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FINAL EVALUATION OF THE ULCOS TGR-BF PILOT TESTS PERFORMED AT THE LKAB EXPERIMENTAL BLAST FURNACE[1]

Pettersson Mikael[2]
Sikström Peter[3]
Eklund Nicklas[4]

Abstract

The LKAB Experimental Blast furnace, situated in Luleå, Sweden was first operated in 1998. Since then, a large number of varying projects have been completed at the Experimental Blast Furnace. One of the projects that recently have been finalized is the Ulcos-BF pilot tests, using the developed blast furnace concept. Ulcos – Ultra Low CO_2 Steelmaking – is a project consisting of 48 companies and organizations from a total of 15 European countries. All of the major European steel producers are represented within the project. The aim of the project has since the start been to develop new technologies for steel production, in order to reduce emissions of CO_2 by at least 50% from today's best known steel making routes. During 2007, the first campaign within the Ulcos project was conducted. Since then, a total of 3 campaigns, have been successfully operated using the Ulcos-BF process. With the experiences gained during the tests at the Experimental Blast Furnace, the Ulcos-BF process is now planned to be scaled-up to an industrial scale. This paper gives a summary of the experiences and results gained within the Ulcos project from 2007 until 2010, while operating different versions of the Ulcos-BF process. The paper also describes the method of planning, conducting, evaluating and finally scaling up results from a successful project into a commercial demonstration plant.

Key words: LKAB; Experimental blast furnace; Ulcos; CO_2.

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[2] Senior metallurgist, Technical customer services, Marketing and Logistics, LKAB, Sweden.
[3] General Manager, Technical customer services, Marketing and Logistics LKAB, Sweden.
[4] Manager, Ironmaking, Research and Development, LKAB, Sweden.

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1 INTRODUCTION

Over the last 50 years major efforts have been made to improve blast furnace technology, as well as to increase the blast furnace efficiency. Better raw material qualities for pellet, sinter and coke together with injection of varying materials have all led to an improved and more efficient blast furnace process.
However, the blast furnace is still the main producer of CO_2 within an integrated steel plant. The need of carbon for reduction of iron ore makes CO_2 emissions inevitable from the blast furnace process of today. Carbon dioxide is recognized to be one of the main greenhouse gases, contributing to global warming. Analysis show that the concentration of CO_2 in the atmosphere is now higher than in any time during the last 650 000 years [1]. The large increase of CO_2 concentration in the atmosphere has mainly occurred during the industrial time and is explained by National Oceanic and Atmospheric Administration's (NOAA) to be caused by human activities. In figure 1, the change of CO_2 concentration in the atmosphere can be seen. The increase since pre-industrial time is calculated to 36%. Measurements performed at the Mauna Loa observatory on Hawaii show that the average yearly increase of CO_2 concentration is 2,07 ppm/year [2] during 2002 until 2011. The rate of increase has doubled compared to what was observed during the 1960s The CO_2 concentration for February 2012 was measured to 394 ppm[3].

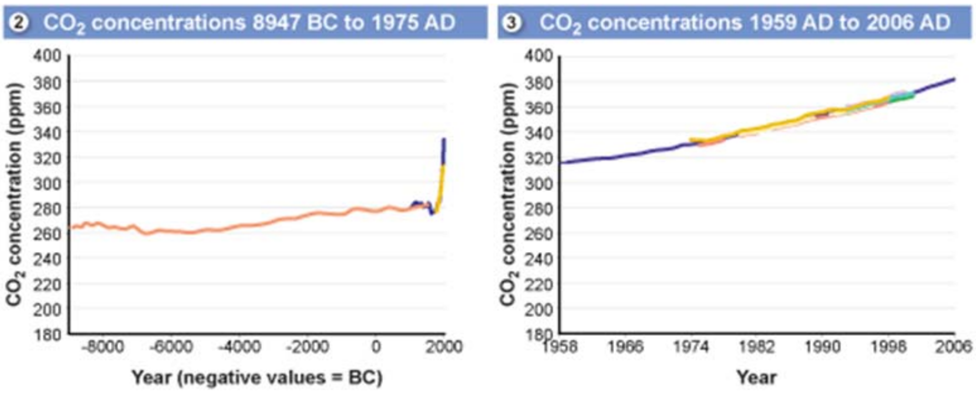

Figure 1. Atmospheric Concentrations of CO2 in Geological Time and in Recent Years [1].

