TOP GAS RECYCLE BLAST FURNACE DEVELOPMENTS FOR LOW CO2 IRONMAKING

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Abstract

The ULCOS blast furnace process (ULCOS-BF) aims at minimising the CO₂ emission of the blast furnace by at least 50%. This process is based on the replacement of hot blast by oxygen, the recycling of hot decarbonated top gas into the lower shaft and normal hearth tuyeres, and the capture of CO₂ and its storage in a geological trap (full CCS process). The paper highlights the main technologies of this ULCOS-BF process, and the expected benefits for CO₂ mitigation. The ULCOS blast furnace process has been demonstrated during three campaigns of 7 weeks by coupling the LKAB’s Experimental Blast Furnace in Luleå to a pilot VPSA unit for CO₂-removal. The concept, preparation and results of the campaigns are described. Following the success of these experiments, studies for the construction of a demonstration unit are currently in progress.

Key Words
Blast Furnace, Top Gas Recycling, CO₂ reduction

Introduction

It is widely recognised that CO₂ in the atmosphere is the main component influencing global warming through the green house effect. Since 1896 the concentration of CO₂ in the atmosphere has increased by 25% [1]. The steel industry is known as an energy intensive industry and as a significant emitter of CO₂. In the traditional processes for producing steel, emission of CO₂ is inevitable, especially for the blast furnace process, which is the main CO₂ producer in an integrated steel works. In this process carbon is needed for the reduction of the iron ore.

Since the 1950s, significant Research and Development effort has been done in Europe to make the blast furnace ironmaking technology and operation more efficient: Improved coke and sinter quality, O₂ enrichment, injection of other reductants like coal and natural gas, burden distribution, measurement technologies etc. In the 1950s the reductant rate was about 1000 kg/thm, and has since then been reduced by a factor of 2 thanks to the European collaborative research work (ECSC and RFCS respectively) [2] and the implementation of the improvements.

The reducing agent consumption at the conventional blast furnace is nowadays with circa 500 kg/thm approaching only 5% above the lowest possible thermodynamic values under classical blast furnace operation [3,4]. Therefore minor effects will be gained by further energy optimisation programs at these existing conventional process routes. Breakthrough ironmaking technologies are required for further significant reduction of carbon consumption or CO₂ emission. Several technologies have been
proposed for further reduction of the fossil carbon usage and the reduction of the CO₂ emission in the blast furnace process itself [6]: Recycling of CO from the blast furnace top gas, Usage of Biomass, Substitution of CO by H₂ as a reducing agent, Usage of Carbon-lean Direct Reduced Iron (DRI), Usage of Hot Briquetted Iron (HBI) or Low Reduced Iron (LRI), Usage of Carbon-lean electrical energy and CO₂ Capture and Storage (CCS).

Ultra Low CO₂ Steelmaking programme
The most advanced program to explore and develop such breakthrough technologies is running in the European Union, widely known under the name of ULCOS which stands for Ultra Low CO₂ Steelmaking. This program has been launched in 2004 as an answer to a joint call of the European 6th Framework Programme and Research Fund for Coal and Steel [7].

This program was set up by a consortium of the major European steel companies (ArcelorMittal, Tata Steel Europe, ThyssenKrupp Steel Europe, Ilva, Saarstahl - Dillingen Hütte, Rautaruukki Oyj, voestalpine Stahl, SSAB) and LKÅB aiming at the Research and Development of technologies to produce steel with at least 50% lower CO₂ emissions compared to today’s steelmaking benchmark. In total 48 companies and organisations from 15 European countries were involved in the ULCOS project. Some activities were related to the FP 6 programme, officially ended in 2010, and 2 of 4 correlated projects funded by RFCS ended at the same time as well. The total budget for the ULCOS FP6 and RFCS projects amounted to 76 M€. The cooperative research and development initiative led to numerous ideas to reach the objective. The four most promising solutions have been selected for further exploration: Blast Furnace (ULCOS-BF), Smelting Reduction (HISARNA), Direct Reduction (ULCORED) and Electrolysis (ULCOWIN/ULCOLYSIS) [5].

