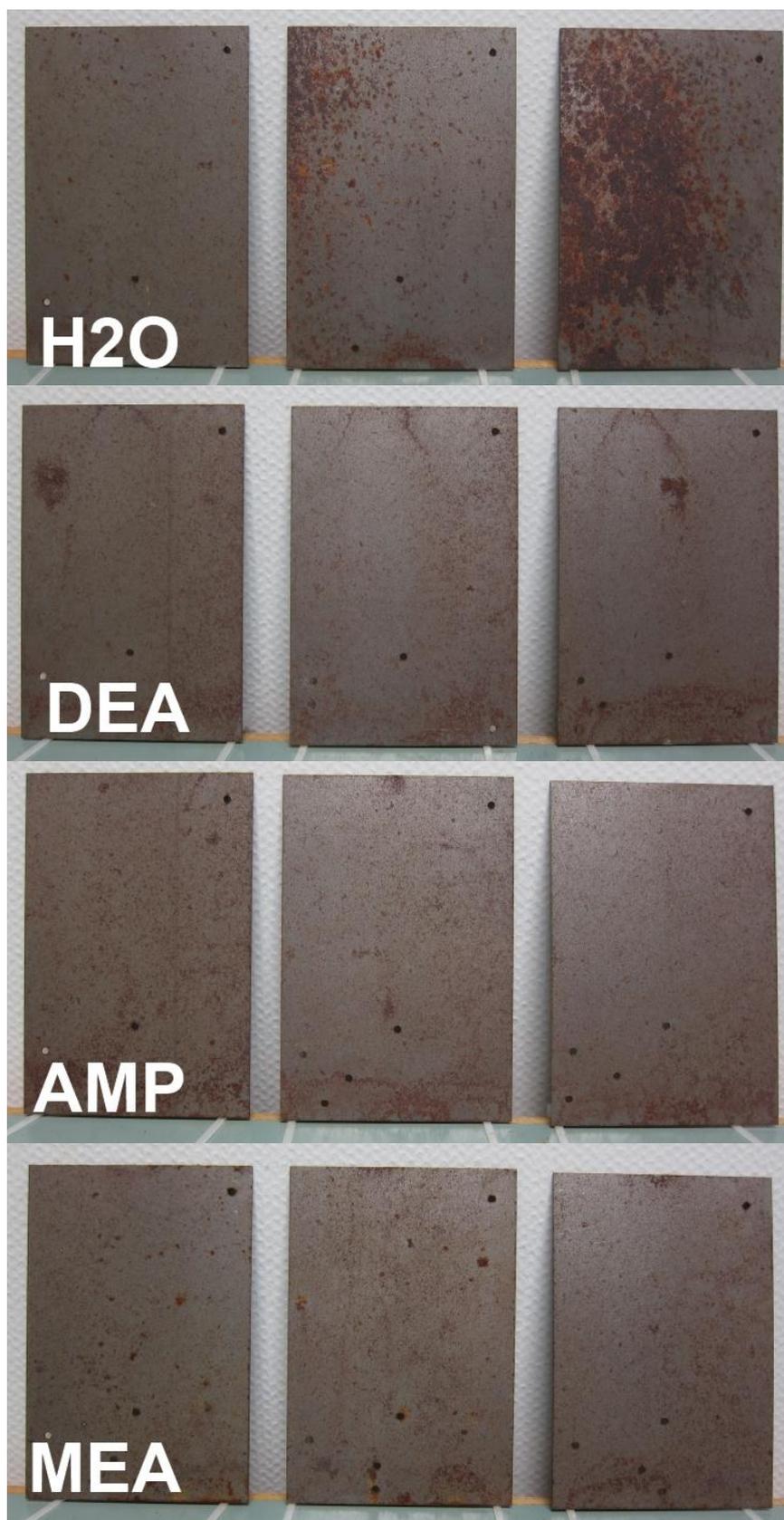
Figure 20: *The upper side of the samples exposed to ion rinsed water and the noted amines after three months exposure at the Skøyen station.*
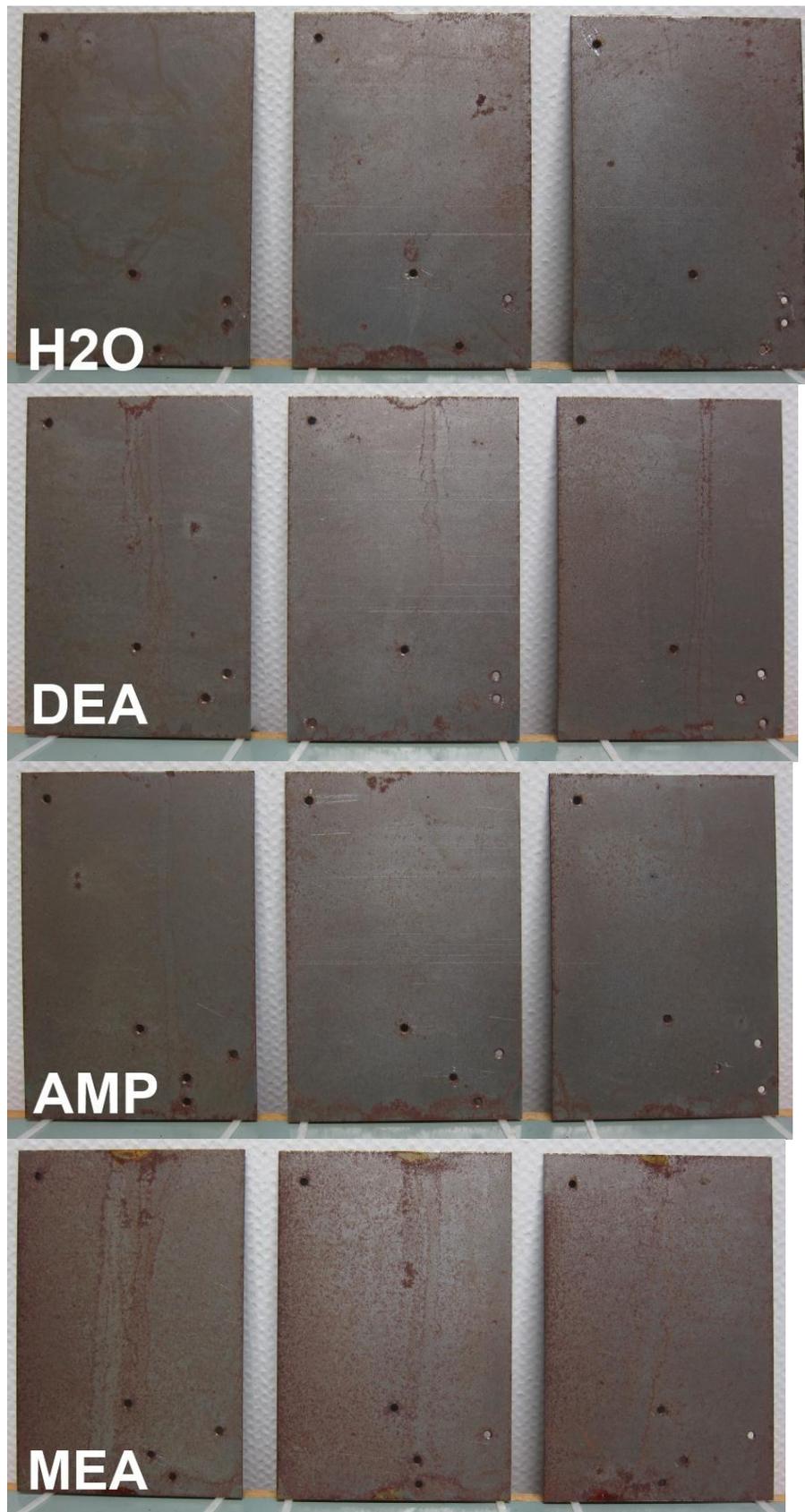
Figure 21: *The underside of the samples exposed to ion rinsed water and the noted amines after three months exposure at the Skøyen station.*
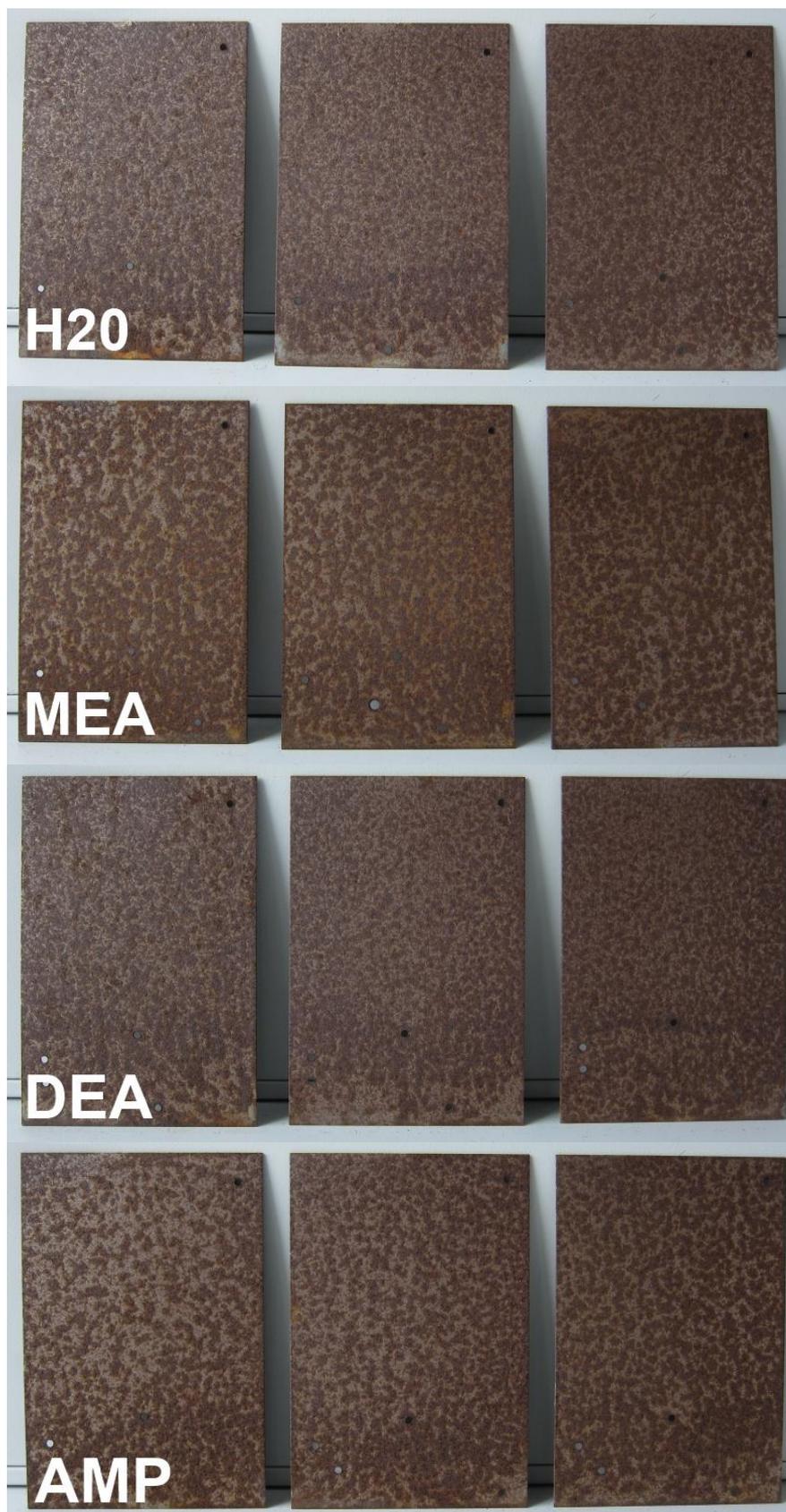
Figure 22: *The upper side of the samples exposed to ion rinsed water and the noted amines after 12 months exposure at the Skøyen station.*
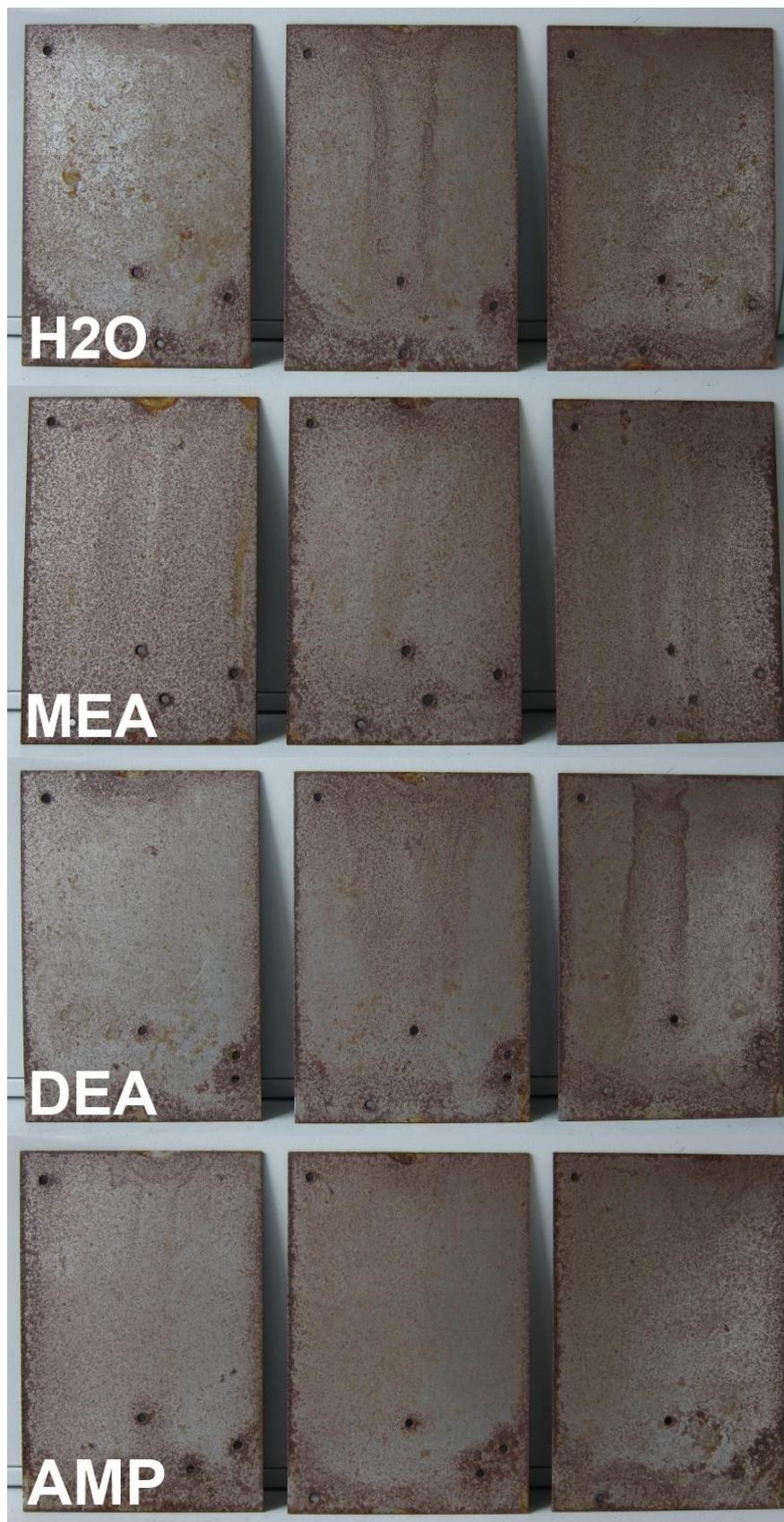
Figure 23: *The underside of the samples exposed to ion rinsed water and the noted amines after 12 months exposure at the Skøyen station.*

Figure 24 and Figure 25 show the upper and under side, respectively, of the samples exposed to ion rinsed water and MEA after 12 months exposure at the three stations, Borregaard, Birkenes and Tananger. The pictures for MEA applied at Skøyen were shown in Figure 22 and Figure 23.
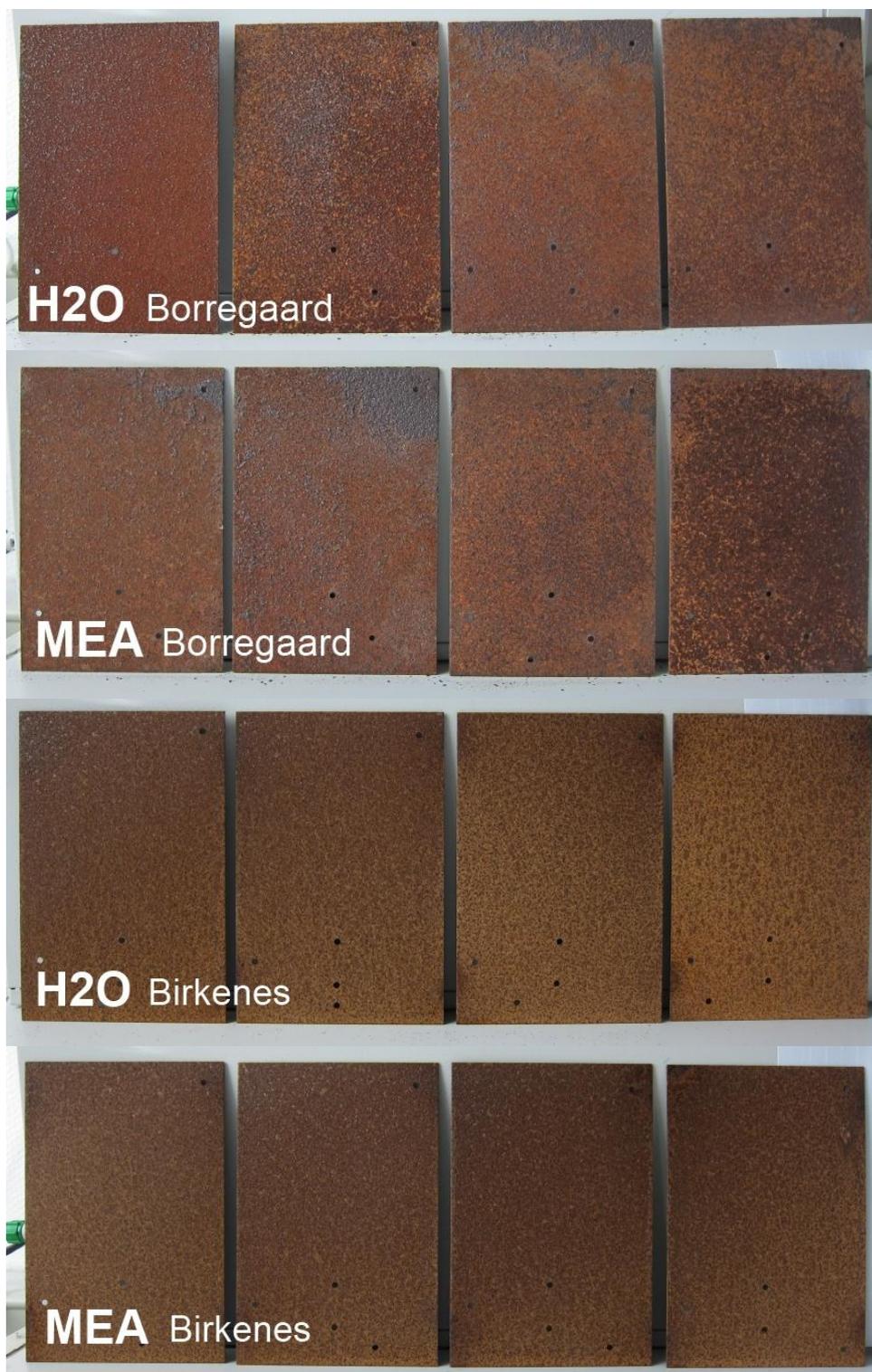
Figure 24:   The upper side of the samples exposed to ion rinsed water and MEA after 12 months exposure at the three stations Borregaard, Birkenes and Tananger.