Although, the blast furnace process has been improved and the need for reductants almost reduced by half, from 1000kg/tHM to approximately 500kg/tHM, the concern regarding emission of CO_2 still remains. Calculations show that the efficiency of a well operated blast furnace is now only 5% above what is according to thermodynamically limits possible to reach [4]. This means that it is not expected to reach any significant carbon savings or reduced CO_2 emissions using the blast furnace process as it is operated today. In order to meet the demand for a breakthrough technology, able to further improve the carbon savings and also drastically reduce the CO_2 emissions from the steel making process, the ULCOS project was launched in 2004.

2 ULCOS PROJECT

Ultra Low CO_2 Steelmaking i.e. the ULCOS program was started in 2004, as an answer to the challenges rose especially by EU and European national levels. The target was to develop one or several process routes in order to reduce the emissions of CO_2 by at least 50% from the best steel making technologies known today[5].

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The ULCOS consortium consisted originally of 48 European companies where LKAB was taking part as the only iron ore producer. Companies from a total 15 different countries launched this cooperative research and development initiative in order to reach the target that was set. The project was financially supported by the ULCOS Consortium, involving the major European steel producers (ArcelorMittal, Tata Steel, Thyssen-Krupp Steel, voestalpine, RIVA, SSAB, Ruukki, Saarstahl and Dillinger Hüttenwerke) and LKAB, and by the European Union.
The first step in the project was to identify processes that could meet the requested results and also determine if they could be scaled up to a commercial size. During 2004-2006, a large number of possible process routes were evaluated and finally a short list with promising processes was created. The four most promising processes where chosen for further and more detailed studies. One of the chosen paths was the ULCOS blast furnace concept, ULCOS-BF.

2.1 ULCOS-BF Concept

During the evaluation of possible processes using blast furnace technology for steel making, the recycling of decarbonated top gas was found to be the most promising one in order to operate a blast furnace with very low CO_2 emissions. Recycling carbon monoxide and hydrogen to the furnace as a reducing agent would decrease the need of fossil coal while at the same time capturing CO_2 for storage could result in reduced CO_2 emissions by at least 50% per ton produced steel. This process path was decided to be tested in the LKAB Experimental Blast Furnace.
The process using recycled hot reducing gas to the blast furnace had been tested earlier. The most recent tests were performed in Russia during 1985-1990[6]. Also earlier ideas regarding circulation of top gas to the blast furnace had been described as early as the 1920´s[6].
The tests at Toulachermet, were conducted during a total of 13 campaigns[7]. The process involved recycling of top gas that first was treated using chemical adsorption in order to remove CO_2. The cleaned reducing gas was then heated in hot stoves before being injected through the tuyeres were it replaced the normal hot blast. During the trials, 250 000 ton of hot metal was produced and the coke rate was reduced from 606 to 367 kg/tHM. Also a productivity increase of 27,3% could be obtained during the tests and approximately 1700 tonnes of hot metal was produced daily. The silicon content in hot metal was also lowered from 2,6% for the reference case down to 2,2% during the recirculation tests.
During the period of evaluating process routes for the ULCOS blast furnace, four different recirculation processes were assessed. The three versions resulting in the highest calculated carbon savings were decided to be tested in pilot scale. The versions are hereafter referred to as version 1, 3 and 4. Version 2 was abandoned due to the lower calculated carbon savings. The first test was scheduled for the autumn 2007, and the place chosen for this was the LKAB Experimental Blast Furnace in Luleå.

