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Conduction and evaluation of temperature, CO and O_2 measurements

in the calciner of kiln 11 in Lägerdorf to define

optimized set points for calciner temperature

Bachelor Thesis

Process Engineering

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Abstract

The topic of this thesis is an operational test in the plant Lägerdorf measuring CO, O_2 and temperature along the calciner aiming at optimized set points for calciner temperature. Kiln stops and CO stratifications could be reduced.

Data for this study were collected in several measuring campaigns in August and September 2016. Lowering the temperature of the calciner from 930 °C to 890 °C in steps of 10 °C and the use of two different measuring instruments required extensive measurement activities. In a detailed overview the paper provides all data concerning process parameters, CO and O_2 concentrations and local temperatures.

First, the results of the measuring campaigns reveal that the CO concentration in the whole calciner is higher than 0,5 %. Second, the precombustion chamber, has a positive effect on the CO concentration. The measured O_2 concentrations support the data of the CO concentrations, but also influence their height. Finally the calciner temperatures vary strongly, so a redefinition is rather difficult.

On the basis of these results two installations in the calciner are described, which should generate a better mixing of fuel, air and hot meal. A reduction of CO concentrations and a better distribution of O_2 concentrations could be achieved.

Sworn statement

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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Markus Berndt

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List of abbreviations

AF	Alternative fuel
Al_2O_3	Alumina
$CaCO_3$	Limestone
CaO	Free lime
CARDOX	System for high pressure coating removal
CO	Carbon monoxide
CO_2	Carbon dioxide
Destrü	Destination residuals
EBS-pellets	Alternative fuels (Plastic)
FeO_3	Iron
Fluff	Airworthy material (Plastic)
NiCr-Ni	Nickel chrome - nickel
NO	Nitrogen monoxide
NO_x	Nitrogen oxide
O_2	Oxygen
PCS7	Process control system
Serox	Alumina corrective
SiO_2	Cilicium dioxide
TF	Traditional fuel
TIS	Technical information system
VC-Rate	Precalciner rate

1 Introduction

The following section presents the activity of Holcim (Germany) GmbH and the assignment of the bachelor thesis. The background and the goal of the task are also explained.

1.1 The Holcim (Germany) GmbH

The Holcim (Germany) GmbH is a subsidiary company of LafargeHolcim Ltd., one of the largest building material producers worldwide with its headquarter in Jona/Switzerland. In 90 countries Lafarge Holcim is represented with 100.000 employees. The business includes cementitious materials, concrete and other services around these products (Holcim, 2015, p. 1).

In northern Germany Holcim is the biggest building material supplier and was established in Lägerdorf 150 years ago. The location Lägerdorf is the oldest producing cement plant worldwide. Around 320 employees work in different fields of activity (Holcim, 2014, pp. 2–3). The total input for the clinker production is 2.6 Mio t / a which includes all raw material and fuels. The total output is around 1.3 Mio t clinker a year which is ground with other additives for the final product cement (Holcim, 2014, p. 16,29).

1.2 Goal and objectives

To produce high quality cement it is a complicated process containing different aggregates and additives. The cement production is a very expensive industry because of the high energy consumption. Especially the chemical reactions require a lot of thermal energy. To stay competitive with a continuous production process of clinker, it is necessary to avoid kiln stops. In order to attain this goal it is required to optimize operational set points for the calciner temperature.

"The calciner in Lägerdorf of kiln 11 is currently operating at 910-935 °C with fully decarbonized hot meal (99.6 % AVG 2015). Beside the high thermal energy input (150-160 MW) needed to fulfill such temperatures and the accompanying costs for fuels, such high temperatures lead to coating formations in the lowest cyclone stage caused by the dust/ash particles that are in the gas stream. This coating formation leads, when significantly large, to cyclone blockages that cause full system stops and are of dangerous hazards. To minimize the risk of cyclone blockages, the target is a calciner temperature at lowest possible temperatures, that are usually defined by

- certain upper carbon monoxide CO levels (i.e. 1 000 ppm)
- minimum achievable decarbonization degree in hot meal ensuring a free lime (CaO) content in the product clinker below 2,5 % when leaving the kiln

To define these limits, it is necessary to conduct, beside others, specific measurements at different operational temperatures of the calciner.

The goal of this thesis is the conduction and evaluation of temperature, CO and O_2-measurements in the calciner at different calciner temperature set points. To achieve this goal, following objectives will be performed:

- Identification of appropriate measuring points for temperature, CO and O_2-measurements along the calciner covering both, horizontal cross sections and vertical profiles.
- Definition and installation of necessary additional measuring points
- Measurements of CO and O_2 at different temperature set points of the calciner along the measurement points. Repeating measurements upon demand to identify variation of measured data
- Evaluation and analysis of measurement data; graphical visualization (software will be defined or by using MS-Excel)
- Discussion of results and short description of optimization options" (Groß, 2016a, p. 1)

2 Background

The following chapter describes the cement production in Lägerdorf and relevant facts of this research. Chemical reactions and the software used for evaluation are included.

2.1 Cement production at the plant Lägerdorf

For the production of cement minerals of natural source or industrial products can be used. Cement is a hydraulic binder with the main components calcium oxid (CaO) and cilicium dioxid (SiO_2), in small quantities oxide of iron (Fe_2O_3), alumina (Al_2O_3) are contained as well (Duda and Duda, 1985, p. 1; VDZ, 2008, p. 31). Hydraulic binder means a powdery material, which hardens when water is added (Kühl, 1951, p. 3). Raw materials, which include these components, are generally limestone, chalk and clay or limestone and marl.

Lägerdorf plant uses one of four different process routes for the production of cement. The semi wet process method is applied in Lägerdorf. This means the material with a humidity of around 20% of water gets transported into the flash dryer.

Figure 1 shows a flow chart of the cement production in Lägerdorf from the raw material out of the quarry to the final product cement. In Lägerdorf the raw material is chalk, which gets mined. The mining is done using bucket wheel excavators (1), which can remove 10 000 tons of chalk per day. The chalk has a humidity of water of some 23 % and gets transported by conveyor belts into the slurry washdrums (2). The slurry washdrums whitewash the material with water so that the suspension has a humidity of 42 %, which is required to carry the material into the plant. This mixture is pumped from the slurry basins into storage tanks (3) mixed up with sand (4), iron ore and other corrective substances (5). After this process step the mixture is pumped into the filtration (7) and leaves the filtration with a humidity of 20 %. Afterwards conveyor belts transport the filter cake into the hammer mill (8). With the help of hot exhaust gases out of the kiln and the clinker cooler waste air the filter cake gets desagglomerated and dried in the flash dryer (8).

The hot meal is heated up to 900 °C with the counter-flow gases in the cyclone preheater (9). At the same time a part of hot meal is decarbonized. The full decarbonation happens in the calciner (10). Moreover, the rest of the additives (11-12) are mixed with the hot meal. The fully decarbonized hot meal enters the 65 m long rotary kiln (13). The retention time of the material from the kiln inlet to the end is 16-18 min in the kiln. At the end of the kiln the sinter zone with a temperature of 1450 °C is located. Here the clinker minerals are formed.

Leaving the kiln, the hot clinker granulate falls down into the clinker cooler (14) which cools down the clinker to 200 °C using ambient air. After this process step the clinker is stored in clinker halls (15). Out of these halls the clinker gets transported into the cement mills (18-19) and is mixed with other additives (16-17). Behind the mills (18-19) the final product is conveyed into silos for a temporary storage (20) (Holcim, 2012, pp. 1–6).

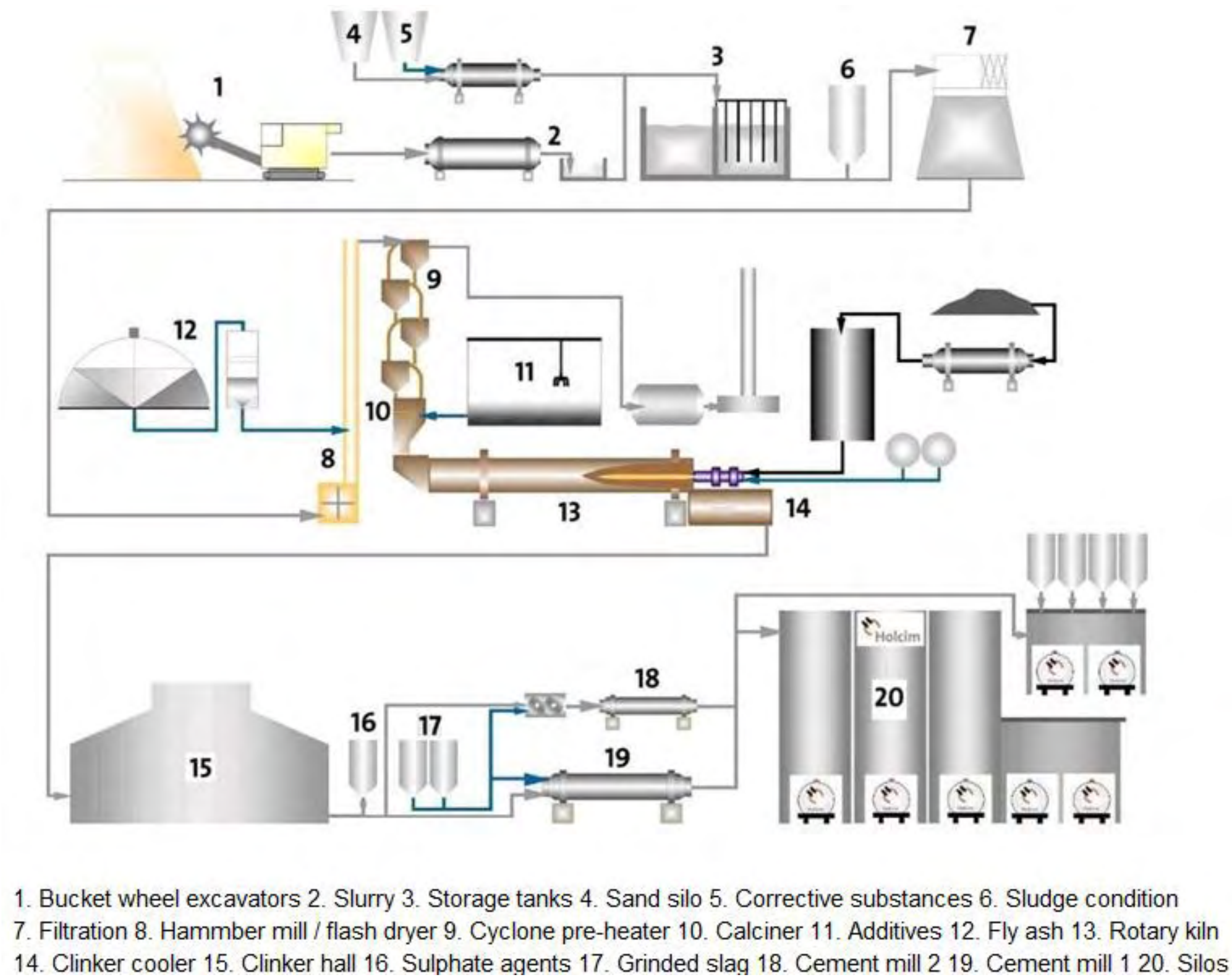

Figure 1: Schematic overview of cement manufacturing in Lägerdorf – process steps and functional units (Holcim, 2012, pp. 1–6)

2.2 Fundamentals of carbon monoxide

During the cement process diverse gases are formed. This chapter deals with the formation and reduction of carbon monoxide (CO), an important gas in relation to cement manufacturing.

2.2.1 Formation and reduction of CO

CO is a highly flammable gas. Together with oxygen (O_2) carbon dioxide (CO_2) can be formed during the combustion. During inefficient combustion without enough O_2 in the calciner or rotary kiln emissions of CO and organic carbon arises. Another source for CO is the heating up of the raw material in the cyclone pre-heater. Some of the hydrocarbons degas and others form CO. This emission of CO can hardly be influenced compared to the CO emissions from combustion. The reaction kinetics are important, that means the combustion has to be over-stoichiometric and has to work with normal temperature to minimize the formation of CO. The minimum temperature for CO burn out is 700 °C (Jennes, 2003, pp. 31–33; VDZ, 2005, pp. 16–18).

2.2.2 Permission limits of kiln exhaust gas

For the kiln exhaust gas different limit relations of gas composition are defined. The Federal Environment Agency fixed these limits. Only the emission of CO is important for this thesis. The daily and half-hour limits for the plant in Lägerdorf are shown in Table 1.

Table 1: Daily and half-hour limits of CO

Emissions in mg/Nm^3 dry	**Daily limit**	**Half-hour limit**
CO	1000	2000
Emissions in %	**Daily limit**	**Half-hour limit**
CO	0.08	0.16

These values get measured at the stack in Lägerdorf. The validated data are reported to the Federal Environment Agency and are available for everyone. Different warning and shut down limits exist for the CO content, which are shown in Table 2. These warnings are installed to avoid gas compositions especially for explosions.

Table 2: Overview of CO-warning-/shut-down limits for the kiln in Lägerdorf

CO- content in %	**Priority**	**Measures**
0,50	MAX 1 /CO_H1	Interlock for fuels (alternative fuels and TF)
1,00	MAX 2 /CO_H2	Stop of AF and TF calciner
1,50	MAX 3 /CO_H3	Stop of main burner and kiln feed
1,80	MAX 4 /CO_H4	Stop and flushing of system with fresh air
2,00	MAX 5 /CO_H5	Hardware shut down and flushing of system with fresh air

2.3 Kiln technology

In the years 1960 to 1970, the development of the kiln technology experienced a profound change. The wet-process of clinker manufacturing where the raw material gets filled up with 30 % of water into the kiln is no longer applied in practice. Now more cost-effective solutions are used. The most popular methods are the dry process or the semidry process.

The semidry process is based on a grate pre-heater before the material is carried into the kiln (Lepol kilns). Almost 8,1 % of the producers of cement work with this technic in Germany. The most commercial method is the semidry process where the material heats up in a cyclone pre-heater. This method is used in Lägerdorf. In the following a rotary kiln with cyclone pre-heater and calciner is described.

The invention of rotary kiln with cyclone pre-heater has changed the complete process engineering of the clinker production. This technology has a number of positive aspects for the cement manufacturing, e.g. higher production capacity, reduction of emissions and most important the lower heat consumption. It is possible to produce 8000 – 12000 tons per day (VDZ, 2008, pp. 50–59).

Figure 2 shows the rotary kiln with cyclone pre-heater, calciner and pre-combustion chamber used in Lägerdorf.

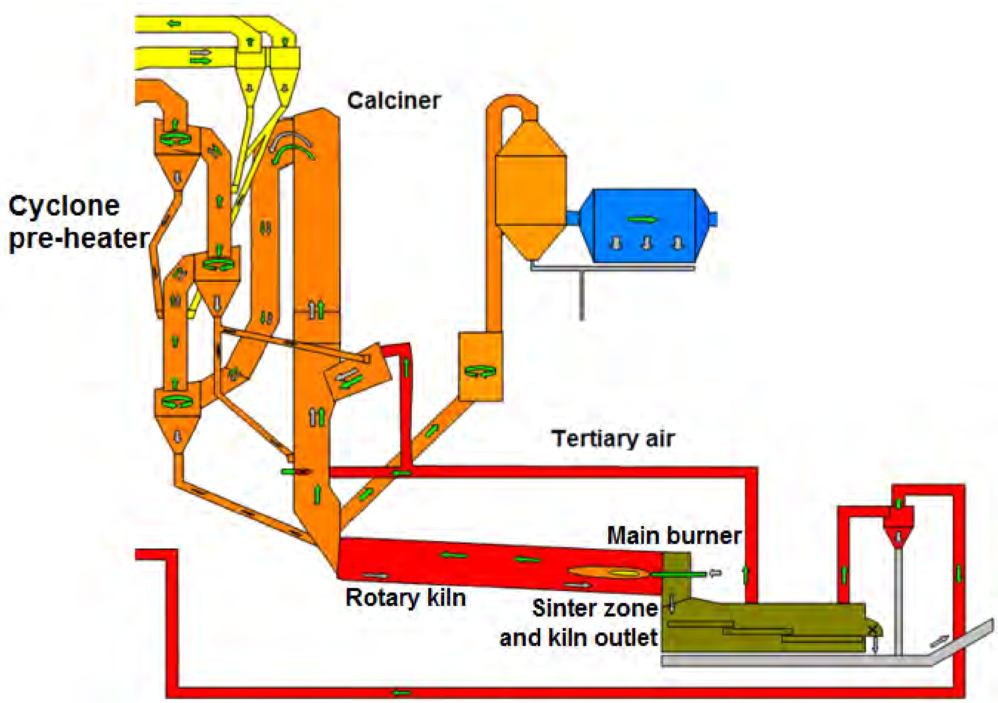

Figure 2: The rotary kiln with cyclone pre-heater, calciner and pre-combustion chamber (Wolf, 2014, p. 2)

The rotary kiln is the main component of the cement manufacturing. Rotary kilns are inclined by 3 - 4° with a diameter up to 6 m. Because of the incline the material gets transported to the kiln outlet. The cement clinker minerals get burnt in the sinter zone, which is a part close to the end of the rotary kiln. This process needs a temperature of 1450 °C. The dwell time is between 20 – 40 min (VDZ, 2008, pp. 57–59). At first dicalcium silcicate (2 $CaO \cdot SiO_2$, belite) is formed. After the hot meal starts to melt, tricalcium aluminate ($CaO \cdot Al_2O_3$), calcium aluminumferrite (2 $CaO \cdot (Al_2O_3)$ and free lime (CaO) are formed. At the end of the process dicalcium silicate turns into tricalcium silicate (3 $CaO \cdot SiO_2$, alite). This silicate is very important for the stability of the cement, in particular the early strength (VDZ, 2008, pp. 36–39; VDZ-Seminar, 2015, p. 3).

The main burner, its flame can be three or four times as large as the diameter of the kiln, is installed at the kiln outlet. The fuel for the burner has to fulfil very specific requirements to guarantee the quality of the clinker. Therefore, the fuel must have a high calorific value (VDZ, 2015, pp. 15–16). The calciner and cyclone preheater will be described in chapter 2.4.3.

2.4 Process technology of pre-calciner

This section describes the process technology of calciner, which is especially important to achieve the desired clinker quality. Calciner differ from their construction forms, concerning for example tertiary air, area for the fuel feed, secondary fuel or geometry. Following the calciner of Lägerdorf is described in detail.

2.4.1 Description and function

The calciner is the reaction room among the rotary kiln and the lowest cyclone stage in the cement industry (Kupper, 1984, p. 9). A calciner is an entrained-flow-reactor, which has the achievement to create an intensive mass and heat transfer between combustion gases and hot meal. Figure 3 shows three basic types of calciners that are used in cement manufacturing.

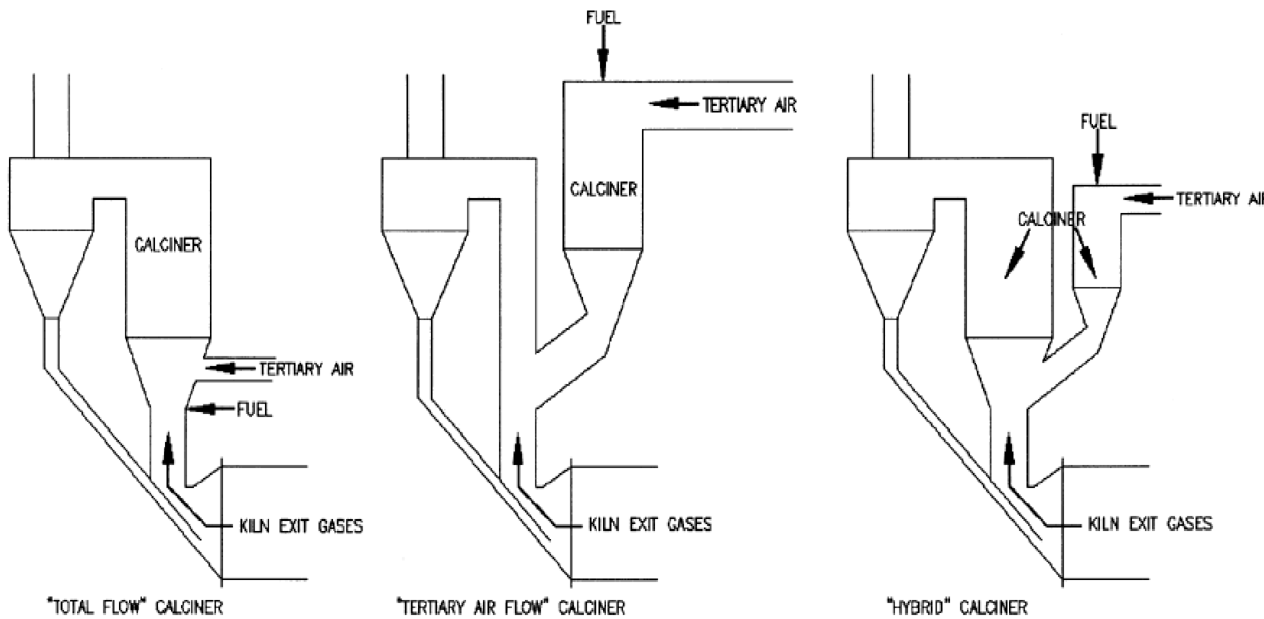

Figure 3: Three basic types of calciner (V. J. Turnell, 2001, p. 374)

The Figure on the left hand side shows the "total flow" or "inline" calciner. The combustion starts at 10-14 vol.-% oxygen content, composed of kiln exhaust and tertiary air. Not shown in the Figure is the pipe for the hot meal that comes out of the second lowest pre-heater cyclone stage. The exhaust gases out of the kiln lift up the hot meal together with the fuel into the calciner and then to the lowest cyclone stage. During this period an intensive mass and heat transfer supports the calcination.

The illustration in the middle shows the "tertiary air flow" calciner. The combustion starts with tertiary air with an O_2 content of 21 vol.-%. The hot meal is placed into the tertiary air or burning area and passes the calciner into the lowest cyclone stage. The same reactions as described above take place during this process.

The last Figure shows the "hybrid" calciner that is a combination of total and tertiary flow calciner. The combustion starts with 21 vol.-% oxygen out of the tertiary flow. This calciner has the same hot meal feed like the "tertiary air flow" calciner. The hot meal arrives at the calciner inlet with a temperature about 720 °C.

For the calcination a temperature about 870-900 °C is needed. All these three types reach this temperature. The calcination and combustion reaction run up at the same time. The speed of reaction depends on reaction kinetics and fines of the hot meal. The calciner volume dimension is sufficient for a total burn out of fuel and hot meal. Current calciners are designed with a residence time of the gas between 3 and 6 seconds.

The flow velocity has to be around 14-18 m/s and higher than 25 m/s at narrowing points. This is necessary to carry the hot meal and fuel through the calciner (VDZ, 2005, pp. 3–5). The first and second calciner shown in Figure 3 are designed for a reduction zone, which is a part of the staged combustion (V. J. Turnell, 2001, pp. 374–375).

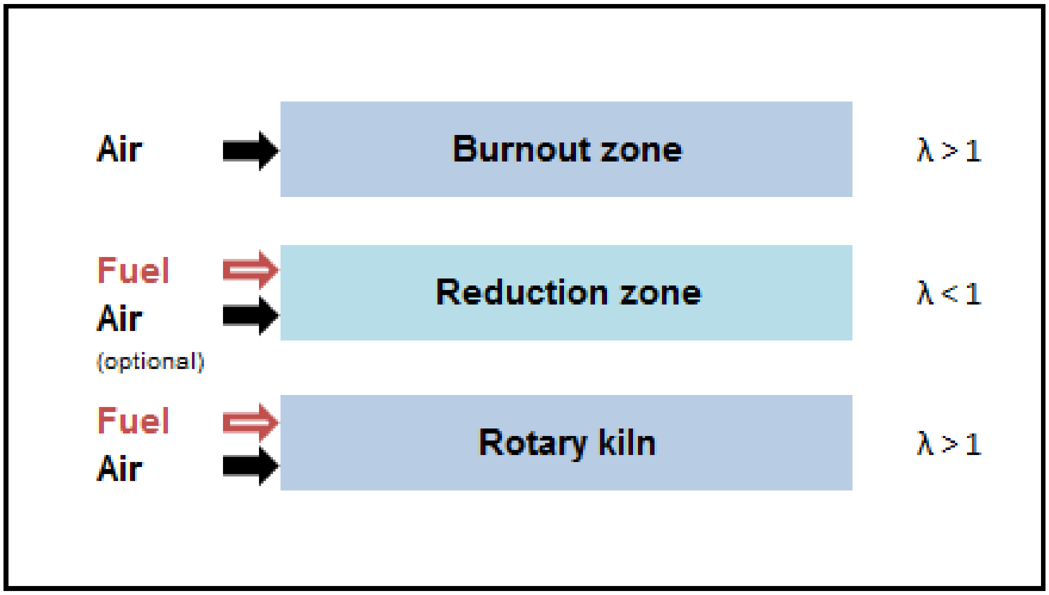

Figure 4: Principle of staged combustion

Figure 4 shows the principle of staged combustion. This technic is used to decrease the NOx-level. The objective is to create a reduction zone by splitting of the fuel- and air-mass flow for the different process steps.

"The air-fuel ratio, or lambda number (λ) determines the mass ratio of air and fuel in the combustion chamber, as it relates to the stoichiometric air-fuel ratio. When λ=1, ideally balanced combustion conditions result in neither oxygen starvation nor excess. A reading of $\lambda < 1$ indicates air starvation (rich mixture), whereas $\lambda > 1$ indicates an excess of air (lean mixture)" (ETAS, 2016, p. 1)

$$\text{Air} - \text{fuel ratio}(\lambda) = \frac{\text{Volume flow}}{\text{Minimum volume flow}} \quad (1)$$

The following Figure 5 shows the location of the three stages in the calciner. The rotary kiln is the first stage with an oxygen environment ($\lambda > 1$). In this area the NO-level increases because of the oversupply of oxygen. The low oxygen ($\lambda < 1$) area follows. It is only practicable for rotary kiln with tertiary air and pre-calcining technology. To achieve this low oxygen area, it is necessary to add fuel into the pipe between kiln and calciner. The fuel uses the oxygen in the gas out of the kiln to reduce the building of NO. In addition the degradation reaction of NO starts. The burnout zone for the complete combustion is located above the reduction zone. This implies an oxygen environment which is accomplished by injecting tertiary air (VDZ, 2005, pp. 16–18).

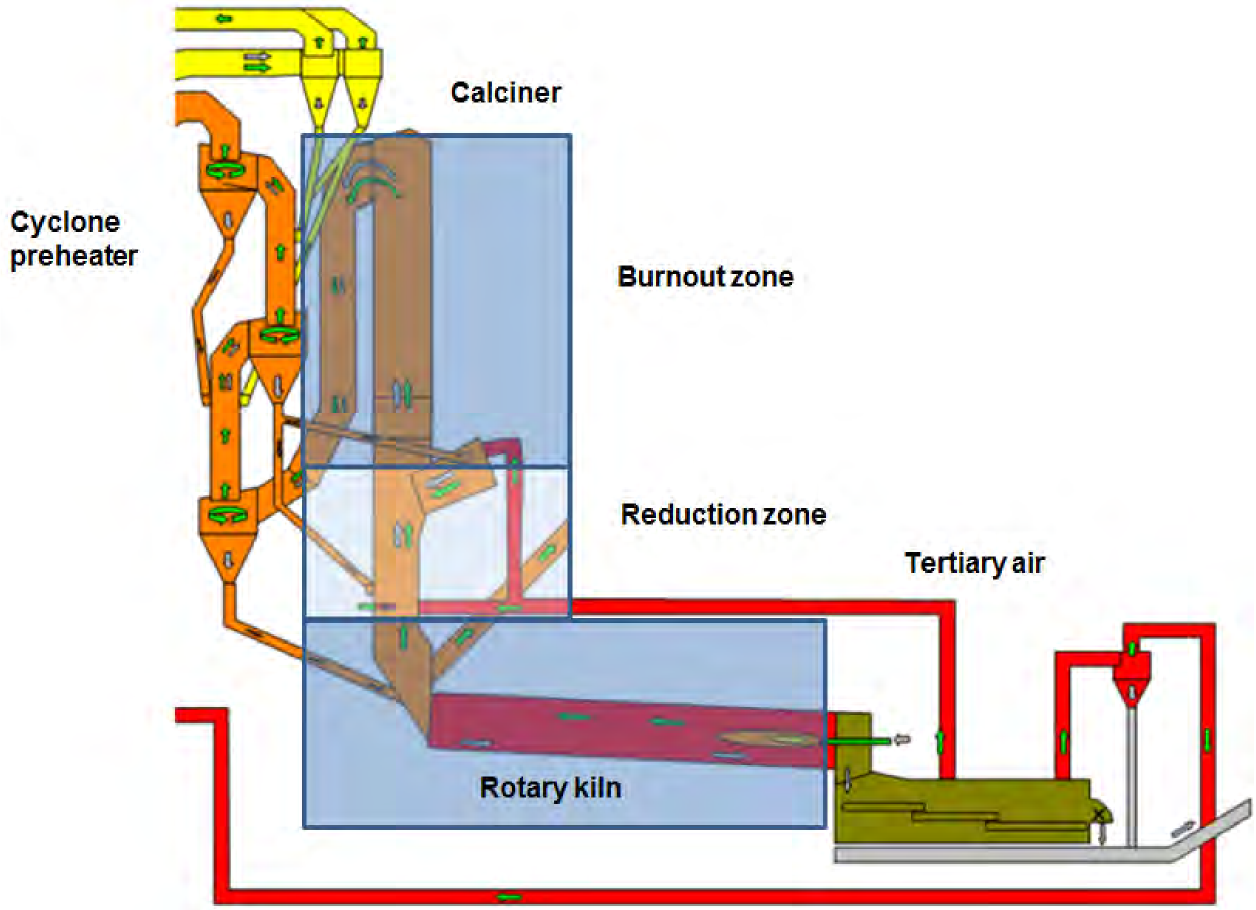

Figure 5: Staged combustion in the calciner (Wolf, 2014, p. 2)

2.4.2 Calcination of hot meal in the calciner

During the combustion degradation reactions of limestone ($CaCO_3$) and formation reactions of free lime (CaO) and Carbon dioxide (CO_2) happen in the calciner. The speed of these reactions depends on the fines of the hot meal / fuel mix and the reaction kinetic. Compared to the combustion the reaction speed of the calcination is much higher. The calcination of limestone is endothermic with the decomposition reaction:

$$CaCO_3 \rightarrow CaO + CO_2 \quad (2)$$

Almost 77 to 78 m.-% of the limestone ($CaCO_3$) out of the raw material dissociate in CaO and CO_2. The energy needed for this reaction is 1750 kJ/$kg_{clinker}$ and the decomposition starts with a temperature of 830°C.

Figure 6 shows the schematic limestone calcination. The heat enters the particle and decomposes the $CaCO_3$ into CaO and CO_2 which diffuse into the environment (Jennes, 2003, pp. 20−28).

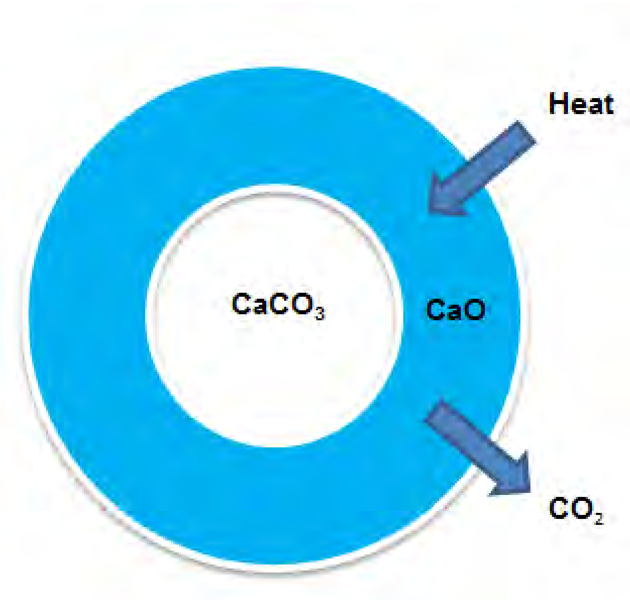

Figure 6: Graphical illustration of limestone calcination

2.4.3 Calciner in Lägerdorf

In 1995 the calciner Prepol_AS_MSC in Lägerdorf was built by Krupp-Polysius AG. The PREPOL_AS_MSC is an inline (AS-air through) calciner with separated tertiary air flow and multistage combustion (MSC). The calciner has a separated tertiary air flow and staged combustion to minimize the CO and NOx formation (VDZ, 2005, p. 37). The calciner of Lägerdorf is schematically shown in Figure 7.

