# Final report

## 1.1 Project details

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|---|---|
| **Project title** | **Predictive Corrosion Monitoring System– Task 2**<br><br>**(in the following abbreviated to PCMS)** |
| **Project identification (program abbrev. and file)** | **64018-0016 (previous 2015-1-12290)** |
| **Name of the programme which has funded the project** | **ForskEL (transferred to EUDP during the project period)** |
| **Project managing company/institution (name and address)** | **FORCE Technology, Park Allé 345, 2605 Brøndby** |
| **Project partners** | **Babcock & Wilcox Vølund, Odinsvej 19, 2600 Glostrup**<br><br>**DTU Risø Campus, Frederiksborgvej 399, 4000 Roskilde** |
| **CVR** (central business register) | **55117314** |
| **Date for submission** | **17 June 2020** |

## 1.2 Short description of project objective and results

**Project Description (English Version)**
The vision of the project is to develop an online PCMS system by measurement of a few, significant flue gas components whereby predicting and facilitating reduction of corrosion rate of steel surfaces in superheaters in Waste-to-Energy boilers. The PCMS system will enable the control system to increase the superheating temperature in order to increase the efficiency of power production.

Long-time tests were made, which should enable the project team to correlate the corrosion on the superheater tubes with flue gas contents. Two of these long-term tests were performed with acceptable results.

The results of the two tests are described below. The corrosion variance of the test results makes a precise algorithm for the soft sensor impossible. The variances have been analysed in-depth and are caused by the variation of "flyash" on the probes. Unfortunately, it was not possible to introduce an automatic cleaning system within the frame of the project.

**Projektbeskrivelse (Dansk Version)**
Formålet med dette projekt er at udvikle en online korrosionssoftware, der ved at måle nogle få røggaskomponenter, for at forudsige korrosionen på ståloverflader i overheaderne på affaldsforbrændings kraftvarmeværker, og dermed muliggøre reduktion af korrosionen på overhedernes stålflader. PCMS-systemet vil kunne give mulighed for at optimere driftstemperaturen således, at der kan opnås optimal energiudnyttelse samtidig med, at korrosionen på overhederen bliver begrænset og derved øge elproduktionen.

Der blev gennemført langtidstest, med henblik på at skabe en korrelation mellem korrosionen på overheadernes ståloverflader og røggassernes indhold af korrosive gasser. To af disse test blev gennemført som planlagt.

Resultatet af de to gennemførte tests er beskrevet nedenfor. Korrosionsvariationerne er desværre så store, at resultaterne ikke kan bruges til at lave en præcis algoritme. Variationerne har være analyseret tilbundsgående og skyldes flyveaske på proberne. Det har desværre ikke været muligt at indbygge et automatisk rensesystem inden for rammerne af dette projekt.

## 1.3 Executive summary

The vision of the project is to develop the basis for an online PCMS that through measurements of few, significant flue gas components can predict and hence optimise the corrosion rate of superheaters in Waste-to-Energy (WtE) boilers in order to increase steam data and thereby the efficiency of power production of plants. In the PCMS Task 2 project we succeeded in obtaining five test runs as planned. Corrosion results were obtained as planned and the IR/UV sensors monitored the flue gas contents as planned.

The development of the PCMS will be utilised in several ways.

- Existing WtE plants equipped with the PCMS can optimise the waste input and the operational condition inducing lower corrosion rates and hence increase the steam data and thereby the efficiency of power production.
- Existing and new plants can minimise the corrosion during transient operation like start-up/shut-down or reduced production demanded by the system administrator.
- BWV can market more competitive waste-to-energy plants with better corrosion warranties if the PCMS is installed.
- FORCE Technology can market services determining the residual service life of superheaters etc. on existing plants and uncover inexpedient operational conditions/types of waste.
- DTU can spread the use of the improved FTIR and UV systems to other projects and companies.

After a pilot test Task 1. Before the long-term test the following actions must be completed:

- Update and test of the FTIR/UV-systems (Done)
- Manufacturing of more HT corrosion probes (19 probes in operation)
- Installation and test of air blasters to clean the probes (not possible)

## 1.4 Project objectives

The end goal of the project (PCMS – Task 2) is to develop an algorithm being the heart of the PCMS. The algorithm will build on data from comprehensive full-scale measurements at the WtE plant, AffaldPlus$^{+}$ at Næstved, Denmark.

The project is aiming at finding correlations between the corrosion rate of superheater tubes, the concentration of critical components in the flue gas and other relevant operational conditions and process variables. To determine the correlations or mathematical model, the huge amount of data from the long-term measurements will be analysed by multivariate/multidimensional regression analysis or other appropriate methods.

Data for correlation analysis comes from the following sources:

1. Corrosion rates determined from weight loss analysis of HT corrosion probe test rings
2. Online flue gas concentrations and temperatures from FTIR and UV probes
3. Online measurements of HT corrosion probe surface temperatures

Hot corrosion of panel walls and superheaters is currently the main obstacle for increasing electrical efficiency of WtE plants. Furthermore, hot corrosion is also responsible for unplanned shutdown of plants because of breakthrough of panel walls or superheaters limiting the plant availability, which is crucial for the economy of WtE plants.

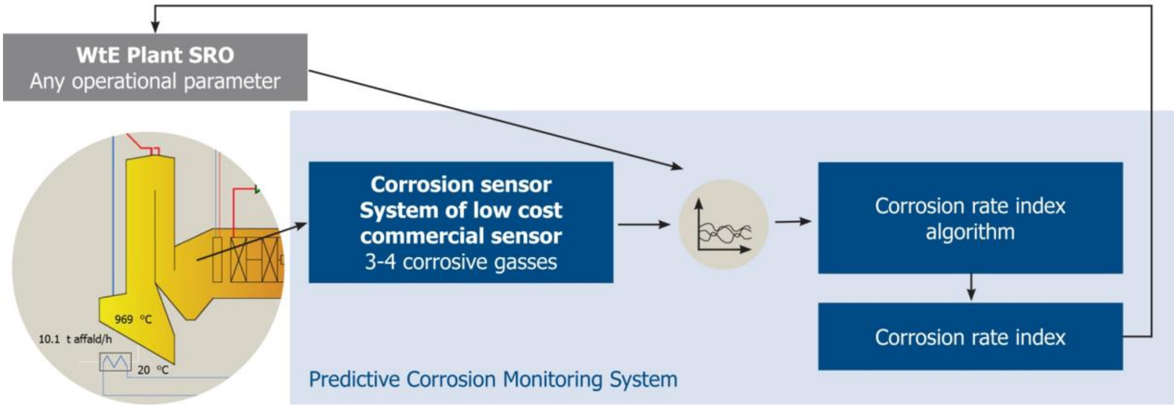



*Figure 1. Vision of the PCMS project: Prediction of the corrosive capacity of flue gasses.*