2.2 LKAB Experimental Blast Furnace

In 1994, a feasibility study was started at LKAB to evaluate the possibility to build an Experimental Blast Furnace [8]. An intermediate step between laboratory and full-scale tests was needed when developing new blast furnace pellets. Testing new materials in a blast furnace not specifically used for hot metal production would also

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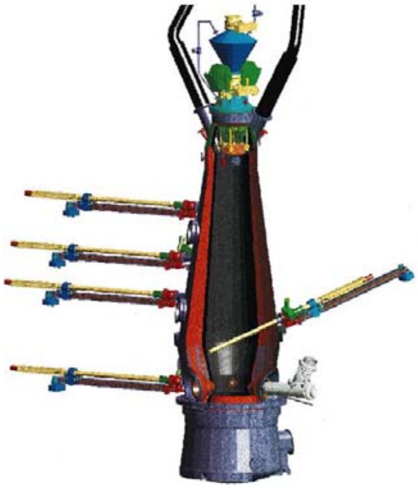
allow tests that one would not dare to perform in a production furnace. In October 1996, the decision was taken by the board of directors to build the equipment and in 1998, the first two campaigns were conducted testing new types of pellets. Until today, a total of 28 campaigns have been performed with individual lengths of 6-10 weeks each.



Technical data of the EBF

Working volume:	9m^3
Hearth diameter:	1,4m
Working height:	6m
Number of tuyeres:	3
Max. Top pressure:	1,5barG
Blast temp.:	1250°C
Blast rate:	1700Nm^3/h
Fuel rate:	~530 kg/tHM
Normal prod:	36 tHM/day

Figure 2. LKAB Experimental Blast Furnace.

The Experimental Blast furnace has significantly contributed to the development of new and improved blast furnace pellets as well as optimization of the burden structure. Also new blast furnace technologies have been developed and tested at the Experimental Blast Furnace.
The Experimental Blast furnace is equipped to handle different types of injection also simultaneously. Gas, coal, oil and fluxes can be injected individually or at the same time. The charging equipment is of a no-bell type. This allows for very accurate charging patterns where the burden materials can be charged in one or different rings.
The possibility to stop and quench the blast furnace quickly makes it possible to evaluate different burdens from the top of the blast furnace to the hearth. Normally, more than 3000 samples of the burden are taken during an excavation at the Experimental blast furnace.

2.3 Planning of the ULCOS campaigns

During the planning of the ULCOS-BF trails, three different types of processes were decided to be tested. All of the processes included the injection of a decarbonated top gas. The position of injection and temperature of the gas varied for the different versions. The different types of blast furnace processes can be seen in Figures 3 to 5.

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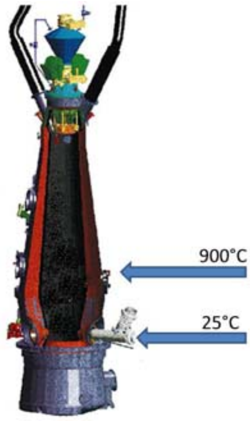

Figure 3. Version 1.

Figure 4. Version 3.

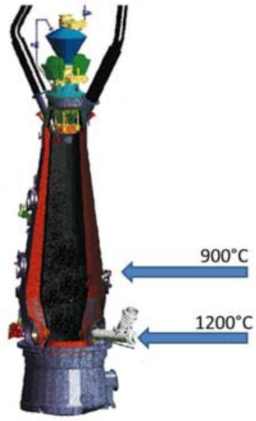

Figure 5. Version 4.

2.3.1 Version 1

The first version shown in Figure 3 has injection of decarbonated top gas at two levels of the blast furnace. The gas injected at the shaft tuyeres is heated to 900°C while the gas injected at the bottom tuyeres is injected at 25°C. At the lower level, also cold oxygen and pulverized coal is injected. Calculations showed that this type of process could result in a carbon saving close to 21%. This version leads to a much lower flow of gas to the bottom tuyeres compared to conventional BF operation. To handle the lower flow a new type of tuyere had to be developed.