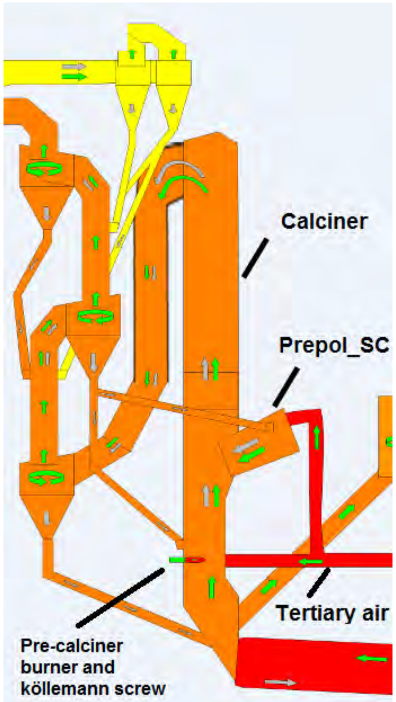

Figure 7: Calciner in Lägerdorf (Wolf, 2014, p. 2)

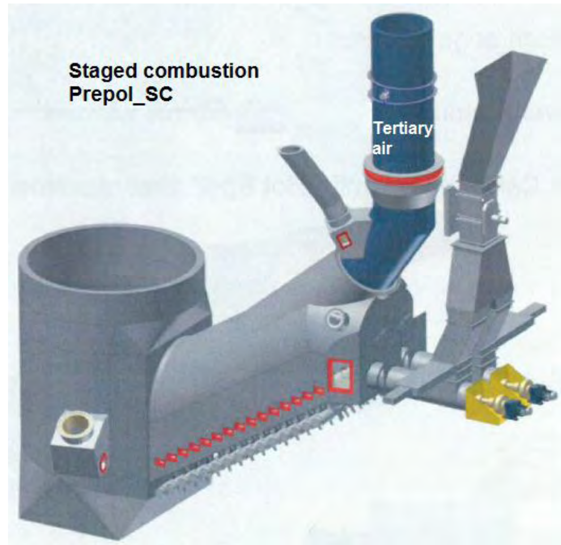

Figure 8: Prepol-SC (VDZ-Seminar, 2015, p. 20)

In 2007, the calciner was extended to a length of 93 m, a volume of 1859 m^3 (Wolf, 2014, p. 1) and a residence time of 4.9 seconds, before it was 2.2 seconds (Groß, 2016b, p. 10). The extension makes it possible to use alternative fuels.

The pre-calciner burner works with pulverized lignite. Additionally in this area alternative fuels can be fed. This material is transported by screw conveyor into the calciner. Two hot meal chutes for the hot meal, which comes out of the second cyclone stage, are located above the burner.

In 2013 a pre-combustion chamber, the Prepol-SC, was installed. Its structure is shown in Figure 8. The Prepol-SC is a pre-combustion chamber, it is able to combust material with a length of 300 mm in 3D. The calciner operates with 100 % of alternative fuels. These include two correctives (iron and alumina) and six different alternative fuels. The alternative fuels get transported with the Köllemann double screw into the calciner.

The mode of operation is as follows: the material is transported by screw conveyor (Köllemann double screw) into the combustion chamber, which contains 15 stages. Every stage uses five nozzels, which from time to time release compressed air to transport the material. Hot meal of the second cyclone stage is used to control the gas outlet temperature at the end of the Prepol-SC. The material is burned out up to 80-90 % at the lowest stage and gets transported into the calciner where the total burn out proceeds. In the Prepol-SC the dwell time is 15-20 minutes compared to the calciner with 4.9 seconds. The Prepol-SC has a capacity of 40 MW and can compensate a quarter of the thermal energy which is needed for the whole production process (Wolf, 2014, pp. 1−2).

2.5 Used software

This section describes the software, which is applied to control the whole cement process with real time data, besides the program is used for the evaluation.

2.5.1 Technical information system

The Technical Information System (TIS) is a combination of a laboratory and a production system developed by the company ABB. TIS collects all data out of different interfaces, which are important for the whole cement manufacturing.
All process data are saved on a main server (7), which is shown in Figure 9. The different interfaces are quality management (1), environmental authority (2), process control system 7 (3), energy management (4), other plants (5) and the incoming and outgoing goods (6) at the plant Lägerdorf. Every plant has different interfaces but an international Holcim standard for the data collection and visualization serves as a basis for all.

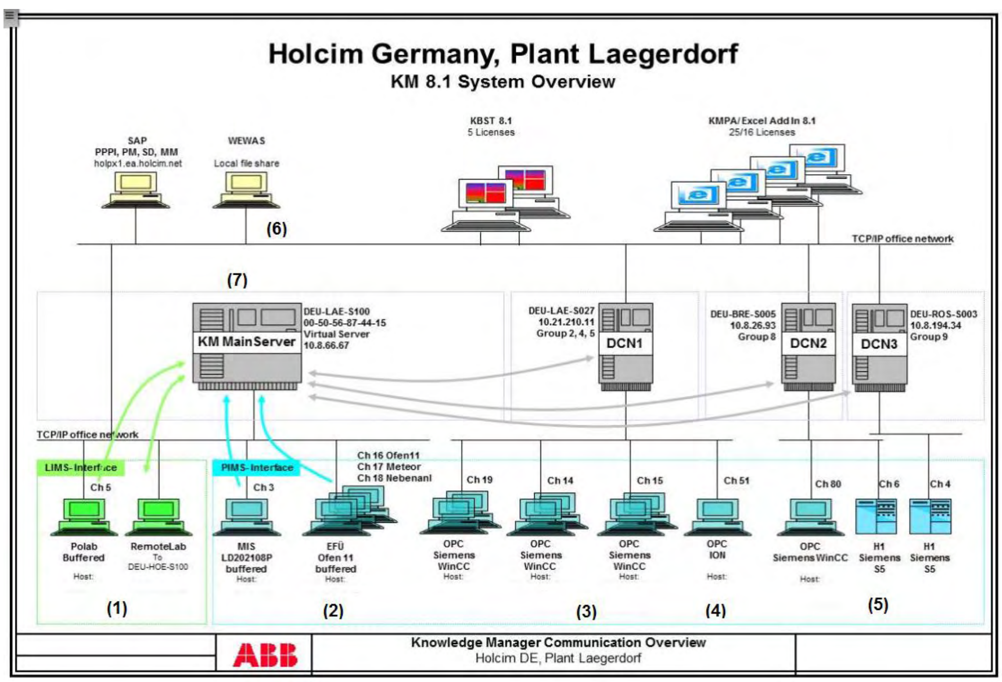

Figure 9: System overview of the plant Lägerdorf (Schändel, 2016)

This system offers the chance to speed up certain circumstances, which require a rapid decision. TIS is available for the whole Holcim company including all countries. For the laboratory, maintenance and production these reports are useful to define / localize problems, for optimizing and monitoring the quality of the clinker and cement. The reports are available for all relevant process data, e.g. various gas measurements, temperatures and mass flows (Schändel, 2016; World Cement, 2014, pp. 1–2).

2.5.2 Process control system SIMATIC

Simatic PCS7 is a process control system developed by Siemens to handle many different production processes at the same time. The control and automation of manufacturing and engineering processes are included. The system is operated by graphical interface, which ensures a quick and precise control. Furthermore all current announcements, alarms and measured values are stored in a database to reproduce problems from the past (Siemens AG, 2016, pp. 4–5).

Two operators in the control station in Lägerdorf control the whole production process of cement. This implies the processing of 7500 measurements and the control of 1200 valves, 600 flaps and 2000 motors (Holcim, 2014, p. 20).

2.6 The measuring devices which are used for the measurements

The following chapter deals with two different types of measuring instruments. These are the testo 350 M/XL, testo 350 and the Siemens ULTRAMAT 23, which is located on 81 m at the preheater tower.

2.6.1 Description of the measuring apparatus testo 350 M/XL and 350

The apparatus testo 350 M/XL is a portable gas analysis box. It is possible to measure different gas parameters depending on the configuration of the testo. Figure 10 shows the control unit, which analyses the gas.

Figure 10: Testo 350 M/XL

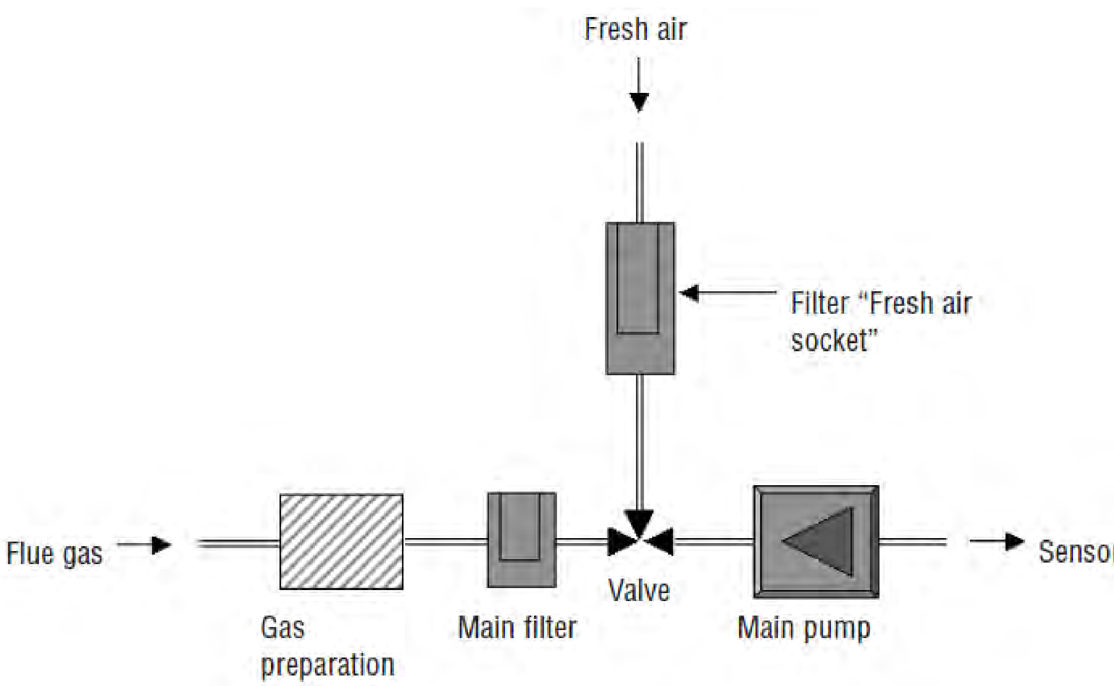

Figure 11: Schematic diagram of testo 350 M/XL (Testo AG, 2002, p. 46)

The testo 350 M/XL contains a small pump which forces gas through the probe socket (1) into the apparatus. The measuring gas gets cooled down to 4-8 °C and the condensate is pumped into the condensate collector (2). The dry gas penetrates the particle filter / dirt filter (3-4) and passes the gas sensors. A small amount of the gas diffuses through the membranes, which analyze the gas and give a signal. The rest of the gas exits through the exhaust outlet (5). When the measurement is finished, the apparatus rinses out the equipment with fresh air (6). This testo 350 M/XL is equipped for the parameters CO and O2 (Testo AG, 2002, p. 46). Figure 11 gives a schematic overview of the main components and gas flow in the testo. The testo 350 is shown in Figure 12. It is an update of the testo 350 M/XL with the same functional principle, but the CO sensor is able to measure a CO concentration until 30 000 ppm (3.00 %), the 350 M/XL can measure CO until 5000 ppm (0.50 %).

Figure 12: Testo 350

2.6.2 Description of the Siemens apparatus ULTRAMAT 23

The gas analyzer ULTRAMAT 23 built by Siemens is designed for measuring four different gas components at the same time (Siemens AG, 2015, p. 19). The ULTRAMAT 23 in Lägerdorf is equipped for CO and O_2. The CO is measured with an infrared detector and the O_2 with electrochemical oxygen sensor (Siemens AG, 2015, p. 30). The ULTRAMAT 23 is calibrated with test gas CO and O_2, see detailed description in chapter 3.4.

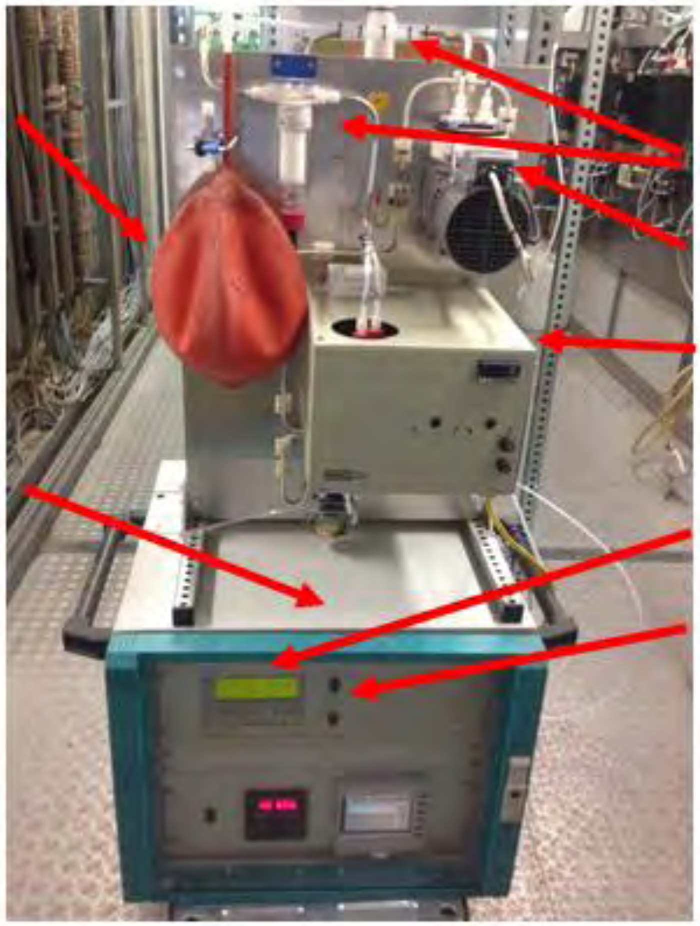

Figure 13: Measurement apparatus ULTRAMAT 23

Figure 13 displays the ULTRAMAT 23. The gas sample taken from the calciner is filled up in the gas balloon (1). The pump forces the gas through two dirt filters into the gas cooler. Downstream the gas cooler the gas has a temperature of 5 °C and the condensate is pumped into a small tank. The dry gas analysis takes place and the digital display shows the result. The volume flow of the pump is 1.5 l/min. The same volume flow is used during the calibration with test gas.

3 Materials and methods

The following chapter describes the current state of the calciner operation in relation to the operational set point for calciner temperature.

3.1 Current state

Through the last years the operational set point for the calciner temperature raised from 860-880 °C (1996) to 930 °C (2016). This temperature is higher than the desired temperature in the calciner. On the one hand it would be advantageous to avoid CO trips and CO shut downs, which often provoke full system stops, therefore these high temperatures are accepted at present. On the other hand it is unfavorable when the calciner operates with these high temperatures for a long time. Consequently the lowest cyclone stage gets overheated which includes hard coating and cyclone blockages. To eliminate these blockages 4 h working time are required on average (2015 evaluation). In 2015 12 cyclone blockages were registered, 12 stops of the whole system were required. Due to these system stops a loss of an annual six-digit amount in Euro had been provoked. To reduce the financial loss and dangerous hazards it is required to minimize cyclone blockages by lowering the calciner temperature (Groß, 2016, p. 10).

3.2 Procedure

The main goal of this work is to define optimized operational set points for the calciner temperature. The plan provides five different measurement campaigns. This includes to lower the temperature of the calciner in 10 °C steps. The measuring point of the calciner temperature is located in the deflection chamber at 75 m. The highest temperature to measure is 930 °C and the lowest 890 °C. At every measurement point the concentration of CO, O_2 and the temperature should be measured.

Prior to every measurement campaign the operator in the control station has to agree to start this campaign to avoid production stops. The production of the clinker has priority and if the system is not tolerant to a temperature change or it does not function well the campaign has to be performed on another day.

Every measurement campaign has the same stop criteria:

- CO shutdown
- Hot meal escape at the kiln inlet
- The quality of the clinker in relation to the CaO content (1-2,5 %)

Their occurrences provoke the stop of the measurement campaign and the adaption of the calciner temperature. To avoid dangerous hazards and loss of production the stop criteria have to be observed.

If it is possible to start the campaign the measurements will be performed with a testo or gas balloons, which are described in chapter 2.6. The first campaign revealed that the CO content is higher than 5000 ppm in the calciner. The testo 350 M/XL is designed for a CO content up to 5000 ppm, consequently the testo 350 M/XL is only suitable for the measurement points in both strings on the floors 45 m and 52 m, this includes 12 measurements. The other measurements are carried out with the testo 350 or gas balloons analyzed with the ULTRAMAT 23.

3.3 Preliminary work

This chapter deals with the preliminary work in relation to the measurements. The locations / set up of the measurements, experimental procedure and the measurement collection are described.

3.3.1 Locations for the measurement points

To receive results for temperature, oxygen and carbon monoxide in the calciner the locations of the measurement points are very important. They are defined together with the process engineer and the kiln master. Most of the measurements can be performed through existing CARDOX openings, pressure ports and other openings. An overview of the measurements with the belonging level and fuel feeding points is given in Figure 14 and 15. 36 measuring points are located on 10 different heights.

Level		North	East	South	West	Amount of measurements	Remark
75m	Train 1				3 x Cardox	3	free for measuring
	Train 2		2 x Cardox			2	free for measuring
71m	Calciner	1 x Cardox	1 x Cardox		1 x Cardox	3	free for measuring
67m	Calciner	1 x Pressure port		1 x Cardox		2	free for measuring
52m	Calciner	1 x Cardox		1x Nozzel		2	free for measuring
	Train 1	1 x SNCR	1 x SNCR	1 x SNCR	1 x SNCR	4	free for measuring
	Train 2	1 x SNCR	1 x SNCR	1 x SNCR	1 x SNCR	4	free for measuring
45m	Train 1		1 x Cardox			1	free for measuring
	Train 2				1 x Cardox	1	free for measuring
	Cyclone 1				1 x Pressure port	1	free for measuring
	Cyclone 2		1 x Pressure port			1	free for measuring
34m	Calciner	2 x Cardox/Pressure port	1 x Pressure port		1 x Pressure port	4	free for measuring
24m	Calciner			1 x Cardox		1	free for measuring
20m	Calciner		1 x Cardox	1 x Cardox	1 x Cardox	3	free for measuring
14m	Calciner			1 x Cardox	1 x Cardox	2	free for measuring
12m	Calciner		1 x Cardox	1 x Cardox		2	free for measuring

Figure 14: Overview of the measurement points (in the calciner / Plant of Lägerdorf)

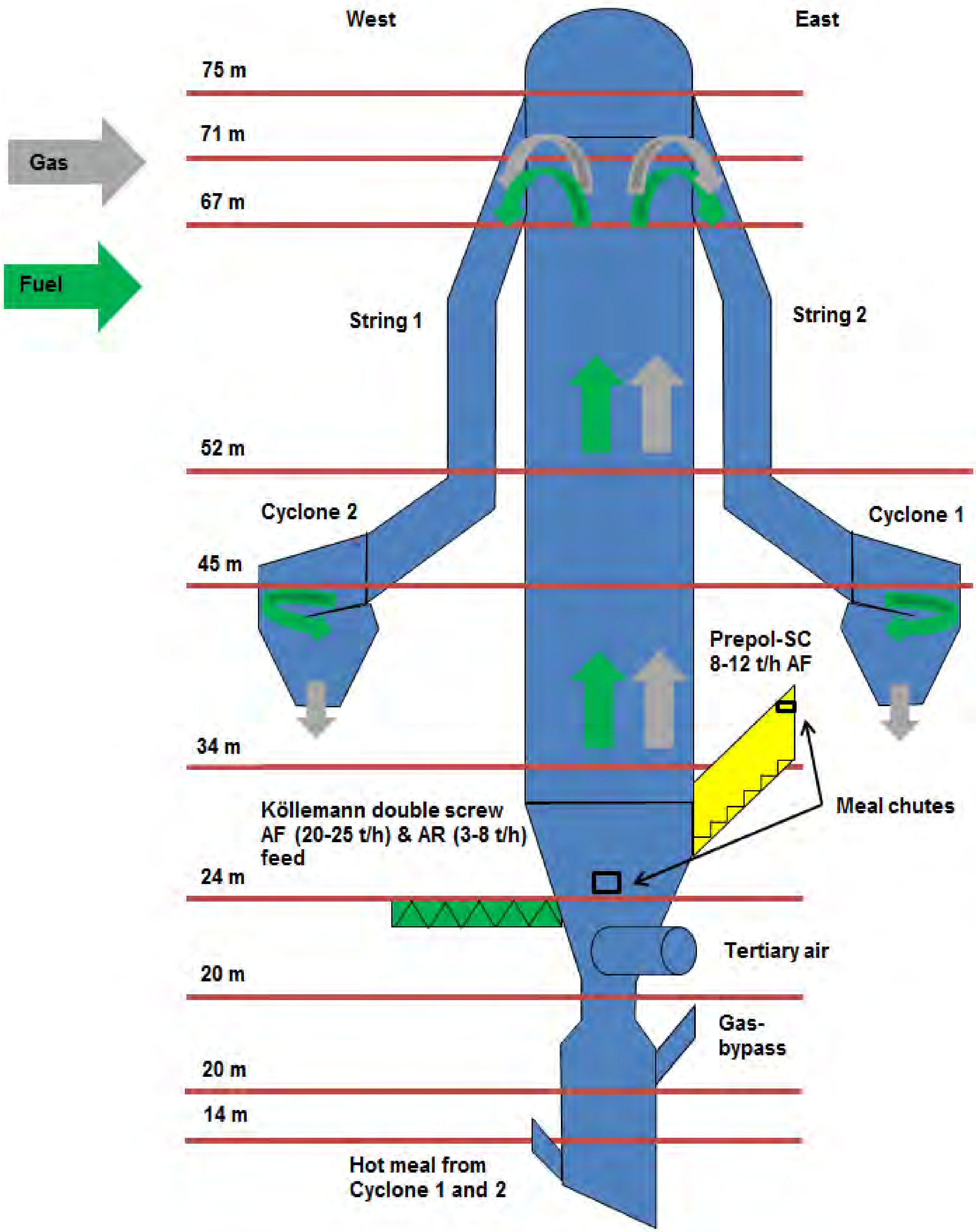

Figure 15: Overview of the measurements together with the belonging level and fuel feeding points

3.3.2 Set up of the measurement

Preliminary work that has to be conducted before the first measurement:

- Putting on special fire-resistant clothes (safety boots, gloves, trousers, jacket and a kind of mask)
- Inspection of the defined measuring points to decide about the opening method
- Switching off big blasters. These pressure vessels have the function to prevent blockages. Filled with compressed air (10 bar) and working with local overpressure, they have to be turned off while working near to them
- Clearing away small blockages in the measurement opening with an iron bar
- Boring of clogged CARDOX openings by a drill machine shown in Figure 16-18. CARDOX is a system to remove blockages by gas blasting using CO_2 at 200 bar and an igniting gas generator lifting the pressure up to 2000 bar, normally used in CARDOX openings to remove cyclone and other blockages.

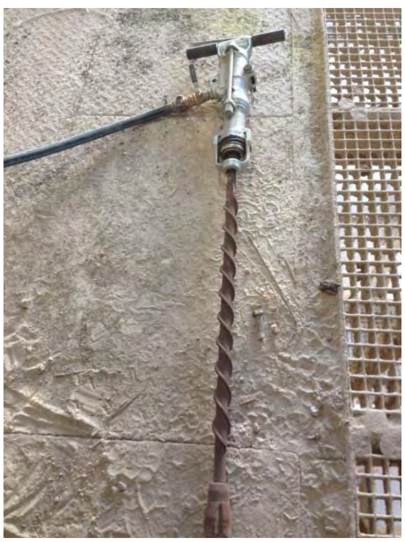

Figure 16: Drill machine

Figure 17: Drill machine and big blaster

Figure 18: Working with the drill machine

3.4 Calibration procedure of the measuring instruments

To receive significant values the ULTRAMAT 23 is calibrated with test gas. The CO-test gas has a CO content of 4.000%. Table 3 shows the measurement result of the calibration.

Table 3: Calibration of the ULTRAMAT 23

Measuring instrument	CO-test gas in %	Measured value in %
ULTRAMAT 23	4.000	4.003

The ULTRAMAT 23 measured a CO content of 4.003 %. This slight deviation can be neglected. Therefore the ULTRAMAT 23 is the reference instrument. To compare the testo 350 M/XL and testo 350 with the ULTRAMAT 23 three gas balloons are filled up with a gas probe out of the calciner. Each measurement apparatus analyses the gas from the same gas balloon. Figure 19 shows the deviation of CO.

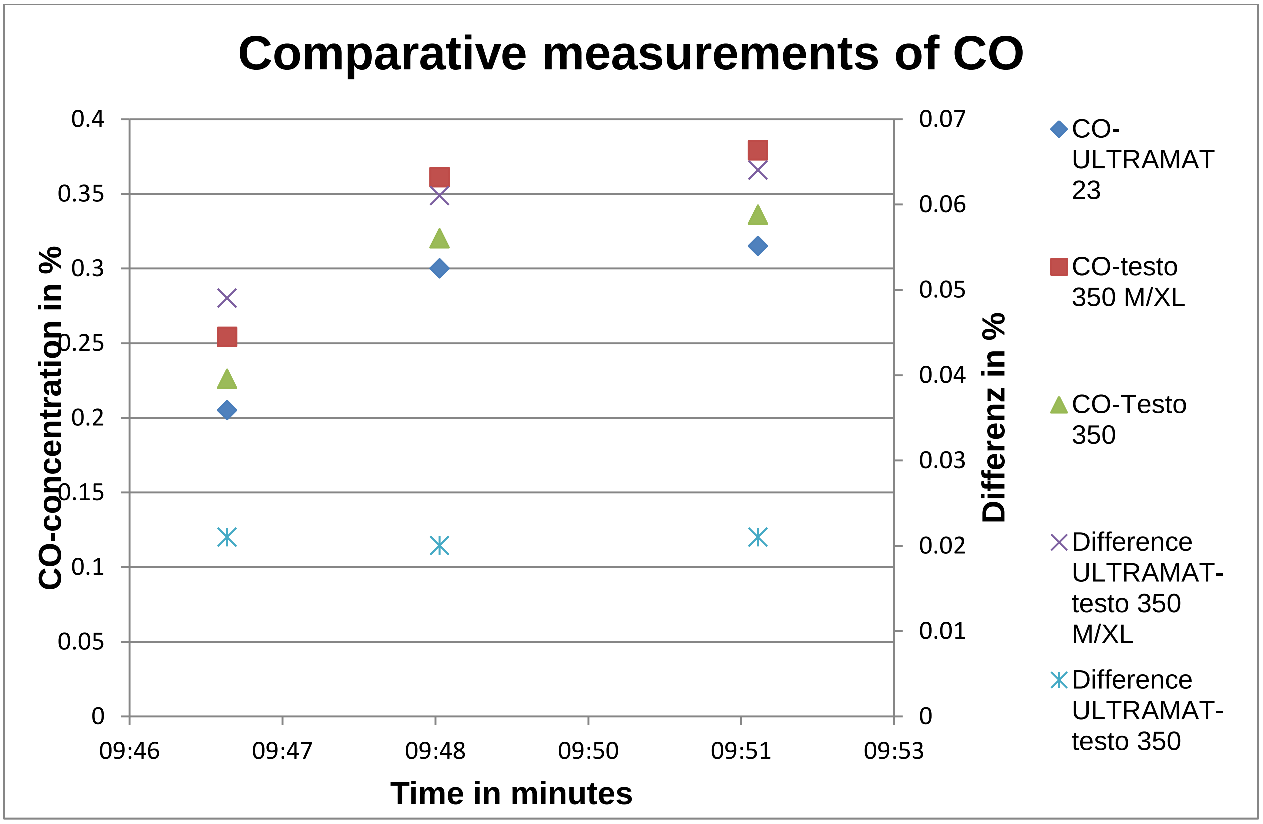

Figure 19: Deviation of CO

The diagram indicates a very small deviation between the ULTRAMAT 23 and both testo. All three measuring instruments provide useful data with a measurement difference between the systems smaller than 0.07 %.

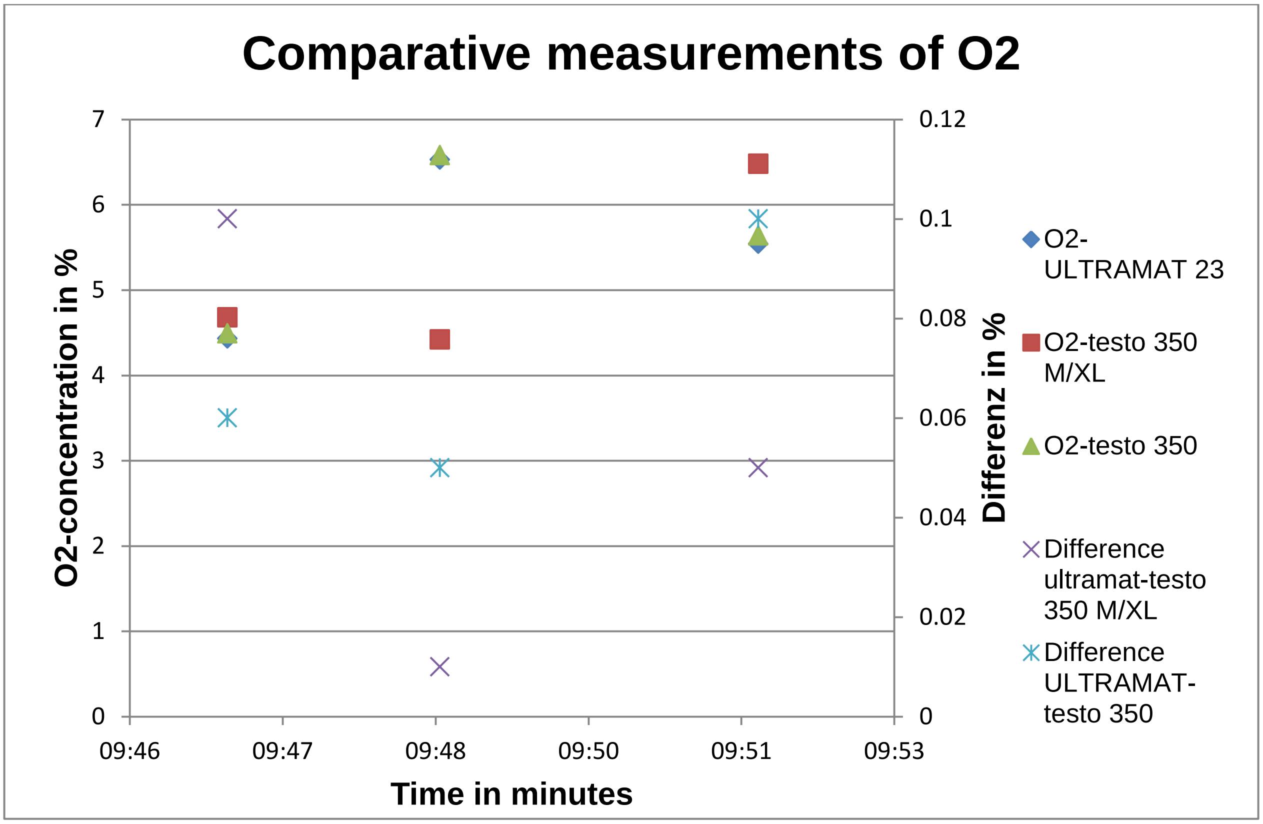

Figure 20: Deviation of O_2

Figure 20 shows the deviation of O_2. According to the chart all three instruments measure comparable values. The measurement difference between the systems is smaller than 0.12 %.

3.5 Experimental procedure

In the following chapter the taking of gas samples and temperature measuring in the calciner is described. During the measurement health and safety of persons is an essential part and described as well.

3.5.1 Taking gas samples

During the taking of gas samples health and safety have top priority. The wearing of special fire-resistant clothes is mandatory (Figure 21). The operator in the control station has to be briefed on which floor the measurement takes place and which big blaster (Figure 22) has to be powered down if necessary (Appendix 41).

Figure 21: Taking gas sample

Figure 22: Big blasters at the calciner

To guarantee the safety the size of a measurement point has to be as small as possible. By using a special adapter the CARDOX opening diameter can be reduced to a size of 20 mm. Figure 23 shows the adapter and Figure 24 a CARDOX opening where this adapter is required.

Figure 23: CARDOX adapter

Figure 24: CARDOX at the calciner

Figure 25: Sicromal-hose

When all preparations have been finalized the measurement process can start. Both testo calibrate themselves with ambient air for approximately 60 seconds. Then the sicromal-hose shown in Figure 25 is placed in the measurement point - it takes about 30 seconds until the measurement is finished. The highest measured value is used for the evaluation.

Before starting the next measurement the testo flushes out with ambient air to minimize incorrect measurement. This procedure is repeated at every measuring point.