Figure 24:   *-Contd.*
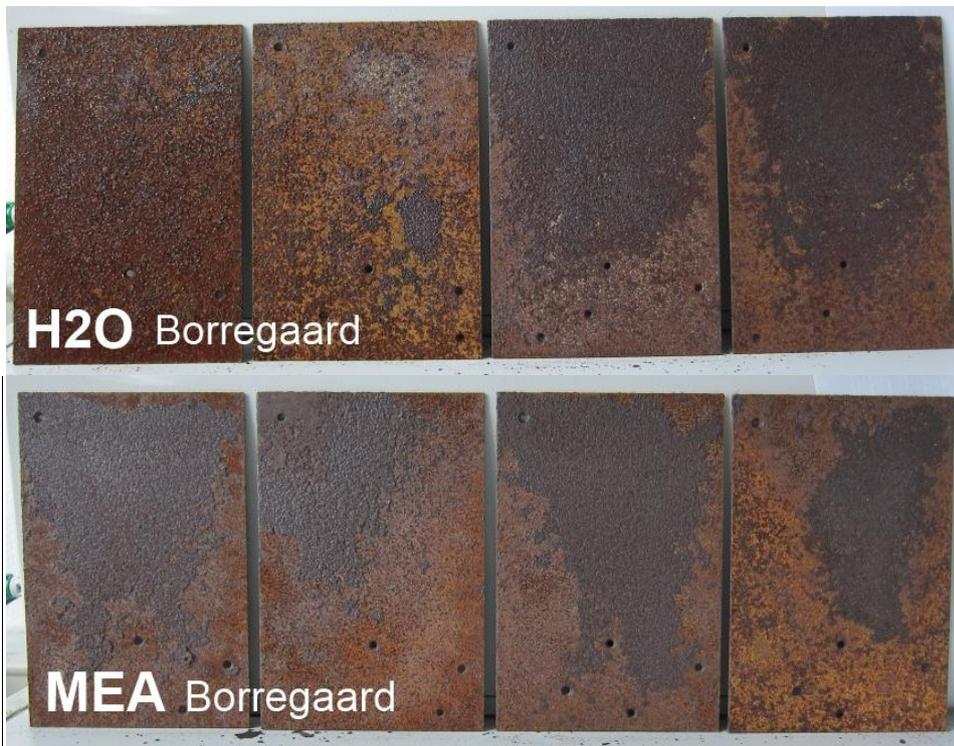
Figure 25:   *The underside of the samples exposed to ion rinsed water and MEA after 12 months exposure at the three stations Borregaard, Birkenes and Tananger.*
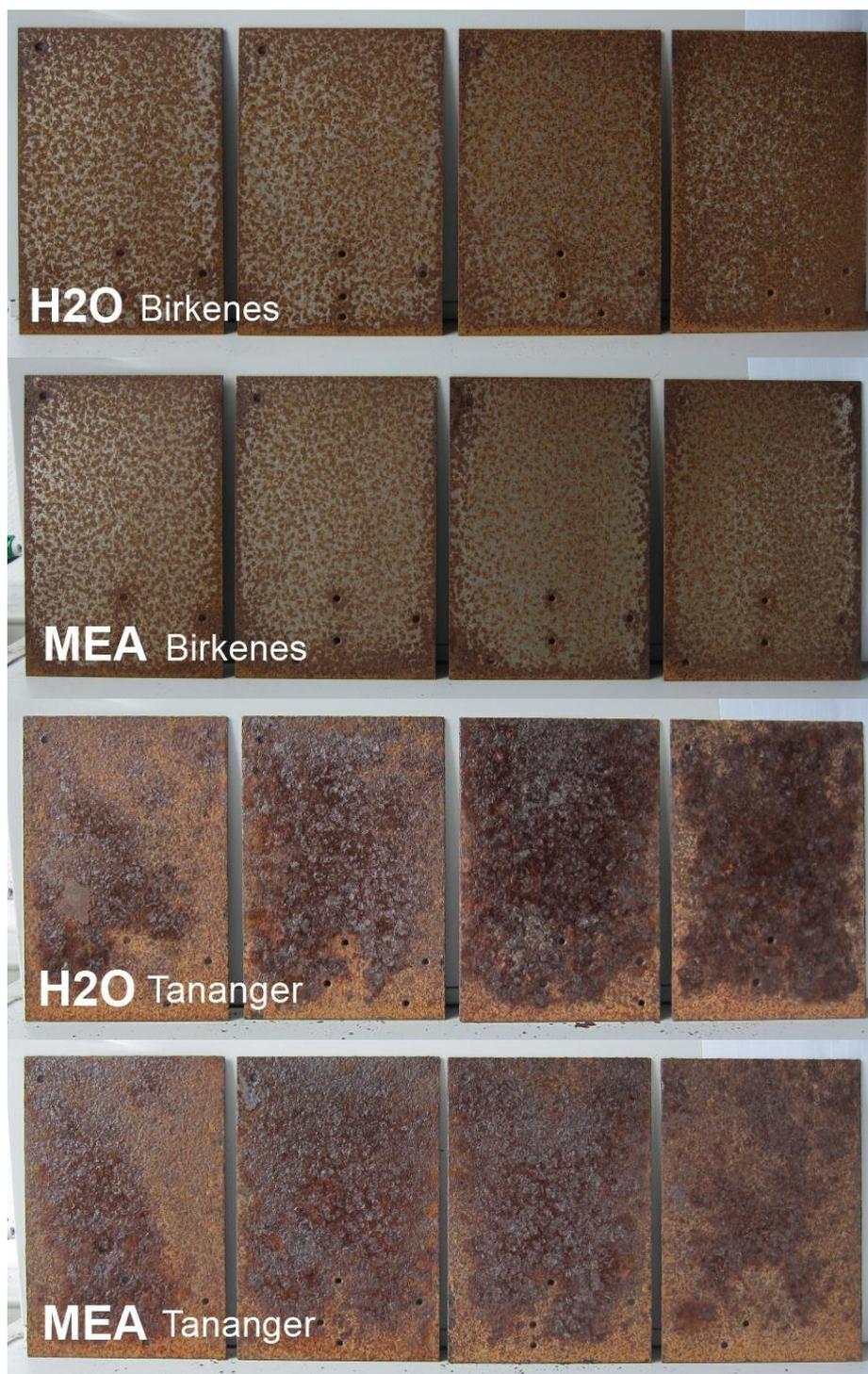
Figure 25:   Contd.

4.2   Passive sampling of pollutants

Table 7 and Figure 26 and Figure 27 show the annual average values for SO_2-concentration in air, pH and aerosol deposition for the four stations.

Table 7:   Annual average values for SO₂ concentration in air with standard deviation for two samplers, pH and aerosol deposition for the four stations.

Station	SO2 (µg m-3)	stdv	pH	Cl (mg m-2d-1)	NO3-N (mg m-2d-1)	SO4-S (mg m-2d-1)	Na (mg m-2d-1)	NH4-N (mg m-2d-1)	K (mg m-2d-1)	Mg (mg m-2d-1)	Ca (mg m-2d-1)
Skøyen	3.0	0.2	5.3	0.61	0.09	0.09	0.32	0.06	0.11	0.03	0.36
Borregaard (SO2/10)	6.3	0.8	4.8	2.26	0.12	1.11	0.76	1.08	0.08	0.08	0.39
Birkenes	4.0	0.3	5.3	0.42	0.03	0.02	0.26	0.00	0.09	0.03	0.07
Tananger/100(not pH)	3.0	1.7	5.9	2.11	0.01	0.11	1.33	0.21	0.08	0.17	0.10
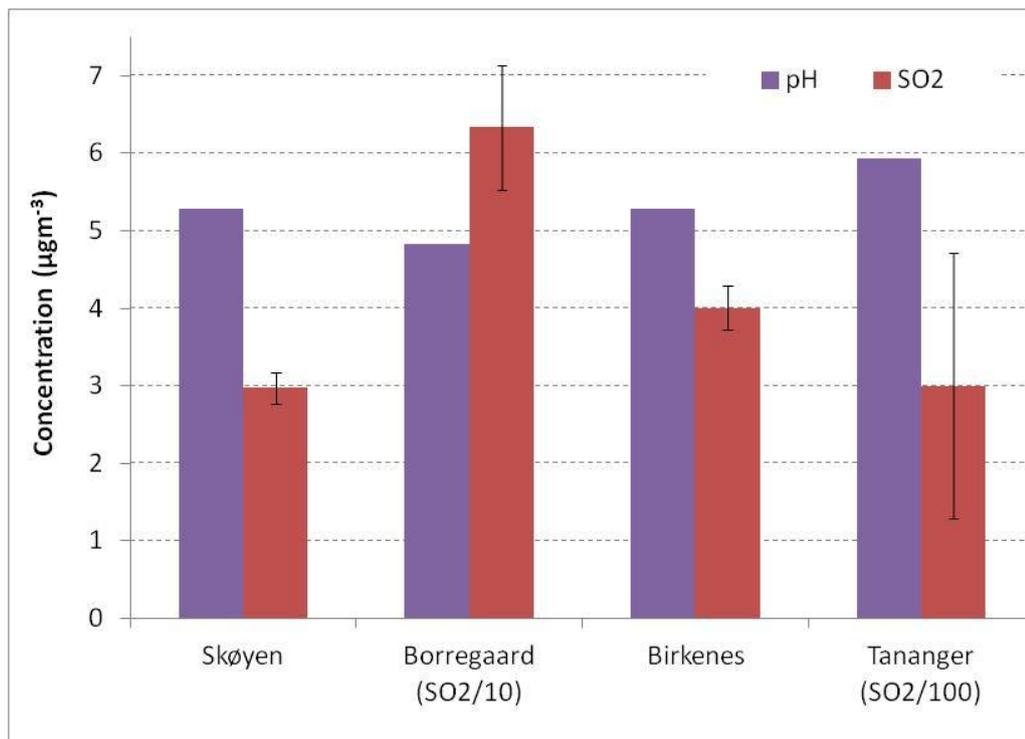
Figure 26:   Annual average values for SO₂ concentration in air and pH for the four stations.
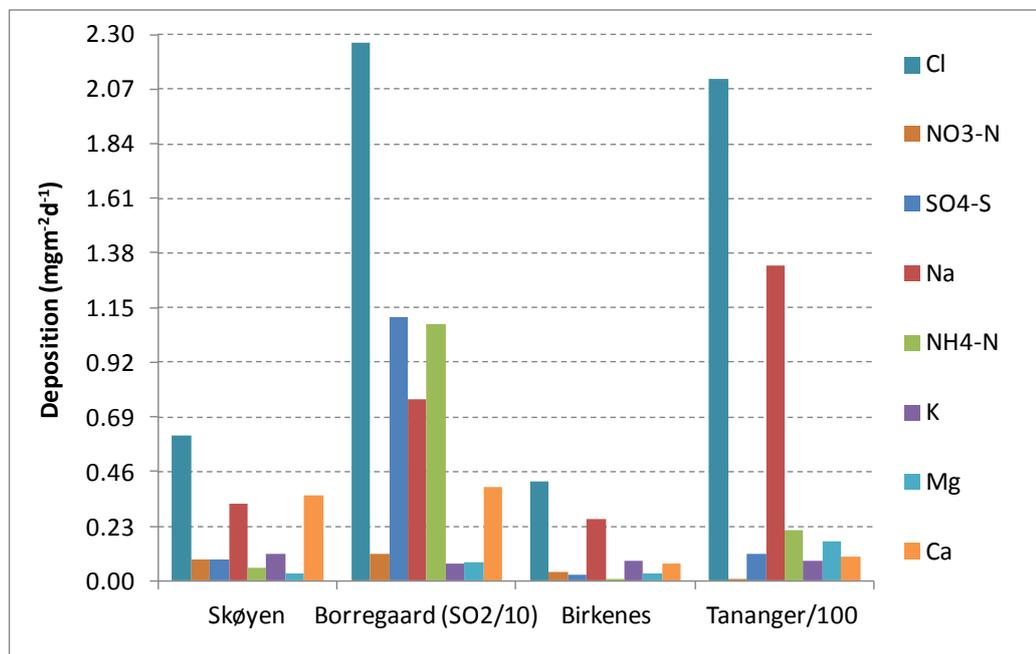
Figure 27:   Annual average values for aerosol deposition for the four stations.

Figure 28 shows the monthly average values for the ionic composition of deposited aerosol at the four stations calculated to mol atomic charge*1000 $m^{-2}d^{-1}$ to enable comparison of the amount of anions and kations. The deposited mol (mol*1000/m^2d^{-1}) of all the species of ions were calculated from the measured weight of deposition (mgm^{2}d^{-1}). This value was used for the mol deposited atomic charge of the single charged ions. For the double charged ions; sulphur in sulphate (SO_4-S), magnesium and calcium, the values for the mol deposition were multiplied with two to give the mol atomic (mol atomic charge*1000/m^2d). Missing anions were assumed to be mostly hydrogen carbonate, HCO_3^-, and are termed as such in the figures. When the value for "missing anions" is negative some kations are missing from the calculation.

Figure 29 shows the monthly average concentration of SO_2 measured in the air by the use of passive samplers and the pH measured in the aerosol washing water at the four stations.