Both ULCOS BF and HISARNA are coal based concepts and can also use biomass as reducing agent. The ULCOS BF technology with top gas recycling and the usage of pure oxygen instead of air has been successfully tested at LKAB’s Experimental Blast Furnace in Luleå, Sweden, in two RFCS projects: ULCOS-NBF and ULCOS TGR-BF RFCS [8,9,10,11]. The HISARNA technology is based on the coupling of an iron bath smelter [13] with a smelting cyclone [12]. A pilot plant with a capacity of 8 t/h has been erected at the Tata Steel Europe site in Ijmuiden, The Netherlands, and the process is currently under investigation in the course of a RFCS project [14]. The ULCORED direct reduction concept is based on the usage of natural gas as reducing agent. This technology is expected to be engineered for a pilot plant with a capacity of 1 t/h, with tests expected from 2013. It is important to know that these three ULCOS breakthrough technologies need to be combined with the CCS technology, in order to reach the goal of 50% reduction of the CO₂ emissions.

The electrolysis concepts ULCOWIN and ULCOLYSIS are based on direct usage of electricity. This technology could produce iron more or less without any CO₂ footprint if C-lean electricity is available in medium to long-term. In the ULCOWIN technique solid iron is produced using a soda suspension of ferrous particles, whereas in the ULCOLYSIS technique iron ore is dissolved in a molten oxide mixture at 1600°C. By applying electricity power iron is produced as liquid metal at the cathode. Both concepts are still under investigation at laboratory scale.

CO₂ reduction in the Blast Furnace route
In the area of the blast furnace the most promising technology to significantly reduce the CO₂ emission is recycling of CO and H₂ from the gas leaving the blast furnace from the top. This Top Gas Recycling (TGR) technology is mainly based on lowering the usage of fossil carbon (coke) via re-usage of the reducing agents (CO and H₂) after the removal of the CO₂ from the top gas. This leads to lower energy requirements. The main technologies of the TGR-BF are:
- the injection of reducing top gas components CO and H₂ in the shaft and hearth tuyeres,
- lower fossil carbon input due to lower coke rates,
- the usage of pure oxygen instead of hot blast air at the hearth tuyere (removal of nitrogen from the process),
- recovery of pure CO$_2$ from the top gas for underground storage,
- In order to reach the 50% CO$_2$ reduction the application of CCS technology is necessary.

As previously mentioned, the concept of top gas recycling has been experimentally tested at the LKAB’s Experimental Blast Furnace (EBF) in Luleå, Sweden [8,9]. The EBF was modified and a gas separation plant based on VPSA technology was built near the EBF. Although the tests at the EBF are considered successful, the industrialisation of the ULCOS-BF technology requires an additional scale up step. A demonstration phase at an industrial blast furnace is planned in the 2$^{nd}$ phase of ULCOS (ULCOS II), where the technologies investigated at the EBF will be explored at the industrial scale for demonstration.

**History of Recycling of Blast Furnace Top Gas**

During the 20$^{th}$ century several new concepts, based on the conventional blast furnace process, have been introduced to lower the reductant rate and to increase the blast furnace productivity. Already in the 1920s Lance [16] developed a concept to inject hot reducing gas into the blast furnace. Figure 3: History of Alternative Blast Furnace processes [15].