2.3.2 Version 3

In version 3, illustrated in Figure 4, the decarbonated gas is heated to 1200°C and injected at the bottom tuyeres. This version was similar to the process operated during the Toulachermet tests in the mid 80´s. The calculated carbon savings for this process route was as high as 25%. However, in order to reach this, the blast furnace had to be operated at a very low RAFT. The highest carbon savings would also be reached while operating at high amounts of pulverized coal.

2.3.3 Version 4

Version 4, as seen in Figure 5, has the highest calculated carbon savings from the model: 26% reduced carbon input could be reached according to initial calculations. Version 4 is operated with heated decarbonated top gas injected in bottom tuyeres and part of the gas also injected through the shaft tuyeres.

2.4 Initial Process and Plant Calculations

Before the first campaign was started, a lot of work was spent calculating and modeling the new process as well as evaluating the changes needed to be done to the Experimental Blast Furnace.
Mass and Heat balance calculations as well as modeling of the inner conditions of the Blast Furnace were performed in order to simulate the changes in position of the cohesive zone. The information and conclusions drawn from the calculations were then used in the decision regarding on which level the shaft injection would be installed (Figure 6).

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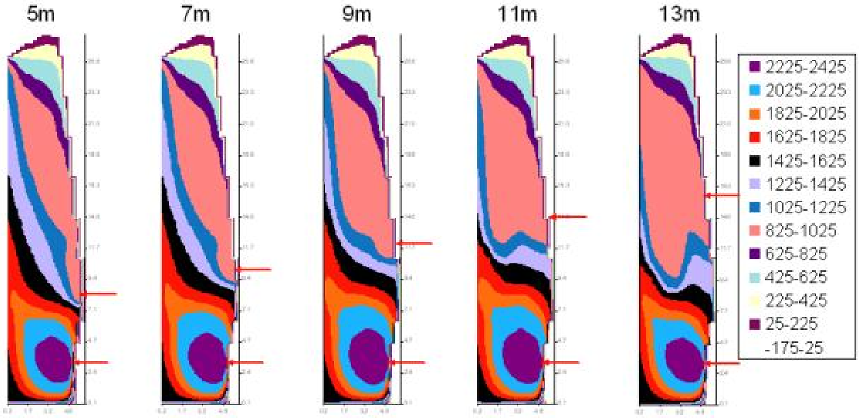

Figure 6. Effect of injection level on cohezive zone shape.

Also the tuyeres were modeled since the ULCOS-BF process was to be operated with a decarbonated gas, resulting in a lower blast volume compared to normal operation.
CFD modeling for all process versions were done in order to study the temperature distribution when injecting decarbonated gas together with cold oxygen and pulverized coal. The main point there was to verify that no hot spot would be generated at the tuyere wall. Also the raceway conditions were evaluated, with the aim to keep the tuyere gas impulse as close as possible to the one in conventional operation.
In Figure 7, the results from modeling version 3 process conditions together with coal injection and pure oxygen can be seen. As expected, the position of the lance is of highest importance in order to keep control over the combustion at the tuyere. The results gained from tuyere calculations were used in order to design and develop a suitable tuyere for the ULCOS-BF process. Also tests in laboratory and pilot scale were conducted prior to the actual campaign at the Experimental Blast Furnace.

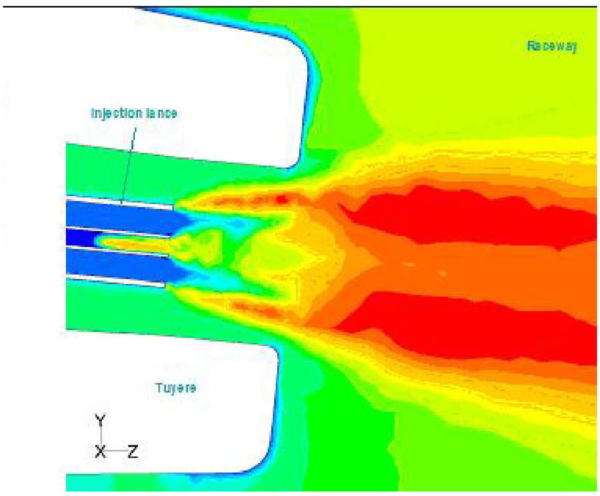

Figure 7. Temperature distribution within the tuyere for version 3.