Table 1 and 2 in Appendix no. 1 show the values for the measured pH, the SO_2 concentration in air and the deposited aerosol in mg $m^{-2}d^{-1}$, and the deposited aerosol in mol atomic charge*1000 $m^{-2}d^{-1}$, respectively.
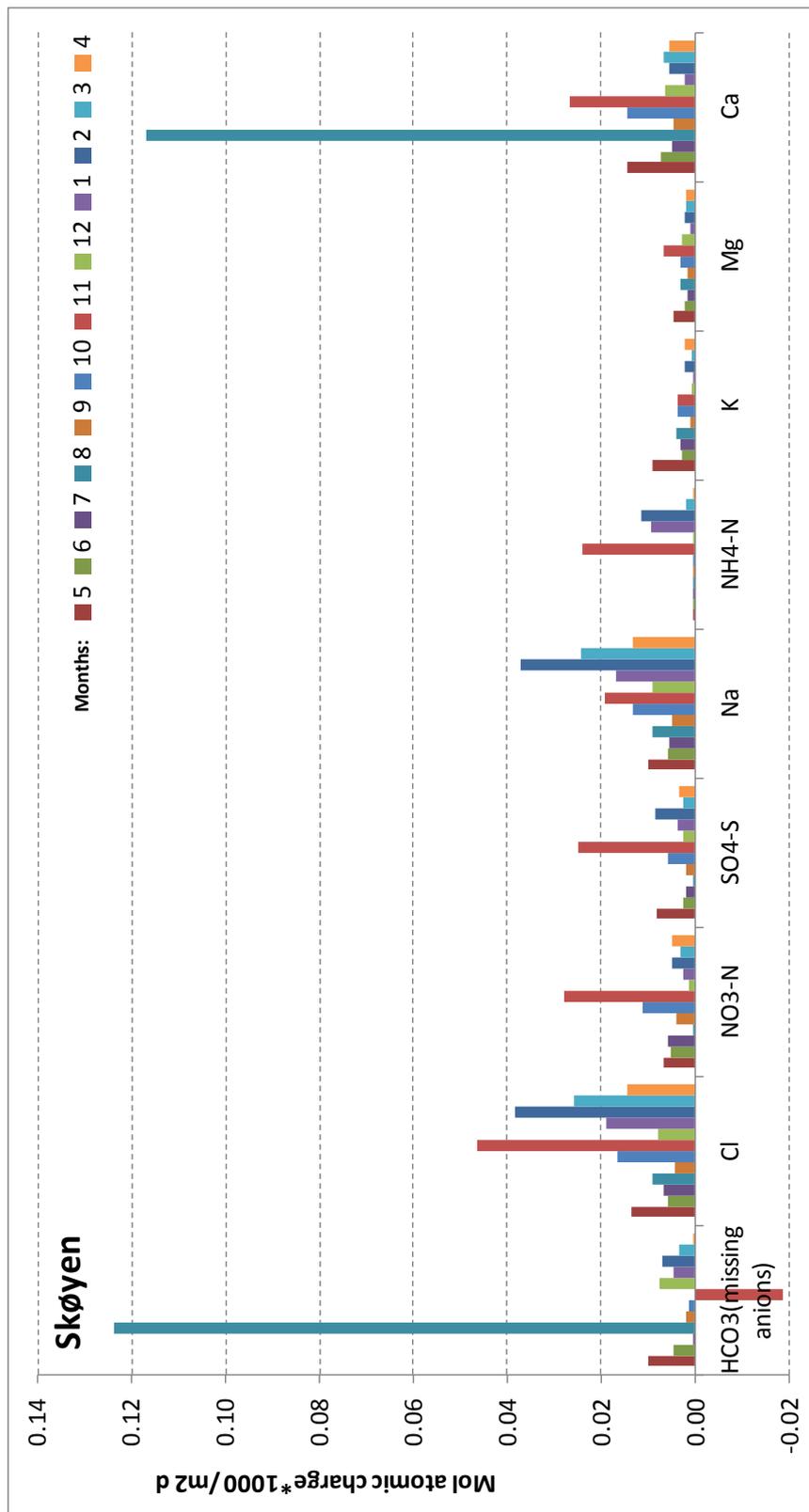
Figure 28: *The ionic composition of deposited aerosol at the Skøyen, Borregaard, Birkenes and Tananger stations.*
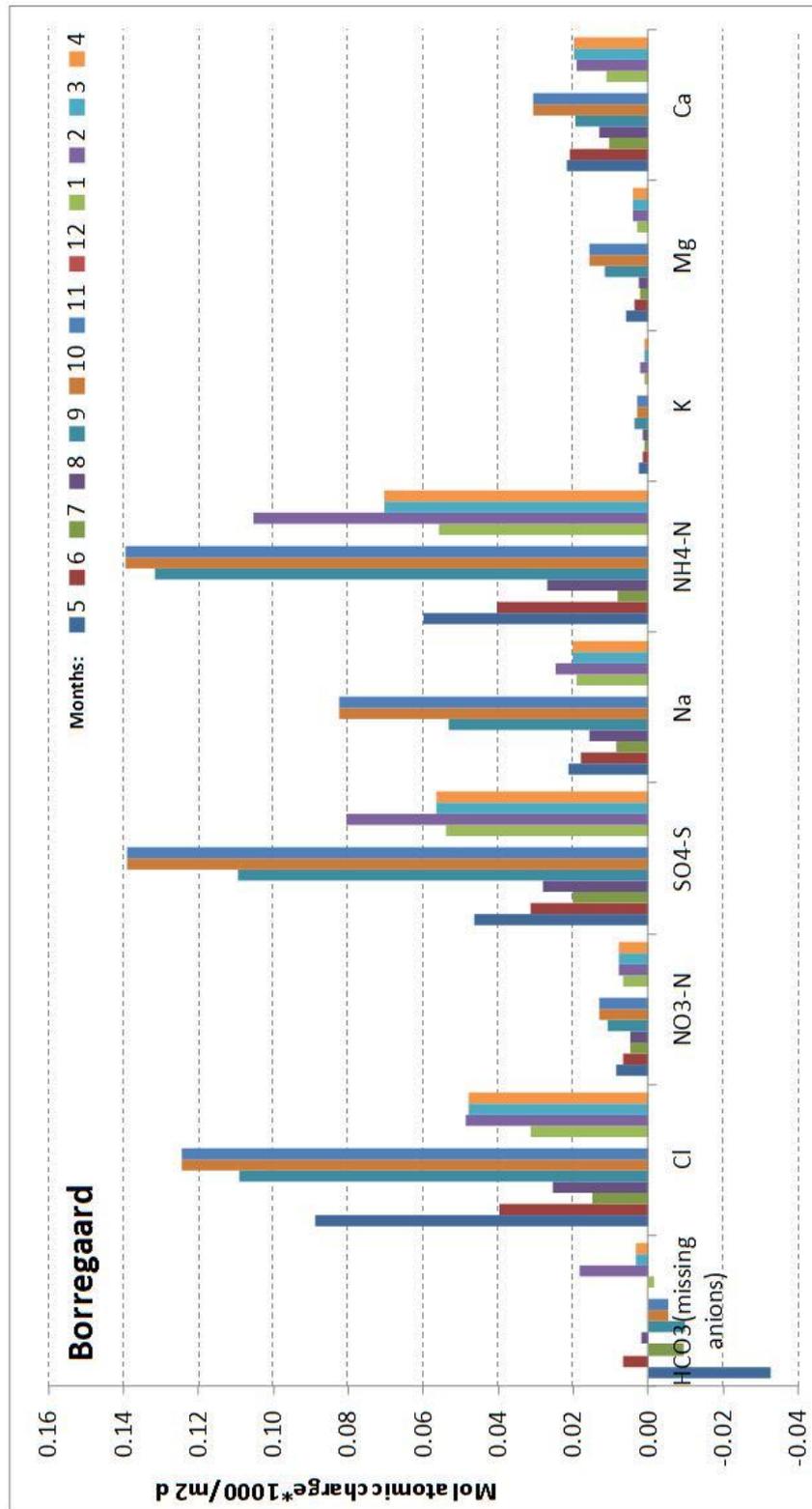
Figure 28: Contd.
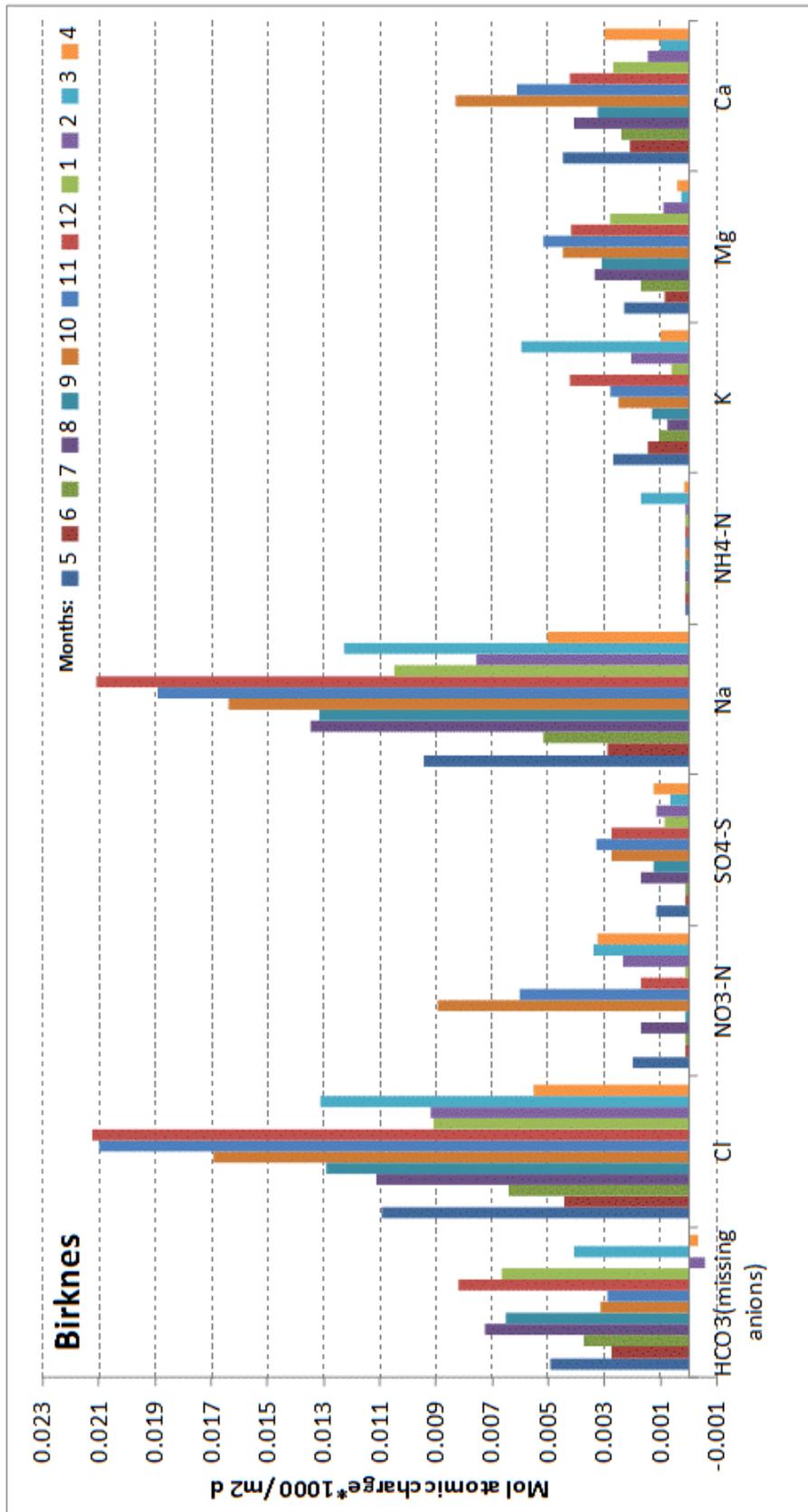
Figure 28: Contd.
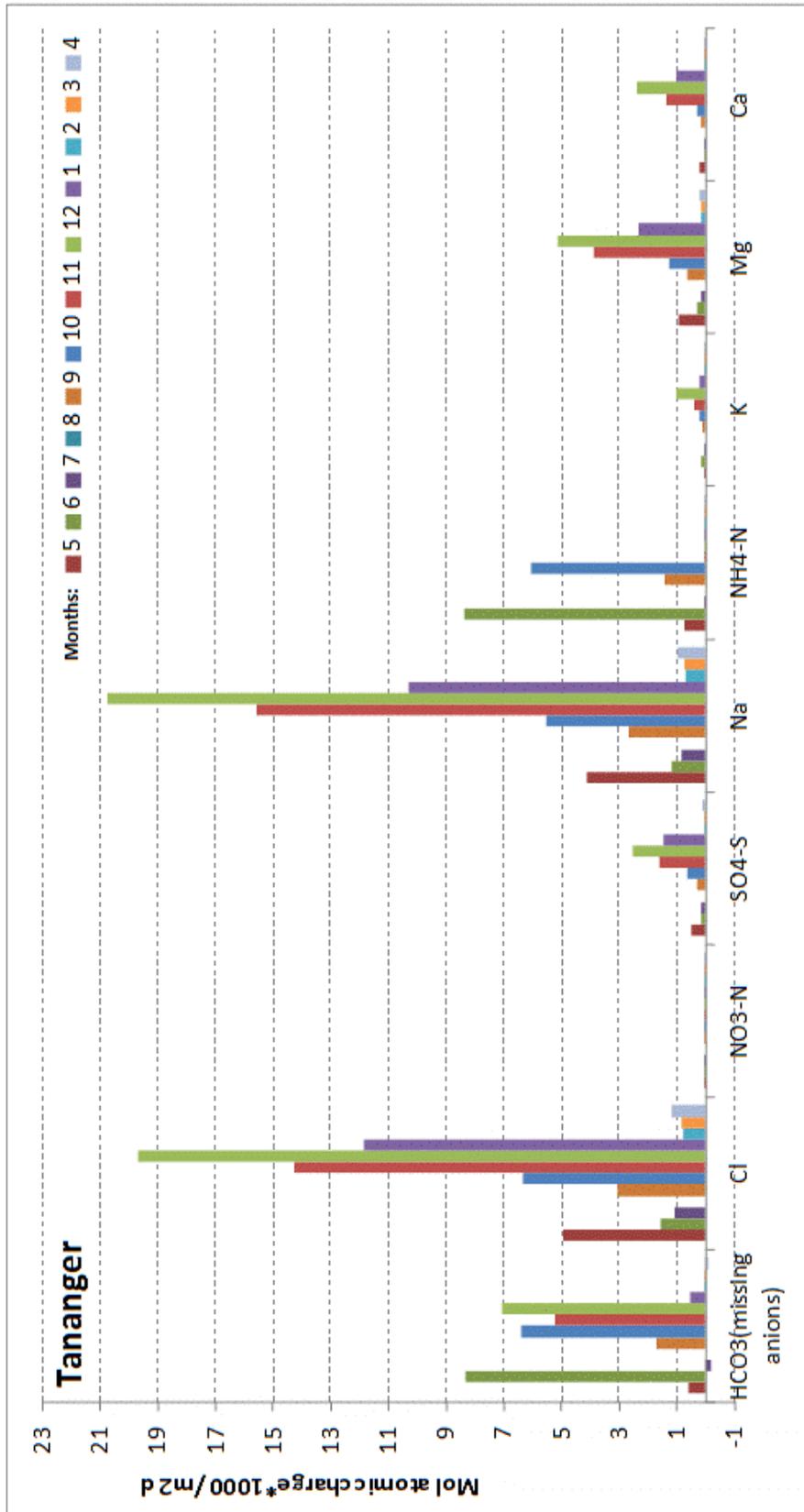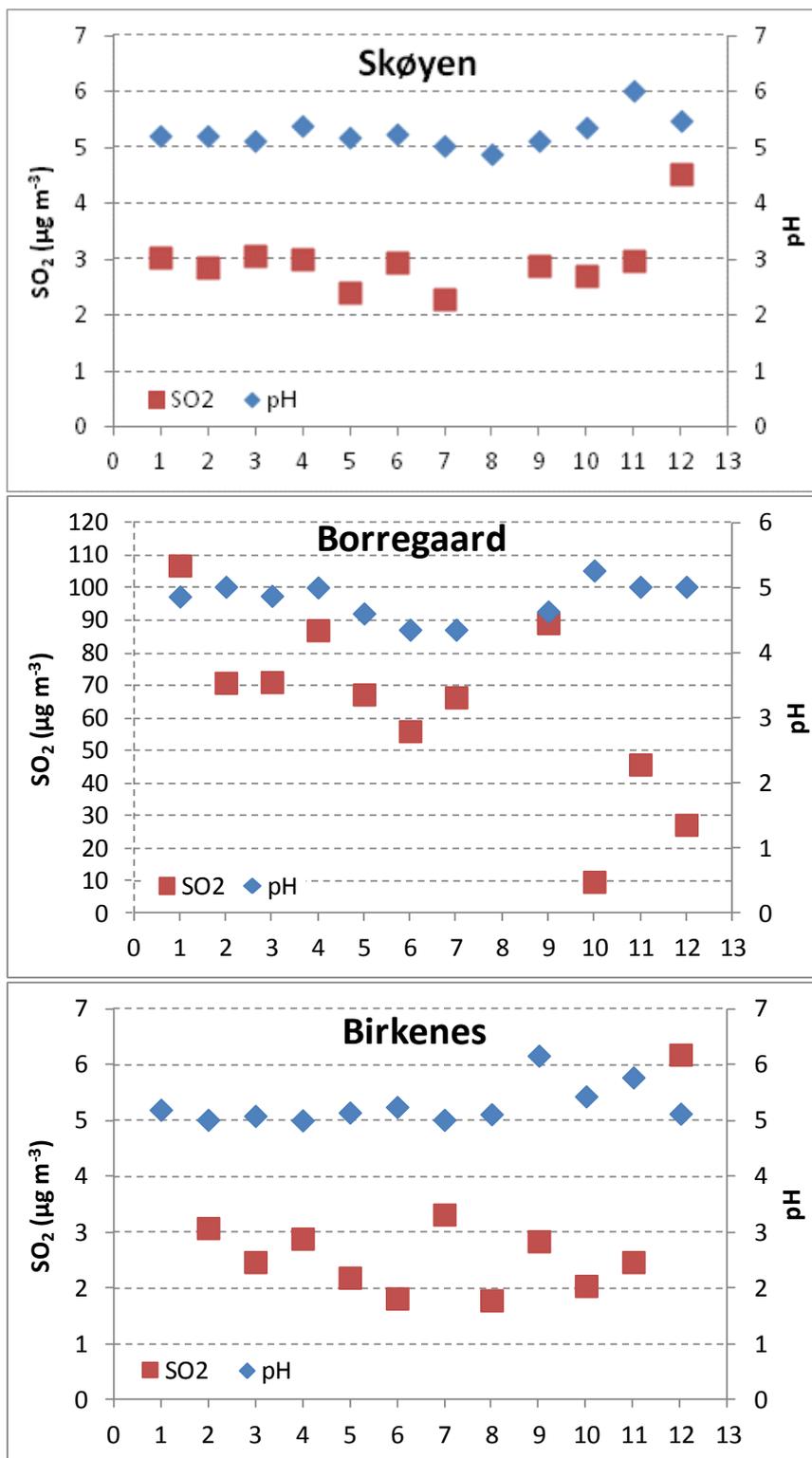
Figure 28: Contd.

Figure 29: *The concentration of SO₂ measured in the air and the pH measured in the aerosol washing water at the Skøyen, Borregaard, Birkenes and Tananger stations.*
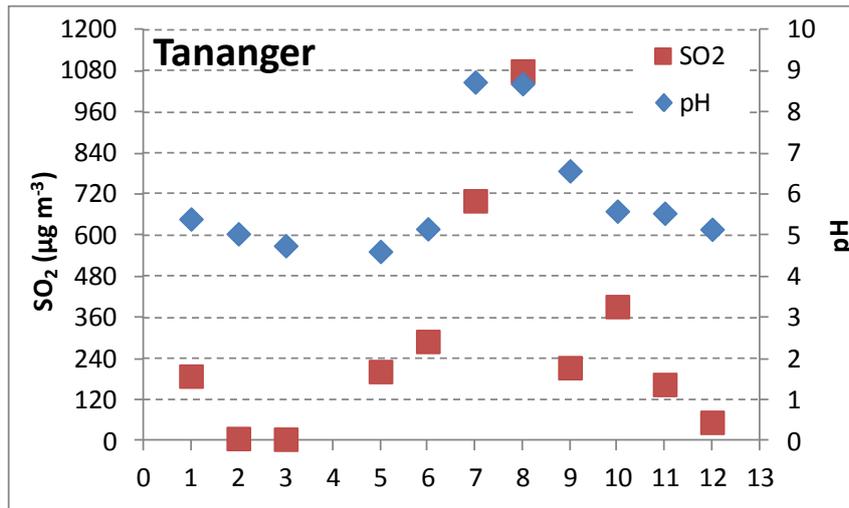
Figure 29:   Contd.

4.3   Climate

Table 8 shows the average annual values for climate parameters for the exposure period obtained from the nearest possible meteorological station with reported data in eKlima (2012)

Table 8:   Average annual values for climate parameters for the exposure period obtained from the nearest possible meteorological station.

	Distance from the field station km	Temperature oC	Precipitation mm
Oslo-Blindern (Skøyen)	3.5	7.7	988
Sarpsborg (Borregaard)	7	8.1	1122
Senumstad (Birkenes)	5	5	1743
Sola (Tananger)	9	9.1	1552

4.4   Analysis of pollution and climate effects on the corrosion rate

The pollution and climate effects on the corrosion rate were analysed by single parameter correlation of the measured pollution factors known to increase the corrosion rate of carbon steel with the measured weight loss of the carbon steel samples. The SO_2 concentration in air, and sulphate (SO4-S) content in the aerosol deposition, the chloride content in the aerosol deposition and the pH showed clear correlation with the carbon steel corrosion. The climate parameters showed no single parameter correlation with the corrosion rate, but the higher corrosion rate at Birkenes than at Skøyen, the two stations with the lowest corrosion, seemed to be explained by the higher precipitation at Birkenes rather than by the amount of pollution, which was higher at the Skøyen station. The Tananger station was omitted from the correlation analysis due to very high pollution values measured during some months which were most likely caused be direct sea spray (very large aerosol) hitting the passive pollution samplers, mostly in months 9 (September) to 1 (January) (Figure 29, Appendix 1, Table 1).

Figure 30 - Figure 32 show the correlation of the annual average values for the SO_2 concentration, chloride content in the aerosol deposition and pH with the carbon steel corrosion based on the values in Table 6 and Table 7.
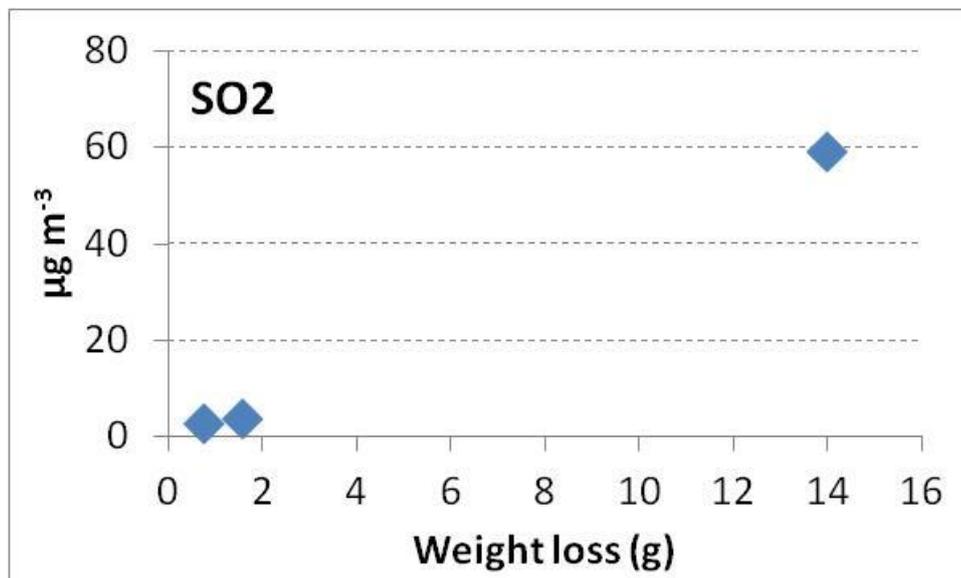
Figure 30:   Correlation of annual average values for the SO_2 concentration, and carbon steel corrosion.
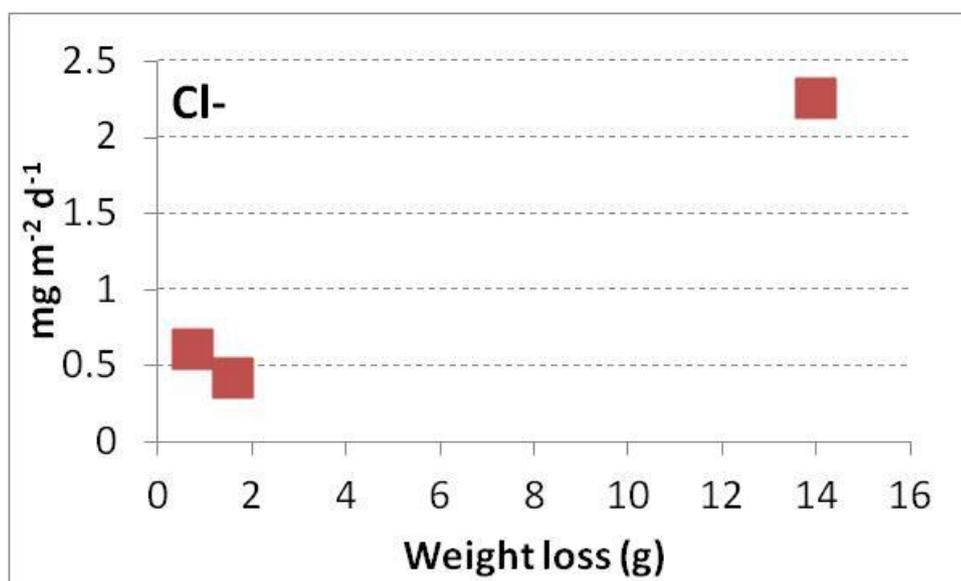
Figure 31:   Correlation of annual average values for chloride content in the aerosol deposition and carbon steel corrosion.
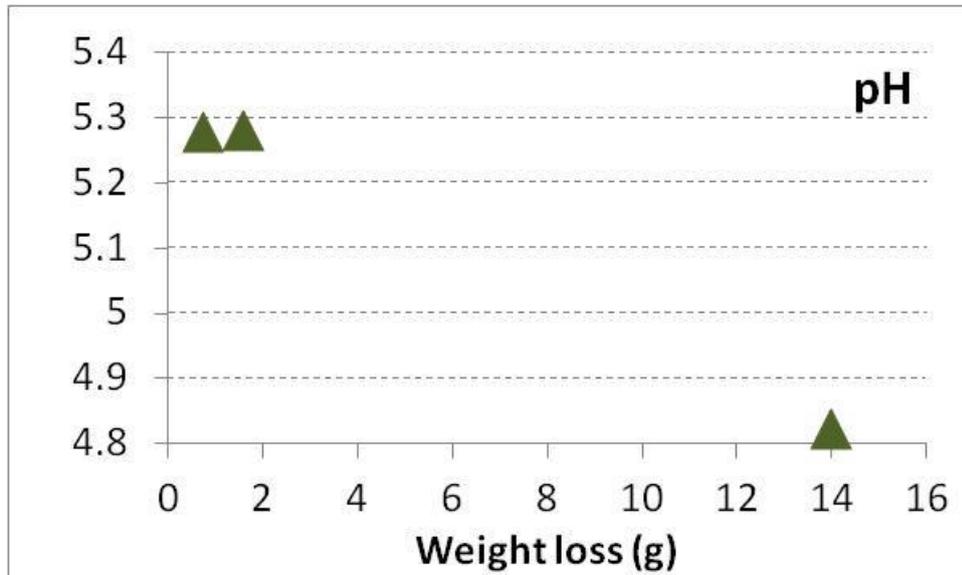
Figure 32: Correlation of annual average values for pH and the carbon steel corrosion.

Table 9 shows the ranking of pollution values, precipitation and corrosion rate between the Skøyen and Birkenes stations.

Table 9: Ranking of pollution values, precipitation and corrosion rate between the Skøyen and Birkenes stations. ">" means that the value for the station is the higher.