The lower gas volume from the tuyeres in the furnace should be compensated by the injection of preheated reducing gas at 1000 °C with 27% CO, 33% H$_2$, and 26% N$_2$ into the lower shaft zone. As a result only 30 % of the coke (at that time 345 kg/thm) would be necessary for the metallurgical blast furnace process. In the mid 1960s this idea was taken up again in Belgium and in the early 1970s the first trials were carried out at a 4.6m hearth diameter blast furnace in COCKERILL-Seraing E [17, 18, 19]. A specific amount of 400 Nm$^3$/thm of reformed gas was preheated up to 1000 °C and injected into the lower shaft. A replacement ratio of 0.22 to 0.26 kg of coke per Nm$^3$ of reducing gas was observed. Further investigations were stopped due to economical reasons such as the high price of natural gas. In the late 1970s Fink started to develop a new process which injects cold pure oxygen, fuel and recycled gas at two tuyere levels [20]. Based on the idea of Fink a process was developed by Lu (Canada) in 1984 for a conventional blast furnace without a second tuyere row [21]. The main feature of this concept was injection of coal to substitute the coke. Both concepts were never realised and ended as a study. Nearly at the same moment this idea was further used by NKK [22, 23] in Japan where a second row of tuyeres was installed in the middle of the shaft. Preheated reducing gas, consisting of recycled top gas without CO$_2$ removal, was injected in these tuyeres. The gas was heated by partial combustion with oxygen. Cold oxygen, coal and cold recycled top gas were injected into the tuyeres of the hearth. NKK tested the process in an experimental blast furnace with 3 tuyeres, an inner volume of 3.9 m$^3$ and a hearth diameter of 0.95 m. The coal injection rate could be increased to 320 kg/thm, while the coke rate could be reduced to 350 kg/thm. The lack of energy in the integrated steelworks by recycling the top gas stopped this process, because of the high price of electrical energy and natural gas in Japan. The first commercial operation of a blast furnace with top gas recycling was performed in the late...
1980s in 12 campaigns by RPA Toulachermet [24] in Russia at blast furnace No. 2 (Volume: 1033 m³). In this all-coke blast furnace concept, hot top gas and almost free of CO₂ was blown into the hearth tuyeres, together with pure oxygen. The decarbonated top gas was heated in hot stoves up to 1200°C. With this new process nearly 250 kt of hot metal was produced. The lowest coke rate achieved was 367 kg/thm, compared to the reference of 606 kg/thm this was a reduction in coke rate of 239 kg (39%). During the campaigns serious tuyere burnouts were seen, leading to changes in the tuyere design. Difficulties with the CO₂ cleaning system finally stopped the process. With the above explained process issues the ULCOS BF concept has been developed during two consecutive RFCS projects, starting in 2004.

The ULCOS Top Gas Recycling Blast Furnace

In the first RFCS project named “ULCOS New Blast Furnace Process”, running from 2004 to 2009 [25], three new process concepts have been developed and investigated by mathematical modelling, metallurgical tests and finally a demonstration at LKAB s’ Experimental Blast Furnace (EBF) in Luleå. In the second RFCS project named “ULCOS Top Gas Recycling Blast Furnace Process” (started in 2009), two additional ULCOS BF campaigns were conducted in order to investigate the new process [29] in more detail. Both projects were subsidised by the European Commission with a budget of around 17 M€. Several theoretical studies have been performed to get a better understanding of the new top gas recycling process.

1. Heat and mass balance models and a 3-D axi-symmetrical model of the blast furnace (Mogador) [26,27] were used for the calculation of the main data and the inner state of the new process in order to select the best operating conditions. Four flow sheet versions have been defined and examined on the possible reachable C-saving and the feasibility to run the blast furnace under these new concepts. The conclusion was that the so-called Versions 1, 3 and 4 should be able to achieve a fossil carbon saving of 21% or higher with a rather high pulverised coal injection level. Version 2 was rejected because of the expected low carbon saving and the necessary challenging technology to heat the recycle gas. In this version the recycled top gas was heated in two steps: a recuperator and further heating by partial oxidation. All versions include CO₂ removal and the injection of CO rich product gas into the hearth tuyeres, the usage of pure oxygen and the injection of coal together with the reducing gas. In Version 1 and 4, product gas is also injected through shaft tuyeres (Figure 4). The differences are the gas injection temperature, and the position of the injection points:

- Version 1: the decarbonated product gas is injected cold with pure oxygen and coal at the hearth tuyeres and hot at the shaft tuyeres; One crucial point in this version is the small cold gas flow rate at hearth tuyere level leading to smaller raceway sizes and higher flame temperatures compared to the classical BF process. Furthermore a new tuyere design due to the small gas flow rates is necessary.