The idea is that the PCMS can predict the corrosive capacity of flue gasses in WtE plants during operation. From a flue gas measurement installed in the plant (*Figure 1*), plant owners can then predict whether the flue gas is "safe" in terms of corrosion or the flue gas is more aggressive. In the latter case, the operators can act accordingly by selecting the proper fraction of waste for incineration and in this way decrease the corrosive ability of the flue gas. Adjusting the operating temperature of the superheater when the flue gases corrosion components vary will also lengthen the lifetime of the superheater panel walls.

## 1.5 Project results and dissemination of results

### Test facilities at AffaldPlus+

The test facilities are located at line 4 at the WtE plant AffaldPlus+ in Næstved.

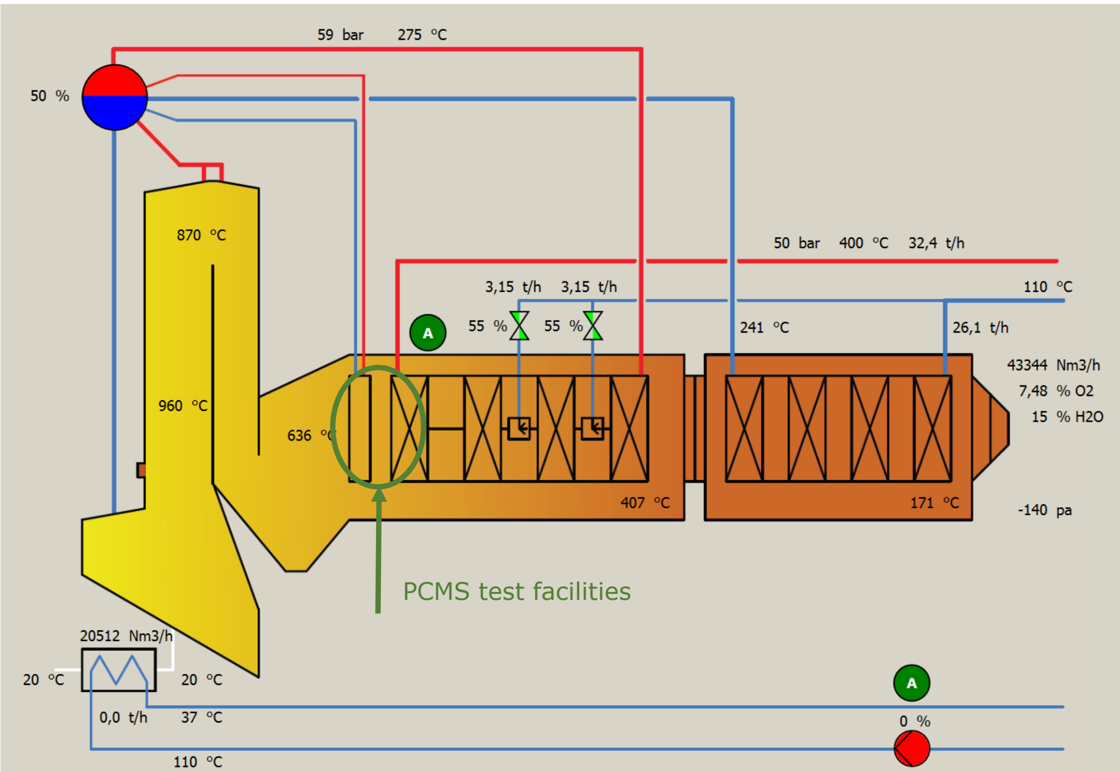



*Figure 2. Location of the PCMS test facilities at line 4 of AffaldPlus+, Næstved.*

We selected the location between the last boiler section and the first superheater section because the flue gas species and corrosion conditions must resemble the conditions at the superheaters.

The test facilities include:

- Upper and lower platform including gangways, stairs, etc.
- 24 guide tubes for the HT corrosion probes, the electro chemical probe and FTIR and UV flue gas measuring probes
- Four guide tubes for probe cleaning system
- Guide tubes for internal camera and light
- Exhaust duct from cooling air outlet to primary fan of WtE line 4
- Scissors lift for handling of HT corrosion probes
- Rack for spare HT corrosion probes
- Workshop area
- Utilities: power, pressurised air, light, etc.
- Video monitoring cameras upper/lower platform

*Figure 3. Guide tubes for probes seen from inside of boiler.*

Guide tubes (24) for probes and guide tubes (4) for probe cleaning system

The design and manufacturing of the guide tubes were done by FORCE Technology while B&W Vølund made the boiler work. The free space between the two boiler sections available for the probes is 1.3 m. The photo shows the finished guide tubes with blanking and clamp flanges in the boiler wall. The vertical centre distance between the guide tubes is 24 cm as is the centre distance between columns A and B. The centre distance between columns A and C is about 88 cm. The total centre distance from bottom to top is 180 cm.

**Preparation of HT corrosion probes for tests at AffaldPlus+**
FORCE Technology had developed and completed a preliminary test of the HT corrosion probe prior to the PCMS project. The first design of the probe (*Figure 2*) was adjusted based on the experiences from the lab test. The technical drawings were updated and the lead-time for the external and internal manufacturing of the probes was estimated to 2-3 weeks.