	Pollution	Precipitation	Corrosion rate
Birkenes		>	>
Skøyen	>		

A classification of the corrosion rates at the stations according to ISO 9223 (ISO 9223) gave the results shown in Table 10.

Table 10: The ISO 9223 corrosion class determined from the measured corrosion rate at the stations.

	Corrosion rate ($g\ m^{-2}\ year^{-1}$)	Class (1-5)	Description
Skøyen	24.8	2	Low
Borregaard	465.8	4	High
Birkenes	52.4	2	Low
Tananger	658.0	5	Very high

4.5 Analysis of corrosion crusts

The corrosion crusts were analysed by scanning electron microscopy with x-ray element analysis (SEM with EDX) performed by the Institute for Energy Technology at Kjeller, Norway. The powdered corrosion crust that had been scraped off the steel plates was used. High magnification images (x1000 to x2500) of the corrosion surfaces and electron count spectrums and tables for the weight % and atom % giving the elemental composition of the corrosion crusts, were obtained. The energy of the electron beam was set to a value to ensure that most of the x-ray scattering used for the element analysis originated from the corrosion crust powder and not from the carbon tape used for the mounting.

Table 11 shows an overview of the samples analysed with the Scanning Electron Microscopy and X-ray analysis.

Table 11: Samples analysed with the Scanning Electron Microscopy with X-ray element analysis.

No.	Station	Applied solution	Crust Upperside and Underside(U+L), Upperside(U), UNderside(L)
1	Skøyen	Water	U+L
2	Skøyen	MEA	U+L
3	Skøyen	DEA	U+L
4	Skøyen	AMP	U+L
5	Borregaard	Water	U
6	Borregaard	Water	L
7	Borregaard	MEA	U
8	Borregaard	MEA	L
9	Birkenes	Water	U+L
10	Birkenes	MEA	U+L

Figure 33 and Figure 34 show the high magnification (x2500) SEM image of the corrosion crust of sample no. 7 (Table 11) and the electron count spectrum for area no. 4 in the image. Table 12 shows the average weight % and atom % of the elements detected in the areas 1-4 in the image. At the Skøyen and Birkenes stations only iron and oxygen were detected in the samples. At Borregaard in addition sulphur was detected in all areas of analysis of the samples. Some carbon from the mounting substrate was observed in all the SEM measurements.

SEM analysis were not performed for the corrosion from the samples exposed at Tananger that had been subjected to sea spray.
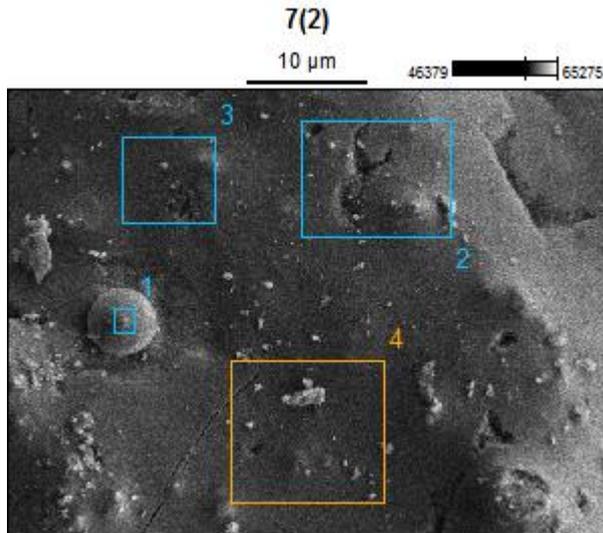
Image Name: 7(2)
Image Resolution: 512 by 384
Image Pixel Size: 0.10 µm
Acc. Voltage: 7.0 kV
Magnification: 2500

Figure 33:   High magnification (x2500) SEM image of the corrosion crust of sample no. 7 (Table 11).
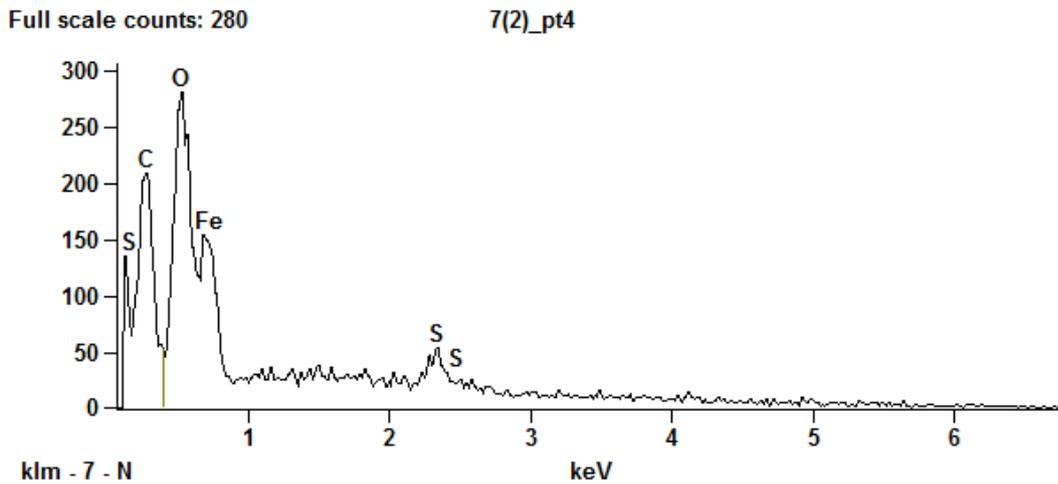
Figure 34:   Electron count spectrum for area no. 4 in the image (Figure 33).

Table 12:   *Average weight % and atom % of the elements detected in the areas 1-4 in the image, Figure 33.*

Weight %	C-K	O-K	S-K	Fe-L
7(2)_pt1	32.18	26.50	4.43	36.89
7(2)_pt2	20.15	30.57	3.07	46.21
7(2)_pt3	20.34	30.59	2.92	46.15
7(2)_pt4	18.75	31.76	3.07	46.42
Atom %	C-K	O-K	S-K	Fe-L
7(2)_pt1	52.19	32.26	2.69	12.87
7(2)_pt2	37.18	42.35	2.12	18.34
7(2)_pt3	37.44	42.28	2.01	18.27
7(2)_pt4	34.90	44.37	2.14	18.58

All the other images, spectrums and tables from the SEM analysis of the other samples in Table 11, similar to Figure 33 and Figure 34 and Table 12, are shown in Appendix no. 2.

5   Discussion - The corrosion potential of the atmosphere

The loads of amines (MEA, DEA and AMP) applied to steel and copper samples would according to modelling represent 10 years of maximum annual deposition and 700 times this load in the laboratory tests, and 65 years of maximum annual deposition in the field tests. The corrosion observed on the steel samples in the laboratory tests were in all cases smaller than the weight loss of clean uncorroded samples due to the corrosion layer stripping procedure and thus below the detection limit for this technique. The weight increase of the samples after exposures showed however a larger weight increase for the samples sprayed with only ion rinsed water than for those sprayed with an amine solution. This was the case both for samples exposed continuously to a fine spray of amine aerosol of the initial lower used concentration and dose and for samples exposed to the high load (700 times initial dose) of the amines (Figure 8 and Figure 10). This finding was confirmed by visual observation of the samples surfaces (Figure 11 to Figure 13). The likely explanation for this protection of the samples was that the amines formed a thin film on the surface that hindered the oxidation of the steel in contact with the atmosphere, i.e. anodic protection of the steel. When SO_2 was added to the airflow through the chamber an increased corrosion was observed on the samples (Figure 9), but no significant difference was observed between samples that were exposed to ion rinsed water and samples that were exposed to amine solution in the SO_2 containing atmosphere.

Very little change was observed on a dry copper sample exposed to the SO_2 containing atmosphere. When a high load of amine (DEA) solution, with pH = 10.7, was sprayed on a copper sample in the SO_2 containing atmosphere, significant dissolution of the copper occurred. When an amine (MEA) load, with pH = 7.7, representing an expected 10 years maximum outdoor exposure was sprayed on the sample, still in the SO_2 containing atmosphere, a significant weight increase was observed due to corrosion of the sample. When only ion rinsed water was sprayed on the sample exposed to the SO_2 containing atmosphere the corrosion rate was higher and a larger amount of corrosion was observed (Figure 14). The corrosion rate and thickness of the corrosion layer on the samples

correlated with the pH in the applied solution: At high amine load, giving a high pH, the copper was dissolved. The DEA solution running off the samples after spraying had a slightly reduced pH probably due to the acidic SO_2. When less of the alkaline amine was added to the samples in the acidic SO_2 containing atmosphere, giving a lower pH, a corrosion crust was established on the copper. When the copper was sprayed with only ion rinsed water in the SO_2 containing atmosphere, giving an even lower pH, a thicker corrosion layer was established. Probably, with the high application of amine the pH was sufficiently high for the copper to dissolve and for a copper amine complex to be established. At lower pH this copper amine complex was probably not established, but rather a sulphite or sulphate containing copper hydroxide or oxide (Graedel and Leygraf, 2000).

The results for the annual corrosion of the steel samples exposed on the four field stations did not show a significant difference in amount of corrosion between samples sprayed with the amine and samples sprayed with ion rinsed water (Figure 18 and Figure 19). However the results for the two stations with the highest corrosion, Birkenes and Borregaard (Figure 18) and the results for the samples that were demounted at Skøyen in the winter (15th January) after approximately nine months exposure (Figure 19) indicated a higher corrosion for the samples that were exposed to the amines. The amine solutions were sprayed at regular intervals to the steel sample surfaces that were shielded from washing by rain, and the amine solute probably accumulated on the surfaces to some extent. This would probably give some freezing point depression for surface water on the samples and increased time of wetting in the cold season with frost, and this could explain the increased measured corrosion in the winter time.

The corrosion products at the four stations had a different appearance (Figure 20 to Figure 25). The lowest corrosion was measured at the Skøyen station. The corrosion on the upper side had a dark reddish "spotted" appearance whereas little corrosion was observed on the underside. At the Birkenes station the measured corrosion rate was slightly higher than at Skøyen. The samples from Birkenes had the most even corrosion of the all the sites, with a light reddish corrosion layer on the upper side and a slightly darker corrosion layer with small spots on the underside. The samples from both Borregaard and Tananger had coarser corrosion layers, with the coarsest layers at Tananger. The upper sides were smother than the under sides. The undersides of the samples from Borregaard had large blackish areas where the corrosion seems to have loosened (Figure 25), where as the undersides of the samples from Tananger had coarse and thick layers that attached to the samples.

The SEM analysis showed only iron and oxygen in the samples from Skøyen and Birkenes, but in addition some sulphur in the samples from Borregaard. The relative atomic content (%) of iron and oxygen (Fe/O) was for all the samples approximately ½, which corresponds to iron(II) hydroxide, Fe $(OH)_2$, or some form of iron(III) oxide-hydroxide, x-FeOOH. The inclusion of SO_2 in the samples from Borregaard, in what could be $Fe(SO_4)nH_2O$ (Graedel and Leygraf, 2000), was measured from 1.8 to 4.5 atom % for three samples (one upper side and two under sides). The atom % of S in the corrosion from the underside of one sample was measured from $0.5 - 0.8$ %. The atmospheric corrosion processes that gives the iron oxides, hydroxides and sulphates are well known (e.g. Graedel and

Leygraf, 2000). As no nitrogen (which could indicate that the amines participated in the corrosion reactions) was detected, further examination of the exact mineralogical composition of the corrosion crusts was not performed.

Regarding the environmental measurements it should first be noted that an up to several hundred times higher annual concentration of SO_2 or amount of ions in deposited aerosol was measured at Tananger than at the other three stations (Table 7 and Figure 26). The monthly measured average concentrations of SO_2 and ions in deposited aerosol, except the nitrogen containing ions NO_3-N and NH_4-N (nitrogen in nitrate and ammonia), correlated over the year, with higher concentrations measured from September to March, and the highest concentrations measured from November to January (Figure 28 and Appendix no. 1). This is clearly seen in Figure 28 for the sodium and chloride ions, for which the values for the monthly averages correlates over the year. This is most probably explained by increased amount of sea spray in the winter and near winter months (Henriksen, 1989). The very high SO_2 concentration measured especially in November and December at Tananger is probably due to sea spray depositing on the passive SO_2 samplers and interfering with the analysis. The measured amounts of deposited ammonium at Tananger are much higher than at the other three stations, with the highest values in May, June, September and October. It seems there was a nearby source giving increased deposition of ammonium at Tananger in the spring and autumn. This source has not been identified. The pH was measured to be lowest among the four stations at Borregaard and highest at Tananger (Table 7 and Figure 26). The low pH at Borregaard can probably be explained by the higher measured deposition of acid related SO_4-S. In the three months, September to October, when the SO_4 deposition was the highest at Borregaard the pH was the lowest. The higher pH measured at Tananger correlates strongly with the higher sea salt and general aerosol (except nitrogen ions) deposition from October to January.

At Borregaard a considerably higher SO_2 concentration, deposition of SO_4-S, Cl^-, Na^+ and NH_4-N ions in aerosol, and lower pH was measured than at Skøyen. This is probably explained by industrial emissions from the Borregaard plants. The concentrations of deposited ions in aerosol measured at Skøyen were slightly higher than those measured at the rural station, Birkenes, but the annual average SO_2 concentration was measured to be slightly higher at Birkenes. The annual average pH was measured to be the same at both stations.

The annual average annual temperature at the meteorological stations close to the exposure sites varied from 5°C at Senumstad (Birkenes) to 9°C at Sola (Tananger). The annual average precipitation varied from 988 mm at Oslo-Blindern (Skøyen) to 1743 mm at Senumstad (Birkenes) (Table 8). The measured weight loss due to corrosion was much higher at Tananger and Borregaard than at Birkenes and Skøyen. The higher corrosion at Tananger and Borregaard is explained by the higher impact from SO_2 and especially chloride ions, which are well known to increase corrosion of carbon steel (Graedel and Leygraf, 2000). The highest corrosion was measured at Tananger which had the highest loads (Figure 18). The higher temperature at Tananger, than any of the other three stations, and high precipitation have contributed to the high corrosion at Tananger. The samples from Borregaard lost much of their corrosion crust before

weighing (Figure 17). This may indicate a different morphology and looser corrosion layer on these samples. The slightly higher corrosion that was measured at the Birkenes station as compared to the Skøyen station, where the load of ions in aerosol was measured to be slightly higher (Table 7), may be due to the higher precipitation measured at Birkenes (Table 8) and to a slightly higher concentration of SO_2 (Table 7).

6 Conclusion

6.1 Steel

For an initial amine load representing 10 years maximum "real" exposure applied to steel samples in the laboratory **no difference in corrosion** was observed between samples exposed to amine and the blanks, i.e. samples that were only sprayed with ion rinsed water.

For amine aerosol continuously sprayed on the steel samples and for an amine load representing 700 times the initial dose (100 times the initial concentration applied every day) applied to the samples in the laboratory **a reduced corrosion** was observed for samples exposed to amine compared to the blanks.

The likely reason for reduced corrosion of the samples exposed to the high load of amine in the laboratory was anodic protection of the samples, i.e. the formation of a protective surface film.

For an amine load representing 65 years maximum "real" exposure applied to steel samples in the field **a slight increase in the annual corrosion** was observed for samples with a high corrosion rate (ISO class 4 and 5) and for samples with a lower corrosion rate (ISO class 2) that were demounted in the winter, as compared to the blanks, i.e. samples that were only sprayed with ion rinsed water.

The likely reason for the slightly increased corrosion of the samples exposed to the amine in the field was freezing point depression in the winter due to the applied amine solution.

6.2 Copper

A significant dissolution of a copper sample exposed to high concentration and dose of DEA was observed.

The likely reason for the dissolution of copper was the high pH (10.7) of the DEA solution and the formation of a soluble Cu-amine complex.

A reduction in the corrosion of copper samples exposed to SO_2, and ion rinsed water, was observed when the samples was exposed to a MEA solution.

The likely reason for the protection of copper exposed to SO_2 was the reduction of the SO_2 induced surface acidity due to the application of the MEA solution, and thus of the corrosivity of the environment.

7 References

Berglen, T. F., Tønnesen, D., Dye, C., Karl, M., Knudsen, S. and Tarrason, L. (2010) CO2 Technology Centre Mongstad − updated air dispersion calculations. Update of OR 12/2008. Kjeller, NILU (NILU OR 41/2010).

Botheju, Deshai (2006) Nature, composition and disposal/treatment options of amine degradation wastes generated in post-combustion CO_2 facilities. Report on literature survey. Porsgrunn, Norway, Hydro, Statoil, Skagerak Energi, Norcem, NOAH, NVE (Tel-Tek report no. 2206040-1).

Karl, M., Lopez-Aparicio, S. (2010) Test of the NILU fog chamber as experiment reactor for droplet growth. Kjeller, NILU (NILU OR 58/2010).

eKlima (2012) Meteorologisk institutts klimadatabase. URL: eklima.met.no [Accessed 12 December 2012]

Ferm, M. (1991) A sensitive diffusional sampler. Stockholm, IVL, Swedish Environmental Research Institute (IVL B-1020).

Graedel, T.E., Leygraf, C. (2000) Atmospheric corrosion. John Wiley & Sons, New York (Electrochemical Society Series).

Henriksen, J.F. (1989) Salt- og korrosjonsmålinger på Haugsneset i Tysvær. Kjeller, NILU (NILU OR 21/89).

ISO 9223 (1992) Corrosion of metals and alloys − Corrosivity atmospheres − Classification. First edition, 1992-02-15. Geneva, Switzerland, International Organization for Standardization.

Kucera, V. (2005) EU 5FP RTD Project. Model for multi-pollutant impact and assessment of threshold levels for cultural heritage. Contract no. EVK4-CT-2001-00044. Deliverable 0.2. Publishable final report. Available from: URL: http://www.corr-institute.se/MULTI-ASSESS/web/page.aspx?refid=12 [Accessed 4 March 2013].

Rosenberg, E., De Santis, F., Konotozova-Deutsch, V., Odlyha, M., van Grieken, R., Vichi, F. (2010) Measuring gaseous and particulate pollutants. Instruments and instrumental methods. Chapter 9. In: *Basic environmental mechanisms affecting cultural heritage. Understanding deterioration mechanisms for conservation purposes.* Ed. by: Camuffo, D., Fassina V., Havermans, J. Firenze, Nardini Editore.

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Appendix A

The values for the measured SO₂ concentration in air, pH and the deposited aerosol in mg m⁻²d⁻¹ for the four stations Skøyen, Borregaard, Birkenes and Tananger

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Table 1: The values for the measured SO_2 concentration in air, pH and the deposited aerosol in mg m^{-2}d^{-1} for the four stations Skøyen, Borregaard, Birkenes and Tananger.