Taking gas samples for the ULTRAMAT 23 requires the same health and safety procedure. In contrast to the testo, which analyses the gas sample directly, the ULTRAMAT 23 is installed fixed on 81 meter at the preheater tower where the gas samples get analyzed. The pump (1) shown in Figure 26 forces gas through the sicromal-hose (2) into the balloon (~ 1.5 l/min)(3). The gas passes a dirt filter (4) to protect the pump and the ULTRAMAT 23. It takes on average 10-20 seconds to fill the balloon.

Figure 27 and 28 show the adapter use in combination with the sicromal-hose during a measurement.

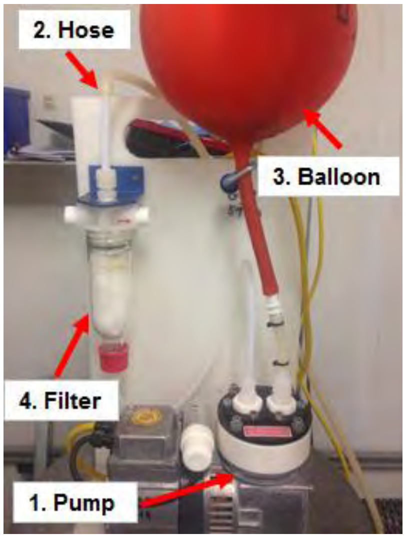

Figure 26: Membrane pump to take gas samples

Figure 27: Measuring at calciner

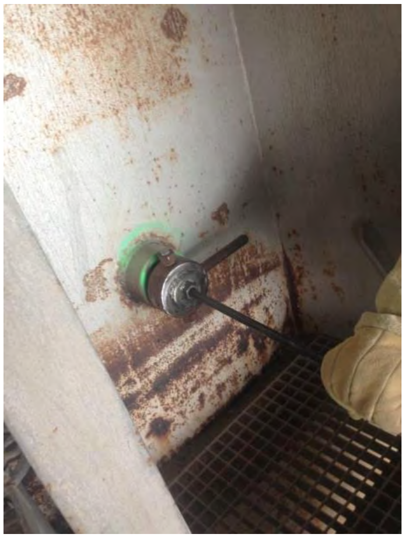

Figure 28: Taking gas samples with a sicromal-hose

3.5.2 Temperature measurements

The temperature measurement is performed under the same health and safety terms. Directly before or after taking the gas sample the temperature is measured with a temperature-measuring instrument (testo 935). This is essential to obtain informative temperature degrees in relation to the gas samples. The temperature sensor (NiCr-Ni) is inserted into the measurement point. The duration of the measurement depends on the fluctuation of the temperature.

4 Results and discussion

The description of the measuring data combined with an inpretation follows in this chapter.

4.1 Measuring campaign at 930 °C

The chart diagram overview_1 930 °C (Appendix 1) gives a summary about the measuring points, which are located on the floors 20 m up to 34 m.

In the left hand the location and the height of the measuring points in the calciner are listed. In the middle of the table the measured data are shown. In the right hand column the process parameters, which are relevant for the analysis of this period, are displayed.

The measured CO concentrations are partially colored according to the switch off limits, described in chapter 2.2.2. They are listed below in "process parameters". On floor 20 m the CO concentration is very low. Therefore nearly no CO enters from the rotary kiln. The CO concentration found in the process parameters and the kiln inlet probe confirms these data.

On floor 24 m the measuring point is located directly above the Köllemann double screw. The CO data is 1.07 %. The concentration is colored in light yellow, because the value is higher than 1.0 %. The O_2 concentration increases to 14.5 %. This high oxygen concentration results from tertiary air dissipated from the clinker cooler and conveyed to the calciner at 22 m. The measured temperature at this point and the temperature of the tertiary air (700 °C) are very low.

On floor 34 m the measuring values are colored in dark yellow, because they range between 0.5 % and 1.0 % CO. The concentration of CO on the east and west side are on a similar level as on the south side. This is an indicator for a poor mixing of CO and O_2 resulting in a poor combustion in general. On the north side the second CO value is quite high, too. To name the Prepol-SC as the reason is not valid, because the Prepol-SC had a standstill during this measurement (see the process parameters).

The CO concentration results exclusively from the fuel feed in the Köllemann double screw. Besides the calciner temperature reaches only 910 °C and not 930 °C as adjusted.

In the overview_2 930 °C (Appendix 2) all CO values are marked yellow and light yellow. Subsequently on the south side the value rises up to 1.33 %. These facts imply a correlation with the fuel feeding already mentioned above. Alternative fuels contain a certain amount of water, as illustrated by Table 4.

Table 4: Water content of alternative fuels

Alternative fuel	Water content in %
Fluff	12 - 20
Filter press cake (box1)	45
Iron corrective (box 2)	10 - 13
Roofing felt (box 3)	5 - 10
EBS-Pellets (box 4)	30
Destrü (Distillation residues) (box 5)	20
Serox (Aluminum corrective) (box 6)	25
Prepol-SC fuel feed (coarse alternative fuel)	20 - 25

A high amount of water is brought into the system by the fuel feed, here the boxes 1, 4, 6 and the Prepol-SC are determinant. To vaporize the water it is necessary to raise a high energy input. The evaporation heat is 2 257 kJ/kg. Subsequently a complete combustion of the fuel feed is possible. At first the fuel feedings get dried, the water vaporizes and the last step is the burnout on the floor 52 m and higher.

The turbulences in the calciner are too low and hence another reason for the high CO concentration on the south side. The fuel feed is transported upstairs without swirl, the heat exchange is not optimized, the material has a poor combustion and CO arises. During this campaign the calciner temperature is 925 °C with fluctuations of +/- 10 °C.

The deflection chamber of the calciner is located on floor 75 m. The gas stream out of the calciner is divided into string 1 and 2. The flow rates are very intense and turbulences arise. The remaining fuel feed, unburned material and gas, burns out. Demonstrated in overview calciner_3 930 °C (Appendix 3), here the average calciner temperature is 921 °C. No value is highlighted in color, because the high turbulences and the resulting heat exchange boost the total burnout of the fuel feed, although box 4 and 6 delivered a high tonnage. This result gets verified by the data on floor 52 m and floor 45 m. Appendix 4 and 5 illustrate the CO concentration in the calciner, string 1 and string 2. On the x-axis the CO concentration in percent is listed, on the y-axis the length of the calciner in meters and on the secondary axis the temperature in degree Celsius.

The diagram clarifies the CO concentration shown in the previous tables. The highest CO concentration on the south side is clearly to be seen. Most of the other measuring data are located in a range between 0.5 and 1.0 % CO. A basic level of CO concentration of 0.5 % during normal operation mode can be assumed.

In appendix 6 the CO and O_2 concentration in string 1 with a temperature of 930 °C is listed. On the south side the O_2 concentration is very low between the fuel feeding on floor 24 m and the measuring point on floor 67 m. This represents another reason for the high CO concentration on the south side.

On the north side the concentration of O_2 at the measuring points is higher, corresponding to a favored combustion. The Prepol-SC influences the O_2 concentration positively, because a separate supply of tertiary air "Top air" is installed, see Figure 7 and 8. The diagram O_2 930 °C (Appendix 7) shows the CO and O_2 concentration for string 2.

4.2 Measuring campaign at 920 °C

The overview_1 920 °C (Appendix 8) depicts, that the CO concentration occurs on a relatively low level on floor 20 m. On floor 24 m and 34 m all CO values are colored. The combustion in this section is poor, although an average calciner temperature of 920 °C is measured.

The measuring points of east and west side are located near to the south side, therefore it is possible to measure CO stratification belonging to the south side, see the left side of the overview. The second measuring value on the north side is significantly higher. The Prepol-SC works during the measurement procedure, indicated in the measurement data "Process parameters". Again the higher CO level is a result of the combustion of alternative fuel containing a higher amount of water.

The lignite dust with a high rate of carbon cannot be the reason for this high CO concentration, because no lignite is burnt in the calciner at that time and lignite dust reacts fast with O_2 resulting in a good combustion with low CO (low water, large surface). On the north side O_2 concentration is 1-2 % higher than on east and west side. In overview_2 920 °C (Appendix 9) it is obvious that the CO values on the north side descend clearly over reaction distance.

Conversely on south and west side the values are higher than 0.5 %, only on floor 52 m the value is 0.282 %. This seems to be a measuring error, caused by drawing false air, underlined by an O_2 concentration of 16 % on the south side, which is unusually high. The values measured on the north side cannot be compared to the values of overview_1 920 °C, because in overview_2 920 °C the Prepol-SC did not work. That means the CO concentration on the east and west side is a result of the basic fuel feed via the Köllemann double screw. The values on floor 75 m persist at a high level, as seen at a temperature of 930 °C. An explanation is turbulences and the complete combustion of the fuels. In overview_3 920 °C (Appendix 10) no CO value is colored, again this is a hint for a good combustion in the deflection chamber. Also 6.74 t/h of lignite are brought in through the calciner and the Prepol-SC works.

In appendix 11 the CO values are located between 0.5 and 0.75 %. From floor 24 m up to floor 34 m the CO concentration rises up, because of fuel input on floor 24 m. On the south side the temperatures vary from 700 °C on floor 24 m up to 900 °C. This low temperature on floor 24 m is potentially a reason for the increased CO concentration. Appendix 12-14 are contained in "List of appendices" but without commenting.

4.3 Measuring campaign at 910 °C

In overview_1 910 °C (Appendix 15) for this campaign the same correlations as in campaign 920 °C and 930 °C are found. On floor 20 m the concentration of CO and O_2 are low, on floor 24 m a CO value of 1 % and a high O_2 concentration of 14.34 % are measured. On floor 34 m the CO concentration in east and west side rise up to max 2.2 %. The O_2 values in east and west are clearly lower than on the north side. The calciner temperature has an average level of 910 °C. The Prepol-SC is in maintenance, so the entire fuel input is provided though the Köllemann double screw.

In overview_2 910 °C (Appendix 16) the calciner temperature has an average level of 919 °C and varies heavily - see the process parameters. All values are colored in light or dark yellow and on floor 67 m on the south side the values are colored in dark red. The CO stratification is clearly recognizable. The temperature is higher than on the north side, the O_2 concentration is much lower. In the deflection chamber the CO value sinks to 0.7-0.8 %, comparable to the previous measurings. The O_2 concentration has a constant level of 7.0 to 8.0 %. In overview_3 910 °C (Appendix 17) none of the CO values is colored and there is no difference between string 1 and 2. The reason is a good combustion in and at the back of the deflection chamber. The calciner temperature is 916 °C, slightly higher than 910 °C adjusted and only with a small variation. Appendix 18-21 are contained in "List of appendices" but without commenting.

4.4 Measuring campaign at 900 °C

In this campaign (Appendix 22) the temperature varies substantially around an average level of 910 °C. The concentrations of CO on floor 20 m and 24 m are on a similar level as described in chapters 4.1 to 4.3. On floor 34 m all CO concentrations are very high (0.8-2.3 %), especially the second value on the north side. The level of O_2 is low (4.1-13.8 %), the temperature with 955 °C very high, eventually due to local combustion of CO during measurement of temperature. The temperature sensor is only 2 mm in diameter so "false air" (fresh O_2 at 21 %) can enter and ignite the present CO. The process parameters reveal that on average 3.75 t/h lignite has been fed and the temperature of the secondary air is very low (565 °C).

In overview_2 (Appendix 23) on the south side similar to the previous campaigns the CO values are high and the O_2 values low. All further CO values are colored yellow. The calciner is filled with 10 t/h out of box 1 and 4, this fuel mixture with high moisture (Table 4) explains the values of CO. The tertiary air temperature has an average level of 205 °C. This value is unrealistic; a damaged measuring sensor seems to be the reason.

In overview_3 900 °C (Appendix 24) no values are colored and no difference between string 1 and 2 is visible. Illustrated by the diagram "CO concentration in the calciner 900 °C" (Appendix 25 and 26). There is no difference between the strings looking at floor 75 m and the CO values. In the calciner the CO concentration goes up and down between 0.5 and 1.0 %. In the diagram (Appendix 27 and 28) O_2-concentration in the calciner O_2 and CO concentration at the north and south side are shown. On the south side the CO concentration has a peak on floor 67 m (1.74 %), on floor 45 m it is on a low level again (0.01-0.18 %).

The corresponding O_2 concentration is very high on the floor 24 m due to tertiary air. On the north side all CO values swing around 0.5 % and the O_2 concentration oscillates around 10 %, only one value sheers away directly above the Prepol-SC.

4.5 Measuring campaign at 890 °C

This measuring campaign is the only one, which is realized with the testo 350 and its measurings take place on one day. Thus the process parameters are the same for the three overviews and the comparability of the single measuring segments is very good. The process parameters illustrate that the adjusted calciner temperature of 890 °C cannot be fulfilled. The campaign is more a confirmation of the values of 920 and 930 °C. During the whole campaign there is no fluff input into the kiln and the calciner, shown in the process parameters in overview_1 890 °C (Appendix 29).

The CO values at kiln inlet are not so high (0.01-0.03 %), although only lignite dust and waste oil are fired. Secondary and tertiary air have no discrepancies and have a normal temperature (890 °C and 690 °C). The CO value on floor 24 m is very high (2.24 %), the values on floor 34 m are similar (2.55 % and 1.93 %). At the north side the CO values are lower and the O_2 concentration higher. The high CO values in the calciner are explainable by the excessive use of the fuel boxes 1 and 4 (6.6 t/h and 4.2 t/h).

In overview_2 890 °C (Appendix 30) the CO concentration on north and south side is very high, but on floor 67 m it decreases strongly. On this floor the temperature is extremely high (1040 °C and 922 °C) and is a reason for the low CO values, where obviously CO burns out. On both sides the O_2 concentration is very balanced. On floor 71 m and on floor 75 m the CO concentrations are unusually low, no other measuring campaign has these extremely low data.

The high CO values on floor 52 m could be a hint. The combustion of the fuel is nearly complete at this floor and only the rests of fuel burn out in the deflection chamber. String 1 and 2 have no measuring differences in overview_3 890 °C (Appendix 31), but the temperatures in both strings on floor 52 m are very high.

5 Conclusion and evaluation

Regarding all measuring campaigns from 930 °C to 890 °C several analogies between the measurings are obvious. The calciner temperature, adjusted in the central control room, corresponds only in a few measuring campaigns with the actual temperature. Because of this fact most of the campaigns cannot be performed with the required temperature. The computer, which manages the fuel input has to control over 10 different material streams. Its oversensitive control behavior causes a wide fluctuation margin of the temperature curve. These not foreseen circumstances prevent the clear set point for calciner temperature as targeted in the bachelor thesis. Besides this, a lot of recommendations can be given.

No CO concentration higher than 0.5 % is measured after the deflection chamber. This positive aspect allows the conclusion that the deflection chamber works perfectly. The unburnt material and gases combust totally in or directly behind the deflection chamber. That applies to string 1 and 2.
Hence the problem of a high CO concentration can be located in the calciner from floor 20 m up to floor 67 m. In Figure 29 all measuring campaigns for the CO-concentration in the calciner (North) are shown. The maximum CO concentration in this sector of 0.5 % up to 0.8 % is visible, that is low compared to other sectors like south.

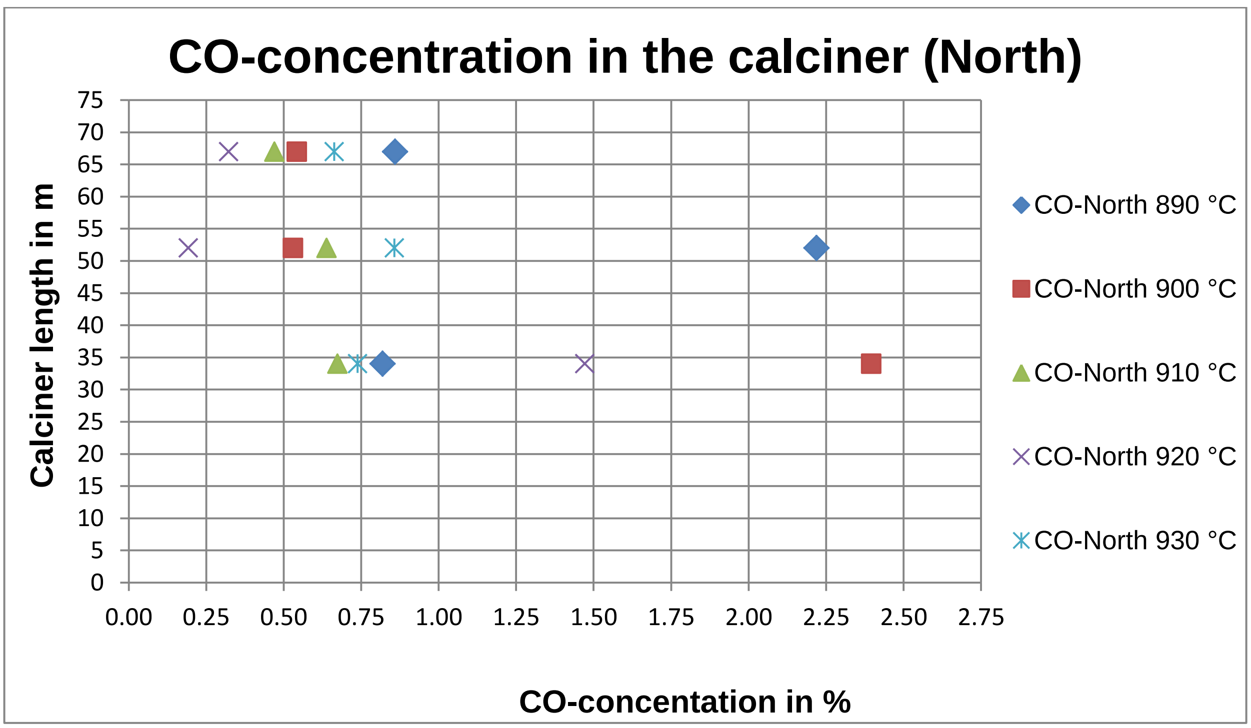

Figure 29: CO-concentration in the calciner on the north side

In Figure 30 all temperatures and corresponding CO concentration on the south side are charted. It is clearly to be seen that the CO concentrations are higher and very unstable compared to Figure 29. These differences in the CO concentration between north and south side get confirmed if looking at the concentration of oxygen.

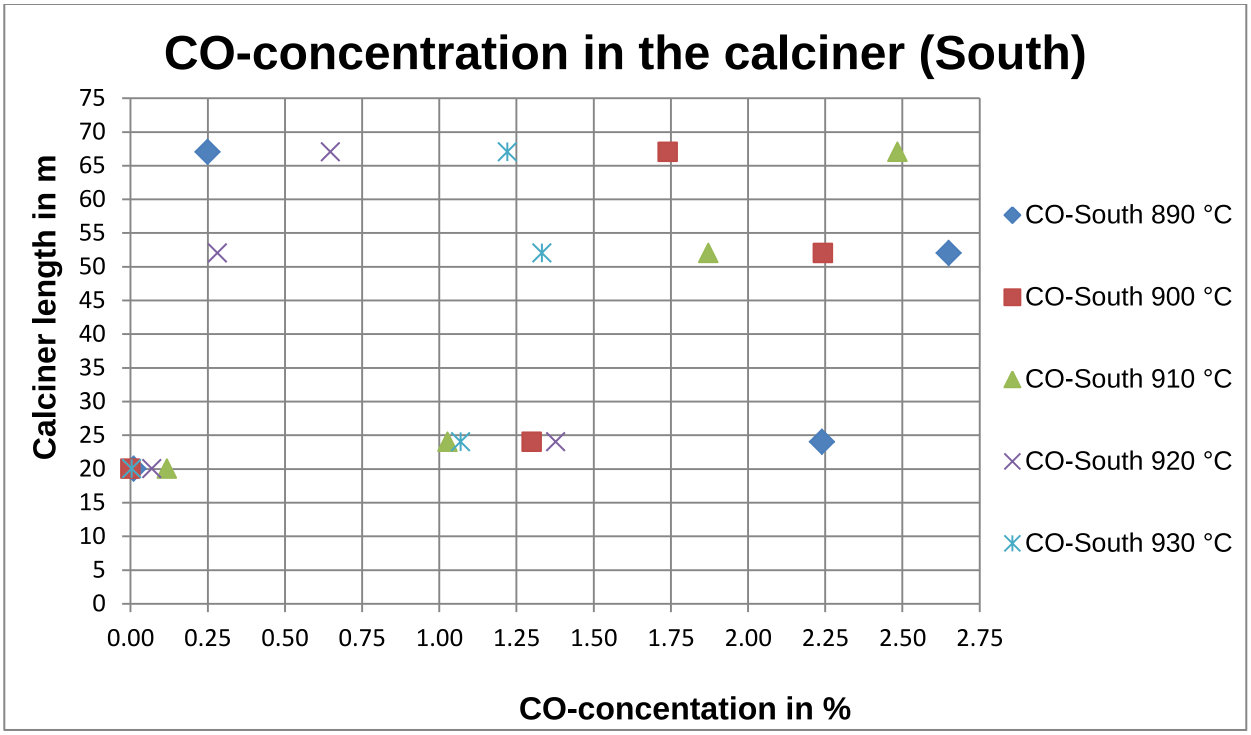

Figure 30: CO-concentration in the calciner on the south side

In Figure 31, showing the O_2 concentration on the south side of the calciner, it can be verified that all O_2 values on floor 20 m are very low. After the addition of tertiary air the O_2 concentration is significantly higher, 12-15 % are reached at all temperatures. On floor 52 m and floor 67 m the concentration of O_2 is constant but very low with 4-6 %.

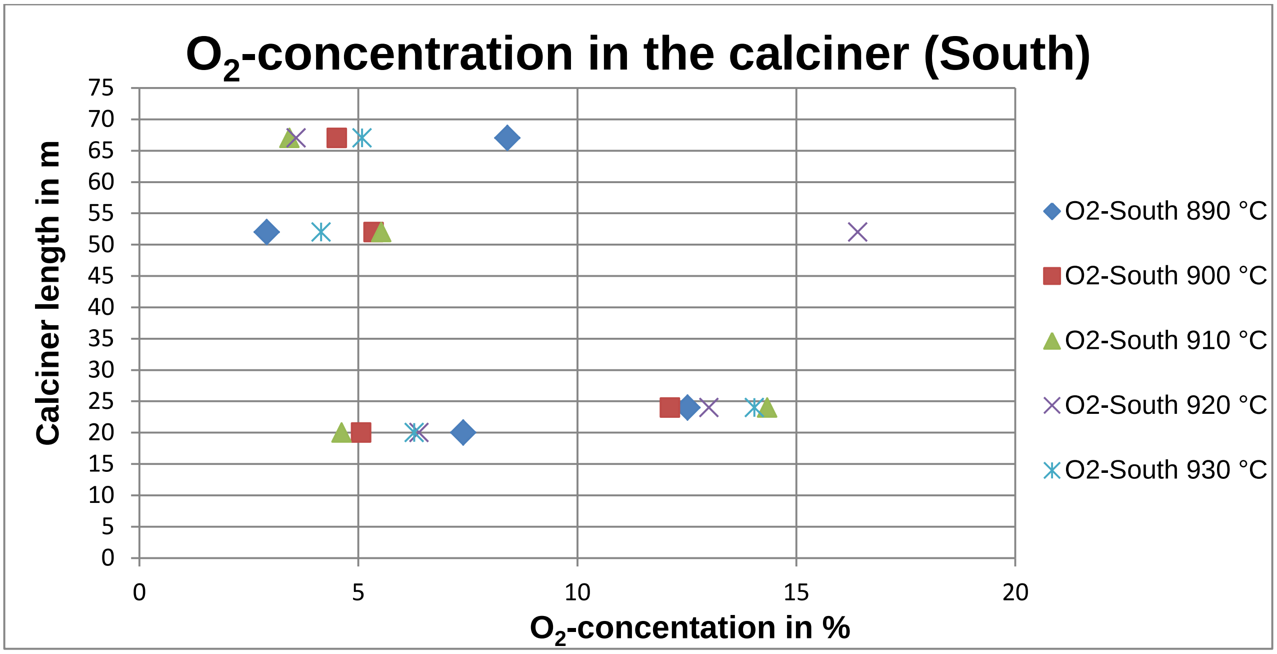

Figure 31: O_2-concentration in the calciner on the south side

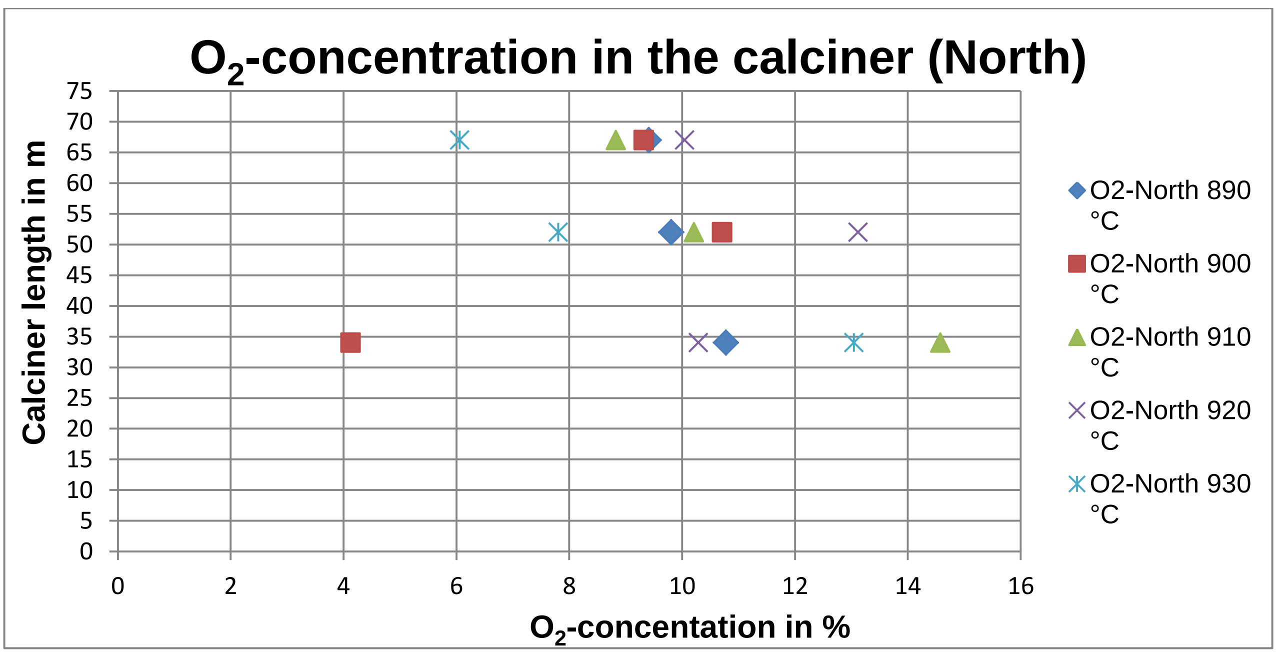

Figure 32: O_2-concentration in the calciner on the north side

In Figure 32 a high O_2 concentration is measured on floor 34 m above the Prepol-SC, which is located at the north side, like on floor 24 m at the south side near to the Köllemann double screw. A part of the tertiary air is fed into the Prepol-SC and near to the Köllemann double screw. On floor 52 m and floor 65 m (North) the O_2 concentration has 9-11 %.

All measuring series show that CO stratification exists on the south side. This is an indicator that there are too small turbulences in the calciner and the fuel input is transported upwards without vortex. The Prepol-SC is another source where CO arises, but in a smaller dimension as expected (Figure 29). The Prepol-SC is installed at the north side and here the CO concentration has prevails data higher than 0.5 %. Compared with the south side where the CO level is much higher, it is obvious that the Prepol-SC has a positive influence on the CO concentration in the calciner, since it is lowering the CO concentration.

In Appendix 36 a descriptive diagram depicts the CO development in the calciner for 24 hours. This diagram is very informative. From 00:00 until 8:00 a.m. a normal CO concentration can be seen. From 8:00 a.m. to 3:00 p.m. the level rises up and many peaks appear. From 3:00 p.m. to 00:00 a similar course like in the beginning with intermediate peaks is shown. The Prepol-SC is in maintenance from 8:00 a.m. to 3:00 p.m.. The chart gives a clear hint, that the working of the Prepol-SC is useful to lower the CO concentration. If the whole fuel input is realized via Köllemann double screw on floor 24 m the CO concentration is significantly higher, demonstrated in Appendix 36 at 8:00 a.m. to 3:00 p.m.. To disperse the fuel through the whole profile and generate a homogenous air fuel mix the turbulence produced by tertiary air is not sufficient. The amount of fuel given into the Köllemann double screw can be on a lower level if the Prepol-SC works. The mixture with air is better, but not really good, because CO stratifications occur at the south side still.

The task of the bachelor thesis to define an "optimized set point for calciner temperature" is not fulfilled. Because of the strong fluctuations +/- 70 °C of the calciner temperature it is not possible to define a new optimal temperature. There are no reasonable data to prove and to justify. Nevertheless, the evaluation of the measurement data reveal, that an operating of the calciner at a set point – depending on the fuel feed (Köllemann double screw and Prepol SC or only Köllemann) of 900 °C is possible without hot meal leagues, CaO quality issues or CO-shut downs. Despite of these findings important information in relation to the CO and O_2 concentration in the calciner have been collected.

6 Future investigations and options

In this chapter improvement suggestions for the problems described in chapter 4 and 5 are presented. Furthermore an outlook is given to continue the operating test for the lowering of the calciner temperature.

6.1 Modification of the calciner and tertiary air

The measuring series have shown that the mixing of the fuel over the whole profile of the calciner is not fulfilled. The tertiary air input in the calciner on floor 24 m is not sufficient to reach the mixing. The Appendix 37 schematically demonstrates the CO stratification in the calciner. To counteract these CO stratifications one option could be to install flameproof attachment in the calciner. A slim profile would help to raise the flow speed and subsequently increase the turbulences in the calciner.

The next step is arising of additional swirl for a further strengthen of turbulences. The related better mixing implies that the fuel input has an earlier combustion and in the deflection chamber only the rest of the fuel burns out totally. At the moment most of the combustion takes place in the deflection chamber.

The calciner with flameproof attachment and the desired flows is shown in Appendix 38. The attachment can be built in a height of 40 m on the south side of the calciner. A curved design and a length of 2-3 m seem to be favorable. Appendix 39 illustrates two possible modifications. The first version uses fireproof stones, which are implemented with the help of threaded bars into the existing refractory structures. The second version uses steel anchors fixed in the refractory structure, then building of the attachment with refractory filler material. Both construction methods loom 200 mm into the calciner. Depending on the condition of the calciner during the next planned kiln stop it is a situational decision which version is easier to realize.

To generate a swirl is a further modification. Last repairs in the calciner reveal that some sort of drill already exists. Not to counteract the direction (right or left) has to be examined on-site and then choosing the favorable option. To strengthen this effect it is possible to swirl the tertiary air input into the calciner on floor 24 m. A method to realize that is shown in Appendix 40. Like the calciner model an attachment is inserted in the pipe of the tertiary air. Its height is 200 mm, to produce a swirl of the tertiary air the attachment is used in a shifted way. The swirl is marked with yellow arrows. The spin direction has to match with the existing calciner spin to avoid a compensation of the effects.

Calciner temperatures up to 950 °C can occur, flow rates up to 30 m/s and high abrasion caused by hot meal and fuel feed. So it is very important to build robust installations. In order to prevent the occurrence of dead space or the tearing away of the refractory attachment, this attachment should not reach in too far into the calciner. In Lägerdorf no experience exists concerning such installations. These would be prototypes, their effects have to be examined.

6.2 Outlook for following measurements

To reach a better and complete combustion in the future it is useful to implement the described improvement recommendations for the calciner and the tertiary air. The next planned kiln stop is a good moment for the realization. Then new measuring campaigns can be started. The analysis of their data can reveal whether the installations help to improve the CO and O_2 values and their mixing. Problems, which occurred in the described campaigns, have to be observed. It is necessary to identify in advance why the calciner temperature fluctuates so violently and why the given temperatures are attained so rarely. As a result of this thesis, a task force of plant staff is formed with a kick-off meeting in October concerning staff from maintenance, process, production and measurement department to identify and solve the dosing issues of the dosing system. A single campaign will provide significant measured values when this problem is solved. Additionally it is practical to install further measurement points listed in Table 5.

Table 5: Further measurement points

Level	**Direction**
52 m	East / West
67 m Calciner	East / West
67 String 1 / String 2	North / East / West / South

At these points the concentration of CO and O_2 is highly of interest. Further information about the CO-concentration in the calciner, especially on the east and west side, would be very useful. If possible it is constructive to carry out a measuring campaign in one day. Then all process parameters obtained for one temperature exist and do not vary. As a consequence it is easier to evaluate the data and the obtained values are more informative.