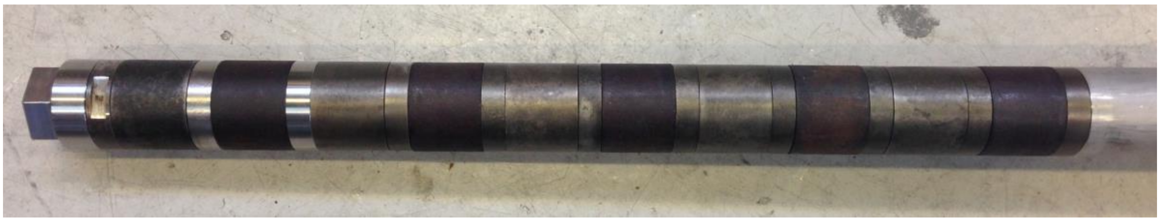


*Figure 2. Top: The HT corrosion probe developed by FORCE Technology prior to this project.*
*Bottom: The tip of the HT corrosion with the 10 test coupons.*

Four probes with the revised design including three-way valves for inlet/outlet air and bracket for attachment to the scissors lift were manufactured for the pilot test. The length of the probes is chosen to ensure that the test coupons are in the main flue gas stream of the boiler.

**Cooling systems for HT corrosion probes**
The facilities are designed for 21 HT corrosion probes divided into three temperature groups of seven probes. Each group has its own independent air-cooling system.
The cooling systems were designed by FORCE Technology.

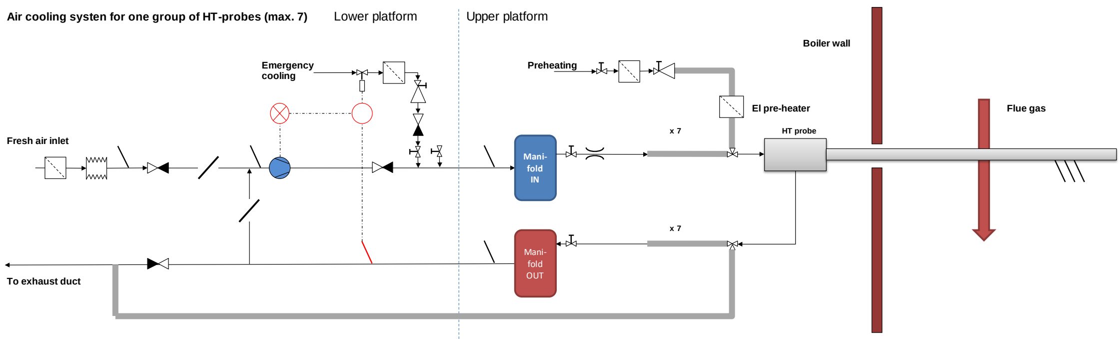



*Figure 5. Diagram of the cooling system for one group of HT corrosion probes. The test facilities have three independent cooling systems operating at different temperatures.*

*Figure 6: Left: The three hot air fans, distribution dampers, etc.*
*Right: Emergency cooling systems and camera.*

On the upper platform is:

- Inlet an outlet manifold
- Shut-off valves for all connections to the probes
- Electrical pre-heater for warming up probes before insertion


*Figure 7.* *1. Inlet manifold for probes columns A and B*
*2. Outlet manifold for probes columns A and B.*
*3. Inlet manifold for probes columns C.*
*4. Outlet manifold for probes columns C.*

The PLC’s control the HT corrosion probe cooling systems and collect data from them. Each PLC is dedicated to one cooling system. We have programmed the sampling and averaging software on the PLC’s to ensure a high quality of all online data collected. A comprehensive watchdog system validates data and warns (SMS, email, etc.) immediately the person responsible for data handling, if data is lost or outside of the validation interval. A dashboard is showing the state of the test facilities at AffaldPlus+ including pictures from the supervision cameras. The dashboard is available via the internet and FORCE Technology uses it for a quick remote control of the state of the test facilities, cooling systems etc.

The PC of DTU is collecting data from the FTIR/UV probes. Data from the internal supervision camera is collected by a dedicated PC also connected to the FORCE domain, while the external supervision cameras are available via the internet. All online data from the PLC’s, DTU’s PC and data from the SCADA system of AffaldPlus$^{+}$ is transferred to a SCADA PC on the FORCE Technology domain. All PC’s and PLC’s are located at platforms at AffaldPlus$^{+}$. Since the FORCE Technology PC’s are connected to the FORCE Technology domain, all data is automatically backed up.

Moreover, we have developed and implemented a system (in MS Excel) for import/collection of offline data from:

- Weight loss analysis of HT corrosion probes test rings
- Chemical analysis of deposits on test HT corrosion probes test rings
- Microscopic analysis of deposits on test HT corrosion probes test rings

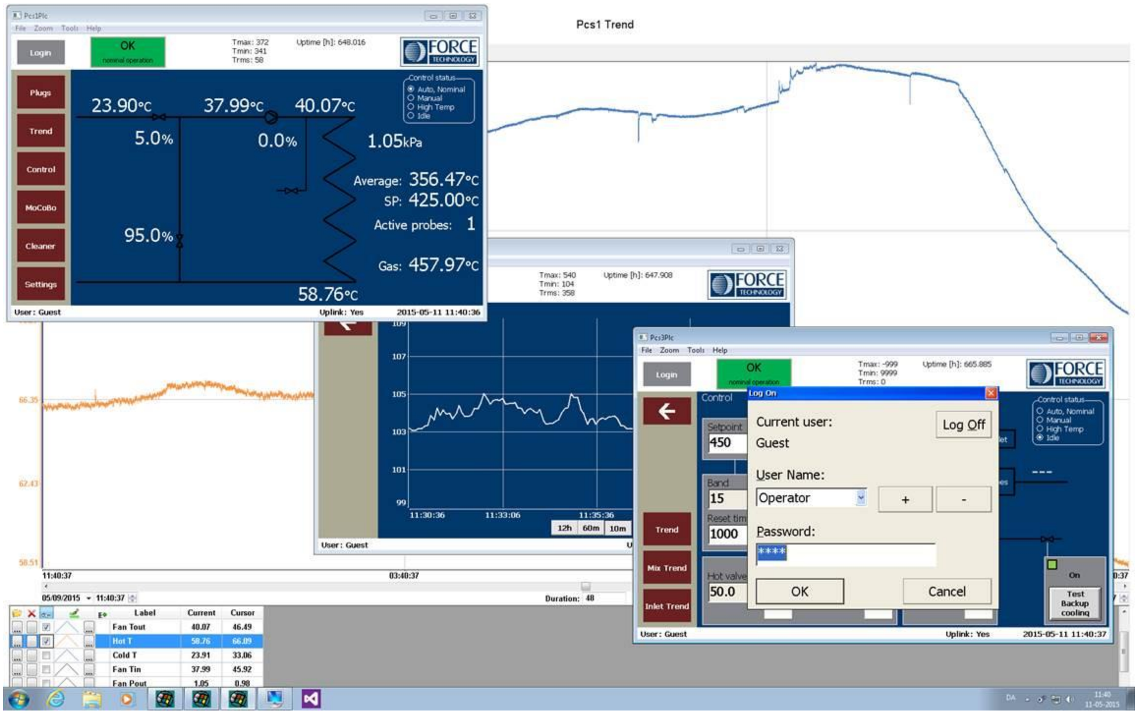



*Figure 8. Collage of screen shots from the PLC's controlling the HT corrosion cooling systems.*

