Evaluation of Ferrous Burden Properties in an Experimental Blast Furnace
After Quenching and Dissection

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ABSTRACT

In 1997 LKAB decided to build an Experimental Blast Furnace (EBF) in Luleå, Sweden. The EBF was built at MEFOS research centre close to the SSAB steelworks in Luleå. The furnace has a flexible design for tests of different process concepts, including injection of pulverised coal, oil and fluxes. The production rate is 30–40 t/day at blast temperatures of 1100–1280 °C, oxygen enrichment up to 50 % in the blast and the possibility to use up to eight different materials in the ferrous burden.

The EBF has a hearth diameter of 1.2 m and a working volume of 8.2 m³. The furnace is equipped with a state of the art system for monitoring and data storage.

LKAB R&D used the EBF mainly for iron ore pellet development, but also for blast furnace process development, together with customers. In total, nine campaigns with a total operation time over 400 days have been completed. Dissections were carried out for seven of the campaigns and nitrogen was used for quenching.

The influence of various process conditions can be observed in the internal state of the EBF when dissected. Among the differences that have been observed is the amount of fine material in the furnace, the presence of channels and voids and the amount of material stuck to the furnace wall. Different ferrous burden materials have been analysed. Differences in alkali, sulphur and zinc levels and the microstructure of different types of pellets are noticed in the lower part of the furnace. Variation in the position, thickness and properties of the cohesive zone formed from different types of pellet or pellet/sinter burden has been observed.

An attempt is made to link the results from the dissection to material properties and process conditions before quenching of the EBF.

INTRODUCTION

LKAB’s experimental blast furnace in Luleå (EBF) was built and commissioned in late 1997, primarily for product development of iron ore pellets. During 1998 to 2001 nine campaigns were conducted to evaluate different types of ferrous burden containing iron ore pellets, sinter and lump ores as well as various process concepts like high coal and oil injection rates with oxygen enrichment up to 43 % oxygen in the hot blast. For seven of the campaigns, the EBF was quenched using nitrogen and dissected. This paper describes the results from these dissections with attention to the properties of the reduced ferrous burden in the lower part of the furnace. The results are compared with laboratory tests on the same materials.

The results from the dissections, with attention to the conditions found in the lower part of the EBF are discussed based mainly on visual observations, material analyses and microstructures together with material test results.

THE EXPERIMENTAL BLAST FURNACE

The EBF was fully financed by the owners of the furnace, LKAB. It is situated at the MEFOS research centre, next to SSAB Luleå works. It is built inside a building used for coal gasification trials in the eighties, thus having raw material handling system, electrical supply and so on. During operation SSAB supplies raw materials, including gases, carries out analyses on hot metal and slag, etc. LKAB and MEFOS are operating the blast furnace in co-operation.
DESCRIPTION OF THE FURNACE

The EBF has been described in detail in other papers\(^1,2\), below is a summary of the plant and operation characteristics.

The EBF plant is shown in Fig. 1. It has a working volume of 8.2 m\(^3\) and a diameter of 1.2 m at tuyere level. From tuyere level to stock line, the height is 6 m and there are three tuyeres placed with 120 degrees separation, each with a diameter of 54 mm, resulting in a blast velocity of 150 m/s at normal blast volume. The furnace is equipped with systems for injecting pulverised coal, oil and other materials.

Great effort has been taken to keep heat losses to a minimum and therefore insulating refractories were chosen. Only the bosh and tuyeres are water-cooled. The blast is normally preheated to 1170°C - 1250°C in pebble bed heaters.

The raw materials system consists of four bins for pellets or sinter, one bin for coke and four small bins for slag formers. The materials are transported to the furnace top by a skip to a receiving hopper. Furnace top pressure can be controlled up to 150 kPa overpressure.

The EBF has just recently been equipped with a bell-less top. The top gas is cleaned in a conventional gas cleaning system. Finally, the top gas is flared in a torch.

The furnace has one tap hole. It is opened with a pneumatic drill. After each tap, the tap hole is closed with a hydraulic mud gun. The hot metal and the slag are tapped into a ladle, transported to the SSAB steel plant, and charged as scrap to the BOF, after cleaning of the slag.

Burden probes are installed at three different levels. There are two horizontal probes, one at upper shaft and one at the lower shaft. The third is an inclined probe at the bosh level. The shaft probes and the inclined probe are equipped for sampling materials and for measuring furnace gas analysis/temperature, during operation.