An optimum adjustment of the calciner temperature cannot be obtained at the moment, only the recommendation to operate close to strong CO formation (close to CO warning at 0.5 % CO) can be given, that is currently around 900 °C. At this point, no quality (CaO) nor safety (hot meal leakages) and no CO shut downs occurred. The present operational trials are the basis for an improved test arrangement. Using suitable measuring instruments is required as well as additional measuring ports in the calciner. These appropriate steps will push the optimization of the calciner temperature. Beside this progress on site, conducting flow modelling using the Finite-Element-Method (FEM) is planned using the experience of HAW Hamburg.

Review of the literature

Duda, W.H., Duda, W.H., 1985. Cement-data-book: [zweisprachig]. Bd. 1: Internationale Verfahrenstechniken der Zementindustrie, 3., neubearb. und Aufl. ed. Bauverl, Wiesbaden.

ETAS, 2016. ETAS Products: Lambda closed.loop control.

Groß, F., 2016a. Bachelor Measurements for lowering the Calciner temperature at cement plant Lägerdorf.

Groß, F., 2016b. PPE PROJECT PEPORT - Report for the qualification process as Process Performance Engineer (PPE) during the Lafarge-Holcim SPREAD (Synergy Program for Reinforcing Engagement and active Delivery) Programm.

Holcim, 2015. Auf einen Blick - Die Unternehmensgruppe. Retrieved 06.09.2016 from: http://www.holcim.de/ueber-uns/auf-einen-blick.html.

Holcim, 2014. -"Herzlich Willkommen im Zementwerk Lägerdorf" - Unternehmenspräsentation Holcim (Deutschland) GmbH.

Holcim, 2012. Zementherstellung im Werk Lägerdorf. Retrieved 05.09.2016 from: http://www.holcim.de/fileadmin/templates/DE/doc/Holcim_Laegerdorf_Flyer_2012.pdf.

Jennes, R., 2003. Optimierung der Verbrennung im Calcinator einer Anlage zur Herstellung von Portlandzementklinker, 1. Aufl. ed. Papierflieger, Clausthal-Zellerfeld.

Kühl, H., 1951. Zement - Chemie. Verlag Technik Berlin.

Kupper, D., 1984. Entsäuerungsverhalten von Zement-Rohstoffgemischen, 1. Aufl. ed. Neubeckum.

Schändel, T., 2016. Explanation of the Technical Information System (TIS) at plant Lägerdorf by Thomas Schändel (Head of automation).

Siemens AG, 2016. Das Prozessleitsystem SIMATIC PCS 7. Retrieved 06.09.2016 from https://www.automation.siemens.com/w2/efiles/pcs7/pdf/00/br_pcs7_2016_de_Web.pdf.

Siemens AG, 2015. Kontinuierliche Gasanalyse-ULTRAMAT 23. Retrieved 06.09.2016 from https://cache.industry.siemens.com/dl/files/616/84233616/att_827671/v1/U23_Handbuch_deutsch_de-DE.pdf.

Testo AG, 2002. Bedienungsanleitung-testo 350 M/XL. Retrieved 06.09.2016 from https://www.testo.de/resources/media/global_media/produkte/testo_350/350_M_XL_454_IM_0973_3501_02_de.pdf.

V. J. Turnell, 2001. Brennstoffwechsel bei Zementdrehrohröfen - Gundlagen und technische Möglichkeiten Teil 2: Technische Möglichkeiten *).

VDZ, 2015. Einsatz alternativer Rohstoffe im Zementherstellungsprozess - Hintergrundwissen, technische Möglichkeiten und Handlungsempfehlungen.

VDZ (Ed.), 2008. Zement-Taschenbuch, 51. Aufl. ed. Verlag Bau + Technik, Düsseldorf.

VDZ, 2005. VDZ-Merkblatt Vt 14 - Betriebsverhalten von Vorcalcinieranlagen.

VDZ-Seminar, 2015. Seminar Z-FOB Moderne Ofen- und Brenntechnik.

Wolf, B., 2014. Beschreibung der Anlage und der gehandhabten Stoffe.

World Cement, 2014. Cementing Ecological Foundations. Retrieved 06.09.2016 from https://library.e.abb.com/public/bb843243b283ffd5c1257b3500307283/World_Cement_Apr_04_St_Lawrence.pdf.

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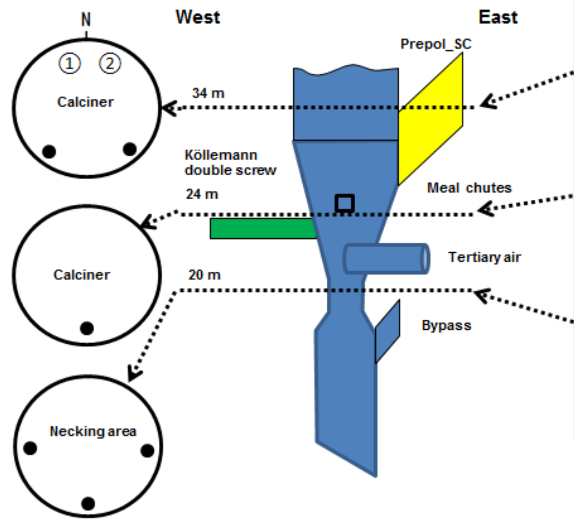
Appendix

Overview 1



Calciner measurement 930 °C

Start time: 09:50 31.08.2016 Ultramat

End time: 10:15 31.08.2016

Observer: Markus Berndt, Florian Groß

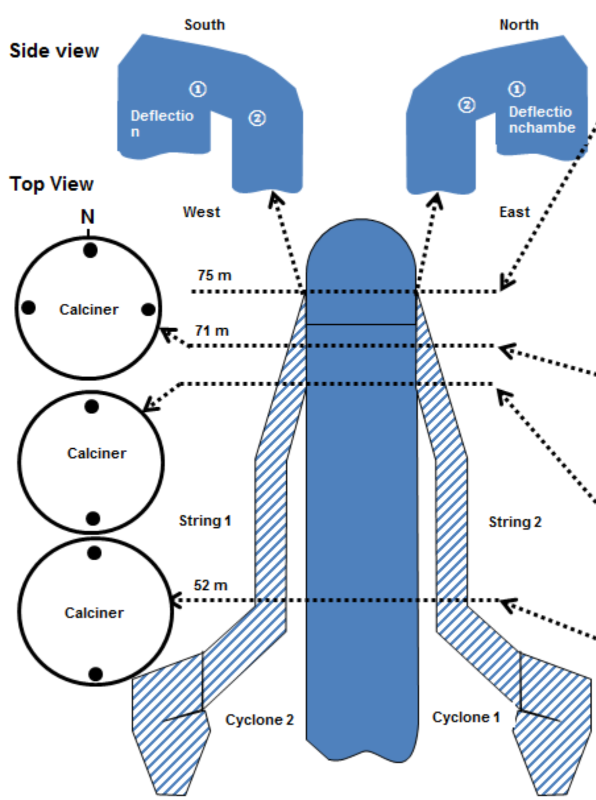
Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
34m	Calciner	CO	%	0.378	0.739	0.791			0.969	
		O_2	%	12.09	13.05	8.73			8.35	
		Nox	ppm	-	-	-			-	
		T	°C	786	818	918			820	
		Time		10:10	10:15	10:20			10:00	
24m	Calciner	CO	%					1.07		
		O_2	%					14.5		
		Nox	ppm					-		
		T	°C					650		
		Time						09:50		
20m	Calciner	CO	%			0.014		0.004	0	
		O_2	%			7.18		6.28	6.92	
		Nox	ppm			-		-	-	
		T	°C			1100		1100	1100	
		Time				10:00		10:05	10:10	

Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	293.88	289.84	295.90
	Energy clinker	kJ/kg	5171.28	4670.39	5421.73
	O2 kiln inlet	%	5.26	4.91	5.95
	CO kiln inlet	%	0.02	0.02	0.02
	NO kiln inlet	mg/m³	1016.05	975.45	1097.25
	Temperature kiln inlet	°C	1179.75	1149.34	1194.95
	Lignite	t/h	6.40	6.02	7.18
	Fluff line 1	t/h	6.06	6.05	6.06
	Waste oil	l/h	986.83	0.00	1480.24
	Thermal input	MW	92.76		
Calciner	Calciner temp. set point	°C	910.56	909.30	913.09
	Lignite	t/h	4.43	3.30	6.69
	Fluff	t/h	6.24	6.09	6.32
	Filter press cake (box 1)	t/h	0.00	0.00	0.00
	Iron (box 2)	t/h	2.53	2.52	2.54
	Roofing felt (box 3)	t/h	2.80	2.21	3.10
	EBS-Pellets (box 4)	t/h	5.03	3.34	5.87
	Destrü (box 5)	t/h	3.45	0.00	5.17
	Serox (box 6)	t/h	6.06	6.02	6.08
	VC-Rate	%	62.61	58.26	64.78
	Thermal input	MW	122.79		
Prepol-SC	Prepol exit gas temp.	°C	0.00	0.00	0.00
	Prepol fuel feed	t/h	0.00	0.00	0.00
	Thermal input	MW	0.00		
Cooler	Secondary air temp.	°C	1058.37	1052.17	1070.78
	Tertiary air temp.	°C	571.21	566.45	580.71

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 1: Overview_1 930 °C

Overview 2



Calciner measurement 930 °C

Start time:	10:00	19.08.2016	Ultramat
End time:	14:00	19.08.2016	

Observer: Markus Berndt, Florian Groß

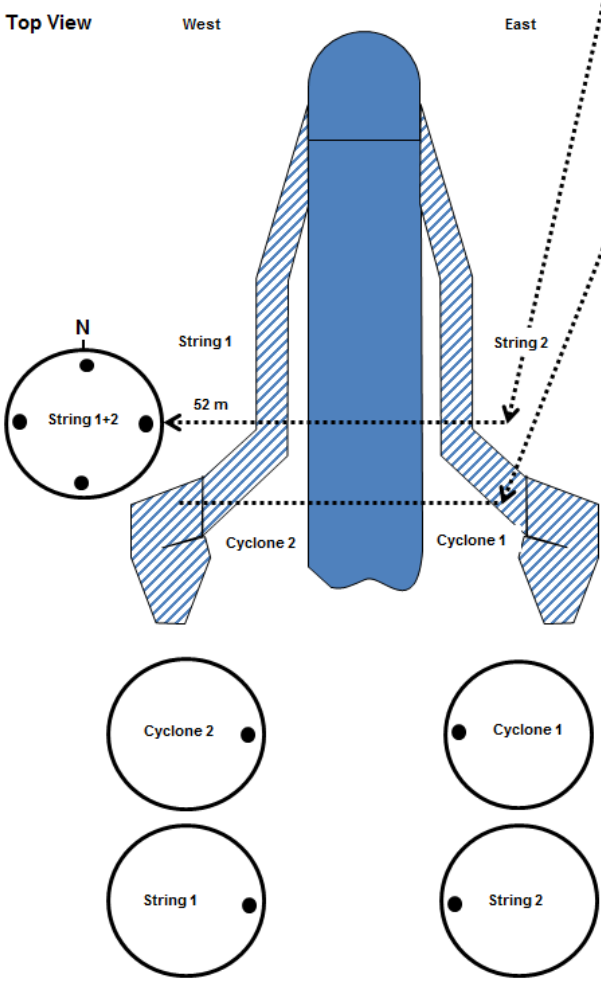
Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
75m	String 1	CO	%						0.562	0.646
		O_2	%						4.81	6.37
		Nox	ppm						-	-
		T	°C						889	838
		Time							13:40	13:50
	String 2	CO	%			0.523	0.786			
		O_2	%			6.67	6.01			
		Nox	ppm			-	-			
		T	°C			824	966			
		Time				11:55	13:30			
71m	Calciner	CO	%	0.364		0.721			0.752	
		O_2	%	7.12		6.23			6.41	
		Nox	ppm	-		-			-	
		T	°C	975		820			843	
		Time		11:35		11:30			11:45	
67m	Calciner	CO	%	0.664				1.221		
		O_2	%	6.06				5.09		
		Nox	ppm	-				-		
		T	°C	911				835		
		Time		10:50				10:55		
52m	Calciner	CO	%	0.858				1.333		
		O_2	%	7.81				4.15		
		Nox	ppm	-				-		
		T	°C	822				1004		
		Time		10:40				10:30		

Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	301.53	295.07	306.13
	Energy clinker	kJ/kg	4611.88	4405.45	4733.46
	O2 kiln inlet	%	4.32	2.86	5.69
	CO kiln inlet	%	0.09	0.02	0.17
	NO kiln inlet	mg/m³	1460.52	1087.41	1701.15
	Temp. kiln inlet	°C	1189.08	1151.50	1220.17
	Lignite	t/h	12.01	9.30	13.86
	Fluff line 1	t/h	1.27	0.00	3.21
	Waste oil	l/h	1899.04	1894.99	1902.74
	Thermal input	MW		104.08	
Calciner	Calciner temp. set point	°C	925.17	917.88	933.23
	Lignite	t/h	0.00	0.00	0.00
	Fluff	t/h	4.23	3.31	4.89
	Filter press cake (box 1)	t/h	0.00	0.00	0.00
	Iron (box 2)	t/h	2.38	2.32	2.46
	Roofing felt (box 3)	t/h	4.82	4.37	5.17
	EBS-Pellets (box 4)	t/h	4.08	3.98	4.25
	Destrü (box 5)	t/h	3.85	3.30	4.25
	Serox (box 6)	t/h	5.43	4.56	5.67
	VC-Rate	%	60.21	57.40	61.38
	Thermal input	MW		93.42	
Prepol-SC	Prepol exit gas temp.	°C	902.81	890.34	919.98
	Prepol fuel feed	t/h	9.14	7.57	9.86
	Thermal input	MW		35.96	
Cooler	Secondary air temp.	°C	997.62	902.70	1169.34
	Tertiary air temp.	°C	785.90	743.25	832.46

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 2: Overview_2 930 °C

Overview 3



Calciner measurement 930 °C

Start time: [redacted] 07:45 12.08.2016 Testo

End time: 10:00 12.08.2016

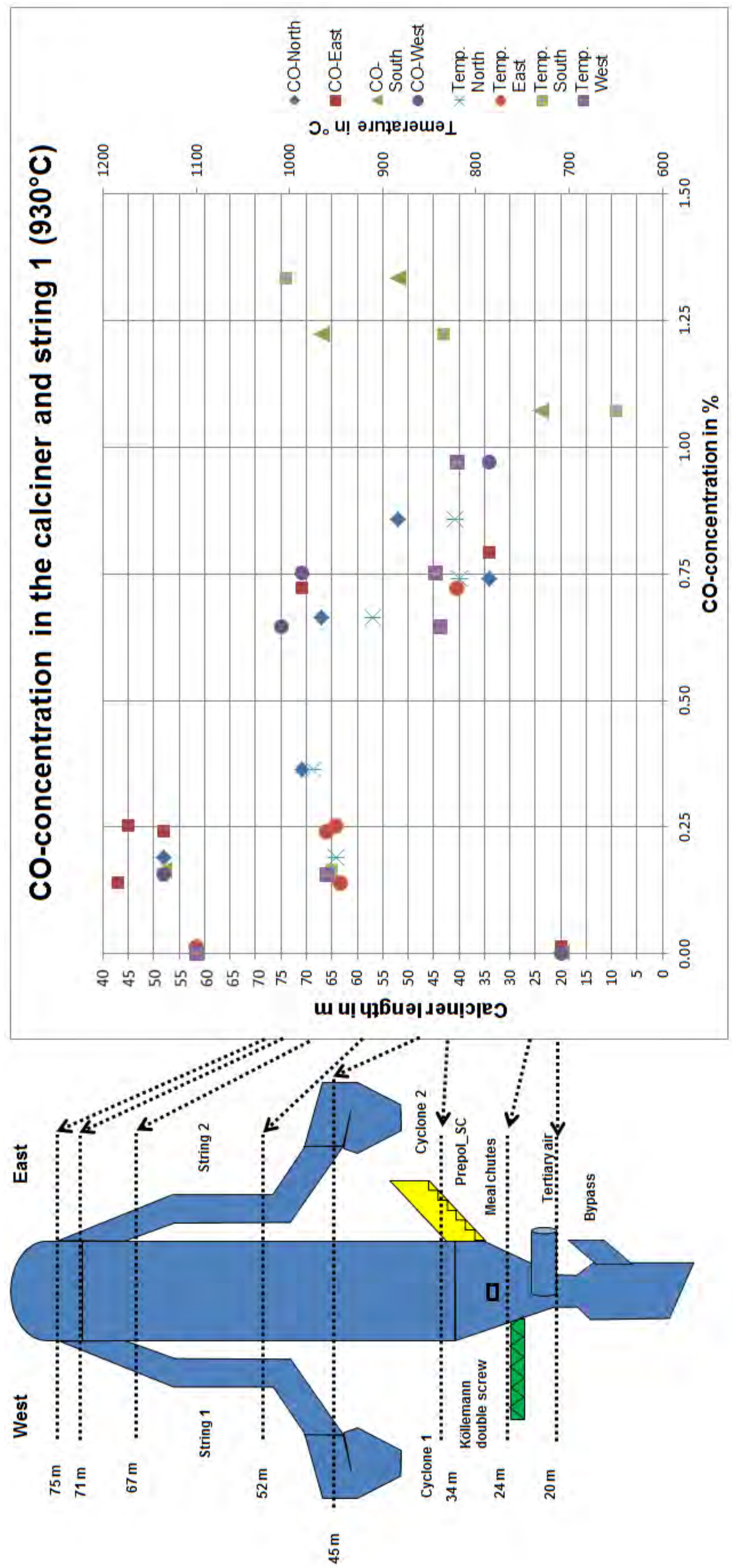
Observer: Markus Berndt, Florian Groß

Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
52m	String 1	CO	%	0.19		0.243		0.165	0.157	
		O_2	%	8.38		5.83		6.43	6.55	
		Nox	ppm	482		454		477	466	
		T	°C	950		960		955	960	
		Time		09:55		08:55		09:10	09:05	
	String 2	CO	%	0.132		0.2		0.185	0.364	
		O_2	%	5.55		4.79		5,87	5.35	
		Nox	ppm	402		491		478	266	
		T	°C	940		970		843	831	
		Time		08:30		08:40		08:50	08:20	
45m	String 1	CO	%			0.253				
		O_2	%			5.36				
		Nox	ppm			324				
		T	°C			950				
		Time				07:50				
	String 2	CO	%						0.17	
		O_2	%						4.99	
		Nox	ppm						253	
		T	°C						955	
		Time							07:55	
43m	Cyclone 1	CO	%						0.01	
		O_2	%						5.22	
		Nox	ppm						292	
		T	°C						945	
		Time							08:00	
	Cyclone 2	CO	%			0.14				
		O_2	%			5.32				
		Nox	ppm			127				
		T	°C			945				
		Time				08:10				

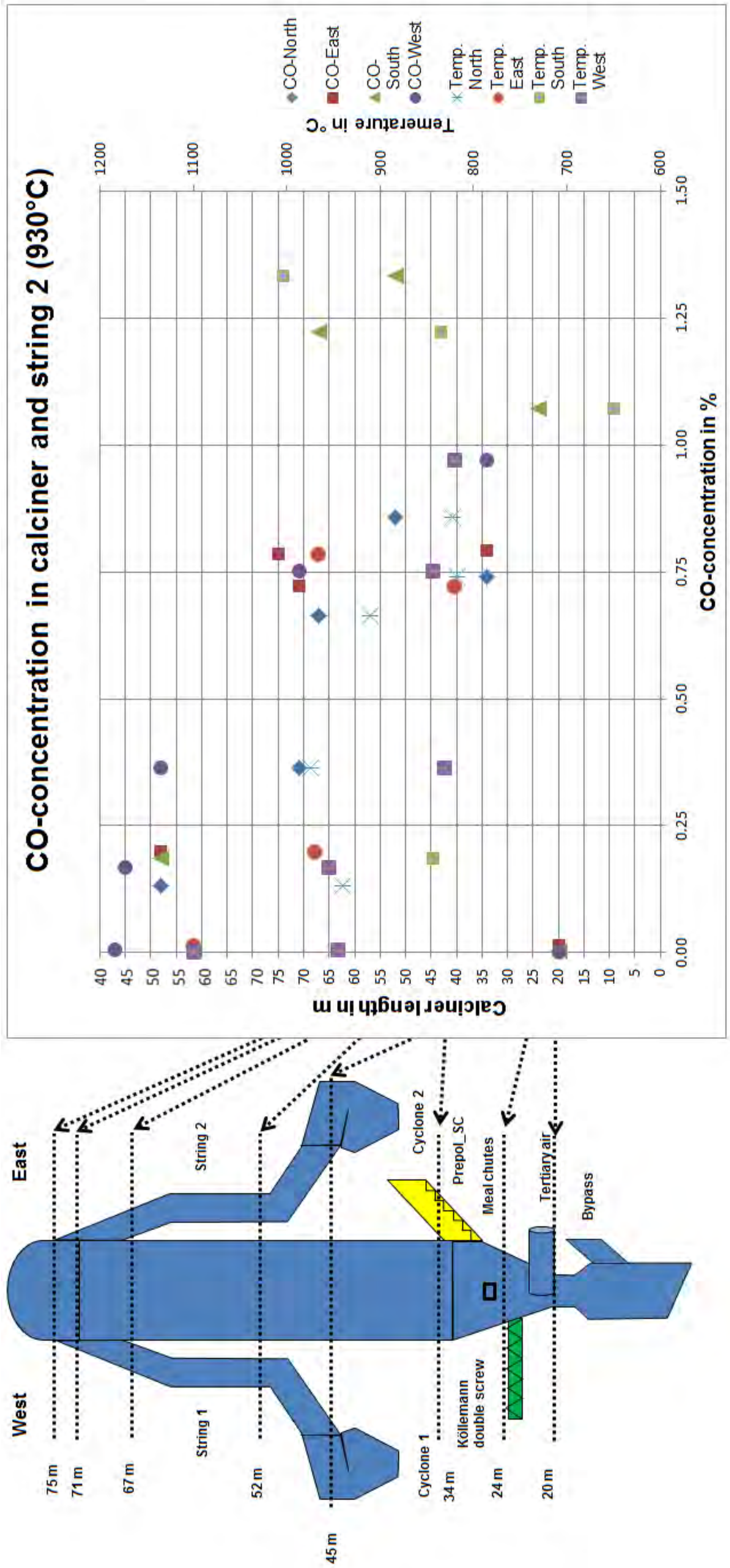
Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	290.27	289.93	290.88
	Energy clinker	kJ/kg	5152.37	5083.59	5275.33
	O2 kiln inlet	%	4.33	4.08	4.71
	CO kiln inlet	%	0.02	0.01	0.03
	NO kiln inlet	mg/m³	867.57	651.07	946.54
	Temperature kiln inlet	°C	1175.43	1172.73	1181.30
	Lignite	t/h	7.49	6.48	8.45
	Fluff line 1	t/h	5.87	4.69	7.05
	Waste oil	l/h	1496.39	1492.75	1498.80
	Thermal input	MW	99.51		
Calciner	Calciner temp. set point	°C	921.28	913.09	943.37
	Lignite	t/h	1.23	0.13	3.49
	Fluff	t/h	6.83	6.09	7.96
	Filter press cake (box 1)	t/h	0.00	0.00	0.00
	Iron (box 2)	t/h	2.53	2.52	2.54
	Roofing felt (box 3)	t/h	2.60	2.07	3.06
	EBS-Pellets (box 4)	t/h	5.18	3.34	7.01
	Destrü (box 5)	t/h	1.99	0.00	3.98
	Serox (box 6)	t/h	6.05	6.02	6.09
	VC-Rate	%	59.37	58.26	60.47
	Thermal input	MW	105.12		
Prepol-SC	Prepol exit gas temp.	°C	829.42	593.45	919.22
	Prepol fuel feed	t/h	6.76	0.00	9.84
	Thermal input	MW	34.63		
Cooler	Secondary air temp.	°C	964.43	885.67	1054.24
	Tertiary air temp.	°C	612.00	593.90	630.11

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

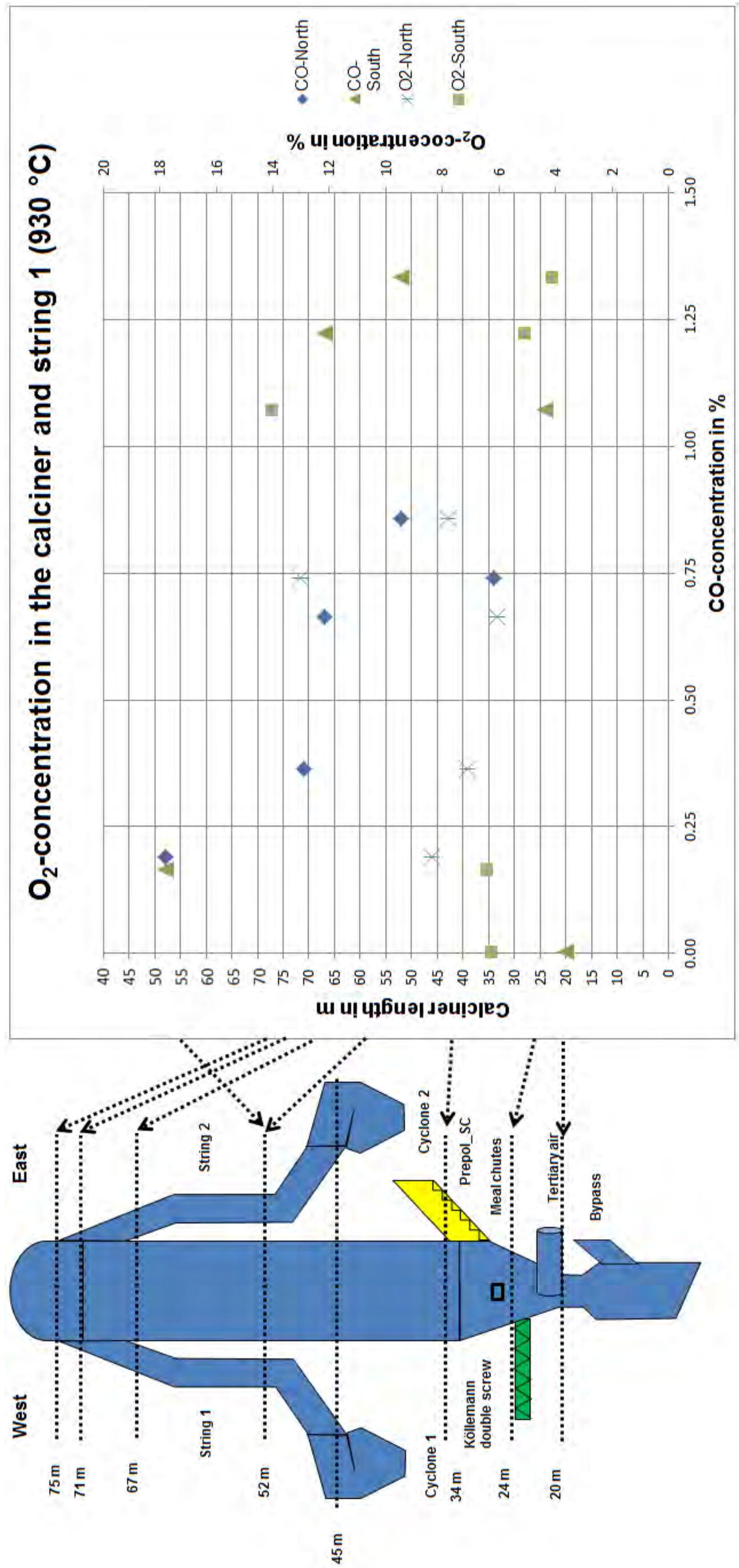
Appendix 3: Overview_3 930 °C



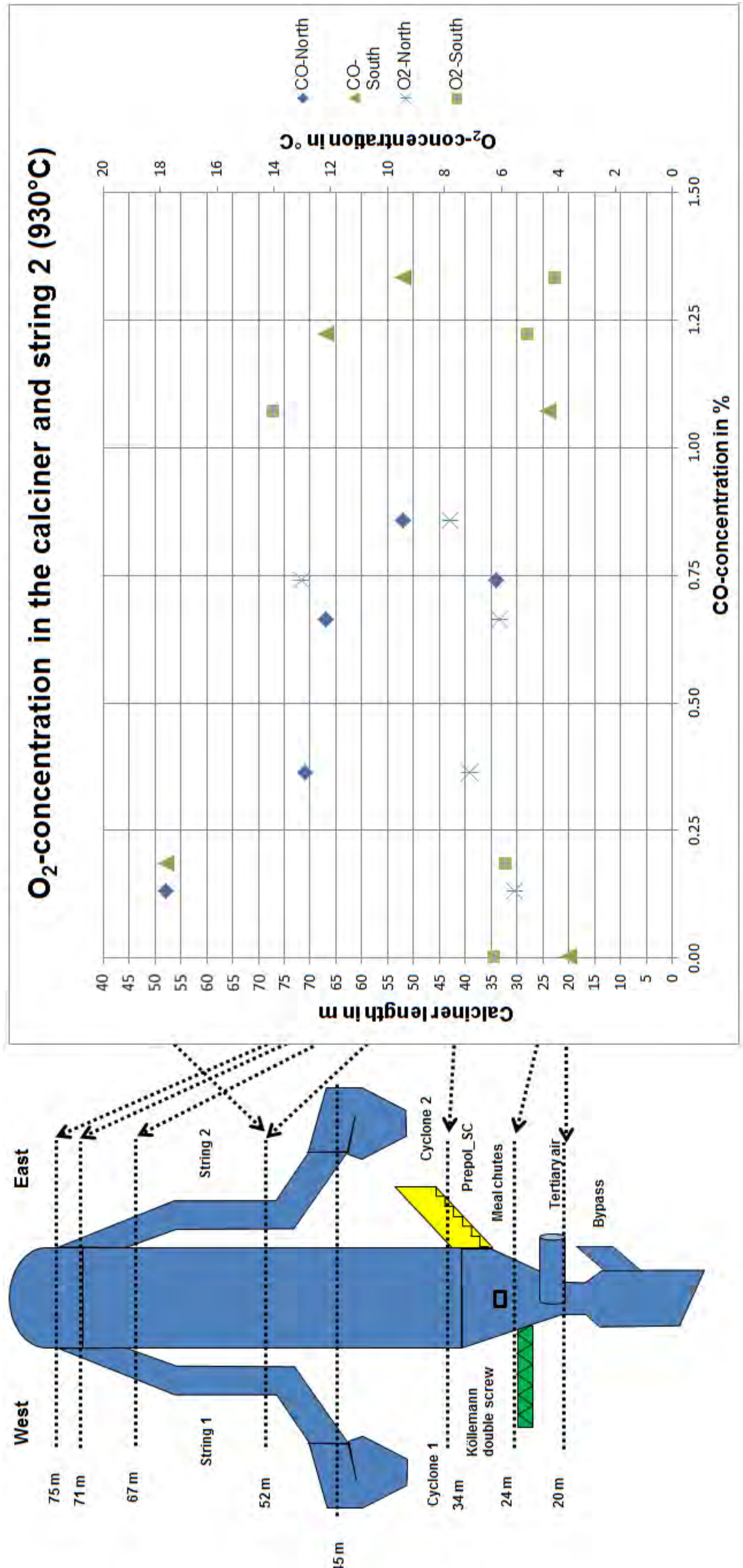
Appendix 4: CO-concentration string 1 (930 °C)



Appendix 5: CO-concentration string 2 (930 °C)

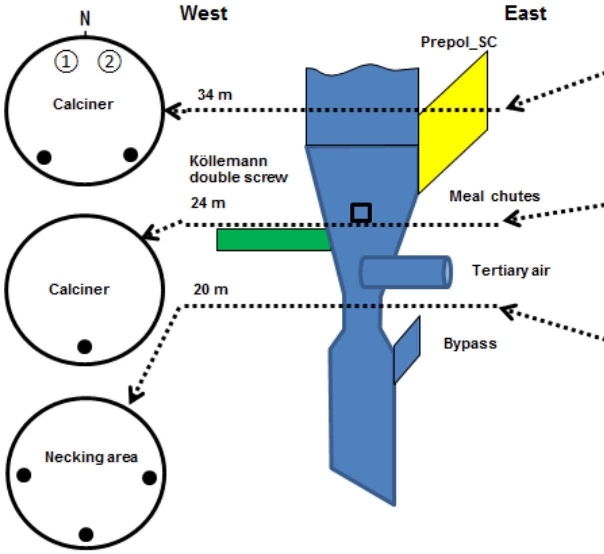


Appendix 6: O2-concentration string 1 (930 °C)



Appendix 7: O2-concentration string 2 (930 °C)