Skøyen	SO2	stdv	pH	Cl	NO3-N	SO4-S	Na	NH4-N	K	Mg	Ca
Month	(µg m-3)			mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1
5	3.0	0.0	5.2	0.479	0.094	0.132	0.231	0.001	0.360	0.056	0.289
6	2.8	0.1	5.2	0.204	0.073	0.041	0.134	0.002	0.115	0.026	0.143
7	3.1	0.1	5.1	0.232	0.080	0.033	0.123	0.002	0.116	0.018	0.098
8	3.0	0.4	5.4	0.326	0.002	0.002	0.210	0.002	0.161	0.039	2.340
9	2.4	0.3	5.2	0.156	0.054	0.032	0.112	0.002	0.041	0.019	0.092
10	2.9	0.1	5.3	0.588	0.156	0.094	0.308	0.002	0.144	0.039	0.288
11	2.3	0.2	5.1	1.642	0.392	0.399	0.443	0.338	0.150	0.080	0.536
12			4.9	0.281	0.018	0.042	0.207	0.002	0.032	0.035	0.130
1	2.9	0.0	5.1	0.673	0.035	0.060	0.386	0.130	0.018	0.014	0.046
2	2.7	0.2	5.4	1.358	0.070	0.134	0.851	0.159	0.092	0.029	0.112
3	3.0	0.1	6.0	0.917	0.045	0.041	0.556	0.026	0.026	0.023	0.132
4	4.5	0.6	5.5	0.515	0.068	0.053	0.308	0.002	0.083	0.023	0.109
AVERAGE	3.0	0.2	5.3	0.614	0.091	0.088	0.322	0.056	0.111	0.033	0.360

Borregaard Month	SO2 (µg m-3)	stdv	pH	Cl mg m-2 d-1	NO3-N mg m-2 d-1	SO4-S mg m-2 d-1	Na mg m-2 d-1	NH4-N mg m-2 d-1	K mg m-2 d-1	Mg mg m-2 d-1	Ca mg m-2 d-1
5	106.9	18.8	4.9	3.146	0.119	0.747	0.488	0.842	0.102	0.070	0.431
6	70.9	4.7	5.0	1.407	0.095	0.502	0.414	0.565	0.049	0.046	0.421
7	71.1	6.9	4.9	0.523	0.068	0.326	0.197	0.115	0.044	0.027	0.207
8	87.0	14.3	5.0	0.904	0.065	0.451	0.364	0.378	0.051	0.032	0.262
9	67.3	2.2	4.6	3.871	0.149	1.754	1.223	1.841	0.149	0.140	0.386
10	56.0	0.4	4.4	4.411	0.181	2.230	1.893	1.953	0.111	0.191	0.614
11	66.4	5.2	4.4	4.411	0.181	2.230	1.893	1.953	0.111	0.191	0.614
12											
1	89.2	15.2	4.6	1.110	0.092	0.866	0.441	0.784	0.044	0.034	0.224
2	9.6	11.0	5.3	1.724	0.109	1.293	0.567	1.477	0.081	0.048	0.384
3	45.7	0.6	5.0	1.701	0.109	0.905	0.463	0.986	0.042	0.049	0.396
4	27.2	9.1	5.0	1.701	0.109	0.905	0.463	0.986	0.042	0.049	0.396
AVERAGE	63.4	8.0	4.8	2.264	0.116	1.110	0.764	1.080	0.075	0.080	0.394

Birkenes	SO2	stdv	pH	Cl	NO3-N	SO4-S	Na	NH4-N	K	Mg	Ca
5	17.0	0.7	5.2	0.387	0.028	0.019	0.217	0.002	0.105	0.028	0.090
6	3.1	0.1	5.0	0.158	0.002	0.002	0.067	0.002	0.056	0.011	0.042
7	2.5	0.2	5.1	0.227	0.002	0.002	0.119	0.002	0.041	0.020	0.048
8	2.9	0.3	5.0	0.394	0.024	0.027	0.309	0.002	0.031	0.041	0.081
9	2.2	0.3	5.2	0.458	0.002	0.020	0.302	0.002	0.051	0.037	0.064
10	1.8	0.1	5.3	0.601	0.126	0.044	0.377	0.002	0.098	0.054	0.166
11	3.3	0.6	5.0	0.744	0.084	0.053	0.435	0.002	0.109	0.063	0.123
12	1.8	0.0	5.1	0.754	0.024	0.044	0.485	0.002	0.166	0.051	0.085
1	2.8	0.6	6.2	0.322	0.002	0.014	0.241	0.002	0.024	0.034	0.054
2	2.0	0.1	5.4	0.327	0.033	0.018	0.174	0.002	0.080	0.011	0.029
3	2.5	0.5	5.8	0.465	0.048	0.010	0.282	0.024	0.234	0.003	0.020
4	6.2	0.0	5.1	0.195	0.045	0.020	0.115	0.003	0.040	0.005	0.060
AVERAGE	4.0	0.3	5.3	0.419	0.035	0.023	0.260	0.004	0.086	0.030	0.072

Tananger	SO2	stdv	pH	Cl	NO3-N	SO4-S	Na	NH4-N	K	Mg	Ca
Month	(µg m-3)			mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1	mg m-2 d-1
5	189.5	136.3	5.4	174.812	0.686	7.705	94.364	10.591	3.391	11.100	4.277
6	7.4	6.8	5.0	54.989	0.876	2.458	27.121	117.107	6.551	3.632	1.660
7	5.3	0.1	4.8	38.583	0.635	2.585	19.853	0.123	0.659	1.996	0.944
8											
9	202.8	220.1	4.6	107.766	0.697	4.877	62.047	19.917	5.004	8.128	3.639
10	290.6	408.6	5.2	224.264	0.431	10.230	127.258	84.839	8.839	15.215	6.106
11	701.0	92.9	8.7	506.105	1.198	26.140	358.109	0.002	15.828	47.182	27.322
12	1079.9	457.9	8.7	697.364	0.054	40.432	477.026	0.002	39.858	62.179	47.511
1	214.1	192.9	6.6	420.906	1.060	23.458	237.231	0.002	8.970	28.669	20.657
2	392.4	287.3	5.6	28.339	0.080	1.361	16.343	0.002	0.639	1.959	0.697
3	165.0	49.6	5.5	29.629	0.274	1.056	17.148	0.628	0.985	1.702	0.688
4	54.6	27.4	5.2	42.019	0.149	1.806	22.311	0.002	0.930	2.536	0.967
AVERAGE	300.2	170.9	5.9	211.343	0.558	11.101	132.619	21.201	8.332	16.754	10.406

Table 2: The values for the deposited aerosol in mol atomic charge*1000 m^{-2}d^{-1} for the four stations Skøyen, Borregaard, Birkenes and Tananger.

Skøyen	HCO3(missing anions)	Cl	NO3-N	SO4-S	Na	NH4-N	K	Mg	Ca
Month	(Mol atomic charge*1000 /m2 d)								
5	0.0099	0.0135	0.0067	0.0082	0.0100	0.0001	0.0092	0.0046	0.0144
6	0.0046	0.0058	0.0052	0.0026	0.0058	0.0001	0.0029	0.0021	0.0072
7	0.0006	0.0066	0.0057	0.0020	0.0054	0.0001	0.0030	0.0015	0.0049
8	0.1239	0.0092	0.0001	0.0001	0.0092	0.0001	0.0041	0.0032	0.1167
9	0.0020	0.0044	0.0039	0.0020	0.0049	0.0001	0.0011	0.0016	0.0046
10	0.0013	0.0166	0.0111	0.0058	0.0134	0.0001	0.0037	0.0032	0.0144
11	-0.0187	0.0463	0.0280	0.0249	0.0193	0.0241	0.0038	0.0066	0.0267
12	0.0075	0.0079	0.0013	0.0026	0.0090	0.0001	0.0008	0.0029	0.0065
1	0.0047	0.0190	0.0025	0.0037	0.0168	0.0093	0.0004	0.0012	0.0023
2	0.0070	0.0383	0.0050	0.0084	0.0370	0.0114	0.0024	0.0024	0.0056
3	0.0035	0.0259	0.0032	0.0026	0.0242	0.0019	0.0007	0.0019	0.0066
4	0.0003	0.0145	0.0048	0.0033	0.0134	0.0001	0.0021	0.0019	0.0054
Average	0.0122	0.0173	0.0065	0.0055	0.0140	0.0040	0.0029	0.0027	0.0179

Borregaard	HCO3(missing anions)	Cl	NO3-N	SO4-S	Na	NH4-N	K	Mg	Ca
5	-0.0327	0.0887	0.0085	0.0466	0.0212	0.0601	0.0026	0.0058	0.0215
6	0.0066	0.0397	0.0068	0.0313	0.0180	0.0403	0.0013	0.0038	0.0210
7	-0.0094	0.0147	0.0048	0.0203	0.0086	0.0082	0.0011	0.0022	0.0103
8	0.0016	0.0255	0.0046	0.0281	0.0158	0.0270	0.0013	0.0027	0.0131
9	-0.0100	0.1092	0.0106	0.1094	0.0532	0.1315	0.0038	0.0115	0.0193
10	-0.0055	0.1244	0.0129	0.1391	0.0823	0.1394	0.0028	0.0157	0.0306
11	-0.0055	0.1244	0.0129	0.1391	0.0823	0.1394	0.0028	0.0157	0.0306
12	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1	-0.0016	0.0313	0.0065	0.0540	0.0192	0.0560	0.0011	0.0028	0.0112
2	0.0181	0.0486	0.0078	0.0807	0.0247	0.1054	0.0021	0.0039	0.0191
3	0.0032	0.0480	0.0078	0.0564	0.0201	0.0704	0.0011	0.0040	0.0198
4	0.0032	0.0480	0.0078	0.0564	0.0201	0.0704	0.0011	0.0040	0.0198
Average	-0.0029	0.0639	0.0083	0.0692	0.0332	0.0771	0.0019	0.0066	0.0197

Birkenes	HCO3(missing anions)	Cl	NO3-N	SO4-S	Na	NH4-N	K	Mg	Ca
5	0.0049	0.0109	0.0020	0.0012	0.0094	0.0001	0.0027	0.0023	0.0045
6	0.0027	0.0045	0.0001	0.0001	0.0029	0.0001	0.0014	0.0009	0.0021
7	0.0037	0.0064	0.0001	0.0001	0.0052	0.0001	0.0010	0.0017	0.0024
8	0.0073	0.0111	0.0017	0.0017	0.0134	0.0001	0.0008	0.0034	0.0041
9	0.0065	0.0129	0.0001	0.0013	0.0131	0.0001	0.0013	0.0031	0.0032
10	0.0031	0.0169	0.0090	0.0028	0.0164	0.0001	0.0025	0.0045	0.0083
11	0.0029	0.0210	0.0060	0.0033	0.0189	0.0001	0.0028	0.0052	0.0061
12	0.0082	0.0213	0.0017	0.0028	0.0211	0.0001	0.0043	0.0042	0.0042
1	0.0067	0.0091	0.0001	0.0008	0.0105	0.0001	0.0006	0.0028	0.0027
2	-0.0006	0.0092	0.0023	0.0011	0.0076	0.0001	0.0020	0.0009	0.0014
3	0.0041	0.0131	0.0034	0.0006	0.0123	0.0017	0.0060	0.0003	0.0010
4	-0.0004	0.0055	0.0032	0.0013	0.0050	0.0002	0.0010	0.0004	0.0030
Average	0.0041	0.0118	0.0025	0.0014	0.0113	0.0003	0.0022	0.0025	0.0036

Tananger	HCO3(missing anions)	Cl	NO3-N	SO4-S	Na	NH4-N	K	Mg	Ca
5	0.6135	4.9308	0.0490	0.4806	4.1046	0.7561	0.0867	0.9131	0.2134
6	8.3226	1.5510	0.0625	0.1533	1.1797	8.3606	0.1675	0.2988	0.0828
7	-0.1944	1.0883	0.0453	0.1612	0.8635	0.0088	0.0169	0.1642	0.0471
8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
9	1.7054	3.0397	0.0497	0.3042	2.6989	1.4219	0.1280	0.6686	0.1816
10	6.3802	6.3257	0.0308	0.6381	5.5354	6.0569	0.2261	1.2517	0.3047
11	5.2350	14.2754	0.0855	1.6305	15.5767	0.0001	0.4048	3.8814	1.3633
12	7.0587	19.6701	0.0039	2.5220	20.7493	0.0001	1.0193	5.1151	2.3708
1	0.5265	11.8722	0.0756	1.4632	10.3189	0.0001	0.2294	2.3584	1.0308
2	0.0334	0.7993	0.0057	0.0849	0.7109	0.0001	0.0163	0.1612	0.0348
3	0.0691	0.8357	0.0196	0.0659	0.7459	0.0448	0.0252	0.1400	0.0343
4	-0.0573	1.1852	0.0107	0.1126	0.9705	0.0001	0.0238	0.2086	0.0483
Average	2.4744	5.4645	0.0365	0.6347	5.2879	1.3875	0.1953	1.2634	0.4760

Appendix B

Results from SEM analysis performed by the Institute for Energy Technology, Kjeller, Norway
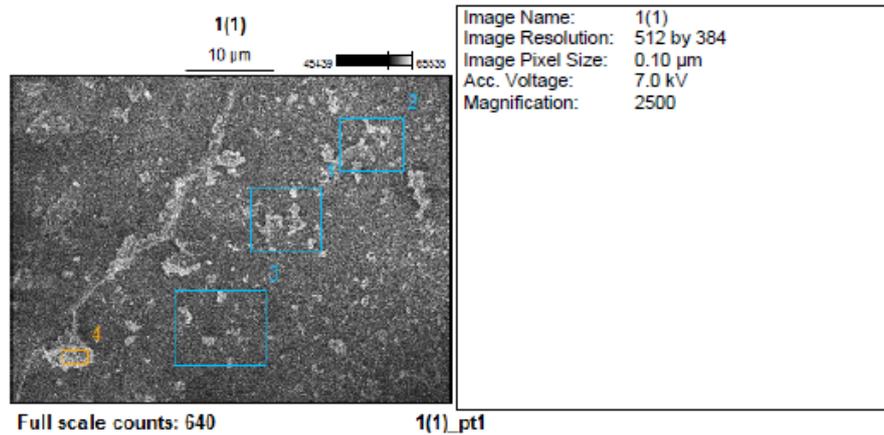
76

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

ifₑ

1(1)

10 μm   45439 ▬▬ 65535

Image Name:	1(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.10 μm
Acc. Voltage:	7.0 kV
Magnification:	2500

Full scale counts: 640   **1(1)_pt1**

klm - 7 - N   keV

Full scale counts: 639   **1(1)_pt2**

klm - 7 - N   keV

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78
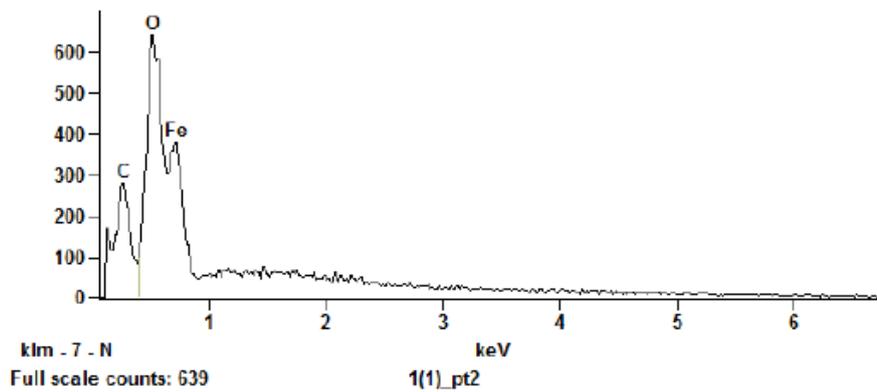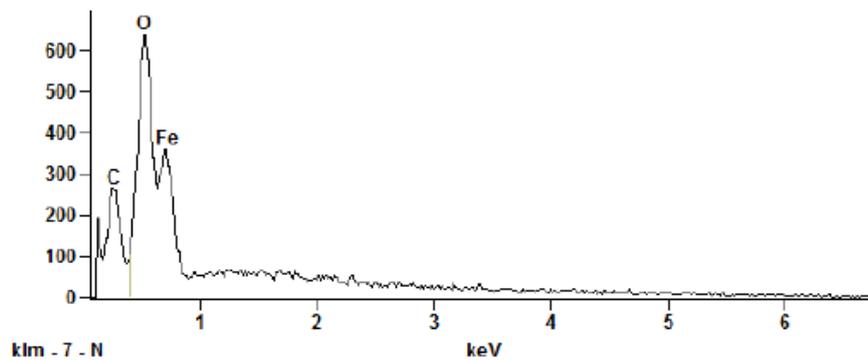
Full scale counts: 576   1(1)_pt3
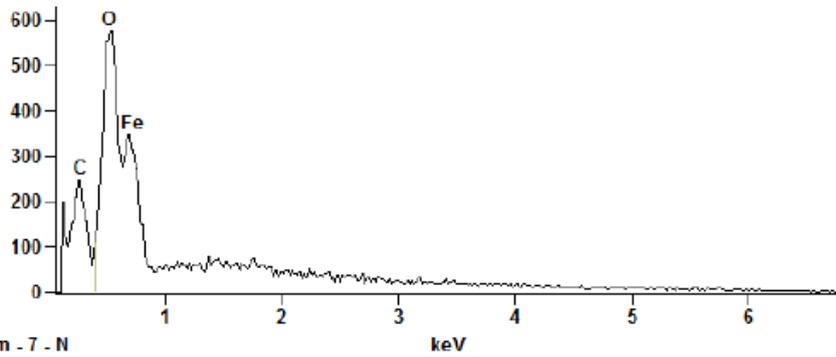
klm - 7 - N

Full scale counts: 433   1(1)_pt4

klm - 7 - N
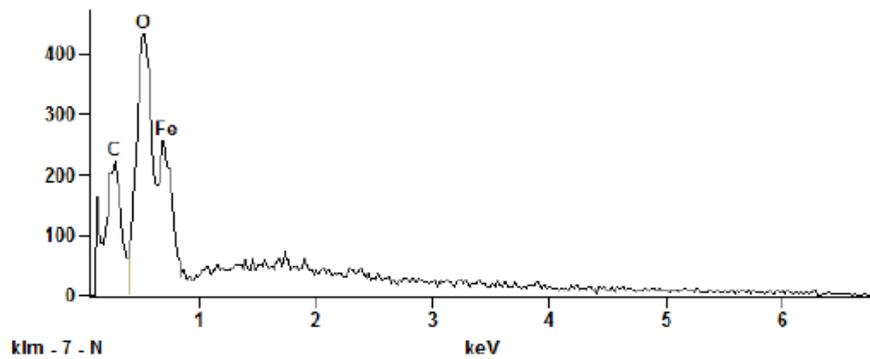
Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Weight %

	C-K	O-K	Fe-L
1(1)_pt1	11.29	33.47	55.25
1(1)_pt2	14.03	35.93	50.03
1(1)_pt3	11.25	33.16	55.59
1(1)_pt4	12.75	34.92	52.33

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
1(1)_pt1	+/-0.47	+/-1.29	+/-2.46
1(1)_pt2	+/-0.58	+/-0.77	+/-1.73
1(1)_pt3	+/-0.48	+/-1.03	+/-2.31
1(1)_pt4	+/-0.60	+/-1.49	+/-2.91

Atom %

	C-K	O-K	Fe-L
1(1)_pt1	23.37	52.02	24.60
1(1)_pt2	27.10	52.11	20.79
1(1)_pt3	23.39	51.75	24.86
1(1)_pt4	25.39	52.20	22.41

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
1(1)_pt1	+/-0.97	+/-2.00	+/-1.09
1(1)_pt2	+/-1.12	+/-1.11	+/-0.72
1(1)_pt3	+/-1.00	+/-1.61	+/-1.03
1(1)_pt4	+/-1.20	+/-2.22	+/-1.24

80

IFE

2(1)

25 µm

49643 ▬▬▬ 65535

Image Name:	2(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.20 µm
Acc. Voltage:	7.0 kV
Magnification:	1200
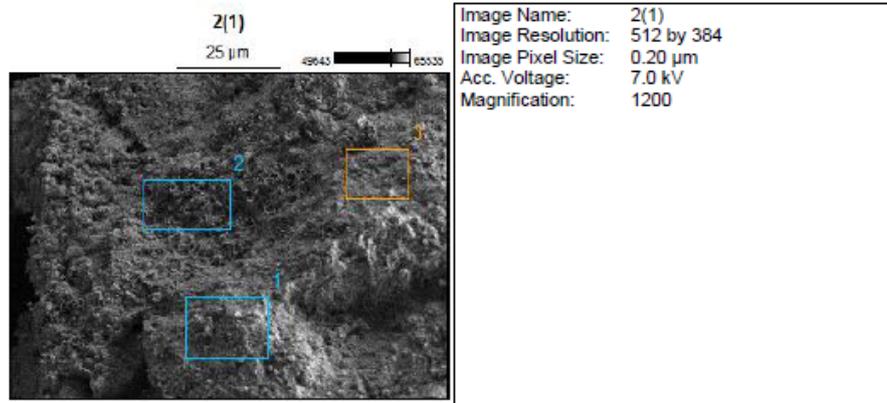
Full scale counts: 485   2(1)_pt1

klm - 7 - N   keV
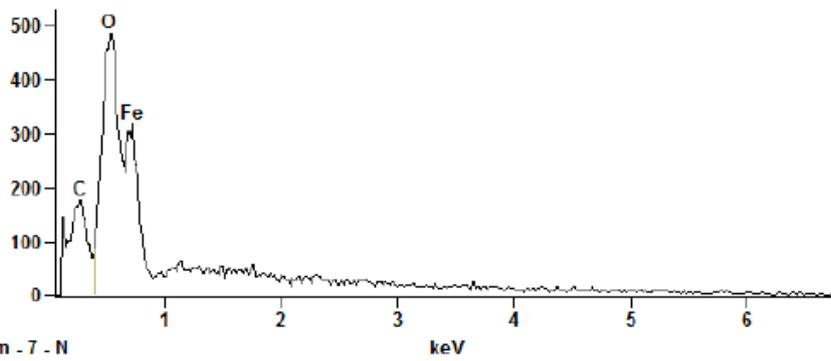
Full scale counts: 486   2(1)_pt2

klm - 7 - N   keV

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

IFE
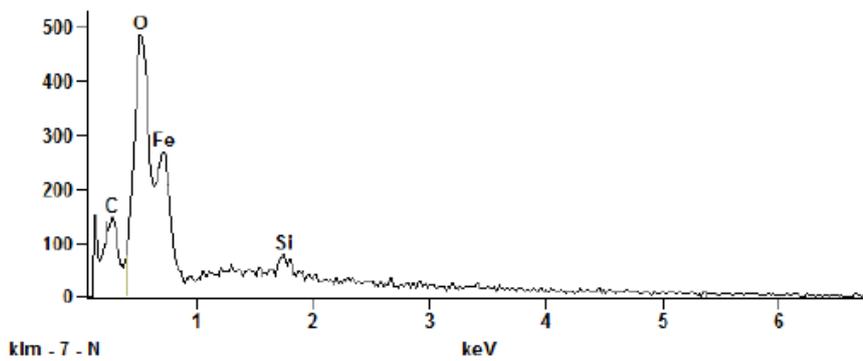
Full scale counts: 507   2(1)_pt3

klm - 7 - N   keV
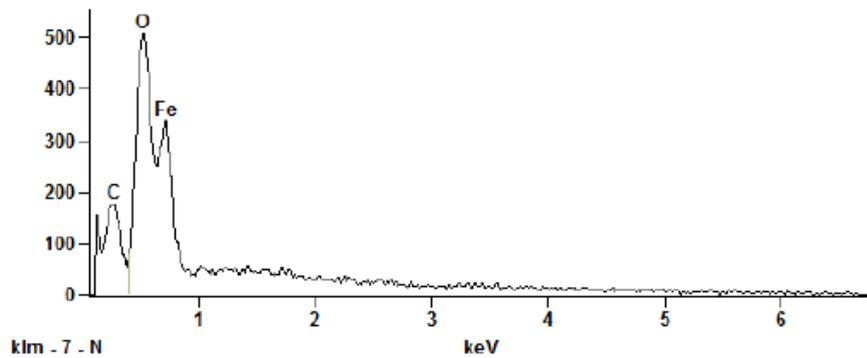
Weight %

	C-K	O-K	Si-K	Fe-L
2(1)_pt1	10.87	33.72		55.41
2(1)_pt2	9.02	33.57	1.20	56.22
2(1)_pt3	11.21	31.42		57.36