**FTIR/UV system for measurements of flue gas properties**

*Figure 9. FTIR and UV probes with automatic extraction systems installed at AffaldPlus+ during the pilot test.*

DTU is responsible for design, test, operation and application of online gas measurement systems by UV and FTIR spectroscopy to be integrated in FORCE Technology's data collection system with HT corrosion probes, etc. Work has been coordinated with other partners through project meetings. The gas measurement system shall provide online flue gas data (gas concentrations of relevant components, temperature) from full scale, long-term measurements with HT corrosion probes inside the existing waste incineration boiler at the plant AffaldPlus+ in Næstved.

FTIR-probe: CO, $CO_2$, $H_2O$, HCl, optical gas temperature.
UV-probe: $SO_2$, $Cl_2$, Na, K, Zn, Pb, particle level.

The gas temperature is measured optically from the thermal radiation from the $CO_2$ band at 4.3 µm. Results has been verified by thermocouple measurements and suction pyrometer measurements. The gas temperature measurement is needed in the software developed by DTU to calculate the gas concentrations. The software to analyse the measured spectra cover the temperature range from 200 to 1000°C, but the range can be extended.

Basic measurements of gas composition is performed by the FTIR, i.e. $CO_2$, water vapour and CO in the flue gas. Similar, HCl is measured by the FTIR probe. Good agreement is seen of results compared with extractive gas sampling see figure 12a and 12b.

Features from $SO_2$, Zn, Pb, Na and K is observed in measured UV-spectra. Good agreement is seen for $SO_2$ over time with extractive measurements, figure 12c. $Cl_2$ was never observed in data which can be explained by Cl2 is very reactive. The UV probe system was not designed for measurement of $O_2$ and NO, but both gas components can in principle be measured by UV spectroscopy. O2 and NO can be included if the design is modified (shorter optical fibre, nitrogen purge of UV system, etc.).
Two temperature-controlled probes, i.e. a UV probe with two UV spectrometers and FTIR probe with a FTIR spectrometer, have been built and installed at AffaldPlus+. The system is designed and manufactured by DTU, i.e. optics, mechanical parts, control system and software for analysis of measured spectra based on DTU expertise. Nevertheless, the FTIR and UV spectrometer are commercial instruments but configured or modified for this special application.

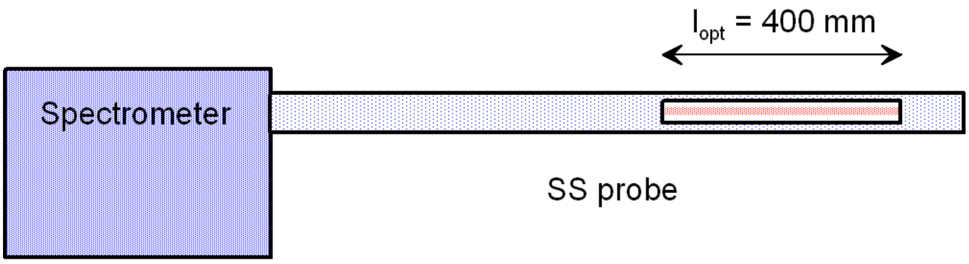



*Figure 10. Concept of gas measurement system. The gas composition is measured of the hot flue gas flow passing a 400 mm long slit in a stainless steel probe forming the measurement volume. Gas spectra are measured with UV or FTIR spectrometer placed in a temperature stabilised housing attached to probe to form one unit. The system is extracted from the boiler during reference measurements, soot blowing, failures, external control (plant and DTU) or manual signal.*

The work was originally defined in six tasks:

1. Preliminary measurements, design and production of FTIR and UV probes
2. Test and calibration
3. Automatic calculation of flue gas concentrations
4. Development of instruments
5. Pilot test with flue gas measurements at AffaldPlus+
6. Full scale, long-term test with FTIR and UV probes at AffaldPlus+

**The UV/FTIR measurement system**
DTU delivers a complete system including two measurement probes and parts needed to control measurement. DTU and FORCE Technology can both follow measurements on-line. It is expected that problems will arise and must be solved as they pop up. Furthermore, running system improvements are foreseen, e.g. basic data is given highest priority and new parameters can be added during test period. Raw data is stored, i.e. improvements in software during the project can be used for analysing “old” measurements.

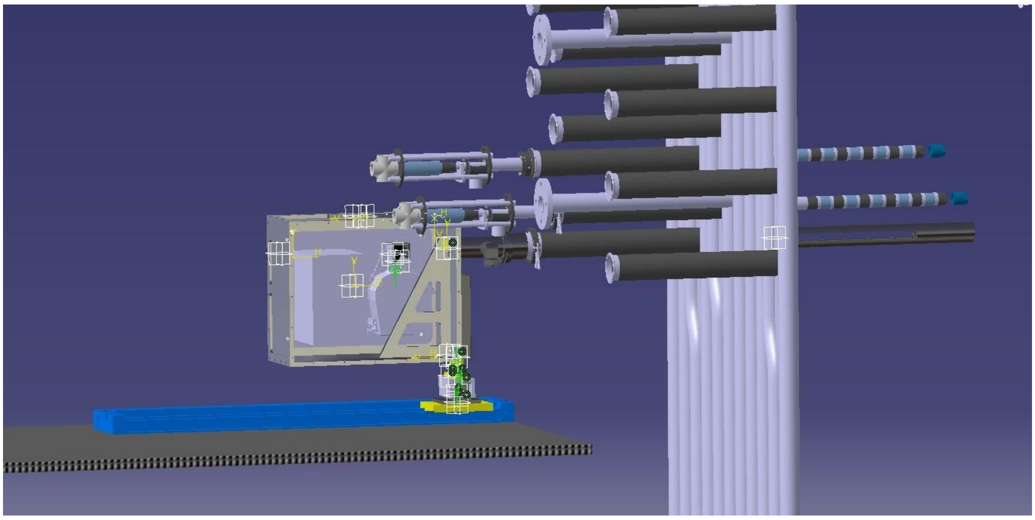


*Figure 11. FTIR probe with extraction system shown with FORCE Technology corrosion probes. Space is limited as the distance between ports in the project is 240 mm, i.e. width of instruments must be less than 230 mm in practise including any fittings, protection shields, thermal stabilisation, etc.*

Ambient temperature in the boiler house varies during the year, typical in the range from 10 °C – 50 °C close to boiler wall, and spectrometers are therefore temperature stabilised for proper operation, e.g. built into special thermo-stated instrument housing. UV and FTIR probes are installed below FORCE Technology's HT-corrosion probes to minimise disturbance from heat.