RAW MATERIAL PREPARATION AND DUST TREATMENT

Test pellets are produced either in the LKAB Steel Belt Plant located in Malmberget or in one of the production plants. A normal test quantity for the EBF is around 1000 tonnes. During production sampling is done at regular intervals and tested for chemical composition, mechanical and metallurgical properties.

The pellets are screened at 6 mm and sampled before they are stored in day bins.

Sinter is normally produced at the customer’s site, top size is 50 mm and the sinter is screened at 6 mm, before being used in the blast furnace. The sinter is sampled and tested in the same way as for the pellets.

Coke is produced at SSAB coke plant in Luleå, close to the EBF and is prepared by screening the production coke to the fraction 15–30 mm. The batch is sampled and transported to the EBF where it is screened at 6 mm and sampled before storing in the day bin for coke.

Fluxes are screened to the fraction 10–20 mm and stored in large bags, and no additional screening of fines is done.
The dry and wet flue dust is sampled twice every shift and analysed. Sampling of the water phase of the wet dust system is carried out once a day.

**OPERATING THE EXPERIMENTAL BLAST FURNACE**

The operation of the blast furnace is very similar to a commercial blast furnace. At blow in, wood and a small amount of charcoal is used as start up burden in front of the tuyeres. Within the first hour, full wind is reached and the blast temperature is in the range of 800-850°C. The blast temperature is increased to the desired set point in the first 24 hours of operation. The amount of reducing agents is slowly decreased during the first 72 hours, to a level corresponding to about 110%, compared to normal operation. After this period, injection of pulverised coal (PC) or oil is started. Operation is stabilised during the next 48 to 72 hours.

The furnace is operated with a productivity ranging from 3.4 to 4.0 t/m³/day. Hot metal and slag composition is kept at set points decided before the campaign. Normal tap-to-tap time is 60-80 minutes, depending on actual production rate and normal tap duration is five to fifteen minutes. Drill diameter varies between 25 and 28 mm, depending on tapping conditions in previous tap. The hot metal temperature is measured with a temperature probe. Hot metal and slag are sampled during each cast and analysed by SSAB Tunnplåt AB. Normal analyse response time is 20 minutes.

The test periods normally start with a transition period where the test material is charged to the furnace for a period of 24-36 hours, corresponding to six to nine throughputs. After that period the actual test starts. The test time depends on what objectives are to be met for the test. A typical test period ranges from two days up to six days. During this time operational data are logged and monitored closely. Sampling of burden materials, using the burden probes, is done once or twice every shift.

Reference material is charged to the furnace at regular intervals to check if there has been any change in the furnace or auxiliary equipment that might influence the operation.

Process data are logged every second and stored in a database, as ten-second and minute averages. These data are transferred at regular intervals to another database where process data calculations are carried out. Data in this database are used for reports, trend charts and mass and heat balance calculations. Chemical analyses for raw materials, hot metal and slag are also stored in this database.

Presently, the experience is that the EBF is capable of simulating the operation of all tested commercial furnaces quite well. It has also proven to be a very sensitive tool for detecting differences in properties for different ferrous burden materials. The response time is shorter for the experimental furnace compared to a commercial furnace. One example is the time for the blast furnace to go from normal heat level to cold condition, is sometimes less than six hours. On the other hand, the blast furnace also recovers quickly to normal conditions, after corrective actions are made.

During the campaigns performed so far, many different process concepts have been tested in the EBF. Examples are:

- 100% pellets as ferrous burden with injection of PC in the range of 0–180 kg/tHM
- Simultaneous injection of PC and fluxes up to 100 kg/tHM and 40 kg/tHM, respectively.
- The slag rate has varied between 75 kg/tHM and 230 kg/tHM.
- Sinter/lump ore/pellets as ferrous burden with pellet ratio from 20% to 60%.
- Oil injection up to 200 kg/tHM.

These various operational modes have given different results not only in consumption figures but also in process characteristics. For example, some of the trials with large amounts of lump ore give dramatically changes in operational stability.

The operational behaviour of EBF has proved to be similar to that of commercial-scale blast furnaces. Among the important areas are formation of different zones inside the blast furnace, the composition of the reducing gas and gas distribution over the radius.