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Si-K	Fe-L
2(1)_pt1	+/-0.55	+/-1.60		+/-2.91
2(1)_pt2	+/-0.58	+/-0.74	+/-0.14	+/-2.82
2(1)_pt3	+/-0.54	+/-0.69		+/-2.59

Atom %

	C-K	O-K	Si-K	Fe-L
2(1)_pt1	22.60	52.62		24.77
2(1)_pt2	19.27	53.82	1.09	25.82
2(1)_pt3	23.78	50.05		26.17

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Si-K	Fe-L
2(1)_pt1	+/-1.13	+/-2.50		+/-1.30
2(1)_pt2	+/-1.24	+/-1.18	+/-0.13	+/-1.30
2(1)_pt3	+/-1.15	+/-1.11		+/-1.18

82

IFE

3(1)

25 µm

47111 ◼◼◼ 62771

Image Name:	3(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.24 µm
Acc. Voltage:	7.0 kV
Magnification:	1000

Full scale counts: 354   3(1)_pt1

klm - 7 - N   keV

Full scale counts: 327   3(1)_pt2

klm - 7 - N   keV
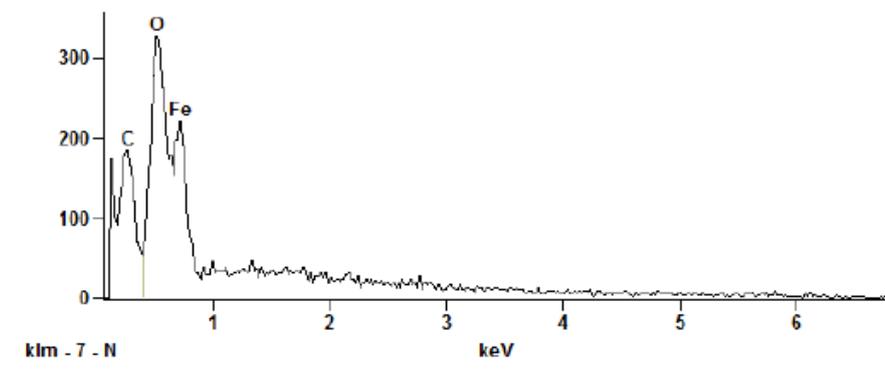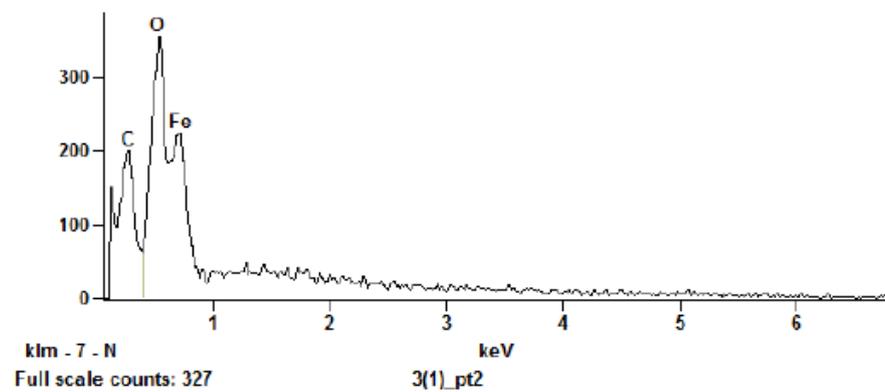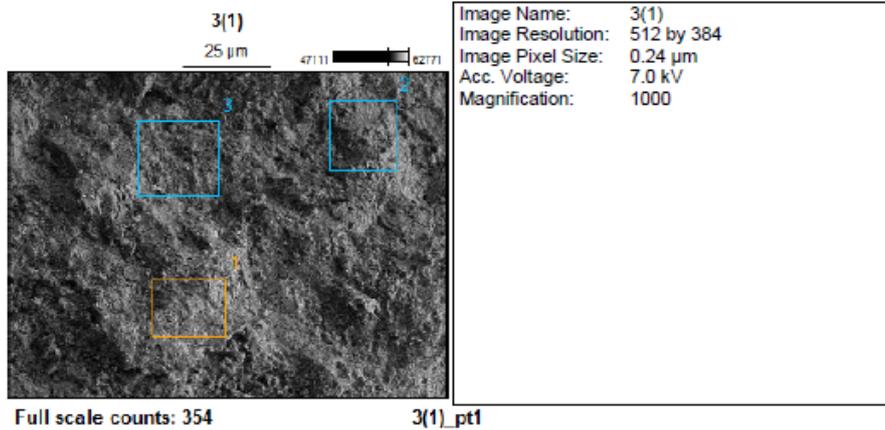
Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Full scale counts: 320   3(1)_pt3

klm - 7 - N   keV
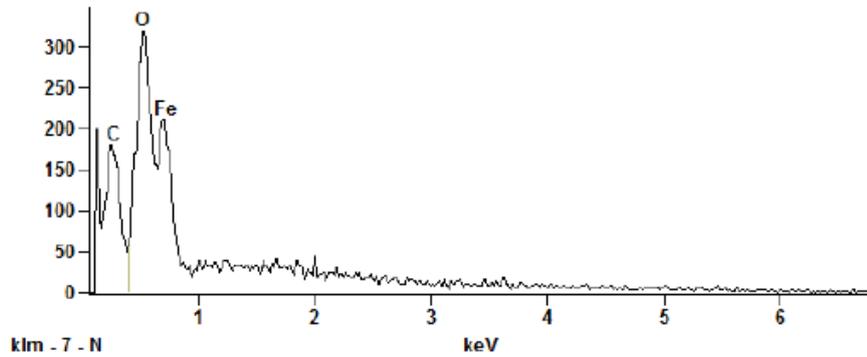
Weight %

	C-K	O-K	Fe-L
3(1)_pt1	16.03	30.13	53.84
3(1)_pt2	15.57	31.17	53.26
3(1)_pt3	15.89	29.03	55.09

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
3(1)_pt1	+/-0.77	+/-1.67	+/-3.01
3(1)_pt2	+/-0.76	+/-1.59	+/-2.91
3(1)_pt3	+/-0.84	+/-0.98	+/-3.18

Atom %

	C-K	O-K	Fe-L
3(1)_pt1	31.92	45.03	23.05
3(1)_pt2	30.88	46.40	22.71
3(1)_pt3	32.07	44.00	23.92

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
3(1)_pt1	+/-1.53	+/-2.50	+/-1.29
3(1)_pt2	+/-1.50	+/-2.37	+/-1.24
3(1)_pt3	+/-1.70	+/-1.48	+/-1.38

84

4(2)

25 µm

Image Name:	4(2)
Image Resolution:	512 by 384
Image Pixel Size:	0.24 µm
Acc. Voltage:	7.0 kV
Magnification:	1000

Full scale counts: 195

4(2)_pt1

klm - 7 - N

keV
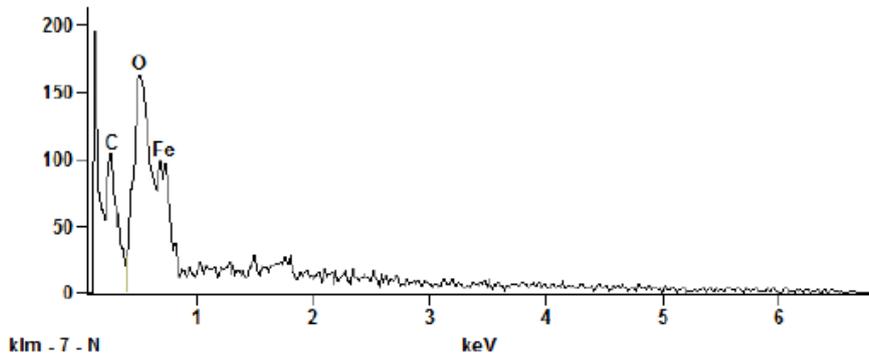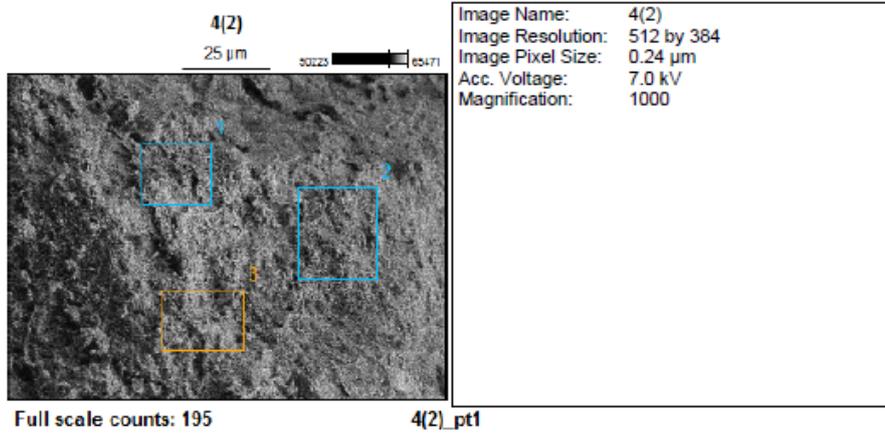
Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Full scale counts: 181   4(2)_pt2

klm - 7 - N   keV
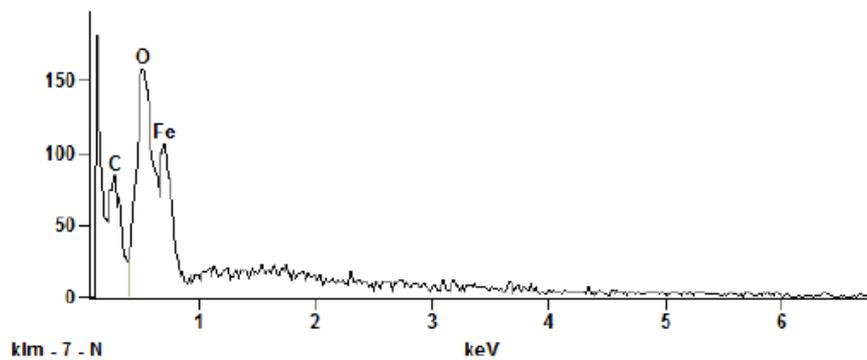
Full scale counts: 150   4(2)_pt3

klm - 7 - N   keV

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86
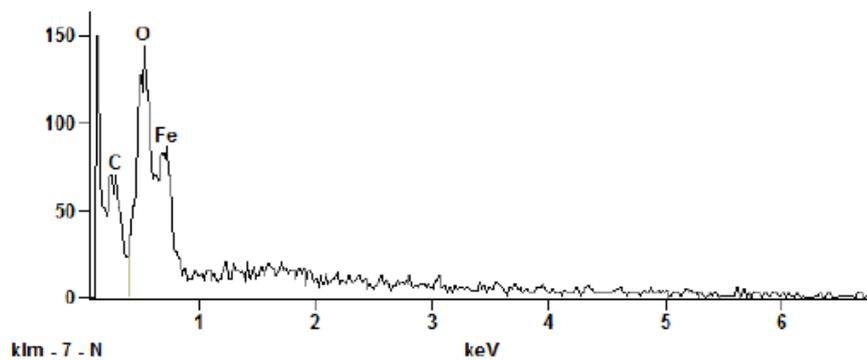
Ife

Weight %

	C-K	O-K	Fe-L
4(2)_pt1	11.63	28.44	59.93
4(2)_pt2	10.74	27.52	61.74
4(2)_pt3	12.68	28.81	58.51

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
4(2)_pt1	+/-1.41	+/-2.23	+/-4.10
4(2)_pt2	+/-1.34	+/-2.15	+/-3.96
4(2)_pt3	+/-1.63	+/-2.64	+/-4.80

Atom %

	C-K	O-K	Fe-L
4(2)_pt1	25.36	46.55	28.10
4(2)_pt2	24.03	46.24	29.72
4(2)_pt3	27.04	46.12	26.84

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
4(2)_pt1	+/-3.07	+/-3.65	+/-1.92
4(2)_pt2	+/-3.01	+/-3.61	+/-1.91
4(2)_pt3	+/-3.47	+/-4.22	+/-2.20

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

5(1)

10 µm

Image Name:	5(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.10 µm
Acc. Voltage:	7.0 kV
Magnification:	2500

Full scale counts: 500   5(1)_pt1

klm - 7 - N

Full scale counts: 572   5(1)_pt2

klm - 7 - N

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88

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

IFE
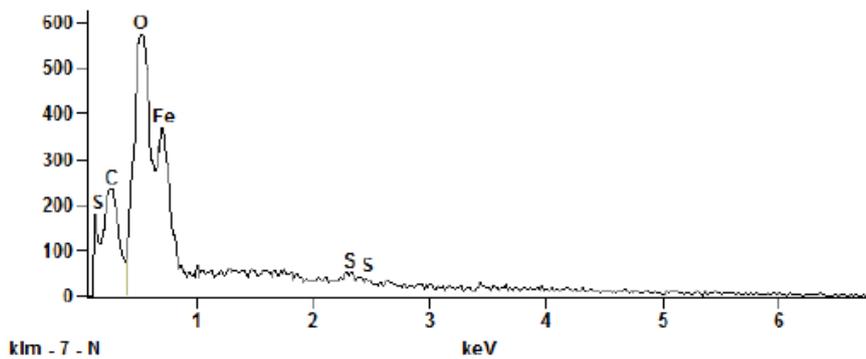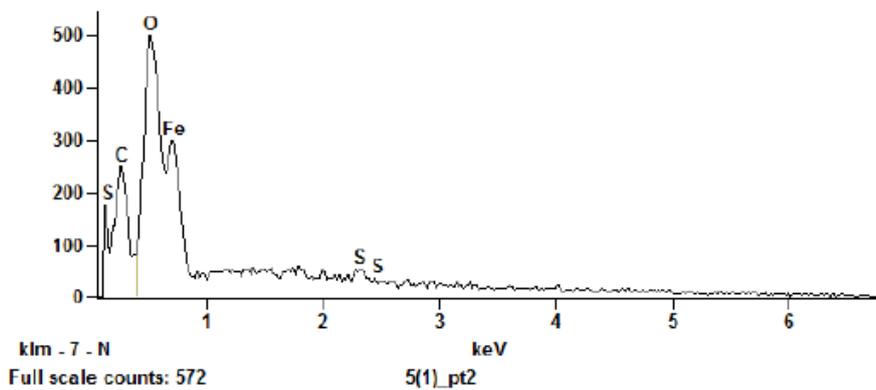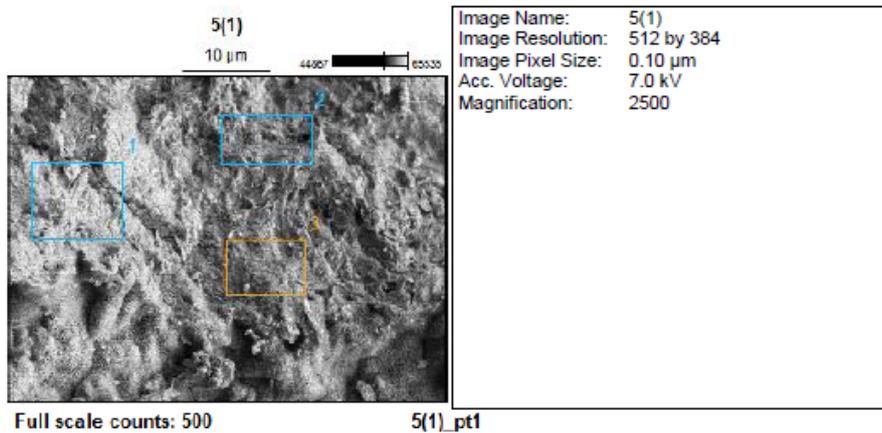
Full scale counts: 684   5(1)_pt3

klm - 7 - N
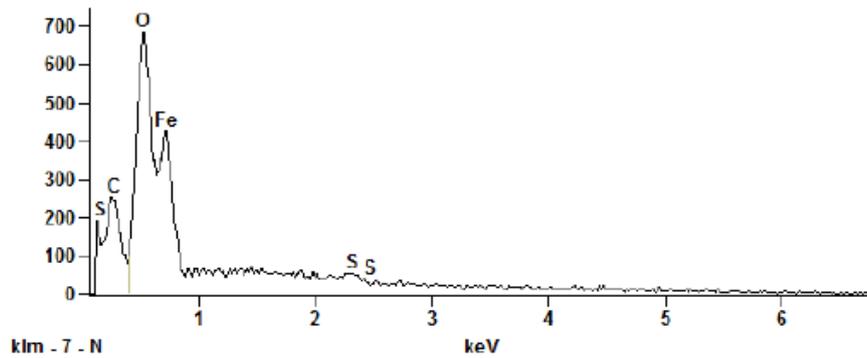
Weight %

	C-K	O-K	S-K	Cl-K	Fe-L
5(1)_pt1	12.89	33.96	1.11		52.04
5(1)_pt2	7.49	36.32	0.62	0.33	55.24
5(1)_pt3	11.51	32.69	0.97		54.83

Weight % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Cl-K	Fe-L
5(1)_pt1	+/-0.60	+/-1.65	+/-0.19		+/-2.93
5(1)_pt2	+/-1.05	+/-0.88	+/-0.22	+/-0.23	+/-3.67
5(1)_pt3	+/-0.47	+/-1.27	+/-0.15		+/-2.37

Atom %

	C-K	O-K	S-K	Cl-K	Fe-L
5(1)_pt1	25.79	50.99	0.83		22.39
5(1)_pt2	15.95	58.03	0.50	0.23	25.29
5(1)_pt3	23.87	50.91	0.76		24.46

Atom % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Cl-K	Fe-L
5(1)_pt1	+/-1.19	+/-2.48	+/-0.14		+/-1.26
5(1)_pt2	+/-2.23	+/-1.40	+/-0.17	+/-0.16	+/-1.68
5(1)_pt3	+/-0.97	+/-1.97	+/-0.12		+/-1.06

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

6(1)