**FTIR probe**

FTIR spectrometers from various manufactures have been considered to detect gases of interest in the project. An OEM FTIR spectrometer from ABB was selected in this process and performance tests have been carried out. Driver for LabVIEW has been developed for the FTIR spectrometer and successfully integrated into automated software for full control of the spectrometer and data collection. The original DTGS detector was replaced by a more sensitive InSb detector from Hamamatsu. The implementation of the InSb detector gave problems as design SNR could not be achieved, as the detector electronics needed modifications. Performance of the FTIR spectrometer with the InSb detector has been raised by a factor 2.5 that is satisfactory. Nevertheless, it is estimated that SNR of spectra can be raised further by a factor 4 using a MCT detector according to ABB. The FTIR spectrometer is built into a thermostated housing to protect the instrument and obtain stable operation conditions to obtain high quality data over time.

*Figure 12. FTIR probe before installation. The probe is mounted with 4 screws on extraction system and can quickly be connected electrically to the control and data system.*

**UV-probe**

Measurement probe for non-intrusive gas measurements over a 40 cm path (position similar to sample of corrosion probes) has been developed and tested in a measurement campaign at AffaldPlus+ using DTU's high-end UV-spectrometer to obtain experience about practical measurement problems and mapping of gas components. The measurement probe and the cooling system were tested for 3 weeks at AffaldPlus+ to monitor deposition of particles on probe and blocking effects of light. The present probe design requires some cleaning, e.g. using pressurised air 1- 4 times a day when probe is taken out by the extraction system for calibration. A modified design is considered to reduce problems with deposits of particles on probe. Additional cross-stack measurements were made by UV spectroscopy to gain knowledge about conditions, i.e. absorption of light by particles and gas. From these measurements, it was decided to use two UV spectrometers with different spectral range to cover all components of interest in the project and to obtain stable measurements without any moving gratings as in high-end UV spectrometers.

**PCMS software gas measurement system**

A sequence of operations is prepared manually and described in a textual *configuration file*. This configuration file is read by the *Sequence Generator*, which converts the textual configuration description into a sequence of commands, which can be used by the *Sequence Execution Engine.* The *Sequence Execution Engine* takes this list and performs the commands one at a time. The commands are:

- Set spectrometer timing
- Move probe in or out reading back and verifying status
- Start spectrometer readout and read the result to RAM
- Read current environment values (temperature, pressure, position, etc)
- Assemble and write to disk an SPC (spectrum file) consisting of a series of spectra and their associated environment data.

**Automatic calculation of flue gas concentrations**

Algorithms and software for automatic calculation of gas temperature and gas composition is required to analyse large amount of raw measurements. Raw data is stored in multi-SPC files together with reference measurements for each set and each spectrum is tagged with information about time and measurement conditions collected by sensors in the system, i.e. all needed information to analyse gas composition can be found in the multi-SPC file. The file SPC format can be read by existing software working with the SPC-format.
Software for automatic gas analysis is needed due to the large number of measurements that are performed day and night over a long period of years. Software for reading the SPC raw data files and perform the gas analysis is written in Pascal to take advantage work on this topic made earlier. The software has been improved and updated during the project. The measured gas concentrations by the PCMS system

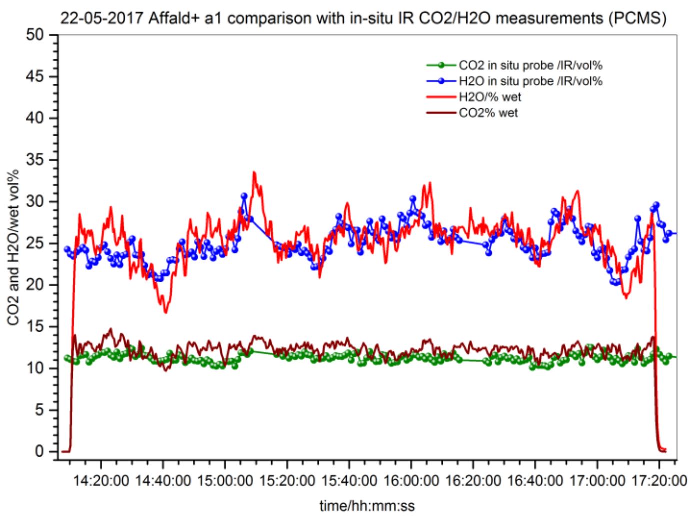



Figure 12a Plot of measured $CO_2$ and $H_2O$ by PCMS system (green and blue curves) compared with extractive gas sampling in the after combustion chamber (EBK) (red and brown curves). The extractive gas measurements are a local measurement and can deviate from the PCMS measurements, e.g. peaks in the local measurements can be smoothed out.