- Version 3: the decarbonated product gas is injected hot at the normal hearth tuyeres together with oxygen and coal. To reach high carbon saving it is necessary to operate with low RAFT and at the same time with high coal injection rate.

- Version 4, the decarbonated product gas is injected hot at the hearth tuyeres and hot at the lower shaft.

The temperature of the recycled gas varies from room temperature to 1250 °C. In all cases at least part of the gas is heated in a regenerative system. The expected fossil carbon savings are for Version 1 21% at a coal rate of 170 kg/thm, Version 3 24% at a coal rate of 180 kg/thm and Version 4 25% at a coal rate of 150 kg/thm.
2. Metallurgical laboratory tests of the ferrous burden behaviour for reduction behaviour, hot degradation and softening and melting under the conditions of the new process regime. Also carbon deposition has been investigated. The inner state of ULCOS blast furnace has been calculated with the Mogador model. The calculated working lines (temperature and gas profile) have been used to set up the reduction experiment for a standard European sinter and LKAB KPBA pellets. At injection level, the reduction degrees attained are evaluated to approx. 85%, being almost identical to the result of Mogador calculations (Figure 5). It could be concluded that the reduction level as calculated under Mogador conditions can be attained with the standard sinter and pellets at the shaft gas injection level.

3. Mathematical modelling of the raceway conditions and gasification tests in both laboratory and pilot scale were done for the design and engineering of the tuyeres under the constraints of simultaneous injection of recycled gas, pure oxygen and pulverised coal (Figure 6). The geometry of the tuyere has been adapted based on the results of the calculations to avoid hot spots and failure during operation and to keep a sufficient impulse of the gas stream to form a raceway with a sufficient depth.

4. A feasibility study at laboratory scale to find a proper technology for heating the recycled CO rich gas, taking into account chemical phenomena like C-deposition and metal dusting. Recuperative and regenerative gas heating systems were evaluated and compared with partial combustion of the gas for gas heating;

5. An evaluation of investment costs and operational costs of the blast furnace top gas recycle configuration.

The results were used to define a test programme at the experimental blast furnace. The EBF was engineered and modified to perform the experimental programme.

The Modification of the EBF

In order to bring the theoretical studies together and to get confidence in its feasibility, this blast furnace Top Gas Recycling concept was tested at pilot scale during three campaigns of maximum 7 weeks at the LKAB’s Experimental Blast Furnace, which main characteristics are given in Table 1. This experimental blast furnace, located in Luleå, Sweden, was chosen as an appropriate unit for testing the ULCOS BF process on pilot scale, (Figure 7). Since 1998 in total 28 campaigns with duration of each 6 to 8 weeks were performed. The working volume of the furnace is around 8.2 m³ with a hearth diameter of around 1.2 m. The production rate is in the range of 36-40 t/d with a reductant rate of ~530 kg/thm. There are three tuyeres and the blast is heated in two pebble heaters.

Table 1: Characteristics of the EBF

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
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<tbody>
<tr>
<td>Working volume</td>
<td>8.2 m³</td>
</tr>
<tr>
<td>Hearth diameter</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Working height</td>
<td>5.9 m</td>
</tr>
<tr>
<td>Hearth tuyeres</td>
<td>3</td>
</tr>
<tr>
<td>Top pressure</td>
<td>1.5 bar</td>
</tr>
<tr>
<td>Pebble bed heaters</td>
<td>2</td>
</tr>
<tr>
<td>Production</td>
<td>36-40 t/d</td>
</tr>
<tr>
<td>Typical tape time</td>
<td>5-10 min</td>
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</table>
For implementing the ULCOS-BF process at the pilot facility several modifications on the EBF and its auxiliary facilities were designed, engineered and installed (Figure 7) to run the 3 preferred Versions. In the vicinity of the EBF a Vacuum Pressure Swing Adsorption (VPSA) gas separation plant for the removal of the CO$_2$ of the top gas was constructed by Air Liquide. The equipment was tested in classical EBF campaigns before the ULCOS campaigns. A safety study was conducted in an extended HAZOP. For a safe preheating, transport and injection of the CO rich top gas, improvements were made on the gas heater and the transport system. The hearth tuyeres were re-designed and installed after raceway calculations (Figure 6). A shaft gas injection system with 3 shaft tuyeres and a gas distribution system was designed and constructed at the EBF (orange part in Figure 7). The pulverised coal injection system was adapted to improve the stability of injection at high PC-injection levels. Finally after the modification and construction the EBF and its auxiliaries (Figure 8) were tested. Thereafter the three selected Versions of the ULCOS-BF process could be tested during three campaigns, in 2007, 2009 and 2010. The modifications were designed such that both conventional and ULCOS mode is possible. Before each campaign the start up was done in conventional mode and after a sufficient reference period of a few days the furnace was switched to the ULCOS mode.