Overview 1



Calciner measurement 920 °C

Start time: 09:30 29.08.2016 Ultramat
End time: 11:50 29.08.2016

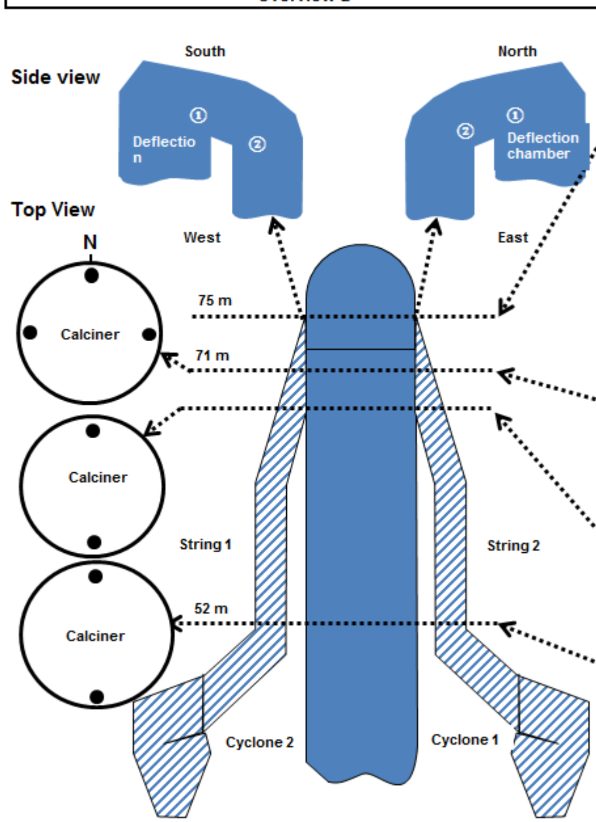
Observer: Markus Berndt, Florian Groß

Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
34m	Calciner	CO	%	0.682	1.472	1.543			1.362	
		O_2	%	11.5	10.29	9.09			9.81	
		Nox	ppm	-	-	-			-	
		T	°C	812	890	830			815	
		Time		09:40	09:50	10:00			09:30	
24m	Calciner	CO	%					1.378		
		O_2	%					13.01		
		Nox	ppm					-		
		T	°C					680		
		Time						11:25		
20m	Calciner	CO	%			0		0.069	0	
		O_2	%			6.47		6.39	6.01	
		Nox	ppm			-		-	-	
		T	°C			791		1026	1100	
		Time				11:35		11:40	11:50	

	Process parameter		AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	319.88	319.37	320.29
	Energy clinker	kJ/kg	4613.57	4463.23	4692.86
	O2 kiln inlet	%	6.76	6.04	7.00
	CO kiln inlet	%	0.01	0.01	0.01
	NO kiln inlet	mg/m³	1531.99	1479.53	1549.48
	Temperature kiln inlet	°C	1149.13	1143.23	1152.52
	Lignite	t/h	9.47	6.91	14.40
	Fluff line 1	t/h	4.41	0.66	6.04
	Waste oil	l/h	44.56	0.00	178.23
	Thermal input	MW	89.60		
Calciner	Calciner temp. set point	°C	928.74	917.69	936.32
	Lignite	t/h	0.00	0.00	0.00
	Fluff	t/h	3.80	2.60	4.60
	Filter press cake (box 1)	t/h	5.71	5.70	5.72
	Iron (box 2)	t/h	2.64	2.64	2.64
	Roofing felt (box 3)	t/h	5.17	5.17	5.18
	EBS-Pellets (box 4)	t/h	5.82	5.28	6.01
	Destrü (box 5)	t/h	6.74	6.00	7.01
	Serox (box 6)	t/h	0.00	0.00	0.00
	VC-Rate	%	65.64	63.72	66.53
	Thermal input	MW	115.78		
Prepol-SC	Prepol exit gas temp.	°C	869.72	858.70	875.47
	Prepol fuel feed	t/h	9.14	8.61	9.88
	Thermal input	MW	40.73		
Cooler	Secondary air temp.	°C	952.07	936.60	978.66
	Tertiary air temp.	°C	733.67	676.97	764.83

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 8: Overview_1 920 °C



Calciner measurement 920 °C

Start time:	09:30	17.08.2016 Ultramat
End time:	14:45	17.08.2016

Observer: Markus Berndt, Florian Groß

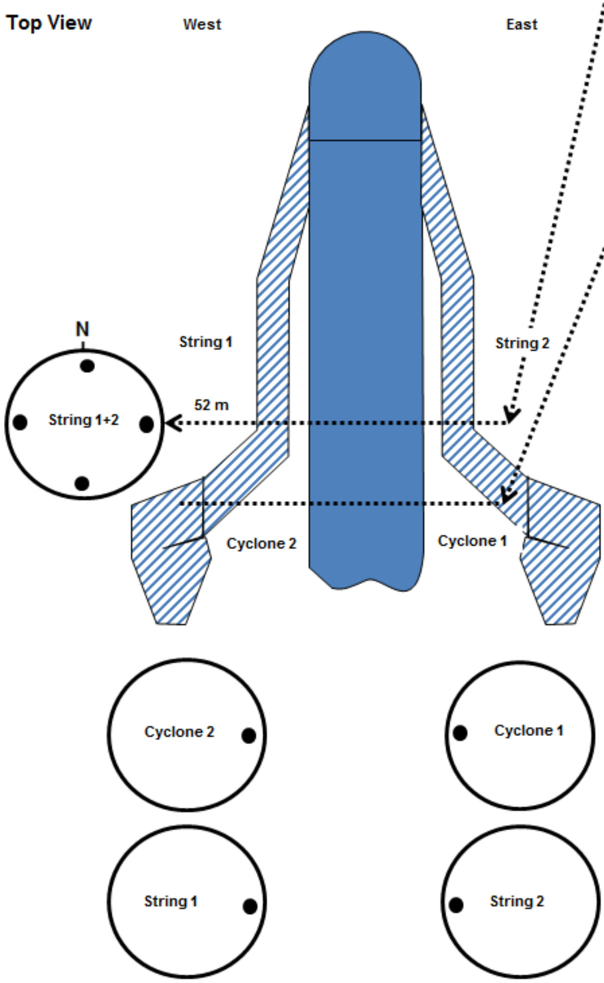
Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
75m	String 1	CO	%						0.695	0.745
		O_2	%						7.17	7.64
		Nox	ppm						-	-
		T	°C						911	915
		Time							14:00	14:15
	String 2	CO	%			0.624	0.72			
		O_2	%			6.81	4.76			
		Nox	ppm			-	-			
		T	°C			916	817			
		Time				13:30	13:45			
71m	Calciner	CO	%	0.332		0.291			0.693	
		O_2	%	9.97		7.84			6.36	
		Nox	ppm	-		-			-	
		T	°C	814		819			866	
		Time		11:30		11:20			11:35	
67m	Calciner	CO	%	0.323				0.648		
		O_2	%	10.05				3.58		
		Nox	ppm	-				-		
		T	°C	848				1017		
		Time		10:50				11:00		
52m	Calciner	CO	%	0.193				0.282		
		O_2	%	13.12				16.41		
		Nox	ppm	-				-		
		T	°C	780				980		
		Time		14:45				14:30		

Process parameter		Unit	AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	291.57	286.56	296.14
	Energy clinker	kJ/kg	4041.29	2040.94	4772.13
	O2 kiln inlet	%	0.58	0.37	1.21
	CO kiln inlet	%	3.17	0.73	4.12
	NO kiln inlet	mg/m³	511.83	335.65	880.28
	Temp. kiln inlet	°C	1203.34	1113.24	1246.45
	Lignite	t/h	10.41	3.18	14.62
	Fluff line 1	t/h	2.90	0.80	4.83
	Waste oil	l/h	2031.84	1878.06	2095.76
	Thermal input	MW	113.56		
Calciner	Calciner temp. set point	°C	926.53	904.08	957.60
	Lignite	t/h	5.48	3.06	9.05
	Fluff	t/h	6.12	5.19	7.21
	Filter press cake (box 1)	t/h	0.00	0.00	0.00
	Iron (box 2)	t/h	2.45	2.28	2.53
	Roofing felt (box 3)	t/h	3.27	1.72	5.17
	EBS-Pellets (box 4)	t/h	3.46	0.08	5.73
	Destrü (box 5)	t/h	2.31	1.00	5.37
	Serox (box 6)	t/h	5.38	5.32	5.46
	VC-Rate	%	55.79	52.70	62.28
	Thermal input	MW	116.13		
Prepol-SC	Prepol exit gas temp.	°C	0.00	0.00	0.00
	Prepol fuel feed	t/h	0.00	0.00	0.00
	Thermal input	MW	0.00		
Cooler	Secondary air temp.	°C	942.35	885.03	985.81
	Tertiary air temp.	°C	740.67	614.72	827.94

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 9: Overview_2 920 °C

Overview 3	Calciner measurement 920 °C	Observer:
	Start time: [redacted] 07:45 11.08.2016 Testo	Markus Berndt
	End time: 11:30 11.08.2016	Florian Groß

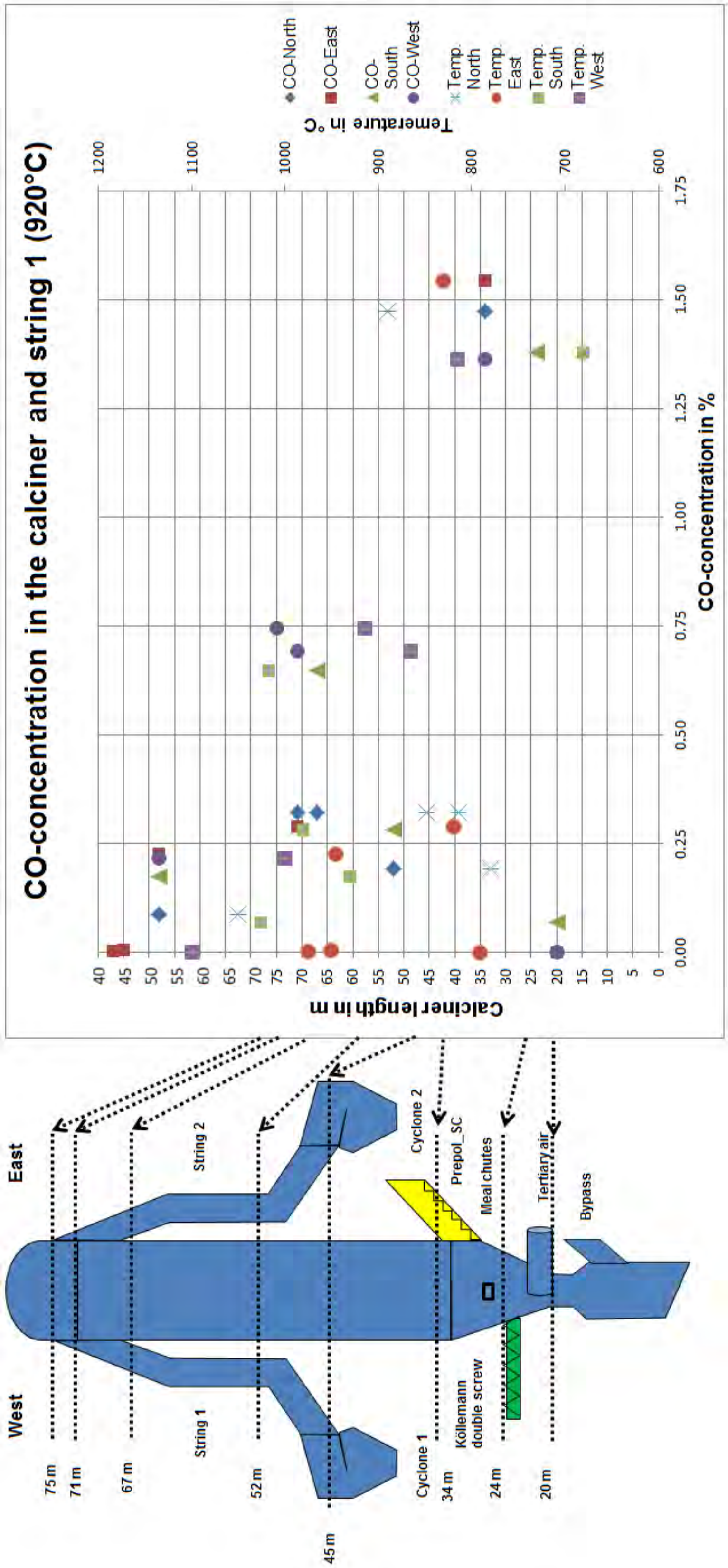


Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
52m	String 1	CO	%	0.088		0.228		0.175	0.216	
		O_2	%	4.39		7.1		6.69	4.93	
		Nox	ppm	578		5,91		434	601	
		T	°C	1050		945		930	1000	
		Time		11:30		11:10		10:15	11:20	
	String 2	CO	%	750		377		34	715	
		O_2	%	4.3		3.79		4	5.81	
		Nox	ppm	506		576		582	369	
		T	°C	1000		960		1045	945	
		Time		10:50		11:00		11:05		
45m	String 1	CO	%			64				
		O_2	%			3.49				
		Nox	ppm			563				
		T	°C			950				
		Time				07:45				
	String 2	CO	%						0.026	
		O_2	%						5.31	
		Nox	ppm						376	
		T	°C						980	
		Time							07:55	
43m	Cyclone 1	CO	%						0.001	
		O_2	%						4.68	
		Nox	ppm						234	
		T	°C						975	
		Time							08:05	
	Cyclone 2	CO	%			0.005				
		O_2	%			7.19				
		Nox	ppm			200				
		T	°C			975				
		Time				08:15				

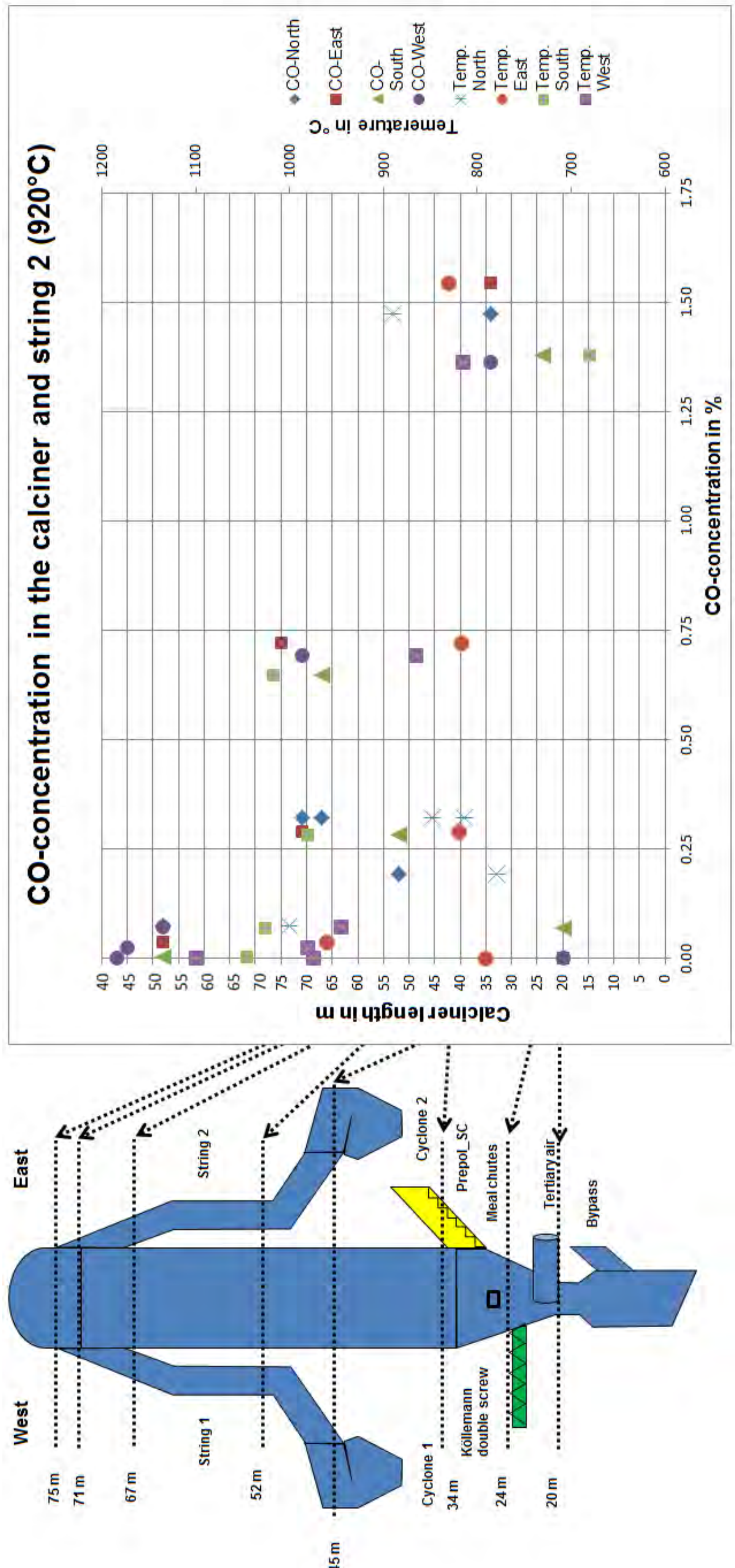
Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	301.14	292.79	305.62
	Energy clinker	kJ/kg	4779.07	4510.64	5015.68
	O2 kiln inlet	%	6.67	6.14	7.17
	CO kiln inlet	%	0.01	0.00	0.01
	NO kiln inlet	mg/m³	1040.76	908.78	1222.39
	Temperature kiln inlet	°C	1169.05	1127.73	1202.84
	Lignite	t/h	5.28	2.16	8.63
	Fluff line 1	t/h	5.65	3.42	8.07
	Waste oil	l/h	1510.42	1383.02	1580.92
	Thermal input	MW		89.62	
Calciner	Calciner temp. set point	°C	925.04	911.33	932.59
	Lignite	t/h	6.74	0.80	9.05
	Fluff	t/h	4.66	2.61	6.39
	Filter press cake (box 1)	t/h	0.00	0.00	0.00
	Iron (box 2)	t/h	2.62	2.43	2.70
	Roofing felt (box 3)	t/h	4.44	3.57	4.66
	EBS-Pellets (box 4)	t/h	4.10	3.34	4.62
	Destrü (box 5)	t/h	4.07	3.34	4.55
	Serox (box 6)	t/h	6.20	5.43	6.42
	VC-Rate	%	64.60	60.99	66.36
	Thermal input	MW		92.63	
Prepol-SC	Prepol exit gas temp.	°C	889.42	880.34	900.10
	Prepol fuel feed	t/h	10.97	10.37	11.44
	Thermal input	MW		50.17	
Cooler	Secondary air temp.	°C	1060.95	983.21	1115.54
	Tertiary air temp.	°C	642.27	597.85	684.95

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

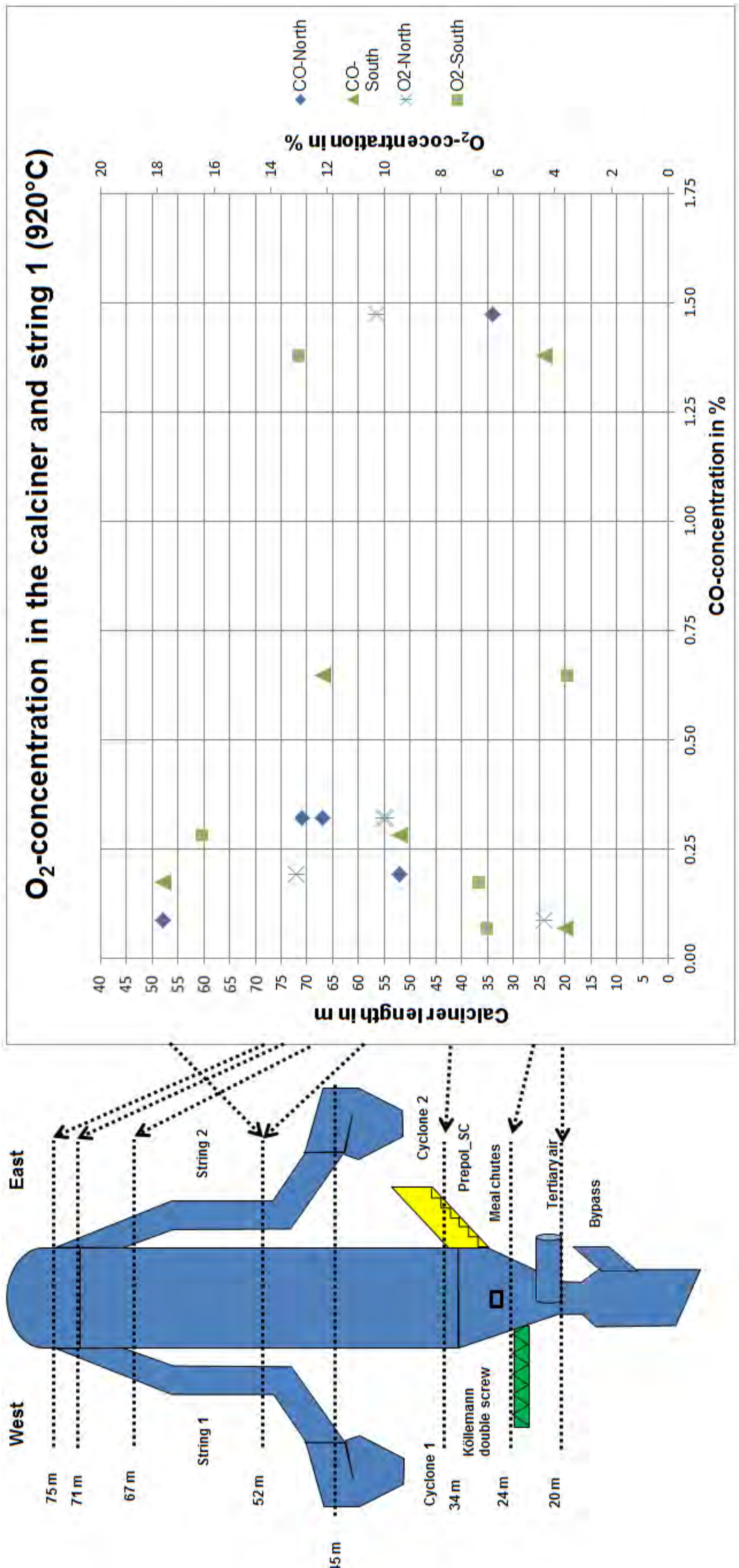
Appendix 10: Overview_3 920 °C



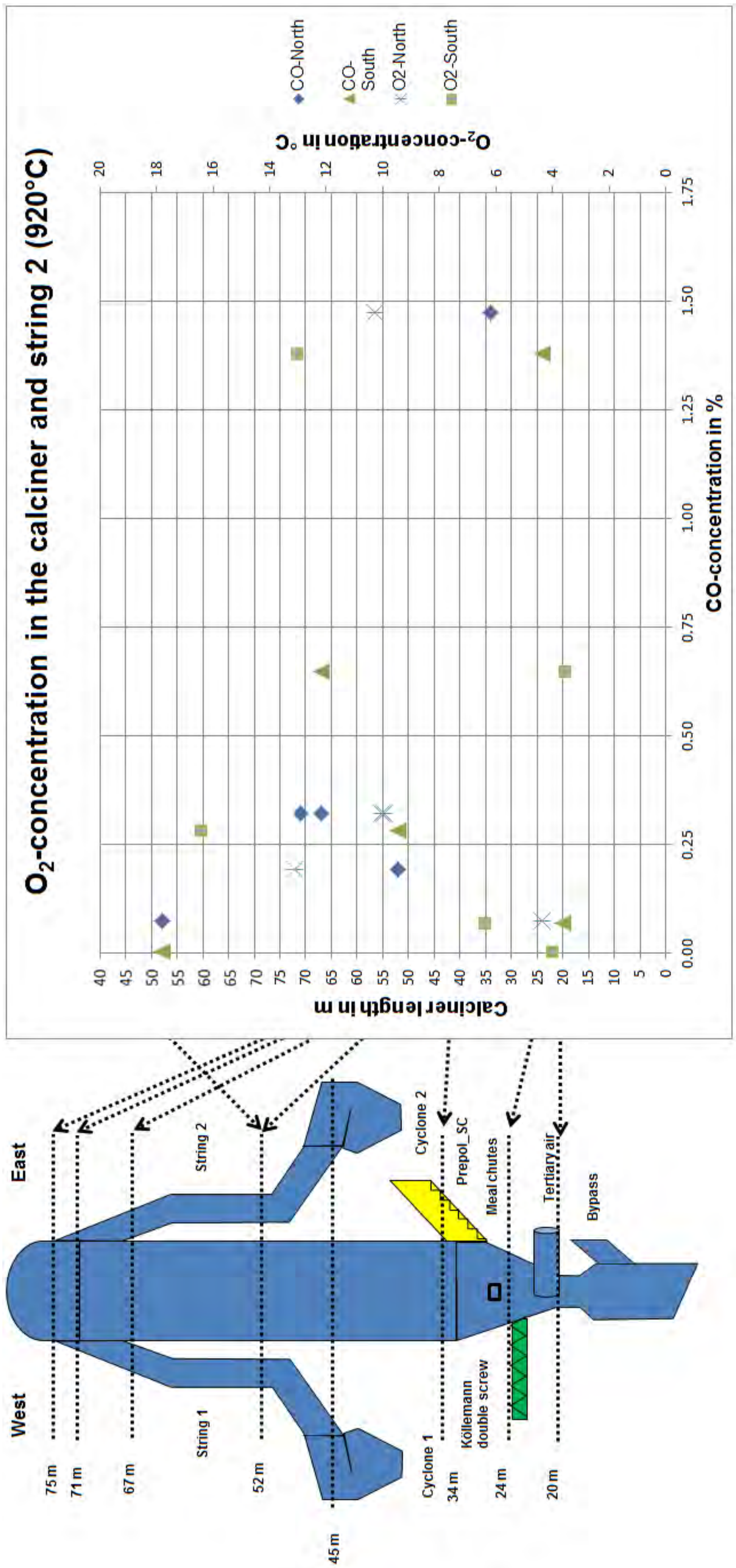
Appendix 11: CO-concentration string 1 (920 °C)



Appendix 12: CO-concentration string 2 (920 °C)

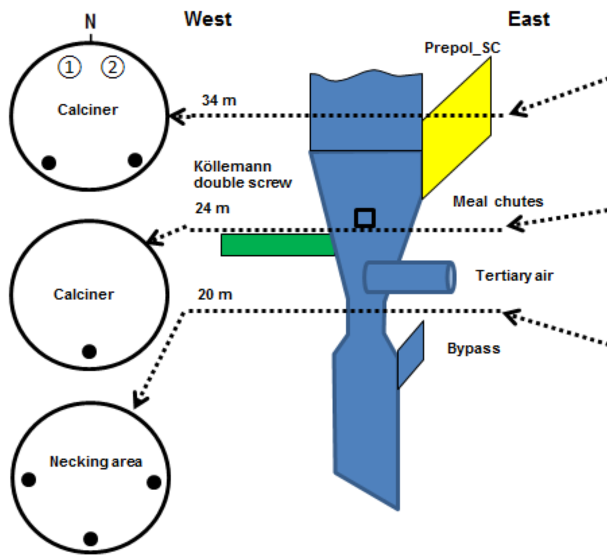


Appendix 13: O2-concentration string 1 (920 °C)



Appendix 14: O2-concentration string 2 (920 °C)

Overview 1



Calciner measurement 910 °C

Start time: 10:25 24.08.2016 Ultramat
End time: 11:30 24.08.2016

Observer: Markus Berndt, Florian Groß

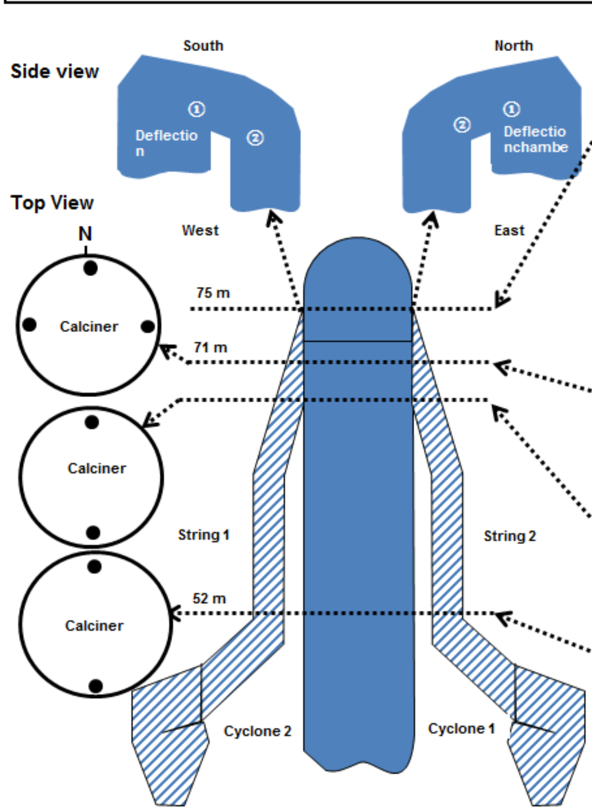
Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
34m	Calciner	CO	%	0.371	0.674	2.256			1.295	
		O_2	%	15.45	14.58	8.53			10.72	
		Nox	ppm	-	-	-			-	
		T	°C	742	769	815			802	
		Time		11:15	11:20	11:25			11:10	
24m	Calciner	CO	%					1.027		
		O_2	%					14.34		
		Nox	ppm					-		
		T	°C					720		
		Time						10:10		
20m	Calciner	CO	%			0		0.118	0.008	
		O_2	%			9.11		4.62	5.73	
		Nox	ppm			-		-	-	
		T	°C			1052		1100	1100	
		Time				10:25		10:35	10:55	

Process parameter		Unit	AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	285.13	284.19	285.87
	Energy clinker	kJ/kg	4860.77	4778.33	4901.99
	O2 kiln inlet	%	4.48	4.48	4.48
	CO kiln inlet	%	0.02	0.02	0.02
	NO kiln inlet	mg/m³	552.66	552.66	552.66
	Temperature kiln inlet	°C	1165.09	1159.45	1167.91
	Lignite	t/h	4.50	4.50	4.50
	Fluff line 1	t/h	6.06	6.05	6.07
	Waste oil	l/h	2393.34	2391.79	2396.42
	Thermal input	MW	96.40		
Calciner	Calciner temp. set point	°C	910.05	908.87	909.66
	Lignite	t/h	0.00	0.00	0.00
	Fluff	t/h	7.45	6.78	7.78
	Filter press cake (box 1)	t/h	2.06	2.06	2.07
	Iron (box 2)	t/h	7.55	7.52	7.62
	Roofing felt (box 3)	t/h	4.65	4.64	4.66
	EBS-Pellets (box 4)	t/h	5.98	5.96	6.01
	Destrü (box 5)	t/h	5.98	5.97	5.99
	Serox (box 6)	t/h	2.00	1.99	2.01
	VC-Rate	%	60.61	59.89	60.96
	Thermal input	MW	115.70		
Prepol-SC	Prepol exit gas temp.	°C	0.00	0.00	0.00
	Prepol fuel feed	t/h	0.00	0.00	0.00
	Thermal input	MW	0.00		
Cooler	Secondary air temp.	°C	988.59	964.37	1000.70
	Tertiary air temp.	°C	786.69	758.97	800.55

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 15: Overview_1 910 °C

Overview 2



Calciner measurement 910 °C

Start time:	07:30	25.08.2016	Ultramat
End time:	11:45	25.08.2016	

Observer: Markus Berndt, Florian Groß

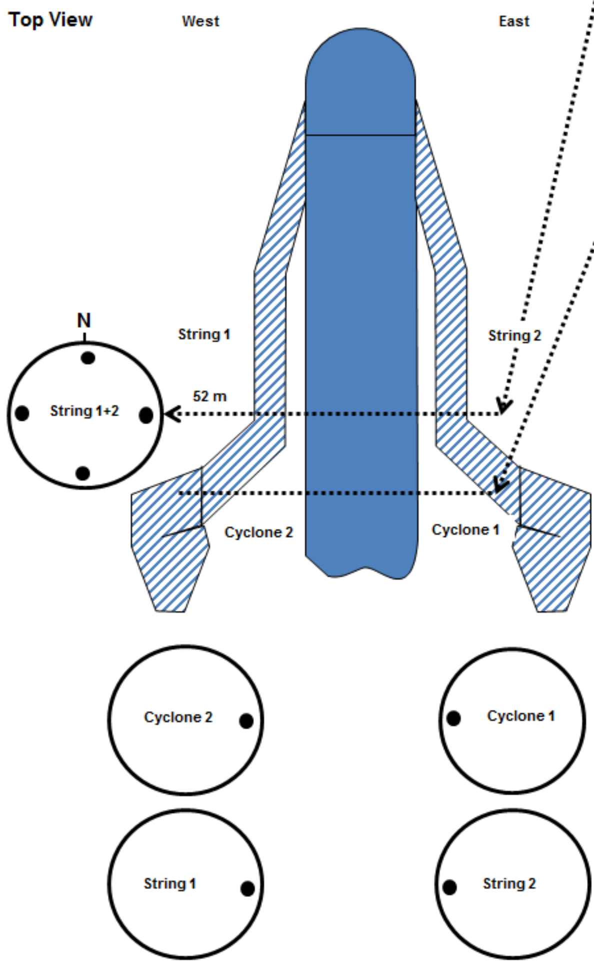
Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
75m	String 1	CO	%						0.816	0.851
		O_2	%						7.81	7.71
		Nox	ppm						-	-
		T	°C						840	920
		Time							11:15	11:30
	String 2	CO	%			0.746	0.794			
		O_2	%			7.22	7.04			
		Nox	ppm			-	-			
		T	°C			917	862			
		Time				10:15	11:05			
71m	Calciner	CO	%	0.564		0.761			1.491	
		O_2	%	9.29		7.16			5.92	
		Nox	ppm	-		-			-	
		T	°C	805		922			865	
		Time		10:00		09:55			10:05	
67m	Calciner	CO	%	0.471				2.484		
		O_2	%	8.83				3.43		
		Nox	ppm	-				-		
		T	°C	800				838		
		Time		09:40				09:35		
52m	Calciner	CO	%	0.639				1.872		
		O_2	%	10.21				5.53		
		Nox	ppm	-				-		
		T	°C	795				896		
		Time		07:35				07:30		