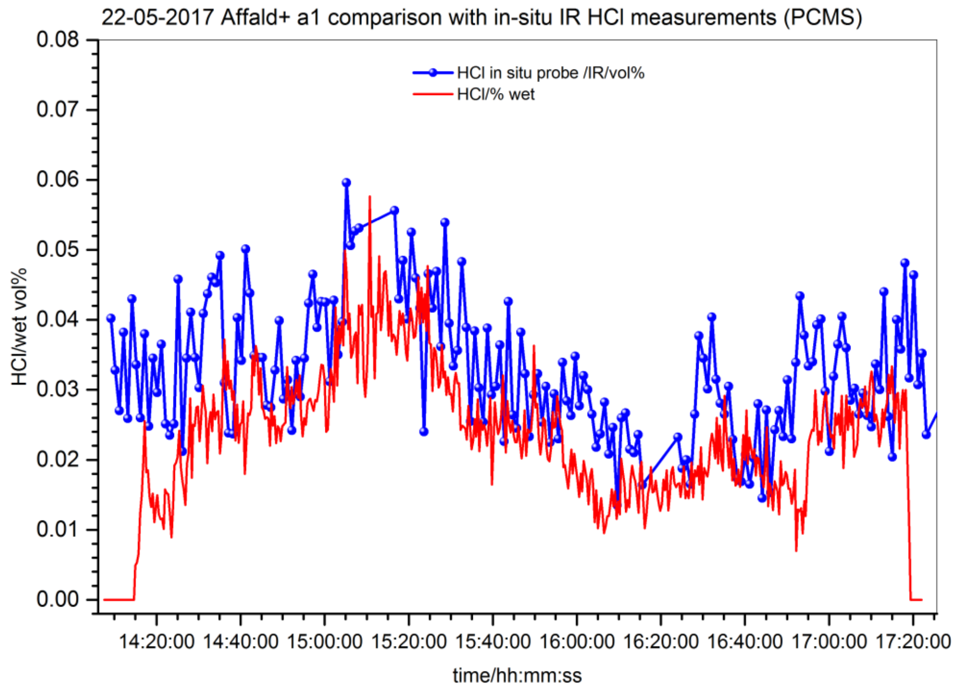



Figure 12b Plot of measured HCl by PCMS system (blue curve) compared with stabilized extractive gas sampling in the after-combustion chamber (EBK) (red curve). The extractive HCl measurement system need several hours to stabilize concentration due to surface reactions, i.e. extractive HCl tends to be lower than in-situ measurements.

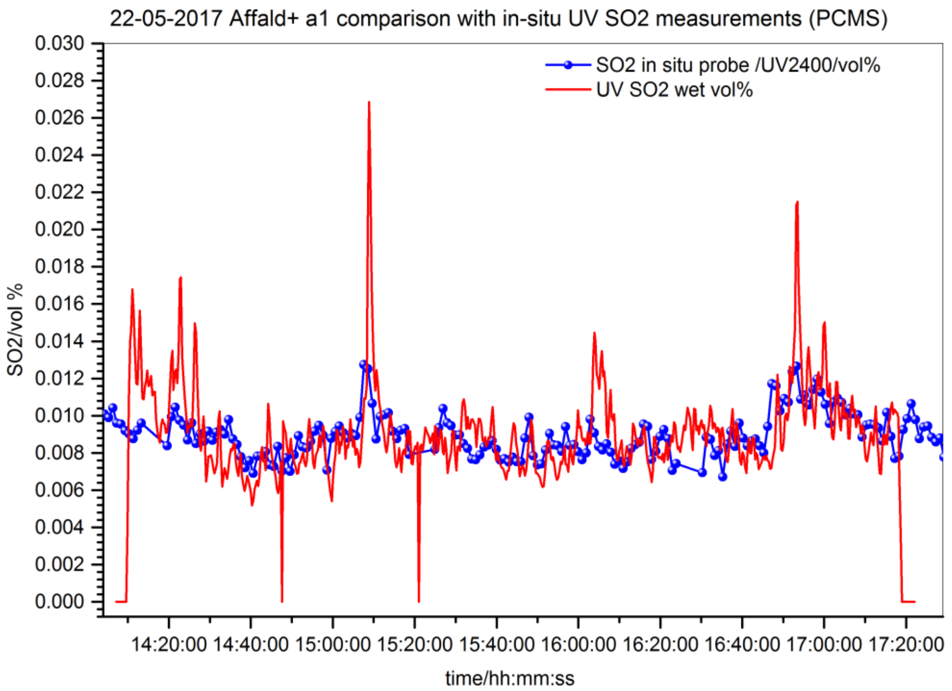



Figure 12c Plot of measured $SO_2$ concentration by the PCMS system (blue curve) compared with extractive gas sampling in the after-combustion chamber (EBK) (red curve).

Software for automatic gas analysis is needed due to the large number of measurements that are performed day and night over a long period of years. Software for reading the SPC raw data files and perform the gas analysis is written in Pascal to take advantage work on this topic made earlier. The software will be improved and updated during the project.


*Figure 13. Ten corrosion coupons after exposure and cleaning.*

**Measurements performed during the project period**
During the project period 3 long-term measurements and 1 short-term measurement were performed. An additional short-term measurement was planned at the end of the project period, but that was cancelled due to the Corona crisis, which made the measurement impossible to carry out

**Long-term measurement 1**
Performed in the period 2017-07-24 to 2017-11-09 during period P4 and P5. The measurement ran to completion without incidents.

**Long-term measurement 2**
Performed in the period 2018-03-21 to 2018-09-19 during period P6 and P7. The measurement was interrupted when Affaldplus+ was forced to do an emergency revision in June, two months ahead of schedule, instead of the planned revision in August. Due to this the probes were taken out and stored with all coupons attached. During storage, probes / coupons were stored wrapped in plastic. After the revision the probes were re-inserted into the boiler in their original place to finish the measurement.

After completion of measurement 2, an inspection of the probes revealed that the housing, distance rings and end nuts were severely corroded. This corrosion hampered the change of corrosion coupons and increased the risk of leaks to the cooling air and therefore it could not be guaranteed that cooling capacity was sufficient. New probe housings were purchased and in addition new end nuts were purchased for change after each test series. This was projected to last for the remaining measurements. As large quantities of thermocouples were also lost during coupon replacements, plenty of new thermocouples were distributed over the most exposed lengths. Purchases were made so that a number of thermocouples could be replaced at each measurement based on experience. In addition, to avoid losing as many thermocouples at coupon change, the probes were modified slightly to ensure easier replacement and to reduce strain on the thermocouples during coupon replacement. This meant a pause before the next planned long measurement.

**Long-term measurement 3**
Performed in the period 2019-01-09 to 2019-01-20 during period P7. Shortly into this measurement, the DTU system suffered a fatal malfunction, which damaged both their sensor packages. As the resulting corrosion of the probes is worthless without the concurrent gas measurements, it was decided to scrap the measurement as the DTU system required extensive downtime.