The Experimental Blast Furnace Campaigns

The objective of the trials was to demonstrate the operation of the EBF in a complete Top Gas Recycling mode with pure oxygen and PCI at the hearth tuyeres. This has been performed under the three defined versions. The ferrous burden consisted of 70% sinter from Rautaruukki Oyj and 30% LKAB pellets. Coke and pulverised coal and flux materials were provided by SSAB. The hot metal production rate was kept at a constant level of 1.5 t/h and the PCI rate was varied between 130 and 170 kg/thm. During the different trial periods the volume of the recycled top gas was maximised in order to get maximum fossil carbons saving. The EBF results have been compared with model calculations. In 2007, during the first campaign (K-20), after a conventional start up, Version 3 and Version 4 were tested (Table 2). The trial started on the 24th of September.

In the second campaign (K-23) in fall 2009 Version 3 was tested again for optimisation (not done in K-20), followed by a test of Version 1. In the third last campaign in 2010 the focus was on Version 4 as it was thought to be a preferred version for the follow-up ULCOS BF demonstration project on industrial scale. During the campaigns in-situ measurements of gas composition and temperature and samples from the burden material were taken from the EBF with the two in-burden probes. For investigation of the burden material behaviour under the new operating conditions, baskets with different sinter and pellet material were charged into the furnace just before the stoppage of the campaign. These baskets were recovered from the EBF during the dissection of the furnace after the quench with nitrogen. This was done during the campaigns in 2007 and 2010 (Figure 9). In the second campaign in 2009 only the quench could be performed due to an unprepared end of the campaign.
campaign (problem in the EBF charging system) and therefore no baskets were charged. Also samples from the cohesive zone have been recovered and size and shape of the raceway measured for further examination. The campaigns started by one week of normal conventional blast furnace operation (hot blast) with sinter, first for heating up and thermal stabilisation and then for establishing a reference for conventional blast furnace operation. After the reference a stop was made for disconnecting the blower and connecting the product gas to the pebble heaters. The start up in the ULCOS mode was made by artificial blast: cold oxygen from the lances and hot nitrogen from the pebble heaters. In progressive steps the nitrogen from the pebble heaters was replaced by decarbonated top gas (product gas) (Figure 10). This start-up was made according to plan and did not bring any difficulty. After 10 days the EBF was stopped and the shaft tuyeres were connected and opened for operation of Version 4.

**ULCOS EBF campaign results**

First it can be concluded that it is possible to operate the ULCOS Top Gas Recycling blast furnace process. No safety issue has been recorded with the new process. The operation of the second important facility, the VPSA was smooth and without any main failures. The connection between the EBF and the VPSA worked very well during the campaigns. However, it has to be noted that changes in top gas composition and amount from the EBF have an immediate impact on the VPSA operation. Both facilities have then to be operated in a very close relationship. The ratio of recycled top gas was approximately 90%. Under the new process the blast furnace operation was experienced as stable with a smooth burden descent and it was easy to maintain the thermal stability. The gas efficiency in the shaft was stable during the different versions and measurements of the in-burden shaft probes showed a good gas distribution. A few equipment failures were recorded at which the EBF had to be stopped during the operation under the new process conditions. Some long stoppages required coming back to the coke rate of the “conventional operation” with cold oxygen and hot nitrogen (artificial blast) operation. The small stoppages required only stopping the gas injection and the addition of some extra coke and/or coal. After start up with nitrogen, when there is no top gas available, the product gas could be recycled again within approximately 1 hour. All problems were solved as forecasted and the thermal stability of the BF was never seriously in danger. Along the campaign, the gained experience and increased confidence allowed progressively to make the EBF recovery faster. Each time during change in Version (3 → 4, 3 → 1) the blast furnace was stopped for approximately 8 hours for making the