A significant amount of laboratory tests were also conducted, studying the behavior of raw materials at different reducing atmospheres. Reduction, softening and melting behavior is some examples of parameters that were observed. The main conclusion was that the burden used in conventional operation was also suitable for the ULCOS-BF operation. As a result, a 70%/30% sinter/pellets mixture was used for the trials.

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2.5 Alterations to the Existing Experimental Blast Furnace

In order to operate the Experimental Blast Furnace using recycled decarbonated top gas, large alterations had to be made. A gas separation unit (a VPSA or Vacuum Pressure Swing Adsorption plant) was built and commissioned by Air Liquide. The refractory materials used in the plant were changed and adapted to the new type of "blast" used during the ULCOS operation. New tuyeres were developed and new equipment for injection of gas and pulverized coal was manufactured. The main focus for the preparation was also to secure a safe operation. This led to that a comprehensive HAZOP study was conducted.

In Figure 8, a drawing for shaft injection points can be seen. The bustle pipe to the upper injection level was installed and connected to the existing bustle pipe. The flow to the shaft injection points was controlled by a regulating valve. During installation, two possible levels for injection were prepared but during the three campaigns that have been conducted so far, only the upper point has been operated. 3 shaft tuyeres were installed separated by 120° as for the hearth tuyeres.

The control system for the hot stoves (actually pebble heaters) was modified in order to handle decarbonated top gas instead of normal hot blast. The complete system was adapted for conventional blast furnace operation using synthetic blast as well as ULCOS-BF operation using decarbonated top gas.

All changes resulted finally in a plant that could be operated in conventional BF mode and then stepwise changed into ULCOS-BF mode, without disturbing the process.

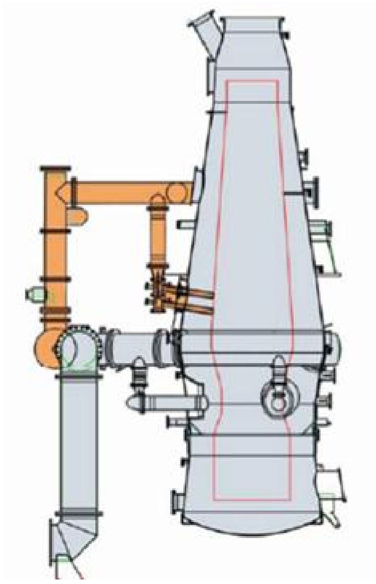

Figure 8. Installation of shaft injection points at the Experimental Blast Furnace.

Before the trials started, extensive training of the personnel was also conducted operating the complete plant at cold conditions using Nitrogen as simulated blast. By operating the plant cold with nitrogen, all systems could be tested and the safety systems checked.

2.6 ULCOS TGRBF Campaigns at the LKAB Experimental Blast Furnace

During the period 2007 to 2010, a total of three ULCOS-BF campaigns have been successfully operated at the LKAB Experimental Blast Furnace. During the trials, all process types initially planned have been tested and evaluated. All campaigns were

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started using conventional blast furnace operation. After a heating period followed by a reference period, the process was gradually shifted to a 100% recycling operation. During the different trials, a large number of variations were made to the process parameters in order to further optimize the new process. PCI, gas flows, temperatures, burden etc. are all examples of variables that were changed during the tests.
Upon finishing the individual campaigns, the Experimental Blast Furnace was quenched and cooled using nitrogen in order to prepare the BF for excavation. By quenching the blast furnace, the complete furnace shaft could be evaluated based on the new operating conditions. Also the cohesive zone, hearth and raceway areas were documented and assessed during the excavation. More than 3000 material samples were taken from each excavation.
During the Experimental Blast Furnace tests, no safety issues were recorded for either the blast furnace or the gas separation unit, VPSA. The gas separation plant showed a smooth and reliable operation. The VPSA plant could at all times provide the required amounts and qualities of gas needed for the ULCOS-BF process [9]. The limit of maximum 3% CO_2 in the recycled gas was at all times kept.