	Process parameter		AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	299.65	284.92	312.73
	Energy clinker	kJ/kg	4930.06	4811.74	5050.62
	O2 kiln inlet	%	5.41	3.62	6.18
	CO kiln inlet	%	0.02	0.02	0.03
	NO kiln inlet	mg/m³	638.96	559.90	993.92
	Temp. kiln inlet	°C	1160.74	701.74	1229.96
	Lignite	t/h	5.71	1.27	7.10
	Fluff line 1	t/h	5.33	1.72	6.05
	Waste oil	l/h	1920.76	1293.29	2481.07
	Thermal input	MW		81.79	
Calciner	Calciner temp. set point	°C	919.49	865.27	980.20
	Lignite	t/h	0.00	0.00	0.00
	Fluff	t/h	3.09	1.00	6.15
	Filter press cake (box 1)	t/h	2.07	1.39	2.81
	Iron (box 2)	t/h	7.90	5.92	10.39
	Roofing felt (box 3)	t/h	4.65	4.45	5.04
	EBS-Pellets (box 4)	t/h	5.19	3.32	6.25
	Destrü (box 5)	t/h	6.99	6.70	7.26
	Serox (box 6)	t/h	2.63	0.21	3.94
	VC-Rate	%	62.55	58.66	67.78
	Thermal input	MW		99.63	
Prepol-SC	Prepol exit gas temp.	°C	858.85	768.89	964.19
	Prepol fuel feed	t/h	8.50	4.26	16.37
	Thermal input	MW		31.84	
Cooler	Secondary air temp.	°C	986.21	933.50	1023.50
	Tertiary air temp.	°C	649.82	316.50	1000.00

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 16: Overview_2 910 °C

Overview 3



Calciner measurement 910 °C

Start time:	[redacted] 08:00 09.08.2016 Testo
End time:	15:00 09.08.2016

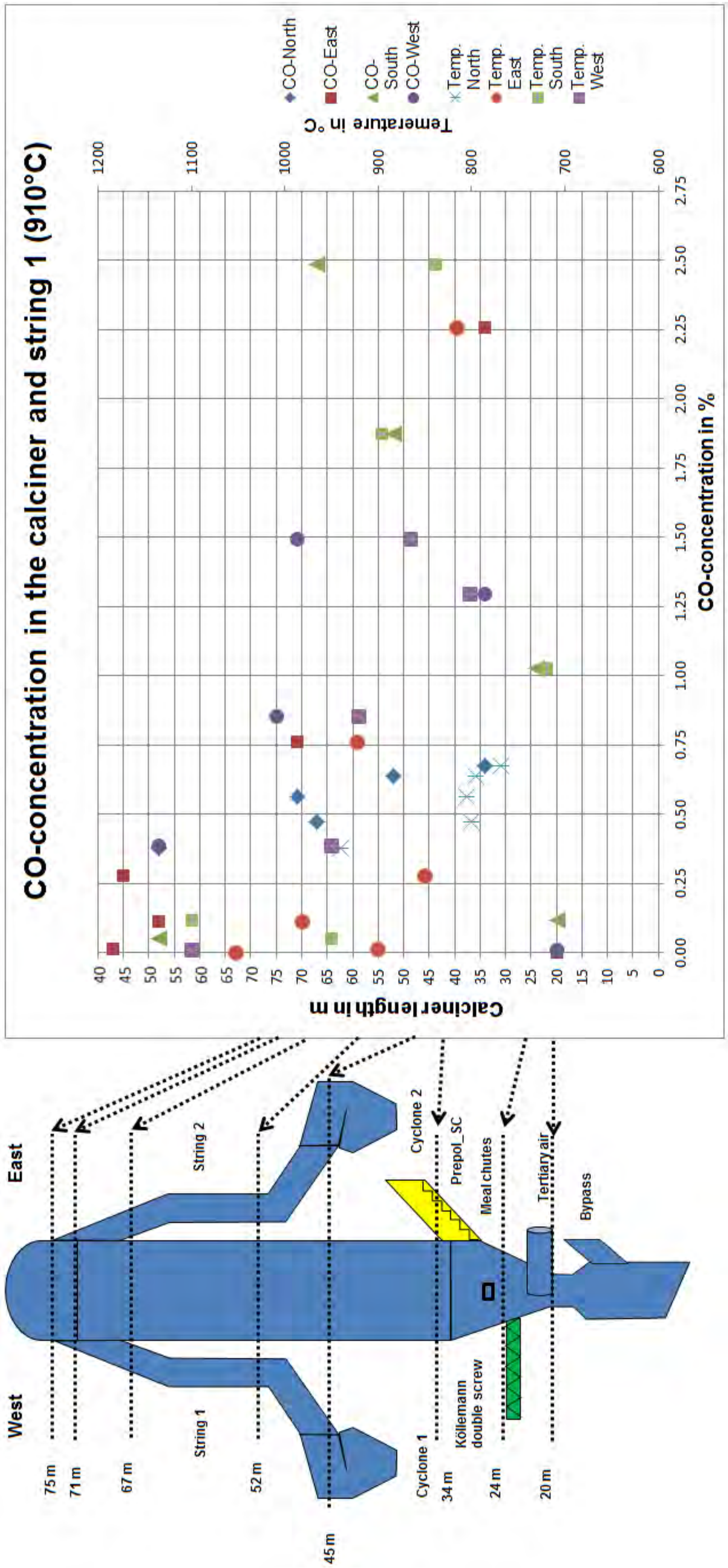
Observer: Markus Berndt, Florian Groß

Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
52m	String 1	CO	%	0.38		0.11		0.05	0.39	
		O_2	%	6.52		4.81		4.51	5.2	
		Nox	ppm	577		541		448	479	
		T	°C	940		980		950	950	
		Time		-		-		-	-	
	String 2	CO	%	0.26		0.16		0.02	0.31	
		O_2	%	6.58		6.39		4.22	4.33	
		Nox	ppm	583		6.23		395	640	
		T	°C	920		900		940	900	
		Time		-		-		-	-	
45m	String 1	CO	%			0.28				
		O_2	%			5.53				
		Nox	ppm			358				
		T	°C			850				
		Time				-				
	String 2	CO	%						0.26	
		O_2	%						5.48	
		Nox	ppm						296	
		T	°C						910	
		Time							-	
43m	Cyclone 1	CO	%						0	
		O_2	%						4.35	
		Nox	ppm						187	
		T	°C						940	
		Time							-	
	Cyclone 2	CO	%			0.01				
		O_2	%			5.31				
		Nox	ppm			350				
		T	°C			900				
		Time				-				

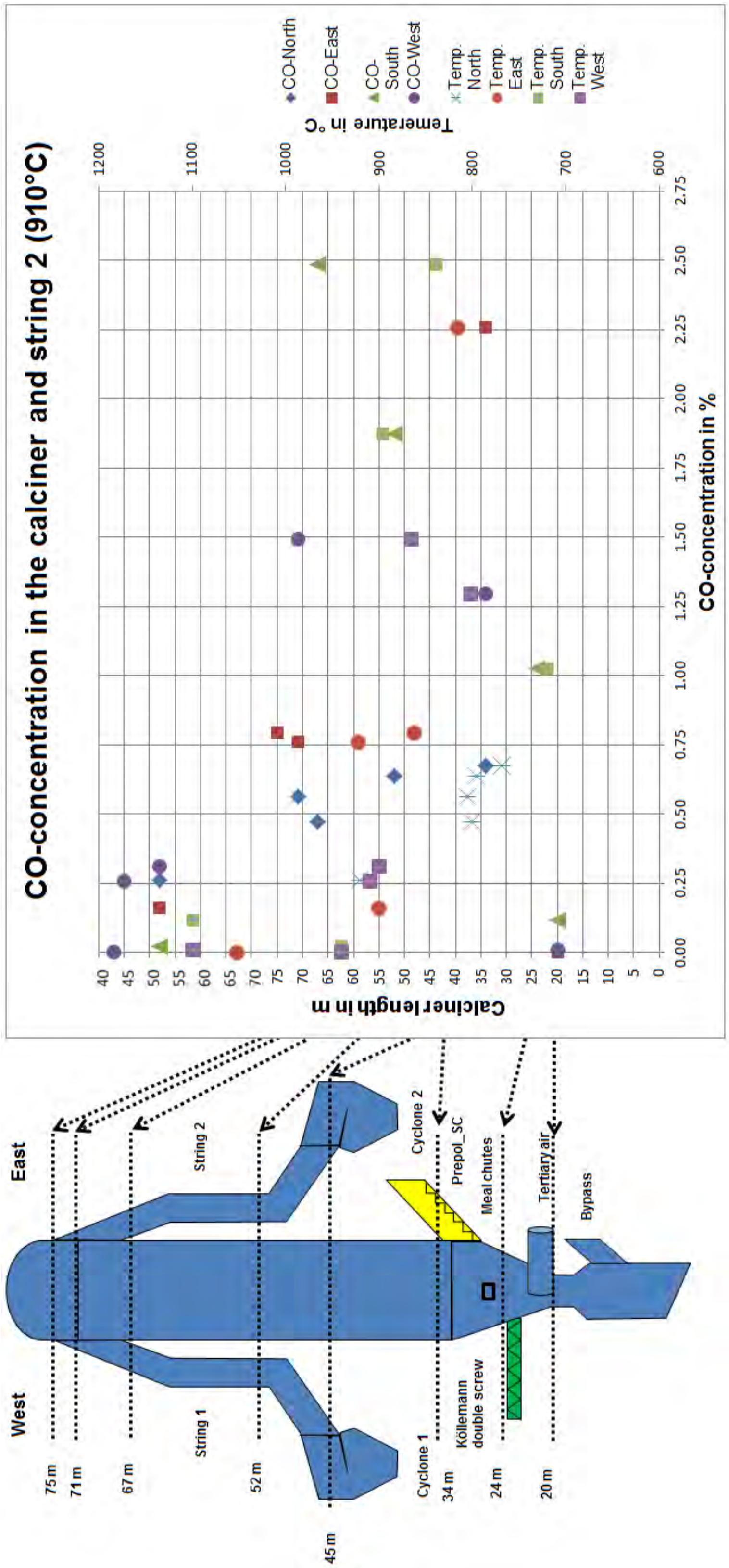
	Process parameter		AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	301.70	275.09	317.42
	Energy clinker	kJ/kg	4781.24	3662.43	6697.54
	O2 kiln inlet	%	3.54	2.39	4.74
	CO kiln inlet	%	0.06	0.00	0.22
	NO kiln inlet	mg/m³	862.84	551.22	1221.07
	Temperature kiln inlet	°C	1177.64	733.47	1267.36
	Lignite	t/h	5.13	4.51	5.95
	Fluff line 1	t/h	6.62	6.04	7.07
	Waste oil	l/h	1481.23	293.04	1512.09
	Thermal input	MW	92.99		
Calciner	Calciner temp. set point	°C	916.68	905.74	925.68
	Lignite	t/h	0.55	0.00	1.71
	Fluff	t/h	4.95	2.09	6.80
	Filter press cake (box 1)	t/h	0.06	0.00	0.41
	Iron (box 2)	t/h	2.23	1.92	2.52
	Roofing felt (box 3)	t/h	2.58	1.86	4.14
	EBS-Pellets (box 4)	t/h	5.17	4.27	5.98
	Destrü (box 5)	t/h	4.37	2.53	5.01
	Serox (box 6)	t/h	4.62	3.76	5.44
	VC-Rate	%	61.48	60.54	63.05
	Thermal input	MW	84.18		
Prepol-SC	Prepol exit gas temp.	°C	505.27	472.54	566.88
	Prepol fuel feed	t/h	8.71	5.31	11.03
	Thermal input	MW	46.64		
Cooler	Secondary air temp.	°C	989.27	916.37	1102.40
	Tertiary air temp.	°C	645.19	606.41	687.65

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

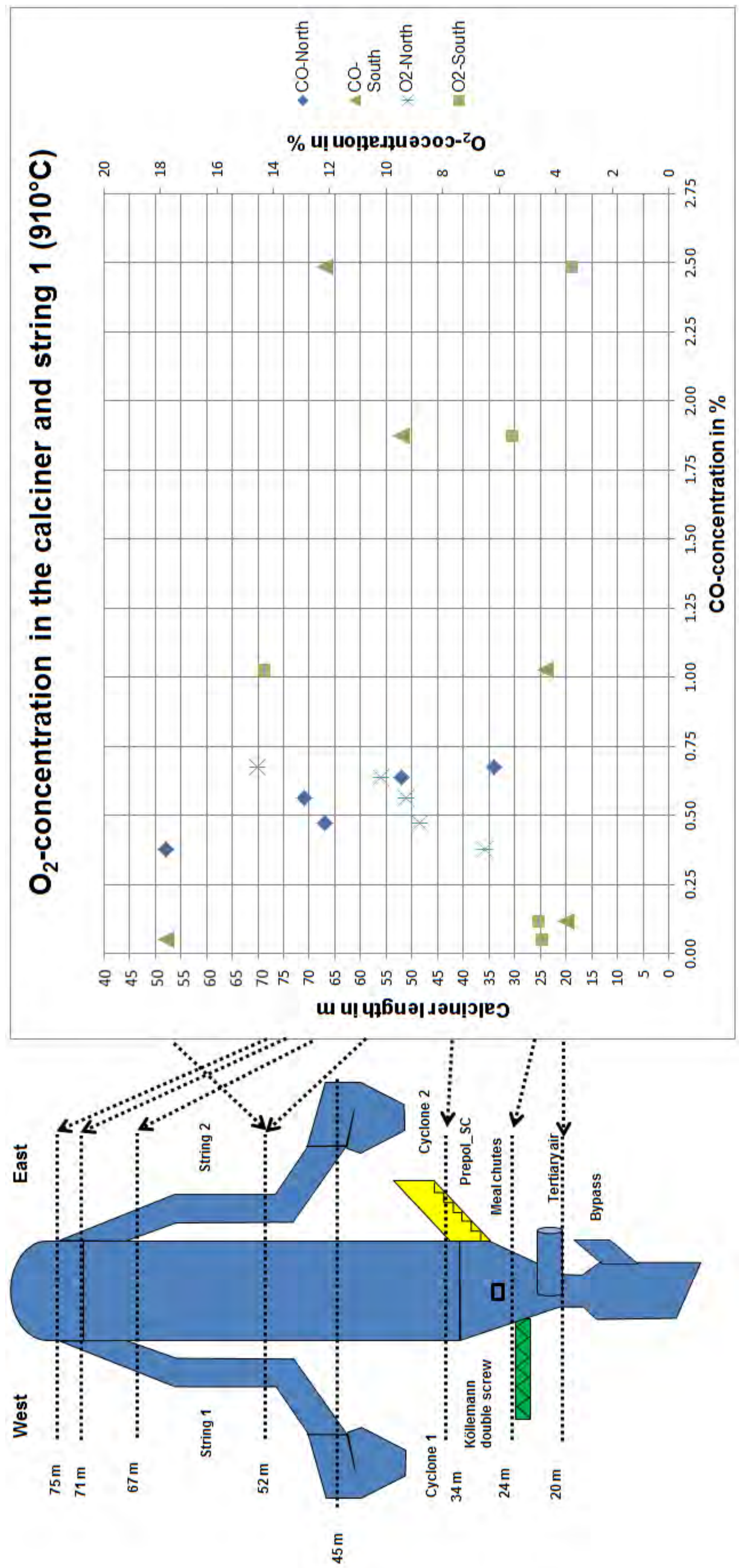
Appendix 17: Overview_3 910 °C



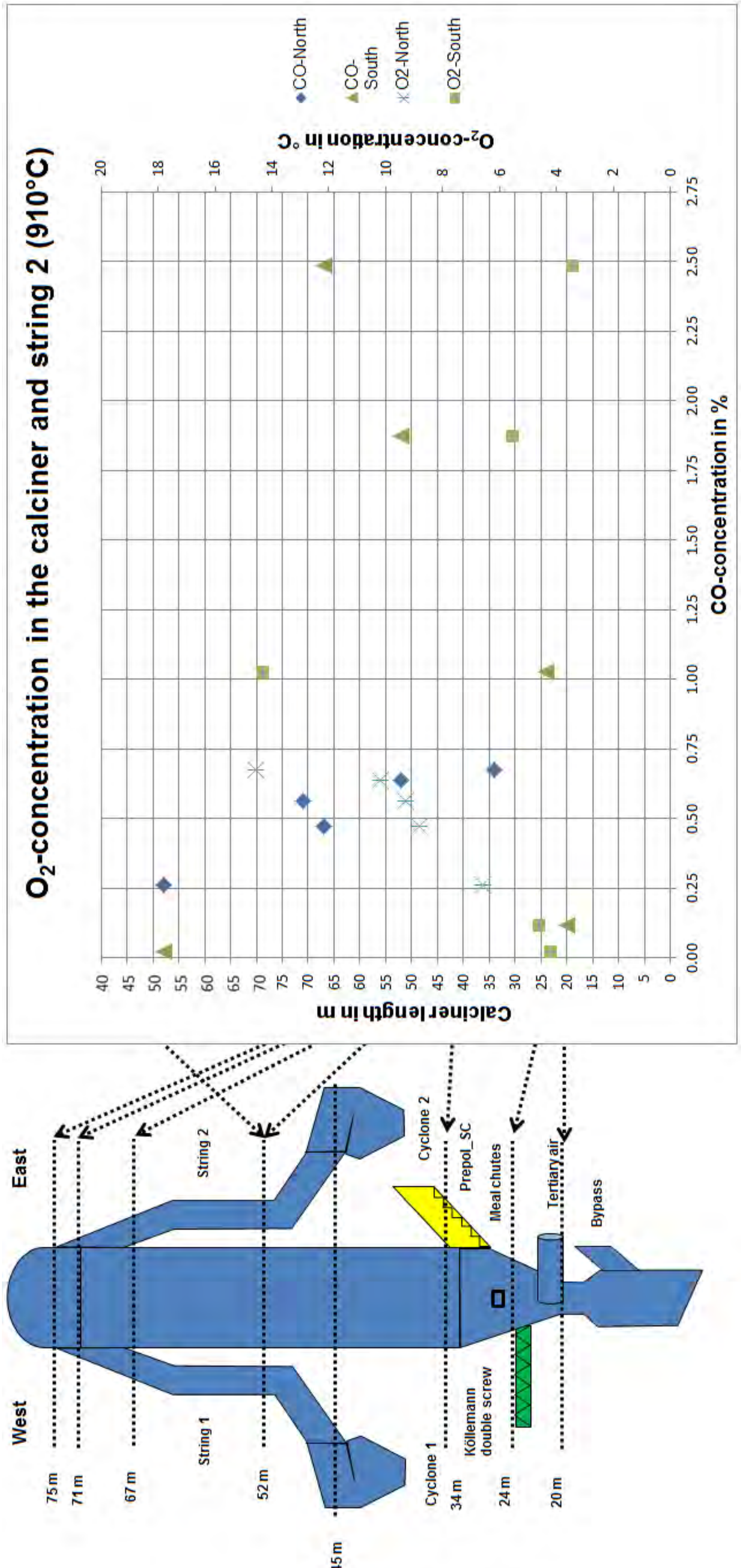
Appendix 18: CO-concentration string 1 (910°C)



Appendix 19: CO-concentration string 2 (910 °C)

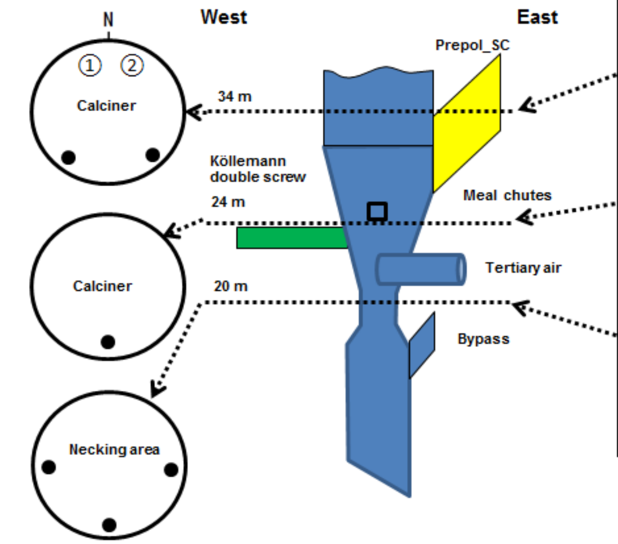


Appendix 20: O2-concentration string 1 (910 °C)



Appendix 21: O2-concentration string 2 (910 °C)

Overview 1



Calciner measurement 900 °C

Start time: 13:35 30.08.2016 Ultramat
End time: 14:15 30.08.2016

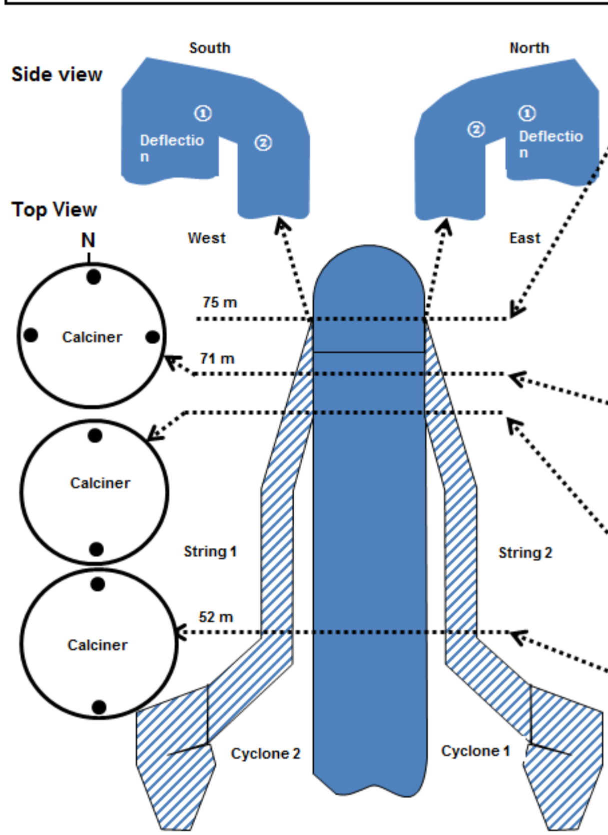
Observer: Markus Berndt, Florian Groß

Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
34m	Calciner	CO	%	1.184	2.396	0.837			0.889	
		O_2	%	12.89	4.13	13.86			10.69	
		Nox	ppm	-	-	-			-	
		T	°C	832	955	923			824	
		Time		13:45	13:50	13:40			13:35	
24m	Calciner	CO	%					1.304		
		O_2	%					12.12		
		Nox	ppm					-		
		T	°C					720		
		Time						14:00		
20m	Calciner	CO	%			0		0		
		O_2	%			7.42		5.07		
		Nox	ppm			-		-		
		T	°C			1100		1100		
		Time				14:00		14:10		

Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	245.41	195.25	295.57
	Energy clinker	kJ/kg	4596.84	4200.60	4993.08
	O2 kiln inlet	%	8.20	7.50	8.91
	CO kiln inlet	%	0.01	0.01	0.01
	NO kiln inlet	mg/m³	1379.10	1268.56	1489.63
	Temperature kiln inlet	°C	1158.47	1118.10	1198.83
	Lignite	t/h	13.41	12.25	14.57
	Fluff line 1	t/h	0.22	0.00	0.44
	Waste oil	l/h	0.00	0.00	0.00
	Thermal input	MW	85.31		
Calciner	Calciner temp. set point	°C	910.84	876.29	945.39
	Lignite	t/h	3.75	3.04	4.46
	Fluff	t/h	4.78	3.16	6.41
	Filter press cake (box 1)	t/h	3.65	2.76	4.54
	Iron (box 2)	t/h	2.17	1.91	2.43
	Roofing felt (box 3)	t/h	0.00	0.00	0.00
	EBS-Pellets (box 4)	t/h	4.01	3.51	4.51
	Destrü (box 5)	t/h	3.87	2.52	5.22
	Serox (box 6)	t/h	0.00	0.00	0.00
	VC-Rate	%	53.84	42.86	64.82
	Thermal input	MW	113.64		
Prepol-SC	Prepol exit gas temp.	°C	813.91	757.80	870.03
	Prepol fuel feed	t/h	6.40	4.51	8.28
	Thermal input	MW	33.62		
Cooler	Secondary air temp.	°C	1050.85	1020.44	1081.26
	Tertiary air temp.	°C	565.97	560.88	571.06

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 22: Overview_1 900 °C



Calciner measurement 900 °C

Start time:	09:25 26.08.2016 Ultramat	Observer:
End time:	11:00 26.08.2016	Markus Berndt, Florian Groß

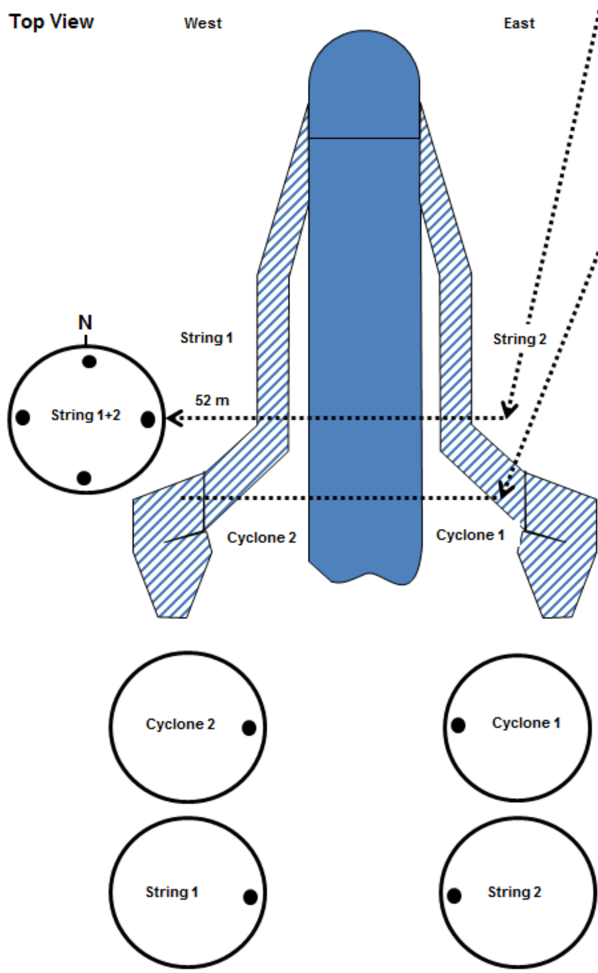
Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
75m	String 1	CO	%						0.693	0.696
		O_2	%						6.94	7.19
		Nox	ppm						-	-
		T	°C						823	808
		Time							10:45	10:50
	String 2	CO	%			0.755	0.772			
		O_2	%			7.23	7.77			
		Nox	ppm			-	-			
		T	°C			811	937			
		Time				10:20	10:35			
71m	Calciner	CO	%	0.521		0.985			0.664	
		O_2	%	9.81		6.21			7.77	
		Nox	ppm	-		-			-	
		T	°C	785		915			821	
		Time		10:00		09:55			10:10	
67m	Calciner	CO	%	0.543				1.736		
		O_2	%	9.32				4.51		
		Nox	ppm	-				-		
		T	°C	802				952		
		Time		09:45				09:40		
52m	Calciner	CO	%	0.53				2.243		
		O_2	%	10.71				5.35		
		Nox	ppm	-				-		
		T	°C	782				914		
		Time		09:30				09:25		

	Process parameter		AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	279.98	278.85	280.80
	Energy clinker	kJ/kg	5113.52	5067.40	5184.85
	O2 kiln inlet	%	3.42	2.85	3.75
	CO kiln inlet	%	0.01	0.01	0.01
	NO kiln inlet	mg/m³	941.25	775.34	0.01
	Temp. kiln inlet	°C	1159.73	1150.58	1167.71
	Lignite	t/h	4.54	1.10	7.42
	Fluff line 1	t/h	2.67	1.10	5.10
	Waste oil	l/h	1285.40	1258.38	1299.34
	Thermal input	MW	84.48		
Calciner	Calciner temp. set point	°C	916.51	910.30	926.82
	Lignite	t/h	0.00	0.00	0.00
	Fluff	t/h	2.26	1.32	3.33
	Filter press cake (box 1)	t/h	5.73	4.25	7.83
	Iron (box 2)	t/h	4.26	1.79	8.25
	Roofing felt (box 3)	t/h	3.10	2.43	3.78
	EBS-Pellets (box 4)	t/h	5.56	4.69	6.01
	Destrü (box 5)	t/h	5.67	4.69	6.01
	Serox (box 6)	t/h	0.00	0.00	0.00
	VC-Rate	%	60.35	59.54	61.38
	Thermal input	MW	117.76		
Prepol-SC	Prepol exit gas temp.	°C	858.33	839.71	868.92
	Prepol fuel feed	t/h	8.01	6.07	8.81
	Thermal input	MW	33.00		
Cooler	Secondary air temp.	°C	973.81	963.58	982.94
	Tertiary air temp.	°C	205.76	200.00	216.23

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 23: Overview_2 900 °C

Overview 3



Calciner measurement 900 °C

Start time: [redacted] 10:30 12.08.2016 Testo
End time: 12:00 12.08.2016

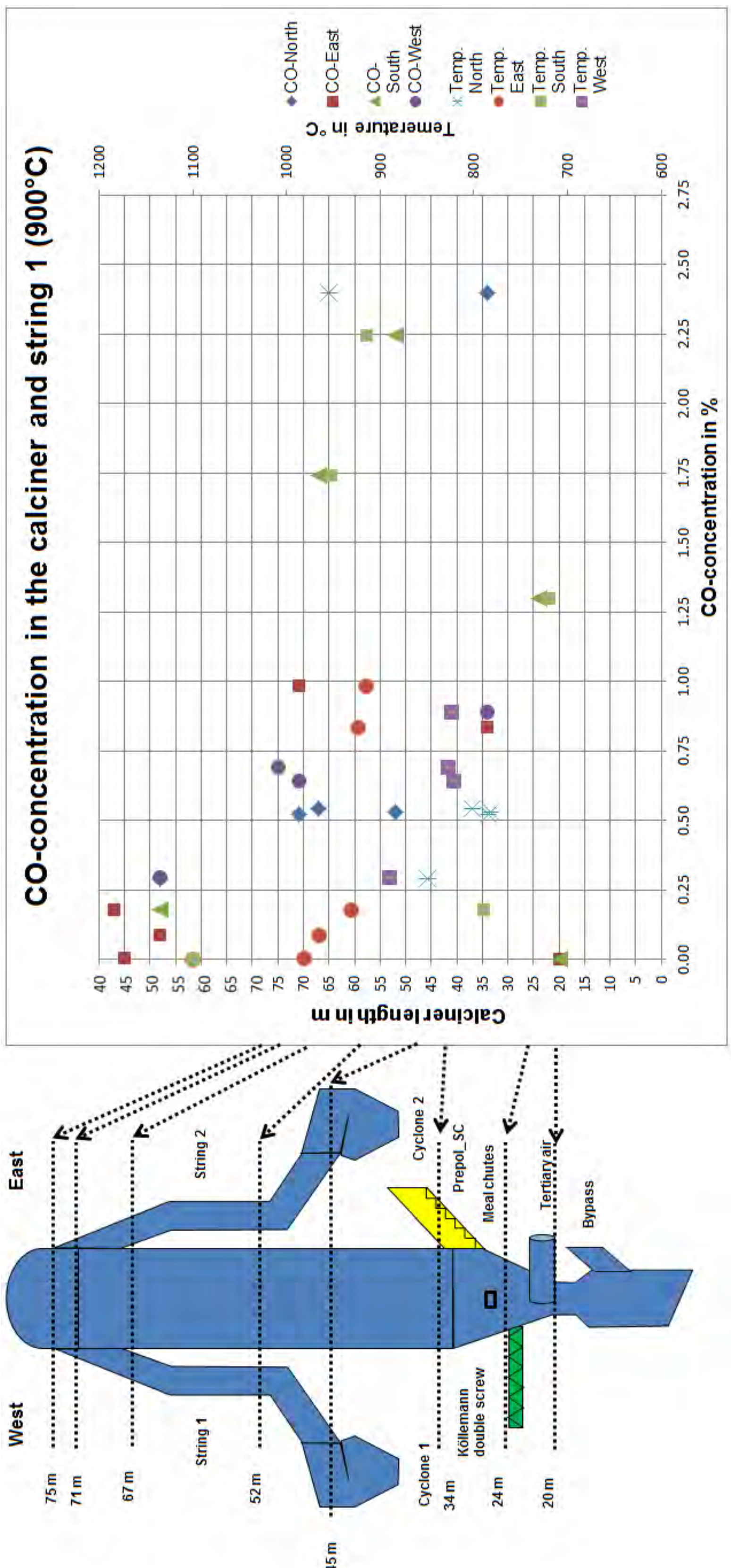
Observer: Markus Berndt, Florian Groß

Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
52m	String 1	CO	%	0.29		0.089		0.179	0.295	
		O_2	%	6.84		6.23		8.25	6.13	
		Nox	ppm	500		468		354	508	
		T	°C	850		965		790	890	
		Time		10:55		11:00		10:45	10:50	
	String 2	CO	%	0.35		0.328		0.026	0.295	
		O_2	%	6.29		7.23		4.17	7.81	
		Nox	ppm	568		523		492	358	
		T	°C	850		850		930	885	
		Time		11:15		11:20		11:25	11:10	
45m	String 1	CO	%			0.005				
		O_2	%			2.59				
		Nox	ppm			794				
		T	°C			980				
		Time				11:55				
	String 2	CO	%						0.013	
		O_2	%						1.33	
		Nox	ppm						349	
		T	°C						1120	
		Time							11:50	
43m	Cyclone 1	CO	%						0.071	
		O_2	%						4.95	
		Nox	ppm						155	
		T	°C						885	
		Time							11:40	
	Cyclone 2	CO	%			0.178				
		O_2	%			5.48				
		Nox	ppm			142				
		T	°C			930				
		Time				11:35				