<table>
<thead>
<tr>
<th>Table 2: Schedule of the first campaign at the EBF, starting on the 24th of September 2007</th>
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<tr>
<td>Conventional start up</td>
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<tr>
<td>Reference Period</td>
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<tr>
<td>Stoppages connecting the VPSA</td>
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<tr>
<td>Period of TG recycling Version 3</td>
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<tr>
<td>Stoppages upon shaft tuyeres</td>
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<tr>
<td>Period of TG recycling Version 4</td>
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<tr>
<td>Optimization coal rate</td>
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<tr>
<td>Pellet Operation</td>
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<tr>
<td>Sinter and pellet operation</td>
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<tr>
<td>Clean-up</td>
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<tr>
<td>week 1</td>
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<tr>
<td>week 1</td>
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**Figure 10:** K-20 results on reductant rate, recycled gas injection and carbon saving

**Figure 11:** K-23 results on reductant rate, recycled gas injection and carbon saving
necessary gas connections to the shaft tuyeres and the change of hearth tuyeres. The changeovers can be seen in Figures 10 and 11.

The laboratory experiments showed that the conventional burden material would not be a problem for the new process. The RDI tests showed a similar disintegration for the conventional as well as for the new process. This was confirmed during the campaigns. No particular process problems were related to burden properties. The results of both probes and excavation samples showed the reduction profile of a centre working furnace: a low reduction level at the wall and a higher level at the centre for both sinter and pellets samples (Figure 12). Tumbling tests on the excavation samples show disintegration behaviour similar to the one of a conventional blast furnace process which corresponds to the lab tests. From the burden testing work it could be concluded that the burden properties as used in today’s conventional blast furnace seem no problem for the ULCOS BF process.

**Carbon Saving**

The results of the ULCOS EBF campaigns are very promising in the light of carbon savings. All three versions tested showed a significant decrease in reductant rate. This was accomplished by the injection of the decarbonated top gas. During the three campaigns the coal and coke input dropped from approximately 530 kg to 400 kg, which represents a considerable carbon saving (Figure 10 and 11). The carbon input was reduced from 470 kg to approximately 350 kg/thm, resulting in a carbon saving of 120 kgC/thm (Figure 13).

Although Version 1 could not be fully explored because of the early stop of the 2nd campaign the maximum reduction in carbon input via coke was 21% (= 115 kg/thm, see Figure 13) compared to the reference period under conventional BF operation. For this version a new tuyere technology was developed. The three installed tuyeres worked very well and after disassembling neither damages nor wear has been observed. The VPSA was able to recycle up to 88% of the blast furnace top gas.

Regarding Version 3 the carbon consumption could be reduced up to 15 % in the first campaign with a top gas recycling ratio of 72%. The results of this version were lower (~15%) than expected from the heat and mass balance calculations (24%) as this was the first experience with top gas recycling mode and the process was not optimized. In the second campaign the results of this version were much better: the maximum reduction in carbon input was around 25% (= max. 140 kg (coke+coal)/thm) with a top gas recycling ratio up to 90%.