**Short-term measurement 4**
Performed in the period 2019-05-14 to 2019-06-14 during period P8. The measurement ran to completion without incidents. The object of this measurement was to investigate if frequent cleaning of ash from the probes could give more consistent data from the measurements. A design change of the thermal insulation of the probes was also tested to improve cooling efficiency. The measurement consisted of one third of a full set, and only tested at

the highest temperature range, 475 °C. The measurement was performed with a 6-day cleaning interval.
The DTU gas measurement system was not installed during this measurement as the focus was on the correlation between ash deposition and corrosion.

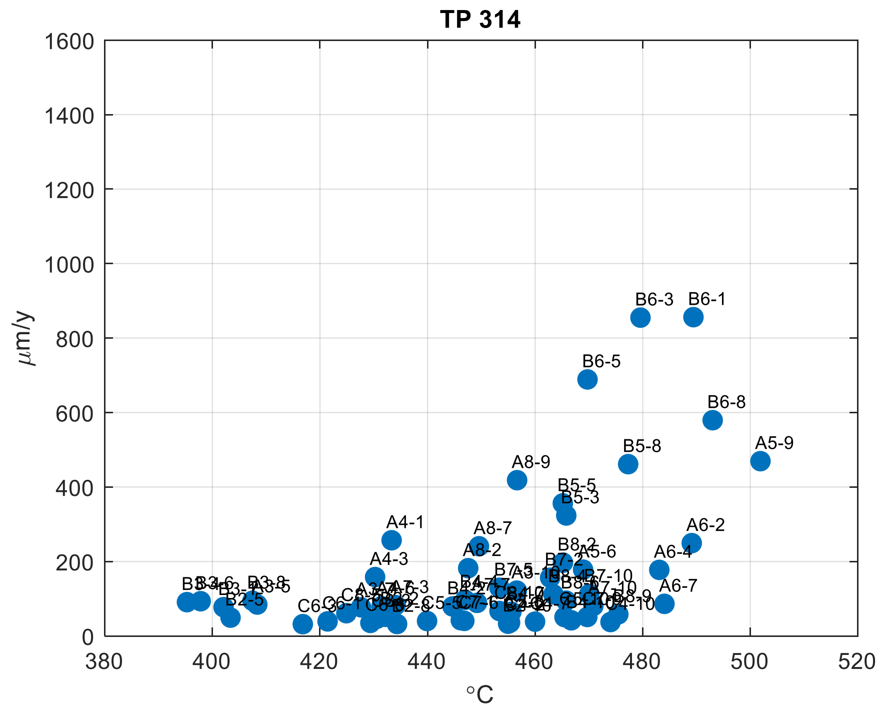
**Short-term measurement 5**
Planned in the period 2020-03-16 to 2020-04-13 during period P9. The measurement was never started as the logistics for measurement completion was made impossible by the Corona crisis lockdown. The measurement would have required a visit to the test site several times a week to manually clean the probes (avg. 4-day cleaning interval). Due to the lockdown Affaldplus+ barred entry to the site.

The measurement would have tested if more frequent cleaning of the probes would have given more consistent corrosion of the coupons as the uneven ash layer is theorised to be the determining factor in the uneven corrosion results.

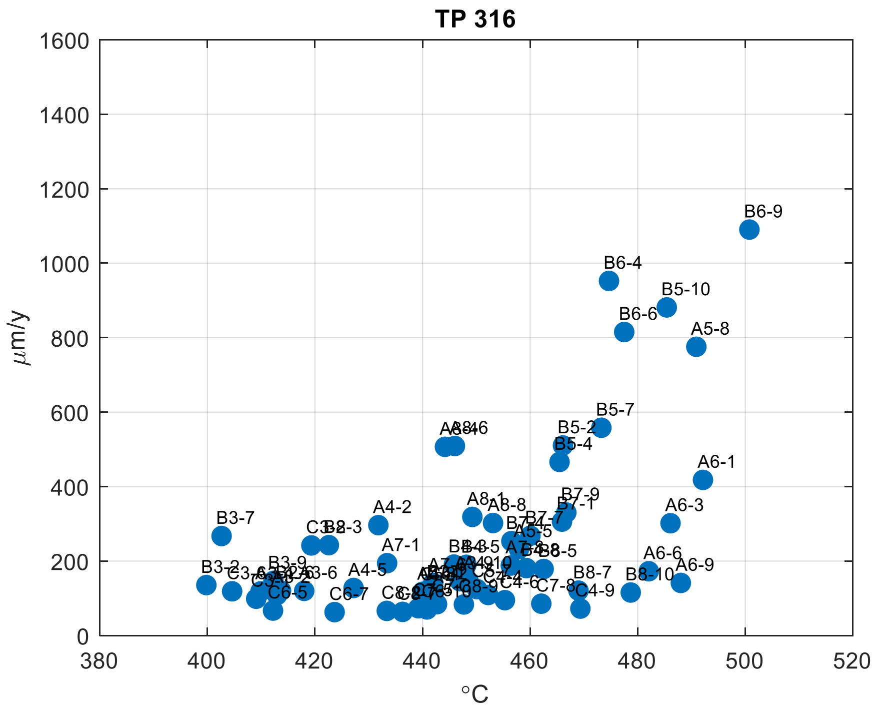
## 1.5 Project results and dissemination of results