25 µm

Image Name:	6(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.24 µm
Acc. Voltage:	7.0 kV
Magnification:	1000
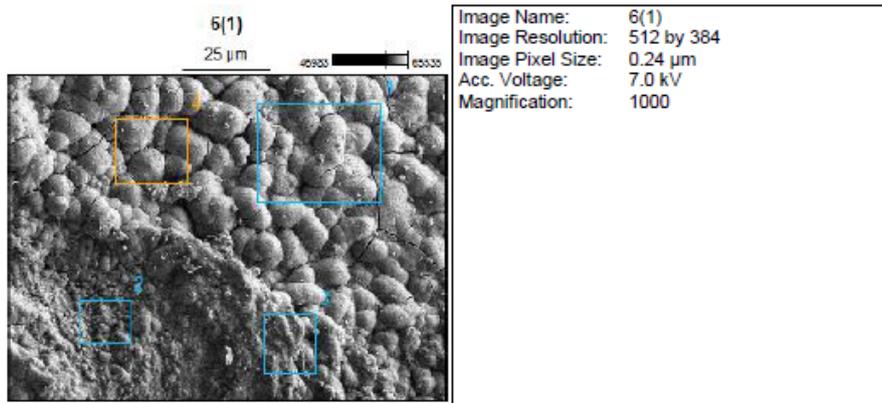
Full scale counts: 473   6(1)_pt1

klm - 7 - N   keV
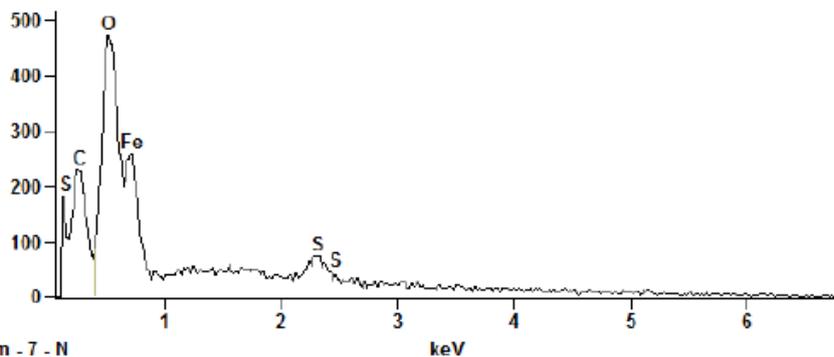
Full scale counts: 491   6(1)_pt2

klm - 7 - N   keV

90

IFE
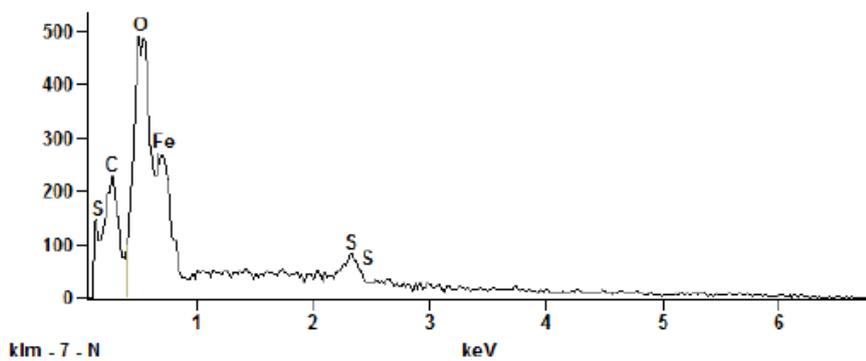
Full scale counts: 317   6(1)_pt3

klm - 7 - N   keV

Full scale counts: 327   6(1)_pt4

klm - 7 - N   keV
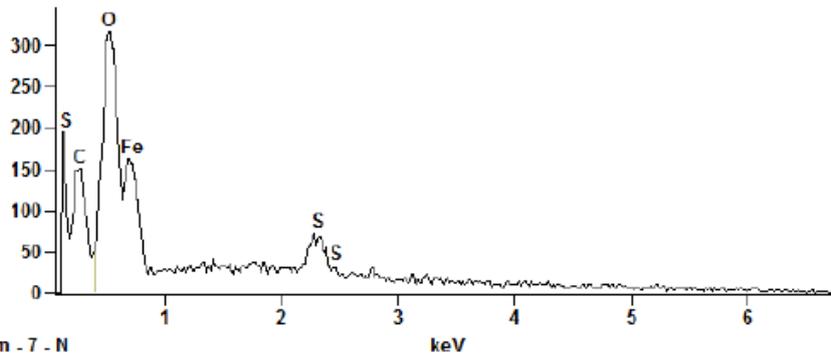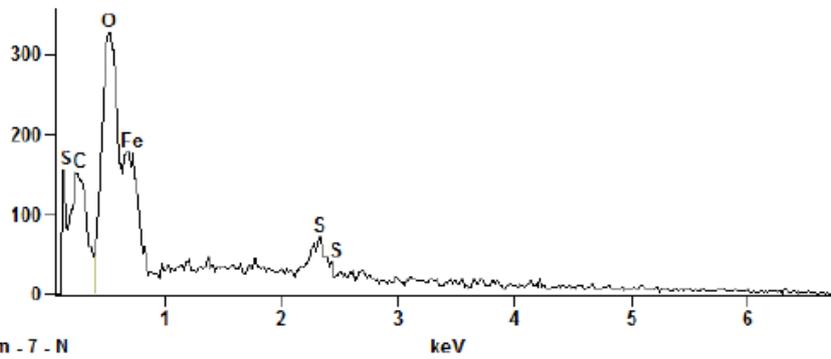
Weight %

	C-K	O-K	S-K	Fe-L
6(1)_pt1	15.28	38.44	3.16	43.11
6(1)_pt2	13.79	33.40	2.75	50.06
6(1)_pt3	12.86	33.83	5.61	47.70
6(1)_pt4	14.92	30.80	3.99	50.28

Weight % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
6(1)_pt1	+/-0.71	+/-1.68	+/-0.45	+/-1.79
6(1)_pt2	+/-0.62	+/-1.35	+/-0.23	+/-2.55
6(1)_pt3	+/-0.92	+/-0.99	+/-0.61	+/-3.47
6(1)_pt4	+/-0.79	+/-1.49	+/-0.51	+/-2.60

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Atom %

	C-K	O-K	S-K	Fe-L
6(1)_pt1	28.00	52.85	2.17	16.98
6(1)_pt2	27.22	49.49	2.03	21.26
6(1)_pt3	25.41	50.17	4.15	20.27
6(1)_pt4	29.64	45.92	2.97	21.47

Atom % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
6(1)_pt1	+/-1.30	+/-2.31	+/-0.31	+/-0.71
6(1)_pt2	+/-1.23	+/-2.00	+/-0.17	+/-1.08
6(1)_pt3	+/-1.82	+/-1.48	+/-0.45	+/-1.47
6(1)_pt4	+/-1.57	+/-2.22	+/-0.38	+/-1.11

92

7(1)

25 µm

Image Name:	7(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.24 µm
Acc. Voltage:	7.0 kV
Magnification:	1000

Full scale counts: 292   7(1)_pt1

klm - 7 - N   keV

Full scale counts: 280   7(1)_pt2

klm - 7 - N   keV

Page 16 of 27

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

IFe
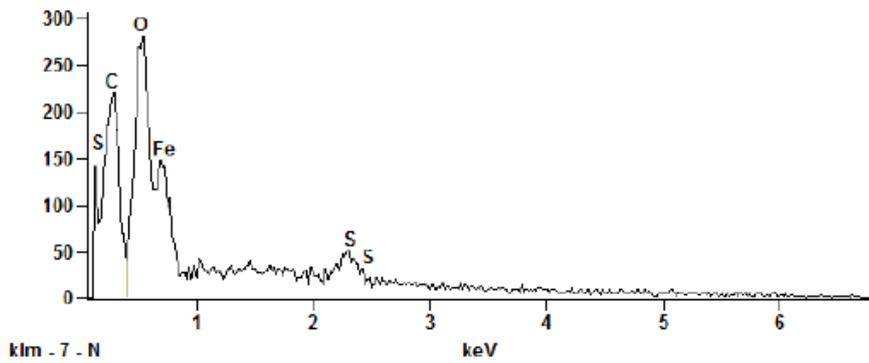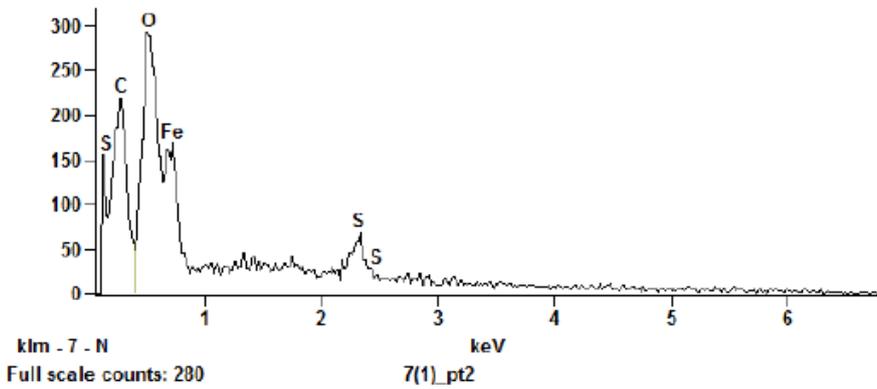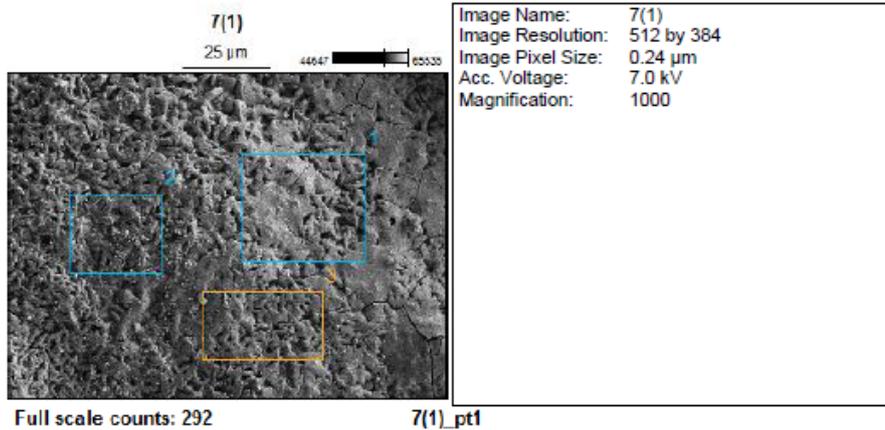
Full scale counts: 268   7(1)_pt3

klm - 7 - N   keV
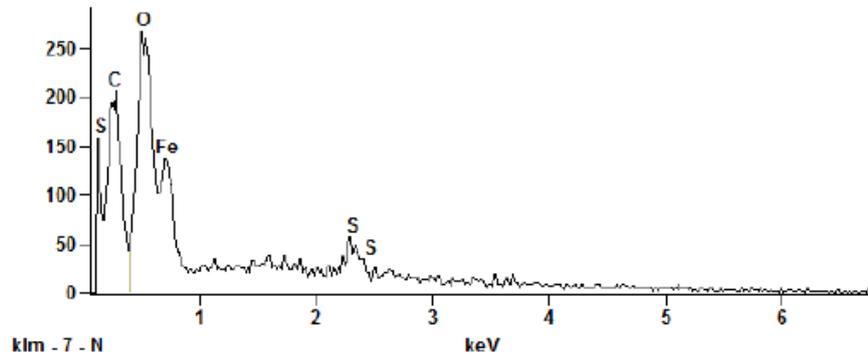
Weight %

	C-K	O-K	S-K	Fe-L
7(1)_pt1	19.01	31.77	3.49	45.73
7(1)_pt2	20.72	32.40	3.55	43.32
7(1)_pt3	19.92	35.12	3.46	41.51

Weight % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
7(1)_pt1	+/-0.85	+/-1.88	+/-0.28	+/-3.26
7(1)_pt2	+/-0.85	+/-1.90	+/-0.50	+/-3.32
7(1)_pt3	+/-0.96	+/-2.27	+/-0.32	+/-3.90

Atom %

	C-K	O-K	S-K	Fe-L
7(1)_pt1	35.20	44.17	2.42	18.21
7(1)_pt2	37.21	43.67	2.39	16.73
7(1)_pt3	35.25	46.66	2.29	15.80

Atom % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
7(1)_pt1	+/-1.58	+/-2.61	+/-0.19	+/-1.30
7(1)_pt2	+/-1.53	+/-2.56	+/-0.34	+/-1.28
7(1)_pt3	+/-1.71	+/-3.01	+/-0.21	+/-1.48

94

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Image Name:	7(2)
Image Resolution:	512 by 384
Image Pixel Size:	0.10 μm
Acc. Voltage:	7.0 kV
Magnification:	2500

Full scale counts: 336   7(2)_pt1

Full scale counts: 295   7(2)_pt2
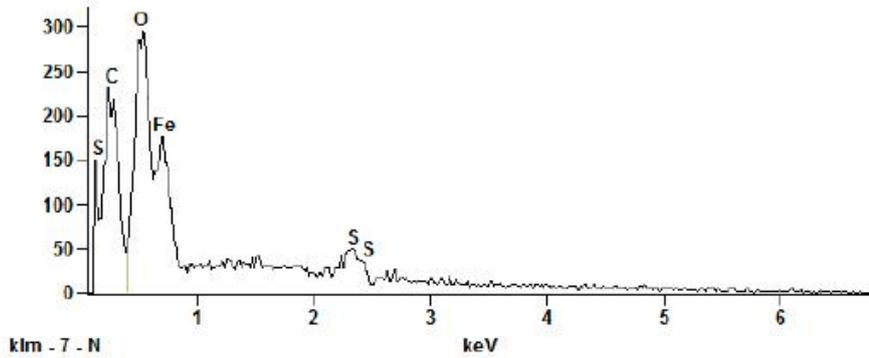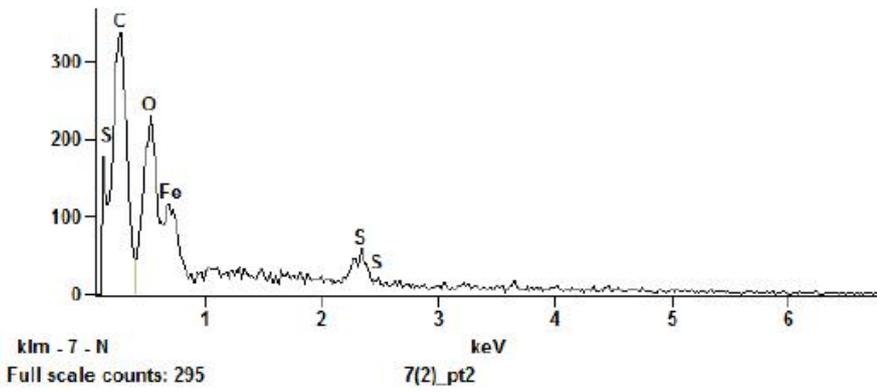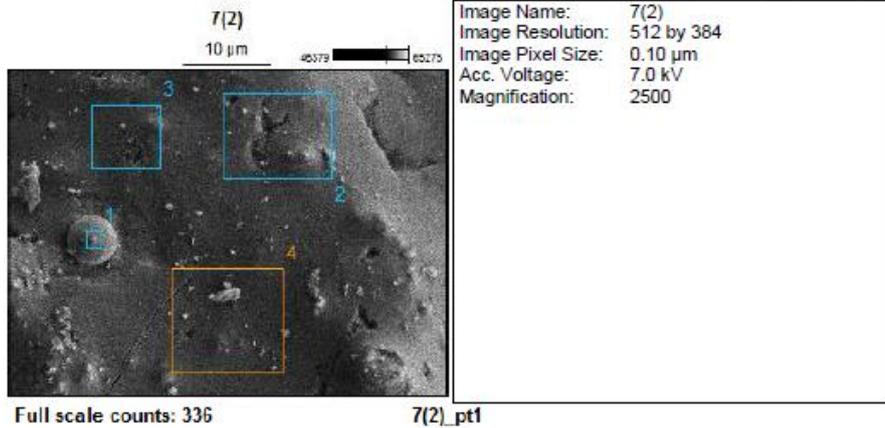
Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Full scale counts: 289   7(2)_pt3
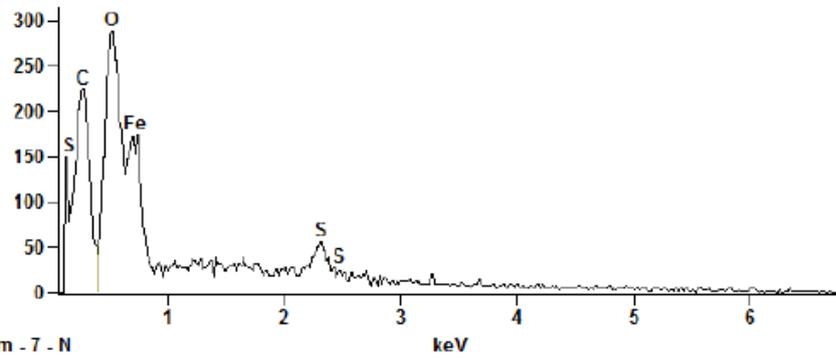
klm - 7 - N

Full scale counts: 280   7(2)_pt4

klm - 7 - N

96
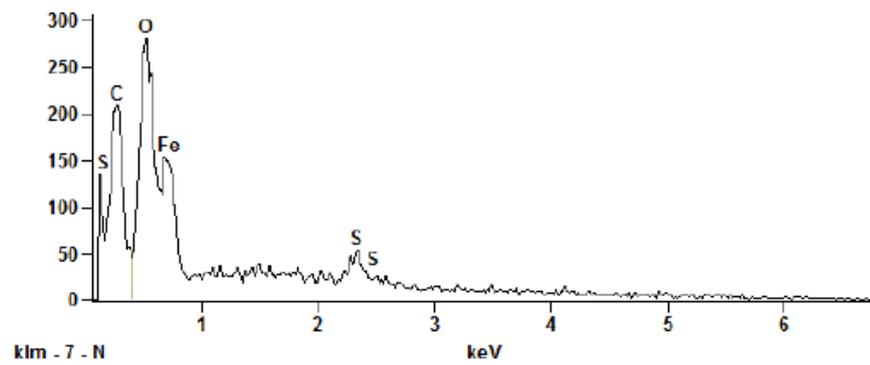
Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Weight %

	C-K	O-K	S-K	Fe-L
7(2)_pt1	32.18	26.50	4.43	36.89
7(2)_pt2	20.15	30.57	3.07	46.21
7(2)_pt3	20.34	30.59	2.92	46.15
7(2)_pt4	18.75	31.76	3.07	46.42

Weight % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
7(2)_pt1	+/-0.96	+/-1.06	+/-0.50	+/-2.97
7(2)_pt2	+/-0.79	+/-1.64	+/-0.47	+/-2.93
7(2)_pt3	+/-0.81	+/-1.68	+/-0.27	+/-2.97
7(2)_pt4	+/-0.97	+/-1.11	+/-0.32	+/-3.79

Atom %

	C-K	O-K	S-K	Fe-L
7(2)_pt1	52.19	32.26	2.69	12.87
7(2)_pt2	37.18	42.35	2.12	18.34
7(2)_pt3	37.44	42.28	2.01	18.27
7(2)_pt4	34.90	44.37	2.14	18.58

Atom % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
7(2)_pt1	+/-1.56	+/-1.29	+/-0.30	+/-1.04
7(2)_pt2	+/-1.47	+/-2.27	+/-0.32	+/-1.16
7(2)_pt3	+/-1.49	+/-2.32	+/-0.18	+/-1.18
7(2)_pt4	+/-1.80	+/-1.55	+/-0.22	+/-1.52

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

IFE

8(1)

25 µm

4760° 65533

Image Name:	8(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.24 µm
Acc. Voltage:	7.0 kV
Magnification:	1000