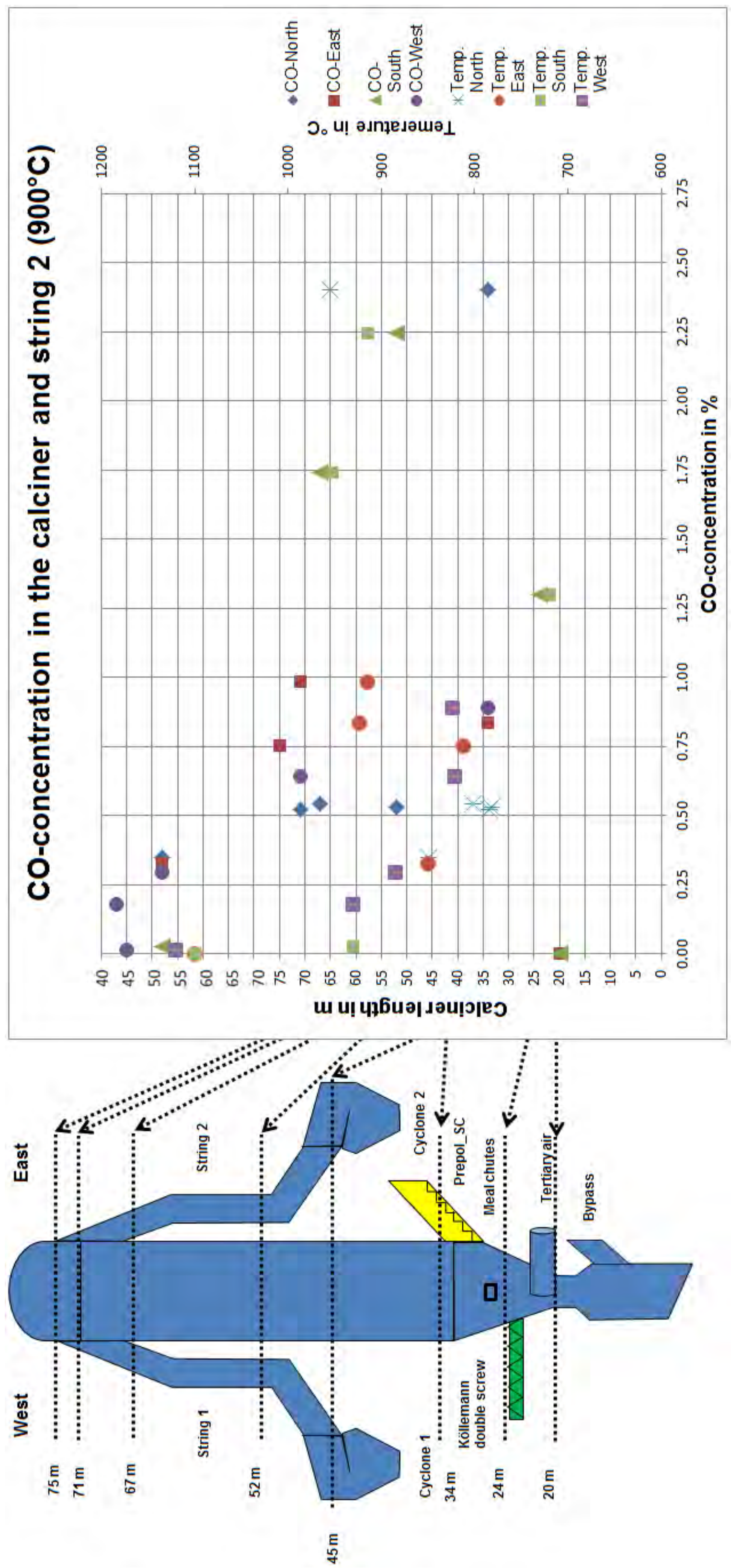
Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	286.81	281.33	289.93
	Energy clinker	kJ/kg	5090.89	5019.81	5195.16
	O2 kiln inlet	%	5.23	4.08	6.02
	CO kiln inlet	%	0.02	0.02	0.03
	NO kiln inlet	mg/m³	781.52	632.81	926.14
	Temperature kiln inlet	°C	1176.36	1172.73	1183.94
	Lignite	t/h	8.14	4.29	11.98
	Fluff line 1	t/h	4.80	0.46	7.95
	Waste oil	l/h	1370.16	1060.74	1498.80
	Thermal input	MW	97.03		
Calciner	Calciner temp. set point	°C	919.45	909.30	931.43
	Lignite	t/h	1.02	0.00	3.85
	Fluff	t/h	6.65	6.09	7.47
	Filter press cake (box 1)	t/h	0.00	0.00	0.00
	Iron (box 2)	t/h	2.51	2.45	2.54
	Roofing felt (box 3)	t/h	2.72	1.61	3.10
	EBS-Pellets (box 4)	t/h	4.77	2.84	7.03
	Destrü (box 5)	t/h	2.92	5.17	0.00
	Serox (box 6)	t/h	6.02	5.92	6.08
	VC-Rate	%	61.19	58.00	64.78
	Thermal input	MW	102.49		
Prepol-SC	Prepol exit gas temp.	°C	880.93	864.99	891.04
	Prepol fuel feed	t/h	8.04	6.90	9.84
	Thermal input	MW	33.79		
Cooler	Secondary air temp.	°C	938.90	925.85	952.75
	Tertiary air temp.	°C	591.02	542.80	615.13

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

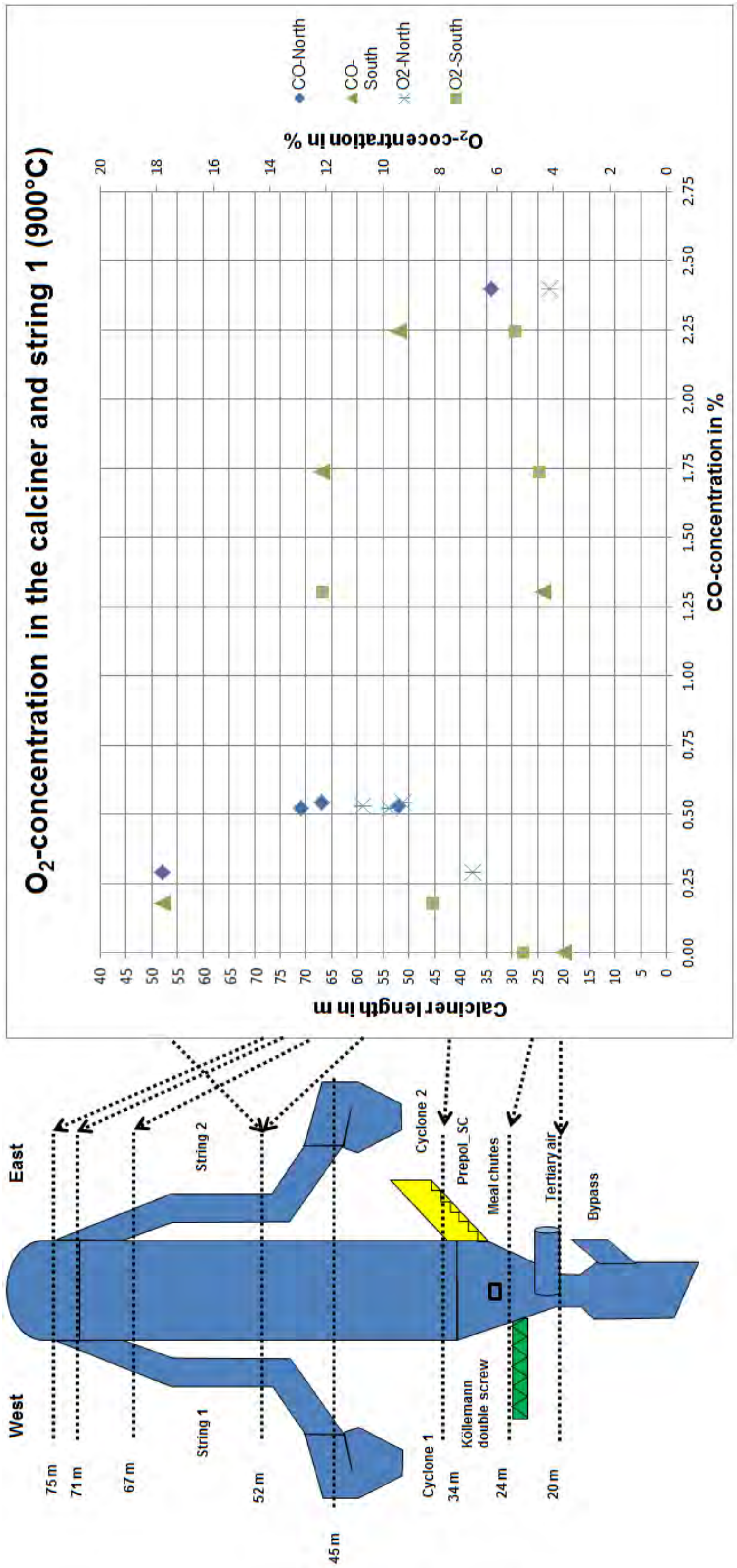
Appendix 24: Overview_3 900 °C



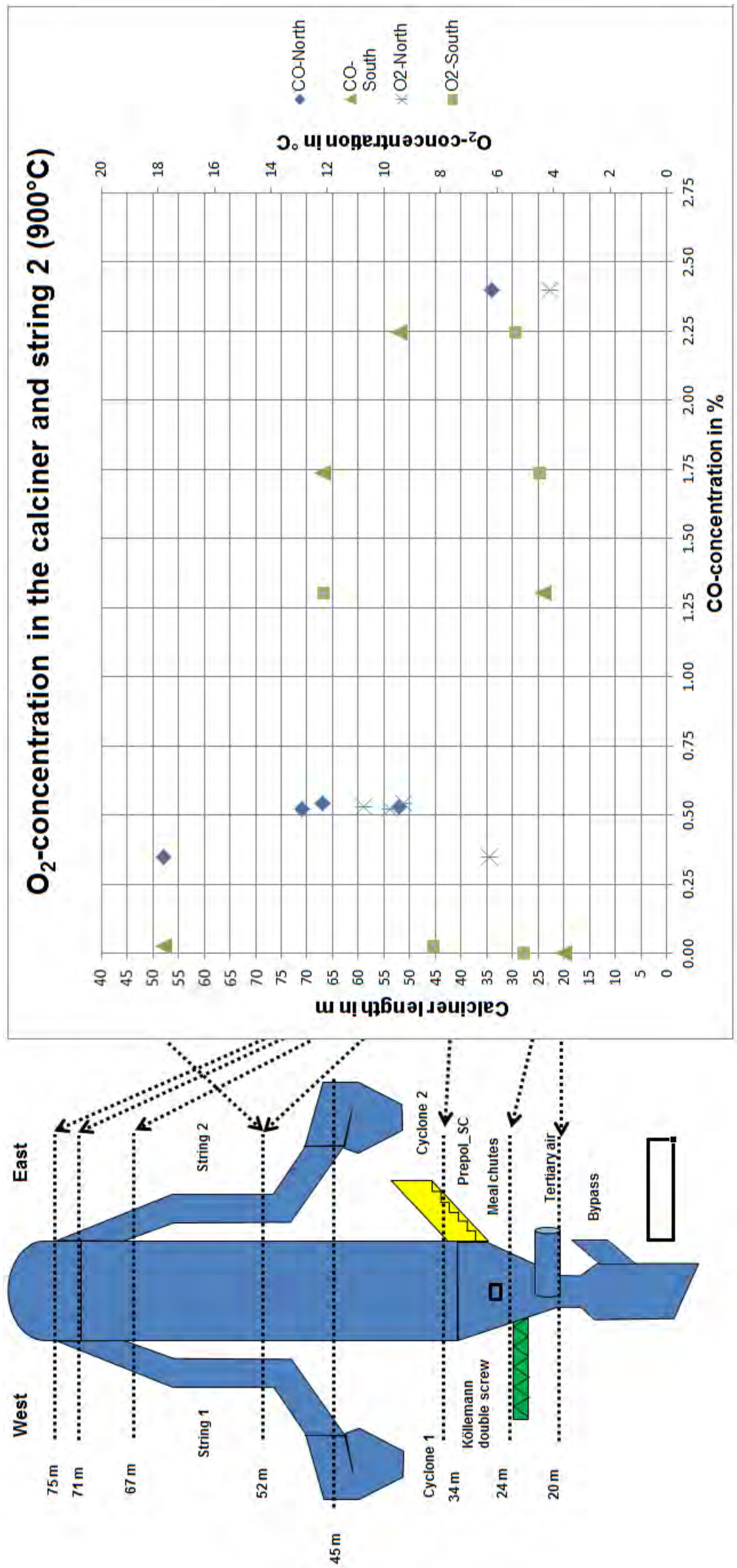
Appendix 25: CO-concentration string 1 (900 °C)



Appendix 26: CO-concentration string 2 (900 °C)

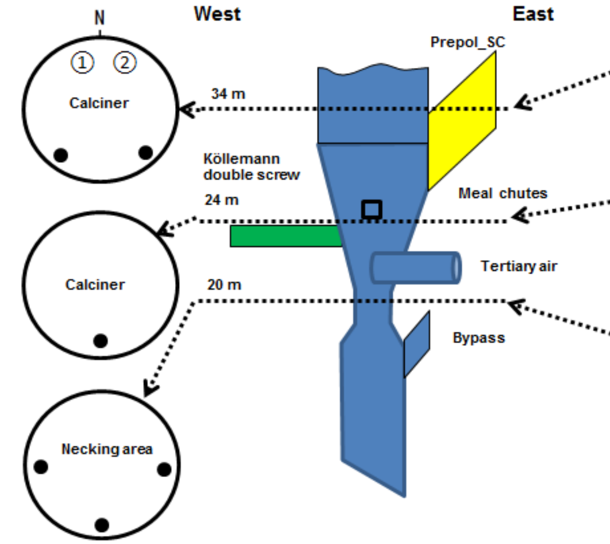


Appendix 27: O2-concentration string 1 (900 °C)



Appendix 28: O2-concentration string 2 (900°C)

Overview 1



Calciner measurement 890 °C

Start time: 10:45 16.09.2016 Testo 350

End time: 11:25 16.09.2016

Observer: Markus Berndt, Florian Groß

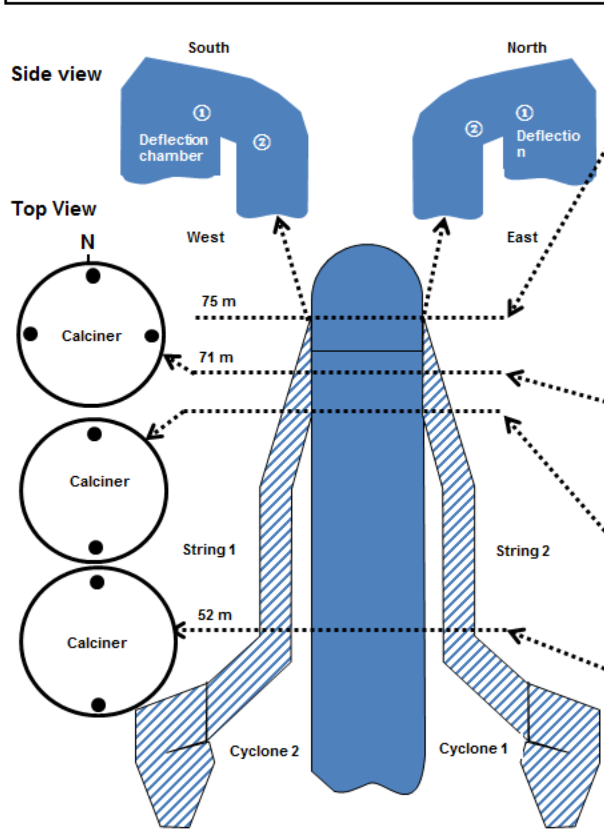
Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
34m	Calciner	CO	%	0.71	0.82	2.55			1.93	
		O_2	%	10:23	10.78	5.68			8.03	
		Nox	ppm	-	-	-			-	
		T	°C	880	911	926			958	
		Time		11:19	11:22	11:25			11:15	
24m	Calciner	CO	%					2.24		
		O_2	%					12.52		
		Nox	ppm					-		
		T	°C					710		
		Time						11:06		
20m	Calciner	CO	%			0.03		0.01	0.01	
		O_2	%			8.39		7.41	13.71	
		Nox	ppm			-		-	-	
		T	°C			1100		1100	1040	
		Time				10:59		10:55	10:47	

Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	285.79	270.26	290.36
	Energy clinker	kJ/kg	4753.11	4652.87	4824.79
	O2 kiln inlet	%	5.30	4.44	6.17
	CO kiln inlet	%	0.02	0.01	0.05
	NO kiln inlet	mg/m³	1473.83	1156.01	1858.48
	Temperature kiln inlet	°C	1201.93	1176.93	1230.68
	Lignite	t/h	11.92	11.40	12.82
	Fluff line 1	t/h	0.00	0.00	0.00
	Waste oil	l/h	1385.00	348.39	1595.12
	Thermal input	MW		87.87	
Calciner	Calciner temp. set point	°C	924.45	910.93	930.80
	Lignite	t/h	3.46	1.58	5.90
	Fluff	t/h	0.00	0.00	0.00
	Filter press cake (box 1)	t/h	6.69	4.01	7.28
	Iron (box 2)	t/h	2.80	2.65	2.84
	Roofing felt (box 3)	t/h	3.62	3.61	3.65
	EBS-Pellets (box 4)	t/h	4.20	0.99	5.99
	Destrü (box 5)	t/h	4.99	4.98	5.00
	Serox (box 6)	t/h	0.00	0.00	0.00
	VC-Rate	%	58.95	57.62	60.25
	Thermal input	MW		90.65	
Prepol-SC	Prepol exit gas temp.	°C	875.88	832.90	915.51
	Prepol fuel feed	t/h	8.83	7.88	9.27
	Thermal input	MW		46.74	
Cooler	Secondary air temp.	°C	890.94	856.74	914.00
	Tertiary air temp.	°C	693.79	664.44	720.94

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 29: Overview_1 890 °C

Overview 2



Calciner measurement 890 °C

Start time: 11:40 15.09.2016 Testo 350
End time: 12:40 15.09.2016

Observer: Markus Berndt, Florian Groß

Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
75m	String 1	CO	%						0.5	0.43
		O_2	%						9.61	10.24
		Nox	ppm						-	-
		T	°C						1004	1002
		Time							12:31	12:39
	String 2	CO	%			0.42	0.38			
		O_2	%			7.06	8.99			
		Nox	ppm			-	-			
		T	°C			952	993			
		Time				12:18	12:26			
71m	Calciner	CO	%	0.35		0.37			0.56	
		O_2	%	8.99		6.47			4.46	
		Nox	ppm	-		-			-	
		T	°C	931		927			974	
		Time		12:05		12:00			12:08	
67m	Calciner	CO	%	0.86				0.25		
		O_2	%	9.41				8.41		
		Nox	ppm	-				-		
		T	°C	922				1040		
		Time		11:54				11:48		
52m	Calciner	CO	%	2.22				2.65		
		O_2	%	9.81				2.91		
		Nox	ppm	-				-		
		T	°C	865				934		
		Time		11:43				11:38		

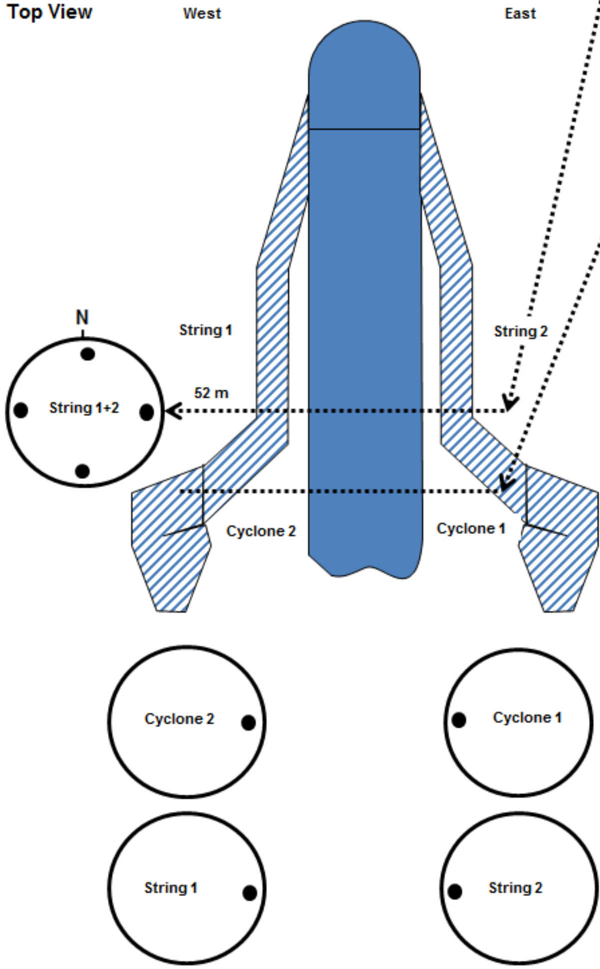
	Process parameter		AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	285.79	270.26	290.36
	Energy clinker	kJ/kg	4753.11	4652.87	4824.79
	O2 kiln inlet	%	5.30	4.44	6.17
	CO kiln inlet	%	0.02	0.01	0.05
	NO kiln inlet	mg/m³	1473.83	1156.01	1858.48
	Temp. kiln inlet	°C	1201.93	1176.93	1230.68
	Lignite	t/h	11.92	11.40	12.82
	Fluff line 1	t/h	0.00	0.00	0.00
	Waste oil	l/h	1385.00	348.39	1595.12
	Thermal input	MW	87.87		
Calciner	Calciner temp. set point	°C	924.45	910.93	930.80
	Lignite	t/h	3.46	1.58	5.90
	Fluff	t/h	0.00	0.00	0.00
	Filter press cake (box 1)	t/h	6.69	4.01	7.28
	Iron (box 2)	t/h	2.80	2.65	2.84
	Roofing felt (box 3)	t/h	3.62	3.61	3.65
	EBS-Pellets (box 4)	t/h	4.20	0.99	5.99
	Destrü (box 5)	t/h	4.99	4.98	5.00
	Serox (box 6)	t/h	0.00	0.00	0.00
	VC-Rate	%	58.95	57.62	60.25
	Thermal input	MW	90.65		
Prepol-SC	Prepol exit gas temp.	°C	875.88	832.90	915.51
	Prepol fuel feed	t/h	8.83	7.88	9.27
	Thermal input	MW	46.74		
Cooler	Secondary air temp.	°C	890.94	856.74	914.00
	Tertiary air temp.	°C	693.79	664.44	720.94

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

Appendix 30: Overview_2 890 °C

Overview 3

Top View



Calciner measurement 890 °C

Start time: [redacted] 14:00 15.09.2016 Testo 350
End time: 15:00 15.09.2016

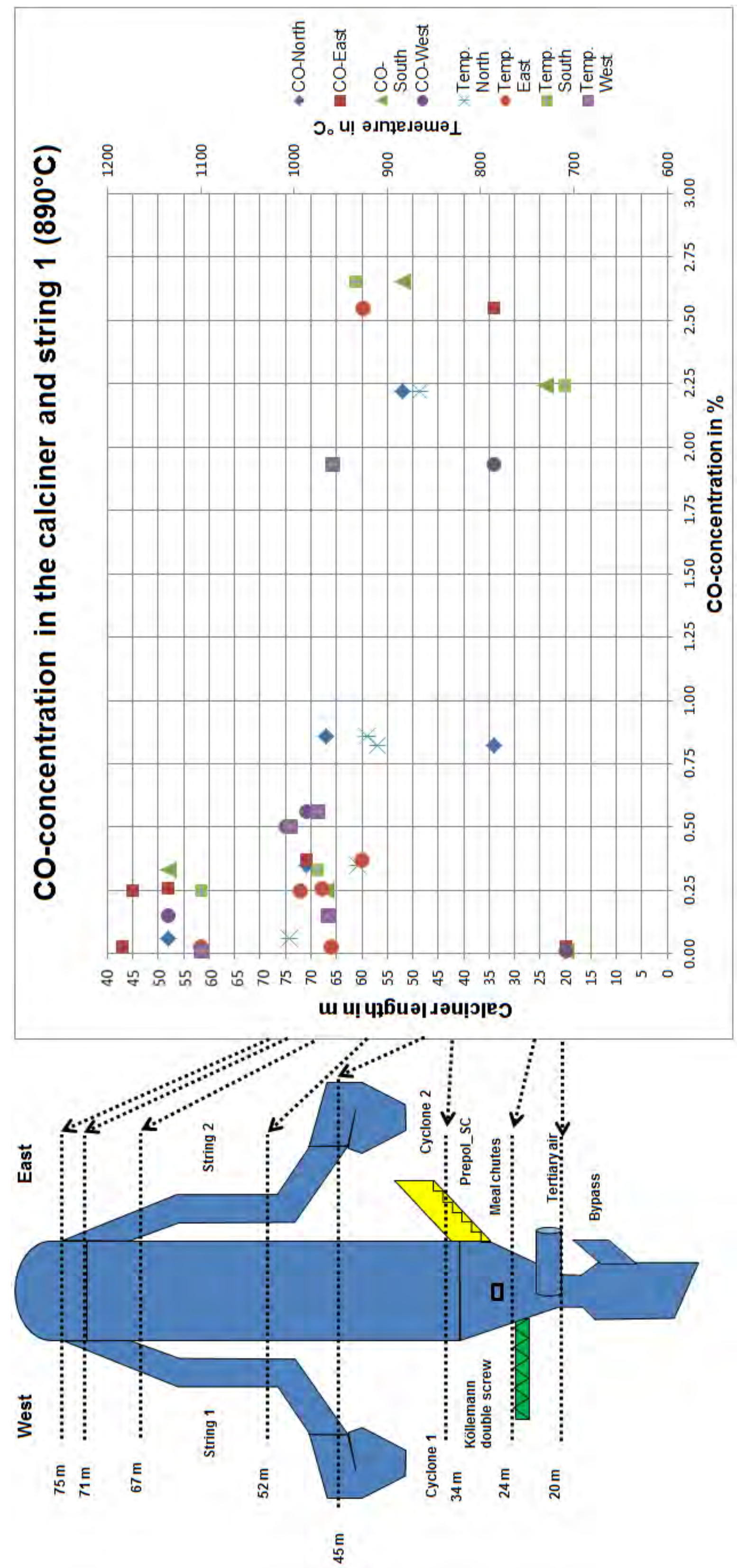
Observer: Markus Berndt, Florian Groß

Level			Unit	North ①	North ②	East ①	East ②	South ①	West ①	West ②
52m	String 1	CO	%	0.06		0.26		0.33	0.15	
		O_2	%	6.7		5.88		4.83	6.43	
		Nox	ppm	-		-		-	-	
		T	°C	1005		970		975	964	
		Time		14:28		14:16		14:20	14:24	
	String 2	CO	%	0.46		0.35		0.05	0.06	
		O_2	%	5.61		5.39		5.5	6.01	
		Nox	ppm	-		-		-	-	
		T	°C	835		990		1040	960	
		Time		14:02		14:08		13:54	13:58	
45m	String 1	CO	%			0.25				
		O_2	%			5.08				
		Nox	ppm			-				
		T	°C			993				
		Time				14:58				
	String 2	CO	%						0.03	
		O_2	%						5.14	
		Nox	ppm						-	
		T	°C						971	
		Time							14:55	
43m	Cyclone 1	CO	%						5.74	
		O_2	%						5.14	
		Nox	ppm						-	
		T	°C						920	
		Time							14:47	
	Cyclone 2	CO	%			0.03				
		O_2	%			6.56				
		Nox	ppm			-				
		T	°C			969				
		Time				14:42				

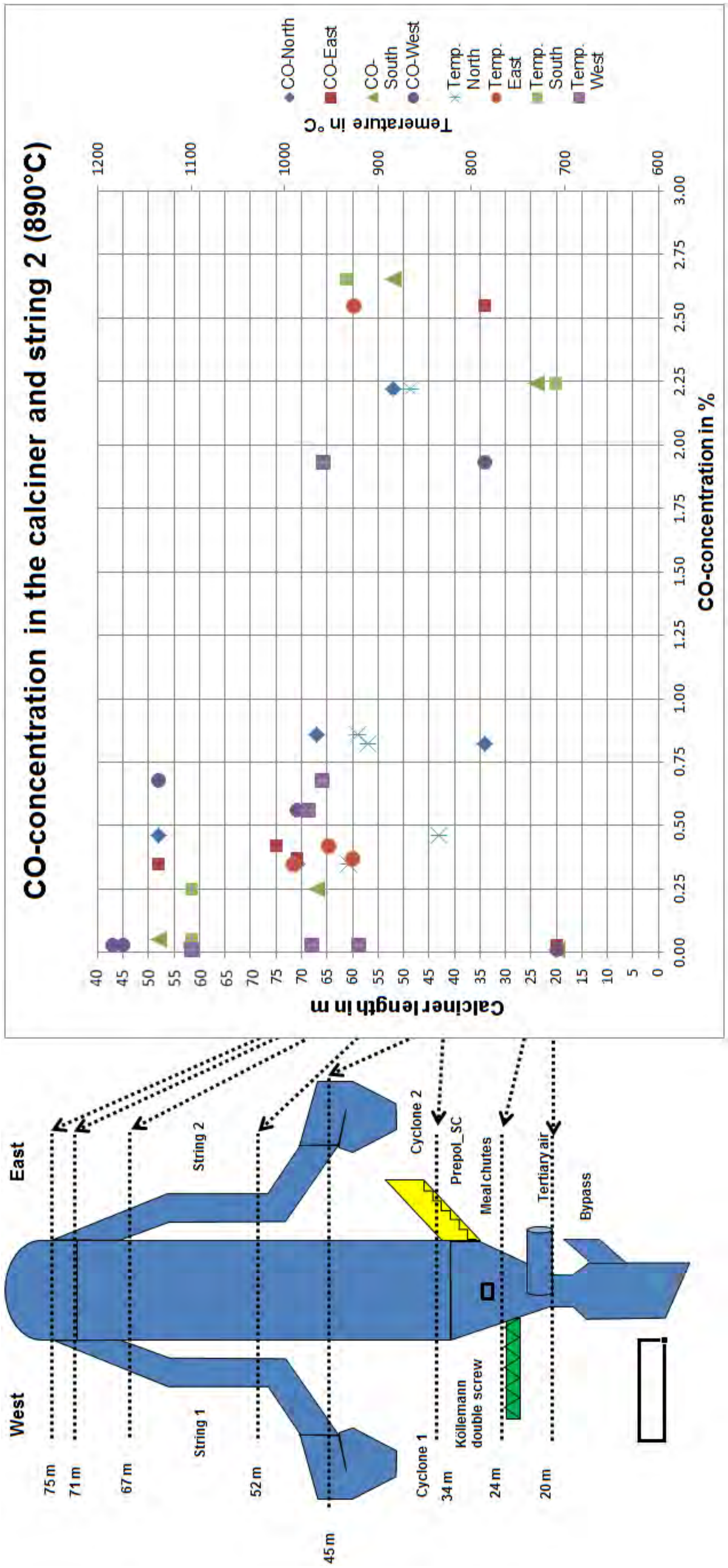
Process parameter			AVG TIS	Min.	Max.
Kiln	Filter cake	t/h	285.79	270.26	290.36
	Energy clinker	kJ/kg	4753.11	4652.87	4824.79
	O2 kiln inlet	%	5.30	4.44	6.17
	CO kiln inlet	%	0.02	0.01	0.05
	NO kiln inlet	mg/m³	1473.83	1156.01	1858.48
	Temperature kiln inlet	°C	1201.93	1176.93	1230.68
	Lignite	t/h	11.92	11.40	12.82
	Fluff line 1	t/h	0.00	0.00	0.00
	Waste oil	l/h	1385.00	348.39	1595.12
	Thermal input	MW		87.87	
Calciner	Calciner temp. set point	°C	924.45	910.93	930.80
	Lignite	t/h	3.46	1.58	5.90
	Fluff	t/h	0.00	0.00	0.00
	Filter press cake (box 1)	t/h	6.69	4.01	7.28
	Iron (box 2)	t/h	2.80	2.65	2.84
	Roofing felt (box 3)	t/h	3.62	3.61	3.65
	EBS-Pellets (box 4)	t/h	4.20	0.99	5.99
	Destrü (box 5)	t/h	4.99	4.98	5.00
	Serox (box 6)	t/h	0.00	0.00	0.00
	VC-Rate	%	58.95	57.62	60.25
	Thermal input	MW		90.65	
Prepol-SC	Prepol exit gas temp.	°C	875.88	832.90	915.51
	Prepol fuel feed	t/h	8.83	7.88	9.27
	Thermal input	MW		46.74	
Cooler	Secondary air temp.	°C	890.94	856.74	914.00
	Tertiary air temp.	°C	693.79	664.44	720.94