Version 4 resulted in a carbon saving of 24% with a top gas recycling ratio of 90%. In terms of coke and coal consumption, up to 123 kg/thm were saved in the new process (Version 4) compared to the reference operation period. From these results a good correlation between the amount of injected (CO+H₂) and the reduction in reductant rate could be determined. Per 100 Nm³ (CO+H₂) injected the carbon input via coke and coal can be reduced by 17.0 kg in average. The experimental blast furnace campaigns proved that it is possible to run a blast furnace process at a much lower fossil carbon consumption level as today’s blast furnaces do. A carbon saving up to 25% was proven by the injection of the reducing decarbonated top gas. This would be a significant drop compared to today’s
best practice blast furnace process. As a matter of fact, the application of this technology on modern blast furnaces would lead to reduce the carbon consumption from a current level of ~405 kgC/thm down to ~295 kgC/thm.

**CO₂ Emission Reduction by the ULCOS Blast Furnace Process**

For the above mentioned results in Version 4, as an example, the direct carbon savings on the blast furnace process will lead to a direct reduction of the CO₂ emission of 24%. However when these savings are considered on an integrated steelworks, they have to be aligned per tonne of hot rolled coil, as at that moment the blast furnace top gas is utilized by the ULCOS-BF process and not available anymore for other heating processes within the plant. Therefore this gas needs to be replaced by other sources, like natural gas. In the ULCOS-project a dedicated team took into account these considerations. Version 1, 3 and 4 showed savings of 12%, 14% and 15% CO₂ per THRC respectively. Another technology has to be applied to reach the ultimate objective to save more than 50% CO₂. This can be achieved by application of the CCS technology.

From the first ULCOS campaign there is a CO₂ reduction of 24% in the BF due to gas recycling plus 52% at the VPSA [25] when considering the storage of the removed CO₂. Maximum 75% reduction of CO₂ emission with respect to the reference period can be identified during the different representative periods of the three campaigns (Figure 14). However considering the whole plant, extra energy (natural gas, electricity) is required to compensate for the decreased amount of blast furnace gas normally used in the plant and for operating the CO₂-removal unit. Anyway, a 60% decrease of the direct CO₂ emission of the integrated steelworks can be achieved. After extraction of the CO₂ from the recycled gas by the (V)PSA, the gas needs to be made storage ready. This will be done by the application of cryogenic techniques.

**Scale-up to Industrial**

The blast furnace is the core of an integrated steelmaking site, and therefore this new process has to be scaled up to industrial size. As the transfer of the EBF ULCOS campaign results is not straightforward, the ULCOS partners decided to move their project into a next phase, ULCOS II, where the new process needs to be demonstrated on an industrial blast furnace. In this up-scaling phase specific attention will have to be paid to the tuyere technology for simultaneous injection of decarbonated top gas (mainly CO and H₂) and pulverised coal under full oxygen, the technology for shaft gas injection, technology for distribution of gas over the radius, especially at the shaft, product gas heating and all kinds of safety issues. The corresponding engineering studies are currently in progress at ArcelorMittal. The core members of the ULCOS consortium have now reorganized in an ULCOS II consortium to continue the developments of the four selected process routes. As far as the ULCOS BF concept is concerned, ULCOS II comprises the demonstration of the Version 4 top gas recycling concept at the ArcelorMittal blast furnace P6 in Florange (France) and at a blast furnace at ArcelorMittal Eisenhüttenstadt (Germany). In France also the storage of CO₂ in deep saline aquifer in Lorraine is foreseen. The first operation in ULCOS BF mode with CO₂ storage is expected in Florange for 2016 and Eisenhüttenstadt without CO₂ storage for 2014.

**Conclusions**

The ULCOS-BF test campaigns showed that the new top gas recycling blast furnace process is feasible and can be operated in a safe manner. It proved to be possible to shift the EBF operation between 4 modes of operation (Conventional, Version 1, 3 and 4). It was possible to operate the blast furnace process and the gas separation plant VPSA in a closed loop. The obtained C-savings were consistent with the predictions from the flow sheet calculations. The tests also indicated that conventional burden materials sinter, pellet and coke are suitable for the ULCOS blast furnace.
process. From the results, a reduction in CO$_2$ emission of an integrated steelmaking site of around 60% per ton of hot rolled coil seems feasible by applying top gas recycling and CCS technology.

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