2.7 Evaluation of Performed ULCOS-BF Trials

After the completion of each campaign, the obtained process data were evaluated. Samples taken during the campaign, both material probes and excavation samples were sent for chemical and metallurgical analysis.
The BF operation during all three ULCOS campaigns was in general easy to control regarding, thermal level as well as the hot metal quality. As calculated, the silicon content in hot metal was significantly lowered from the reference period compared to recycling operation. During the trials, the blast furnace was also operated at varying RAFT. Laboratory tests prior to the campaign had shown that there was no significant difference in disintegration of raw materials by operating in ULCOS-BF mode. This was also confirmed during the trials when material probings were analyzed. No problems related to burden disintegration could be found during the three campaigns.
During the different campaigns, the hot metal quality was kept at a very good level both regarding temperature but also chemistry. Starting the blast furnace after unplanned stops could be done with very small effects on the hot metal and without any significant process disturbances.
Also a significant decrease of the direct reduction rate was observed during the tests. The level of direct reduction proved to be close to what had been calculated prior to the trial.
In table 1, the carbon savings for each version together with the recycling ratio have been listed. A carbon saving of 24% was obtained during tests with version 4.

Table 1. Carbon saving and recycling ration for tested process versions

	Version 1	Version 3	Version 4
Carbon saving (%)	20	23	24
Recycling ratio (%)	85	87	90

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The results proved that there is a possibility to further reduce the need of fossil carbon used in the blast furnace process of today. The results gained, are also close to what was calculated prior to the tests.
The outcomes of the Experimental Blast Furnace tests indicate that a reduced need of carbon combined with a CO_2 capture and storage facility would mean that the target of 50% less CO_2 to the atmosphere could be reached. In Figure 9, The calculated reduction of CO_2 emissions is shown. The results are based on carbon savings reached for the different versions as well as the assumption of an existing CCS. Taking into account the extra energy needed at the steelmaking plant in order to compensate for the decrease in export gas, the CO_2 savings are up to 65% at the level of hot rolled Coil[9].

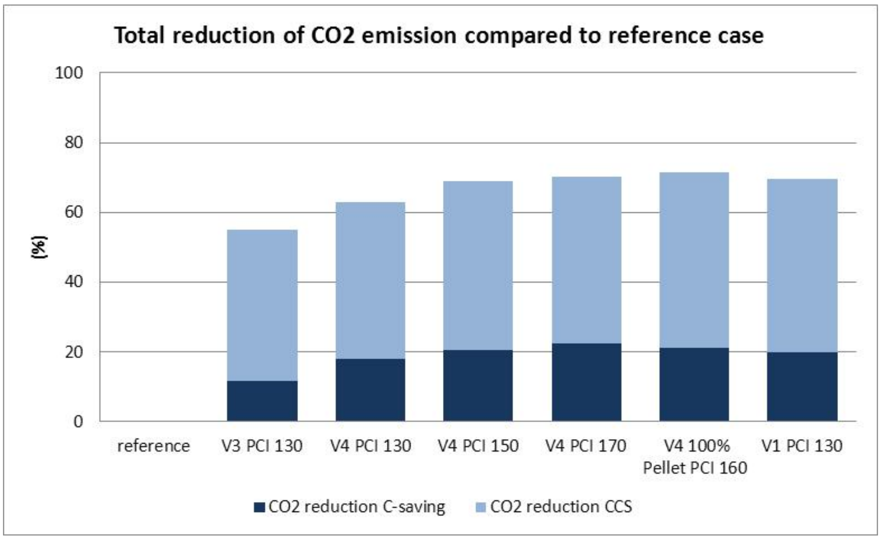

Figure 9. Calculated reduction of CO_2 based on trial results + CCS.