### Results from Measurement 1

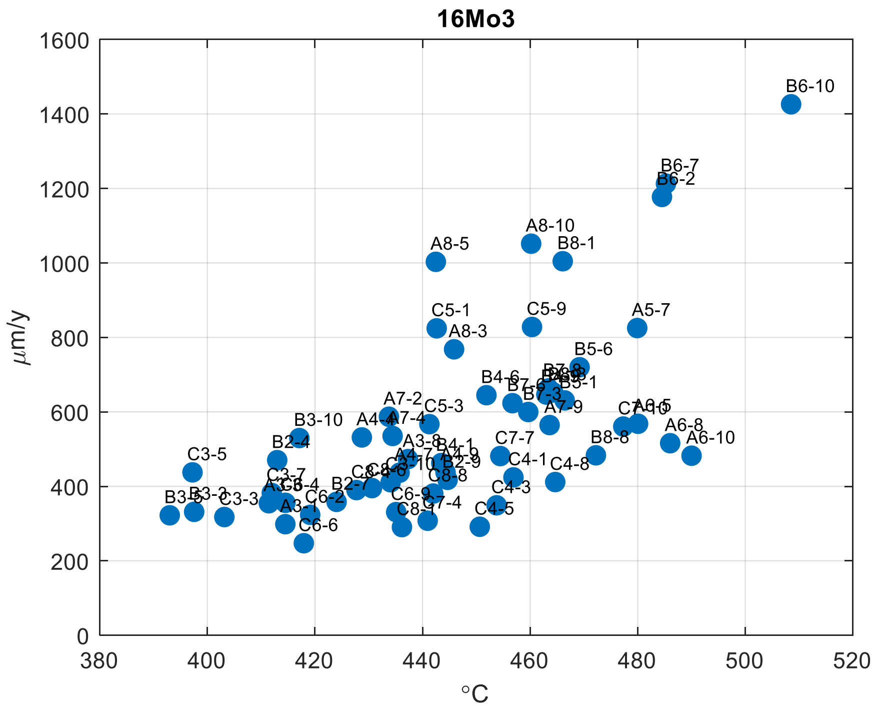
Based on data from measurement 1 the following corrosion of individual coupons are detected:




Corrosion rate for TP314 vs average temperature

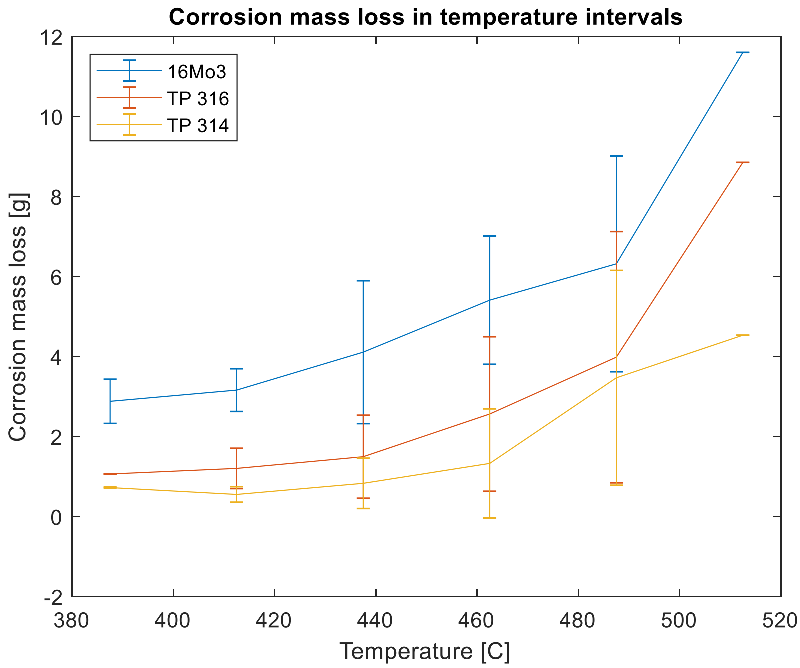



Corrosion rate for TP316 vs average temperature




Corrosion rate for 16Mo3 vs average temperature

Analysing this data, the following result is obtained for all three metals resulted in the conclusion that we reached results as predicted, but due to slug on the probes the results had a two large variance, to programming a reliable soft sensor.




Corrosion rate for all metal alloys vs average temperature with uncertainty intervals


*Figure 14 – Large amount of flyash on the probes – after only 6 days in operation*

The project results are within range of the expected corrosion and temperatures. But unfortunately, the variance of the measured corrosion is so large that a precise PCMS soft sensor algorithm cannot be developed as planned.

The conclusion of the long-term tests performed on the three steel types tested are:

| Steel type (choice) | Maximum annual corrosion | Maximum temperature |
|---|---|---|
| TP314 (best choice) | 400µm/year | <470°C |
| TP316 (good choice) | 600µm/year | <470°C |
| 16Mo3 (economical low temperature choice) | 600µm/year | <440°C |

## 1.6 Utilization of project results

The project partners are considering a PCMS TASK 3 project, where we will improve the air-cooling system on the probes and introduce a high-pressure automatic cleaning system of the probes. The aim will be to develop a soft sensor based on more reliable data. The project participants could consider taking out patents covering the FTIR spectrometers and the soft sensor. A new business plan will be produced based on results. All equipment and systems are ready for future monitoring of superheater steel corrosion.

Throughout the whole world, WtE boilers are being introduced in energy systems. Consequently, there is a continued large demand for the soft sensor for minimising corrosion in the superheaters and increase the temperature (and thereby the efficiency) of WtE power production. The only competitors in the market are the two electrochemical system producers, and they only offer electrodes, they do not have any soft sensor software systems for the control systems on the WtE boilers. During the years the project has been running, the need of a soft sensor solution has remained strong.

*Figure 15 Probes and Coupons ready for new monitoring programmes.*

## 1.7 Project conclusion and perspective

Based on the experimental set-up developed in task 1, inclusive corrosions probes, FTIR & UV probes. A number of short- and long-term measurements have been performed.

In the early stages of Task 2, it was concluded that the desired solution for fly ash cleaning of the corrosion probes with air blasters were not technical feasible. It was therefore decided to continue the experiments without continuous cleaning of the corrosion probes.

The planned test schedule contained a number of long-term measurements to be conducted in task 2. The plan was adapted during the test following analysis of preliminary results from measurement 1 and 2. Extra 2 short-term measurements were added to the test schedule to evaluate the effect of manual cleaning, however due the Corona crisis the 2. short-term measurement was not performed.

The results from the long-term measurements showed a large scattering of corrosion data points. This indicates that the probes are exposed to uneven conditions e.g. falling lumps of ash from the superheater pipes impacted the probe randomly and effected the outcome of the measurements. The short-term measurements were designed to investigate if this effect could be reduced to a reasonable level giving more coherent data.

The outcome of the long-term measurements showed unacceptably large scattering in corrosion data points meaning no algorithm for the soft sensor could be established. Results from the short-term measurement showed a reduced scattering pattern.

The FTIR and UV probes delivered useable data and showed durability in an aggressive environment over long periods. The corrosions probes performed as expected but the results were affected by external factors.

The future perspective is that with adequate cleaning of fly ash that accumulates on the probes, more accurate results are expected. Improved data quality will produce a better basis for the development of the desired soft-sensor for superheater corrosion prediction.