CO-content	Priority
0.5 - 0.99	MAX 1
1.0 - 1.49	MAX 2
1.5 - 1.79	MAX 3
1.8 - 1.99	MAX 4
> 2.0	MAX 5

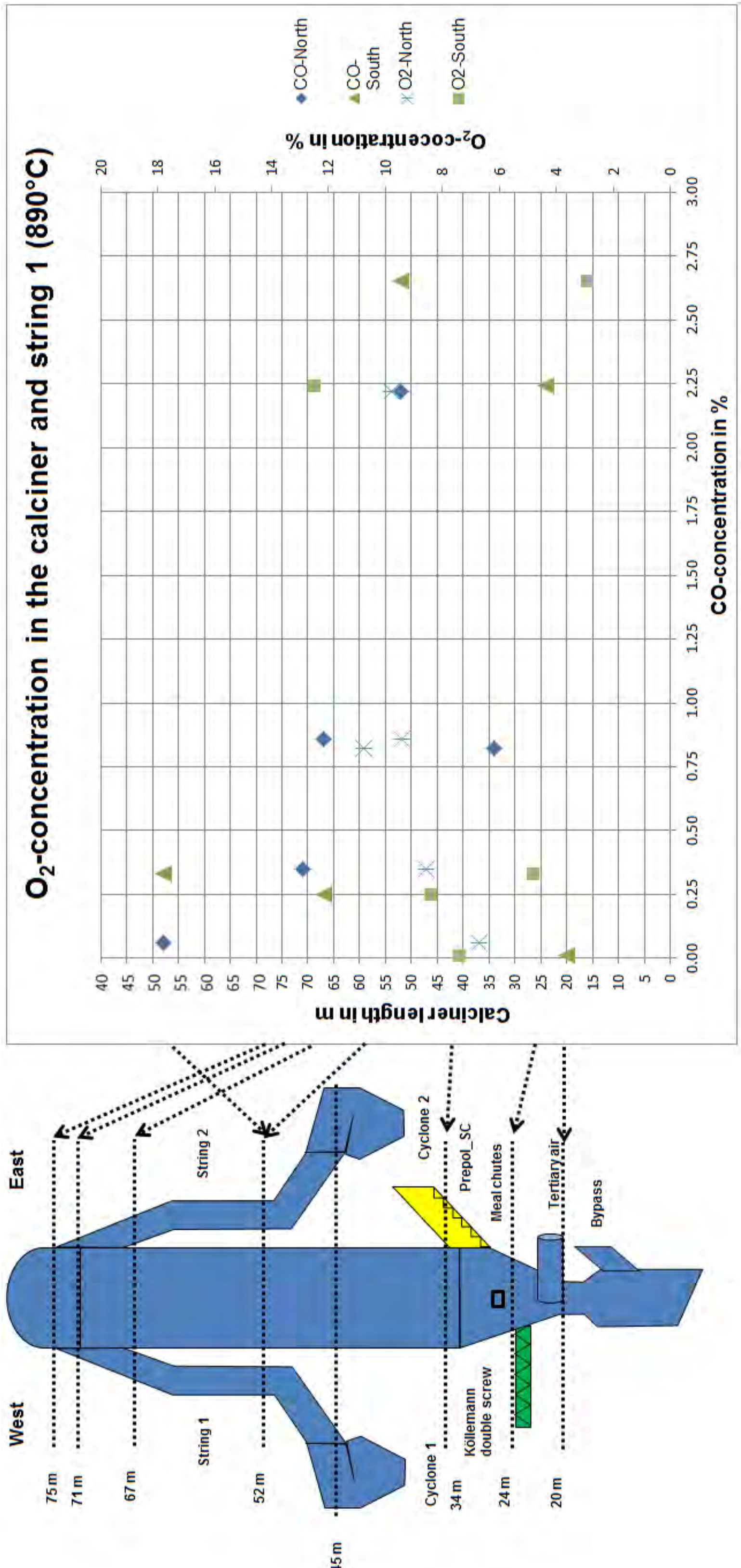
Appendix 31: Overview_3 890 °C



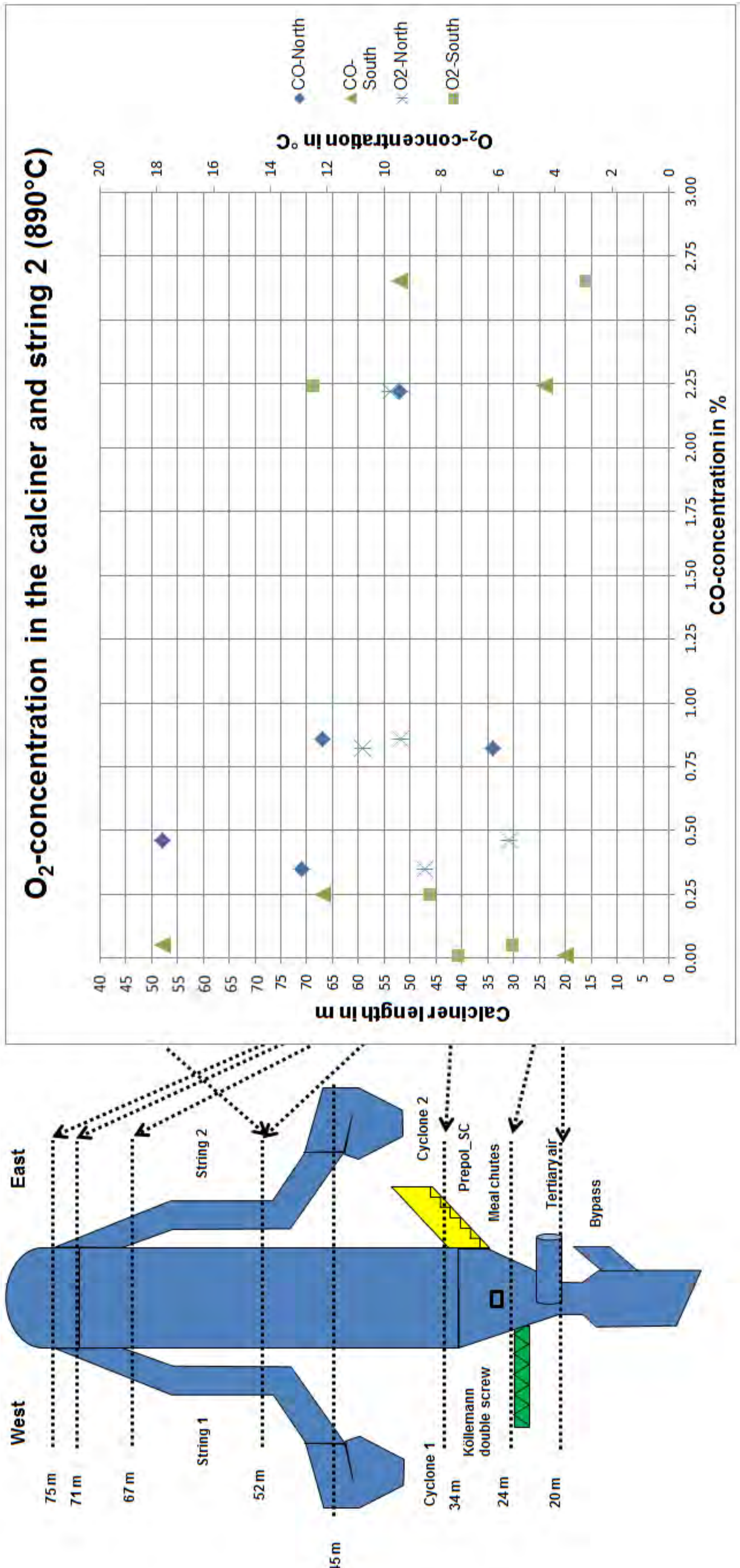
Appendix 32: CO-concentration string 1 (890 °C)



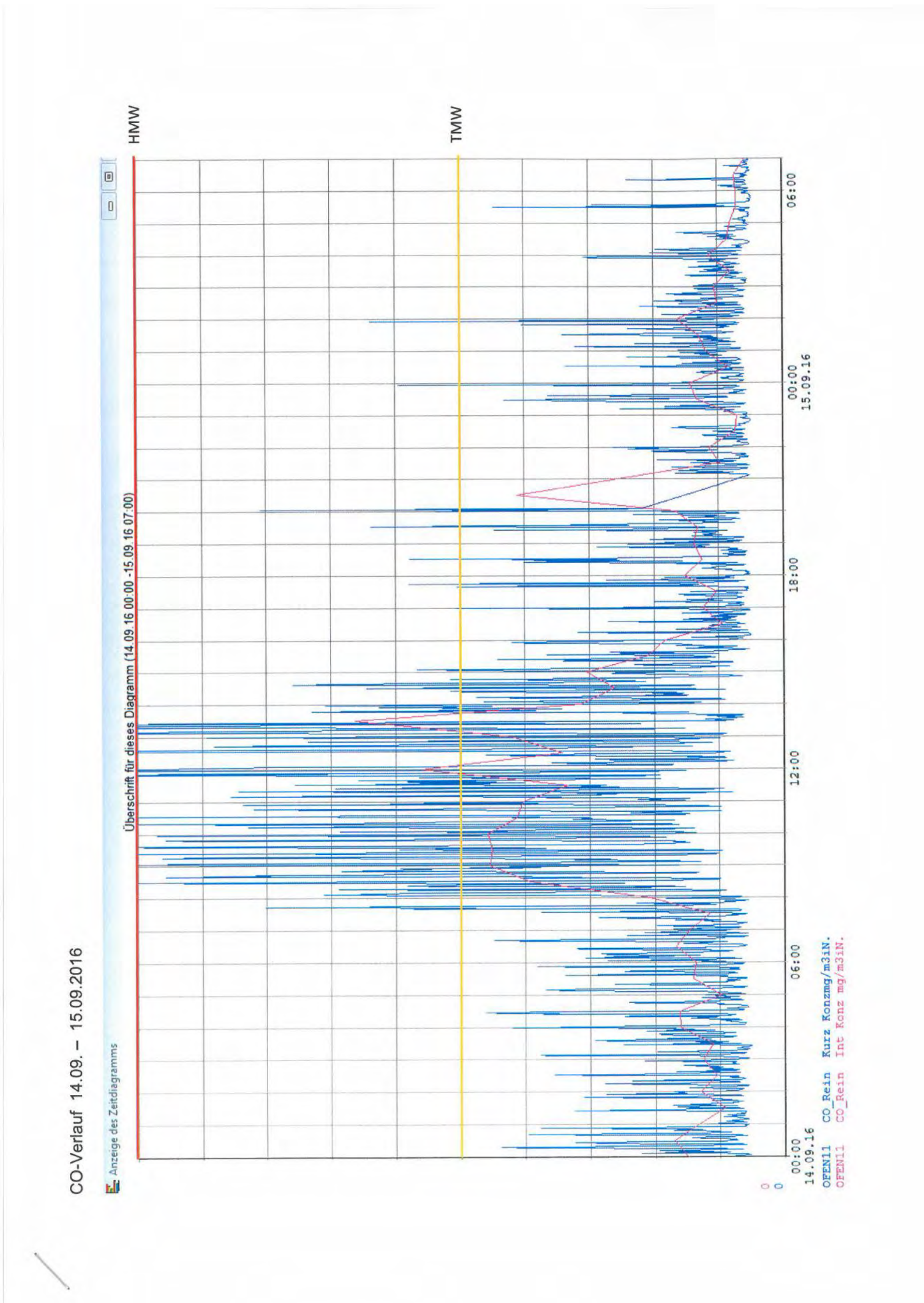
Appendix 33: CO-concentration string 2 (890 °C)



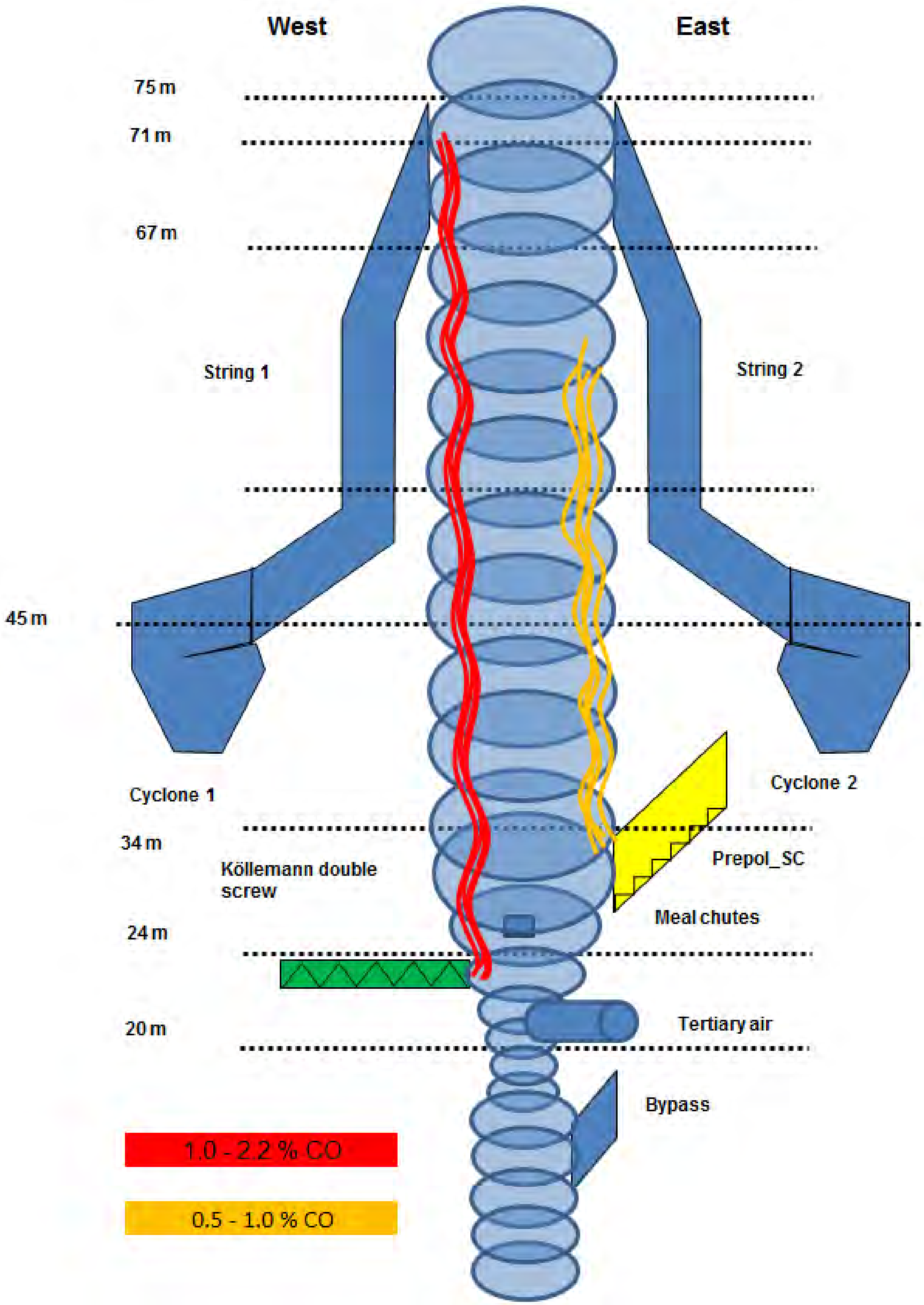
Appendix 34: O2-concentration string 1 (890 °C)



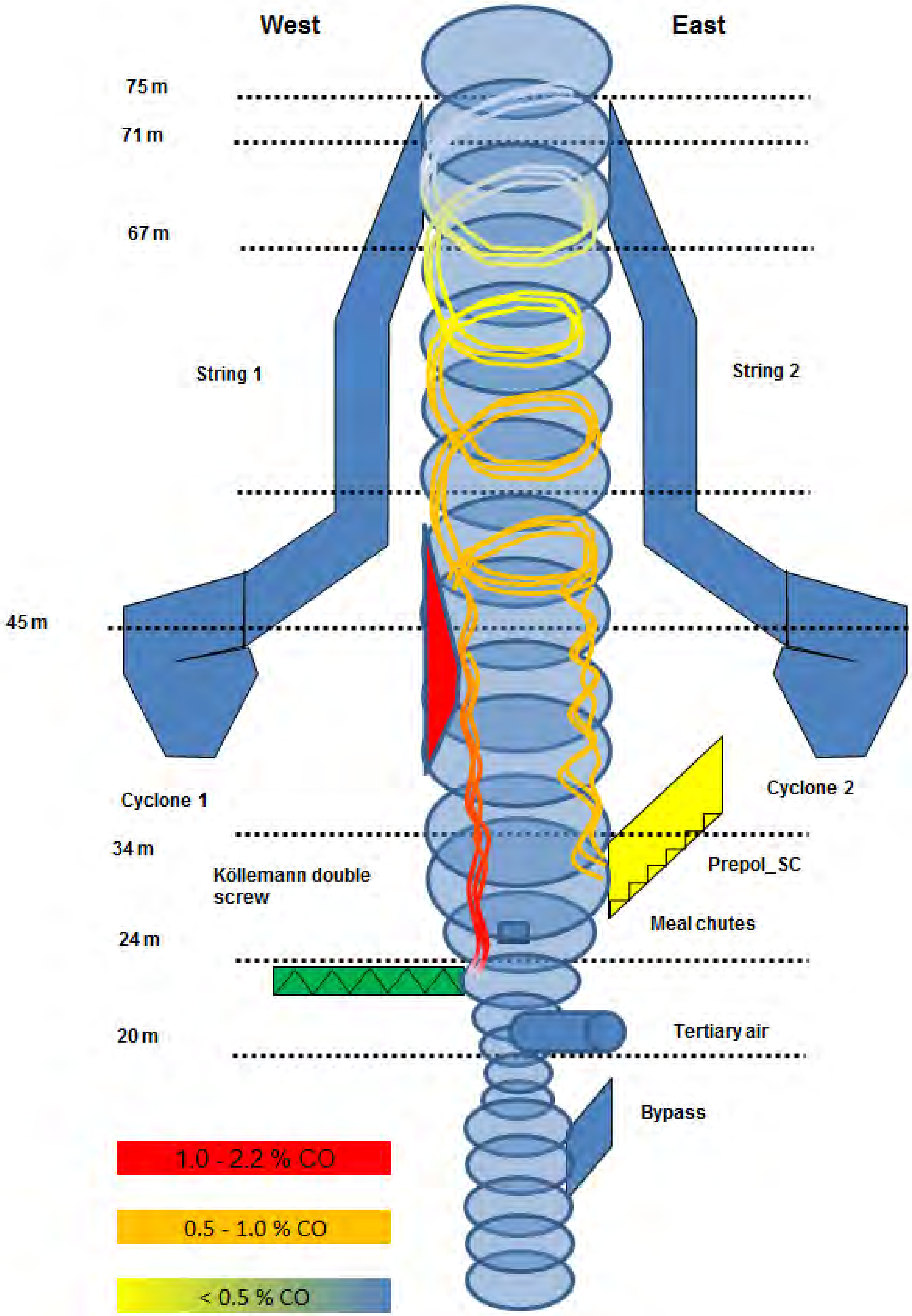
Appendix 35: O2-concentration string 2 (890 °C)



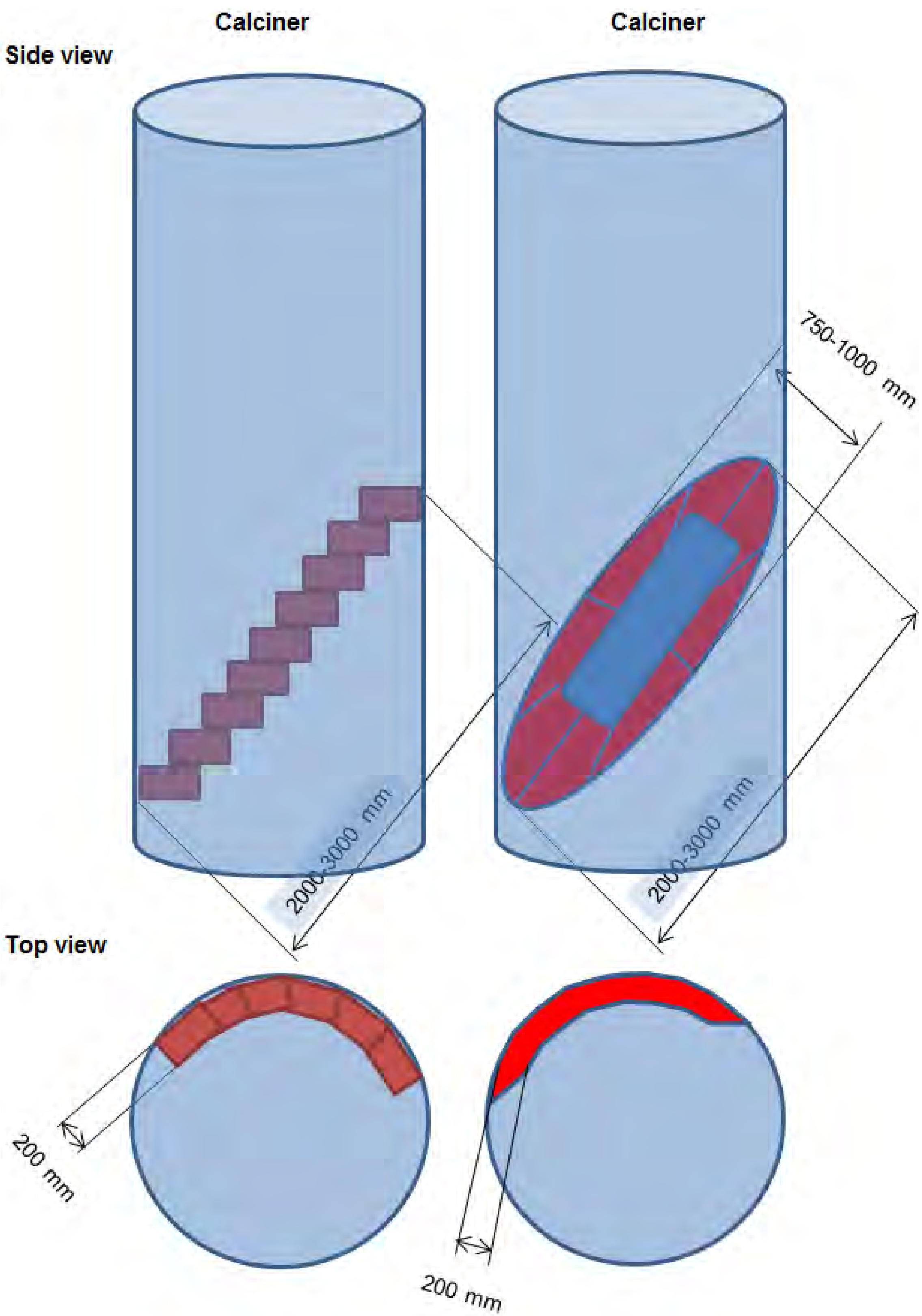
Appendix 36: CO-course (14.09 - 15.09.2016)



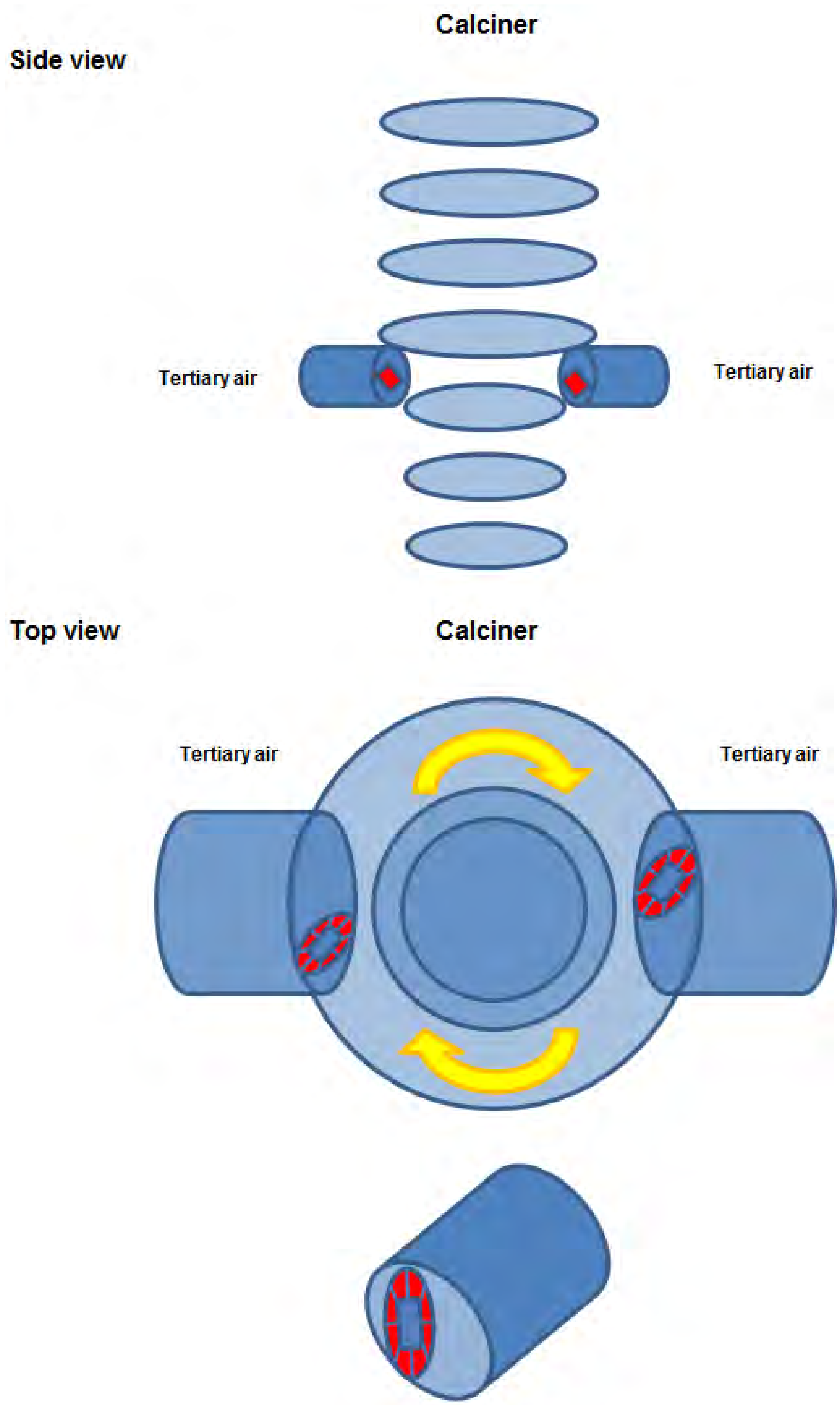
Appendix 37: Schematical demonstration of CO stratifications in the calciner



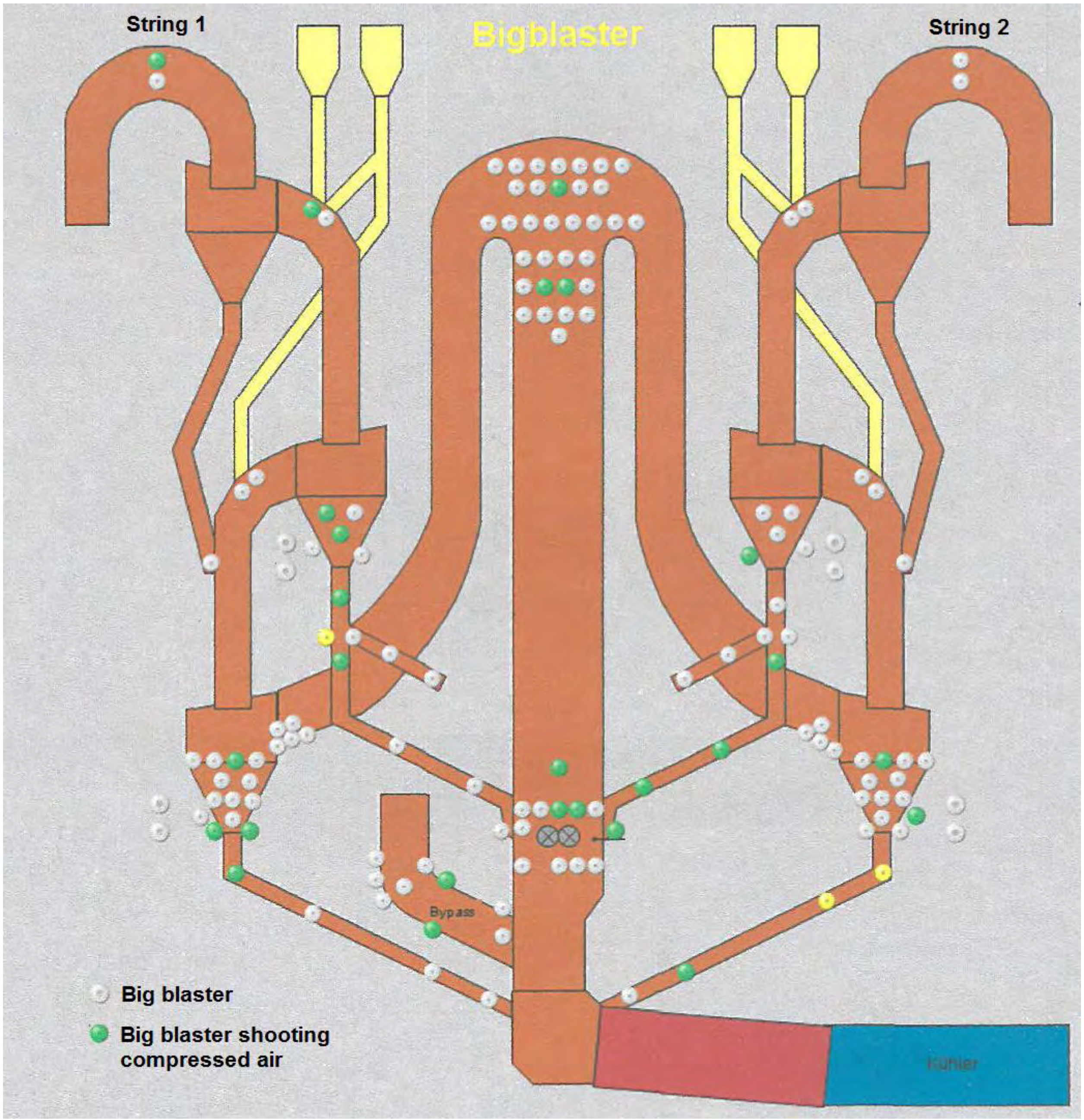
Appendix 38: Modifications in the calciner



Appendix 39: Two possible modifications



Appendix 40: Modification of tertiary air



Appendix 41: Overview of the big blasters at the calciner