Studies of process data also made it possible to determine the exchange rate between decarbonated gas compared to coke and coal. Calculations show that 100Nm^3 ($CO+H_2$) in average replaces 17kg coke and coal. Also this result is close to what was modeled prior to the tests.
During the three campaigns, material probings were operated daily in order to evaluate the performance of iron ore during new blast furnace conditions. In order to collect even more results, gas and temperature probings were performed at two levels of the shaft. This resulted in a large number of material samples that could be connected to a specific atmosphere regarding temperature and gas composition. By comparing samples taken during varied process conditions, the reduction degree could be connected to specific process conditions. The effect of shaft injection could for example be evaluated. Except for one period when operating with 100% pellets, all trials have been conducted using a mixed burden with 70% sinter and 30% pellet. The burden has through the excavation samples been thoroughly evaluated and assessed. In Figure 10, a map showing the reduction degree for pellet samples taken during the excavation of the first trial can be seen. Already at an early stage, the pellet shows a comparably high reduction degree. Based on the charging program used, operating a relatively strong central gas flow, higher reduction degree is expected in the center of the Experimental Blast Furnace. The results for sinter samples are similar, however, pellet tend to have a slightly faster reduction in the upper part of the shaft. From shaft probings it has become clear that the temperature

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clearly affects the reduction variations when operating at a constant injection volume both to the shaft and to the normal tuyeres.

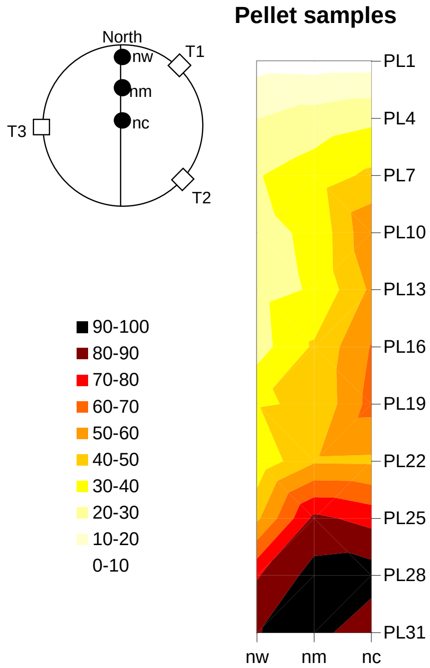

Figure 10. Reduction degree for pellet samples taken during excavation of the first ULCOS trial.

The reduction of iron ore in the shaft is very efficient and the shaft injection seems to have a sufficient penetration into the burden.

3 MOVE TO INDUSTRIAL SCALE BASED ON EXPERIENCES GAINED DURING TESTS AT THE EXPERIMENTAL BLAST FURNACE

After completion and evaluation of 3 very successful campaigns, the results and experiences gained is to be transferred into a larger scale. The initial ULCOS project was reorganized and the ULCOS Consortium has now launched the ULCOS II project. The goal is to demonstrate the tested technology and process at an industrial blast furnace situated at the ArcelorMittal plant in Florange, France. At this site, also the capture and storage of CO_2 will be demonstrated. Tests are also planned to be carried out at the ArcelorMittal plant in Eisenhüttenstadt, Germany. At this location, different technological solutions will be tested prior to the start up at the Florange Site. The first operation of the blast furnace in Eisenhüttenstadt is planned for 2014 and the plant in Florange planned to start by the end of 2015.

4 CONCLUSIONS

During the ULCOS project, a total of three campaigns of 6 weeks each have been conducted at the LKAB Experimental Blast Furnace. The tests have shown that the process can be operated in a safe way without any registered safety issues. The results also show that it is possible to significantly reduce the amount of fossil carbon needed at the blast furnace if operating with recirculated decarbonated top gas. Also applying carbon capture and storage technology could mean that the goal of reducing the emissions of CO_2 to the atmosphere by more than 50 % would be met.

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