Full scale counts: 236   8(1)_pt1

klm - 7 - N

Full scale counts: 265   8(1)_pt2

klm - 7 - N

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98

IFe
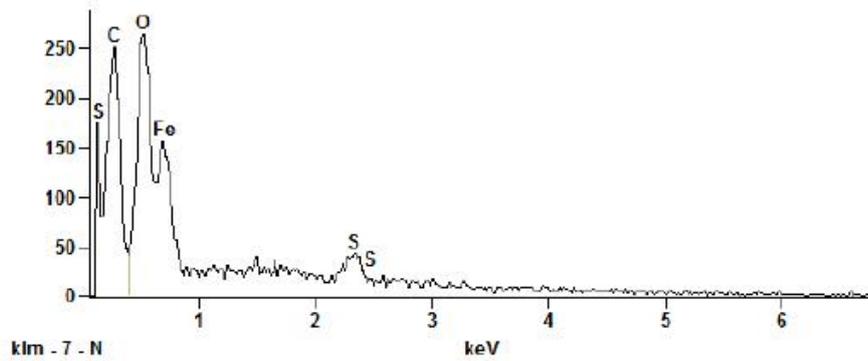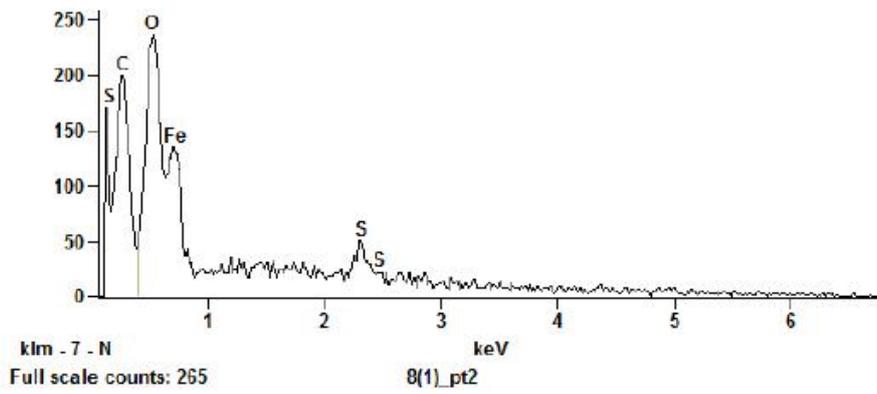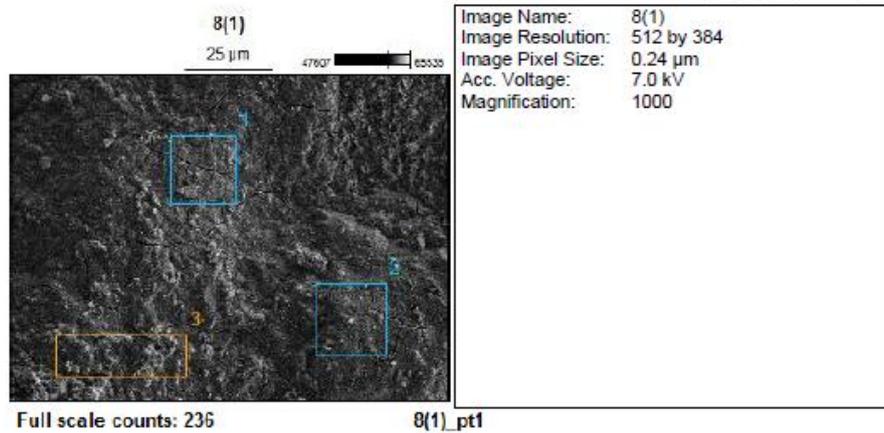
Full scale counts: 209   8(1)_pt3

klm - 7 - N   keV
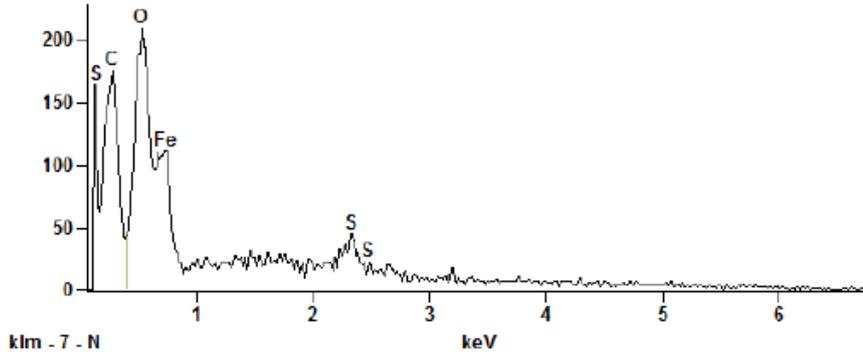
Weight %

	C-K	O-K	S-K	Fe-L
8(1)_pt1	21.31	34.28	3.14	41.27
8(1)_pt2	22.51	31.15	3.75	42.58
8(1)_pt3	21.00	27.87	2.55	48.58

Weight % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
8(1)_pt1	+/-0.77	+/-1.22	+/-0.36	+/-2.48
8(1)_pt2	+/-0.99	+/-1.08	+/-0.50	+/-3.57
8(1)_pt3	+/-0.99	+/-1.09	+/-0.33	+/-3.41

Atom %

	C-K	O-K	S-K	Fe-L
8(1)_pt1	37.32	45.07	2.06	15.54
8(1)_pt2	39.87	41.42	2.49	16.22
8(1)_pt3	39.37	39.24	1.79	19.59

Atom % Error (+/- 1 Sigma)

	C-K	O-K	S-K	Fe-L
8(1)_pt1	+/-1.34	+/-1.61	+/-0.23	+/-0.93
8(1)_pt2	+/-1.76	+/-1.44	+/-0.33	+/-1.36
8(1)_pt3	+/-1.86	+/-1.53	+/-0.23	+/-1.37

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

9(1)

25 µm

47419 ▮▮▮ 65535

Image Name:	9(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.24 µm
Acc. Voltage:	7.0 kV
Magnification:	1000

Full scale counts: 221   9(1)_pt1

klm - 7 - N

Full scale counts: 190   9(1)_pt2

klm - 7 - N

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100

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

IF2
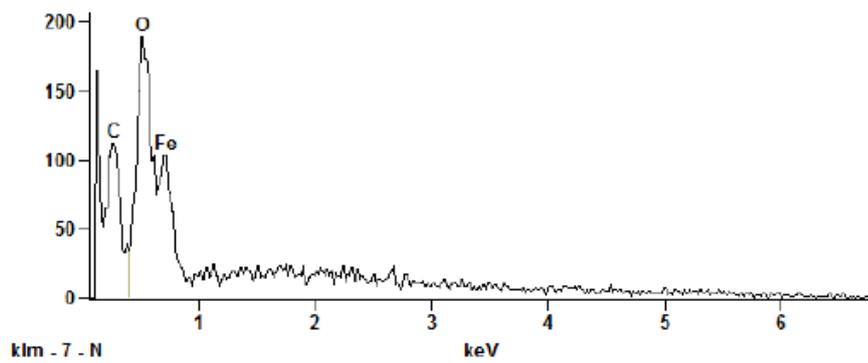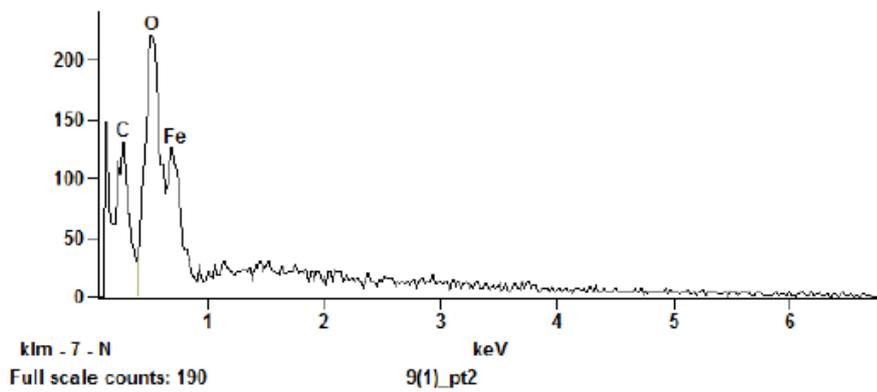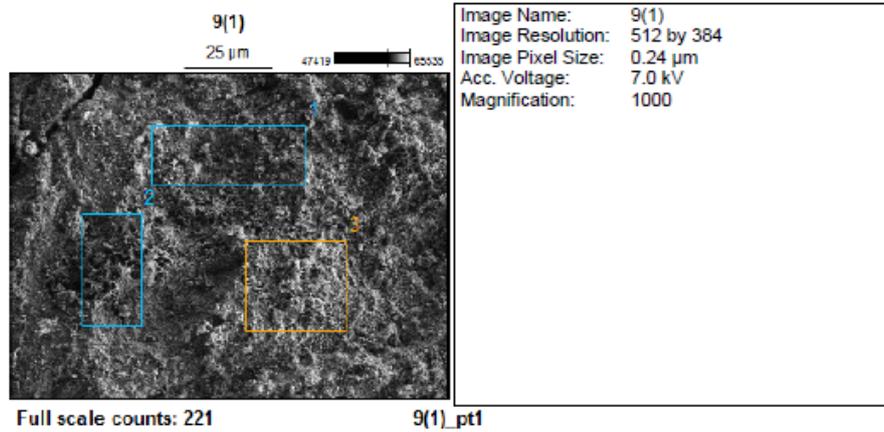
Full scale counts: 230   9(1)_pt3

klm - 7 - N   keV
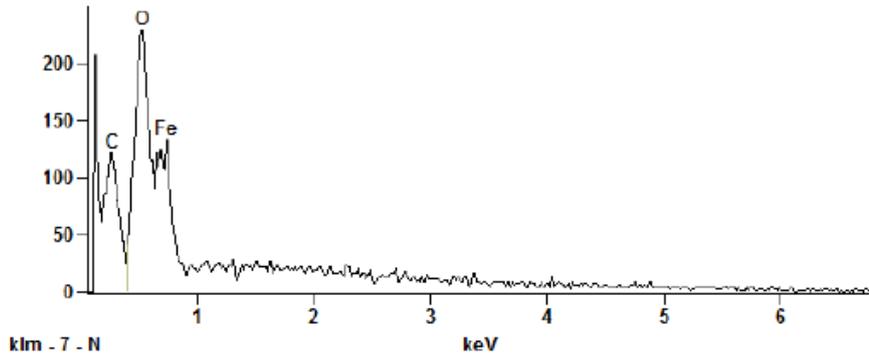
Weight %

	C-K	O-K	Fe-L
9(1)_pt1	14.05	31.36	54.60
9(1)_pt2	14.59	29.87	55.54
9(1)_pt3	13.85	28.20	57.95

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
9(1)_pt1	+/-1.11	+/-2.05	+/-3.79
9(1)_pt2	+/-1.27	+/-2.25	+/-3.97
9(1)_pt3	+/-1.04	+/-1.13	+/-3.30

Atom %

	C-K	O-K	Fe-L
9(1)_pt1	28.47	47.73	23.80
9(1)_pt2	29.80	45.80	24.39
9(1)_pt3	29.17	44.58	26.24

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
9(1)_pt1	+/-2.24	+/-3.11	+/-1.65
9(1)_pt2	+/-2.60	+/-3.45	+/-1.74
9(1)_pt3	+/-2.19	+/-1.78	+/-1.50

Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

10(1)

25 µm

Image Name:	10(1)
Image Resolution:	512 by 384
Image Pixel Size:	0.24 µm
Acc. Voltage:	7.0 kV
Magnification:	1000

Full scale counts: 270   10(1)_pt1

klm - 7 - N

Full scale counts: 255   10(1)_pt2

klm - 7 - N

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102
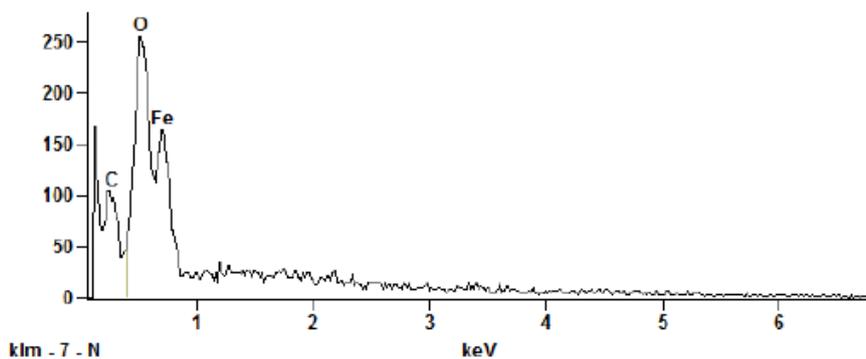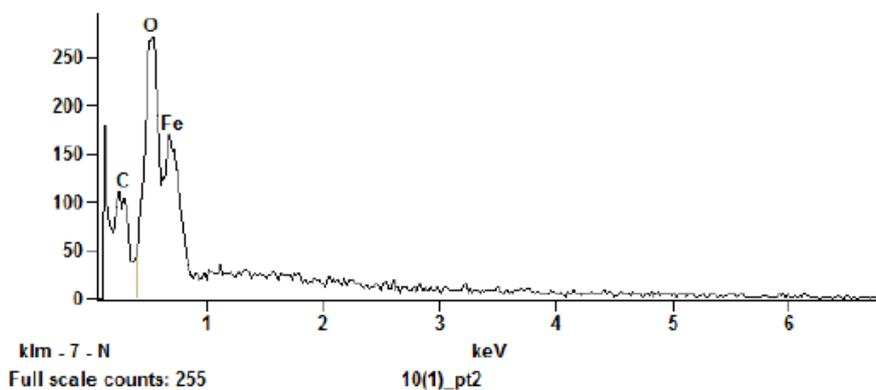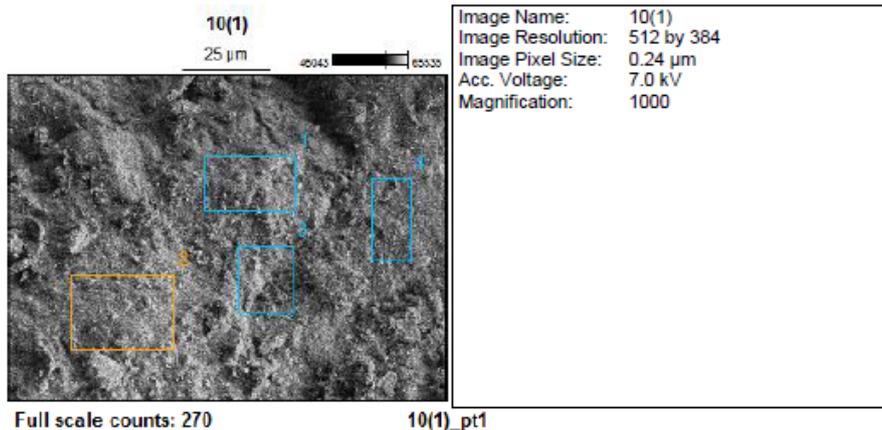
Full scale counts: 259   10(1)_pt3
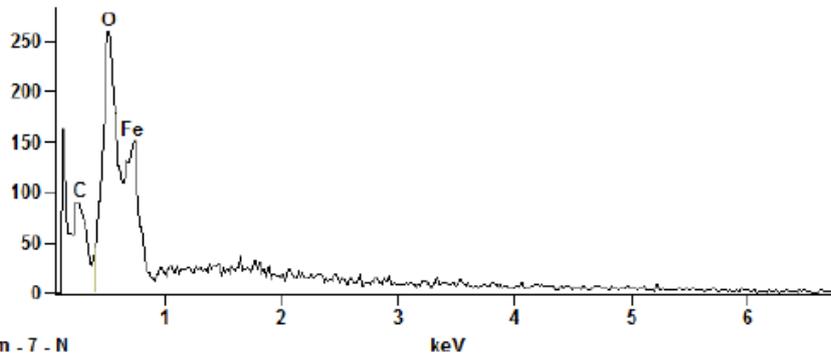
klm - 7 - N

Full scale counts: 246   10(1)_pt4

klm - 7 - N
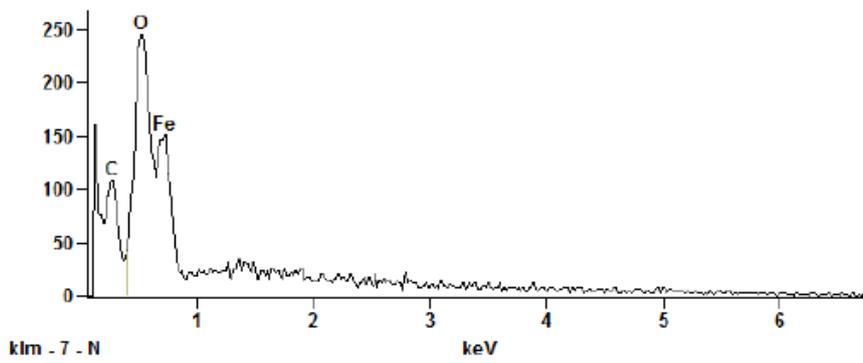
Project: NILU EXIRA-COR
User Name: Trygve Furuseth
Company Name: _

Weight %

	C-K	O-K	Fe-L
10(1)_pt1	11.20	26.87	61.93
10(1)_pt2	12.23	31.08	56.69
10(1)_pt3	9.46	28.67	61.87
10(1)_pt4	11.64	30.17	58.19

Weight % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
10(1)_pt1	+/-0.89	+/-1.71	+/-3.18
10(1)_pt2	+/-0.92	+/-1.03	+/-3.69
10(1)_pt3	+/-1.03	+/-1.96	+/-3.82
10(1)_pt4	+/-0.85	+/-0.97	+/-3.49

Atom %

	C-K	O-K	Fe-L
10(1)_pt1	25.05	45.14	29.80
10(1)_pt2	25.61	48.86	25.53
10(1)_pt3	21.35	48.60	30.05
10(1)_pt4	24.87	48.39	26.74

Atom % Error (+/- 1 Sigma)

	C-K	O-K	Fe-L
10(1)_pt1	+/-1.98	+/-2.87	+/-1.53
10(1)_pt2	+/-1.93	+/-1.62	+/-1.66
10(1)_pt3	+/-2.33	+/-3.33	+/-1.86
10(1)_pt4	+/-1.82	+/-1.55	+/-1.61

**Norwegian Institute
for Air Research**

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TITLE	PROJECT LEADER
Experimental Study Investigating Risks of selected Amines (ExSIRA).	Terje Grøntoft
Task 4: Atmospheric corrosion due to amines	NILU PROJECT NO.
	O-110082

AUTHOR(S)	CLASSIFICATION *
Terje Grøntoft and Thor Ofstad	A
	CONTRACT REF.

QUALITY CONTROLLER: Terje Krognes

REPORT PREPARED FOR:

The Research Council of Norway

ABSTRACT
The effect of selected amines on the corrosion of carbon steel and copper was investigated in the laboratory and in the field. The steel and copper samples were exposed to loads of the amines in the laboratory, representing possible 10 years maximum real exposure due to emission from a CO_2 capturing plant, and to higher doses in the laboratory and in the field. No effect on the corrosion rate for steel was detected for the application of a possible 10 years real maximum dose of the amines in the laboratory as compared to blanks. Application of 700 times higher doses of amines in the laboratory was observed to give anodic protection, and thus reduced corrosion, of steel samples, but to dissolve the surface of a copper sample. The anodic protection was due to the formation of an amine surface film that protected the sample form oxidation. The dissolution of copper was probably due to formation of a copper - amine complex at high pH. A slight increase in corrosion was observed for samples that were exposed to the equivalent of possible 65 years maximum real exposure of amines in the field. This may be explained by freezing point depression and increased time of wetness of the sample surfaces due to accumulation of the amine solute on the sample surfaces in the season with frost.

NORWEGIAN TITLE

Eksperimentell studie – Undersøkelse av risiko for utvalgte aminer (ExSIRA). Task 4: Atmosfærisk korrosjon på grunn av aminer

KEYWORDS		
Carbon capture and storage (CCS)	Air quality	Material decomposition

ABSTRACT (in Norwegian)

Effekten av utvalgte aminer på korrosjonen av karbonstål og kobber ble undersøkt i laboratoriet og ved feltforsøk. Stål og kobberprøver ble eksponert i laboratoriet for doser som representerte en mulig 10 års maksimum eksponering for aminer i utslipp fra CO_2 fangst anlegg, og til høyere doser i laboratoriet og i felt. Ingen effekt på korrosjonshastigheten for stål ble funnet ved påføring av amin i laboratoriet tilsvarende mulig 10 års maksimum eksponering, sammenlignet med blindprøver. Påføring av 700 ganger høyere doser av aminer i laboratoriet førte til anodisk beskyttelse og dermed redusert korrosjon for stålprøver, men til oppløsning av overflaten på kobber. Den anodiske beskyttelsen besto i dannelsen av en amin-overflatefilm som beskyttet prøvene for oksidasjon ved kontakt med atmosfæren. Oppløsningen av kobber skjedde sannsynligvis på grunn av dannelsen av et kobber – amin kompleks ved høy pH. En liten økning av korrosjonen ble observert i feltforsøk for prøver som ble eksponert for doser som representerte mulig 65 års maksimum eksponering for aminer. Dette kan forklares med frysepunktnedsettelse og øket våttid for prøveoverflatene ved akkumulering av amin på prøvene i sesongen(e) med frost.

*   Classification   A   *Unclassified (can be ordered from NILU)*
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