One concern regarding small blast furnaces is if the zones that normally are present in full-scale blast furnaces also exist in the EBF. This is important from many different aspects, but mostly for correct simulation. If there are lumpy or granular, cohesive and dripping zones present in the EBF, the blast furnace process with reduction and melting of the ferrous burden will proceed in the same manner as in a full-scale furnace. In the seven different dissections that have been made so far, the presence of a cohesive zone has been proved, located about 1.5–2.0 meters above tuyere level.

**DISSECTION OF THE EBF**

At the end of seven of the campaigns the EBF was quenched and dissected. During the final hours of operation a number of basket-samples with various test materials were introduced into the furnace.
At shutdown the burden column is flushed with nitrogen gas from the top. The nitrogen then blows down the furnace leaving the furnace through the tuyeres. Within about one minute, the reducing gases are removed and the chemical reactions stop. As the quenching gas is added from the top, an upward moving heat wave, is avoided, thus limiting reactions caused by heat to the oxide material such as further melting and changes of slag composition. The burden in the furnace and the refractories need to be cooled for at least ten days by nitrogen flushing before dissection of the furnace can start. To facilitate access to the furnace interior, the top can be dismounted.

Dissection is carried out much like an archaeological excavation. As long as possible, the original pellet and coke layers are followed. The work is concentrated on the ferrous burden layers. Samples are taken from every layer, according to a predetermined plan. Small samples for microanalysis are collected as well as larger samples for chemical and mechanical testing, sometimes whole structures are preserved, like parts of the cohesive zone or parts of the raceway. Throughout the work great effort is spent on documenting all observations, photographing and video filming, in addition to written documentation.

**DISSECTION DETAILS**

The dissections discussed in this paper were performed in the same manner in all cases. One dissection takes about two weeks to complete and there are about 5 people in the dissection team. The main idea is to remove and sample each layer in the EBF carefully according to a fixed sampling routine, after observing and documenting the shape, position and any anomalies in the layers that might occur.

A significant amount of information and data is generated in each dissection. The samples are further analysed chemically and also characterised by optical microscopy and SEM microscopy. Although the coke is sampled, there have been only a few analyses made on these samples, predominantly because the main objective in these campaigns was to study the behaviour of the ferrous burden materials in the EBF. Coke and fluxes added were also kept at the same quality and size distribution throughout all campaigns.

The main outputs from each dissection are:
- position, shape and characteristics of each individual ferrous burden layer in the EBF;
- assays of ferrous burden materials;
- mechanical strength of ferrous burden materials;
- structure and phases present in individual iron ore pellets sampled in the furnace; and
- analysis of “interesting” anomalies in the furnace, such as scaffolds, dusts, agglomerates and so on.

By combining these outputs it is possible to characterise the overall properties of the burden column as found in the EBF.

**CONDITIONS PRIOR TO QUENCHING**

In Table 1 the composition of the ferrous burden materials (iron ore pellets and sinter) in the different dissections in the EBF are given.

<table>
<thead>
<tr>
<th>Burden</th>
<th>Fe (%)</th>
<th>SiO₂ (%)</th>
<th>CaO (%)</th>
<th>MgO (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2 100% olivine pellet KPBO</td>
<td>66.8</td>
<td>2.20</td>
<td>0.39</td>
<td>1.60</td>
</tr>
<tr>
<td>D3 100% lime/olivine fluxed pellet LOFP</td>
<td>66.9</td>
<td>1.25</td>
<td>1.25</td>
<td>0.85</td>
</tr>
<tr>
<td>D4 100% lime fluxed pellet LFBP</td>
<td>67.2</td>
<td>1.50</td>
<td>1.50</td>
<td>0.30</td>
</tr>
<tr>
<td>D5 100% quartzite/lime pellet KPBA</td>
<td>67.0</td>
<td>2.50</td>
<td>0.60</td>
<td>0.52</td>
</tr>
<tr>
<td>D6 70% sinter 30% KPBA</td>
<td>60.5</td>
<td>4.33</td>
<td>7.16</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>67.0</td>
<td>2.50</td>
<td>0.60</td>
<td>0.50</td>
</tr>
</tbody>
</table>

All pellet types have small slag amounts, 3.8% to 4.7%. The sinter has 13.6% slag (Slag is calculated as CaO+SiO₂+MgO+Al₂O₃).

Some of the operating conditions as an average for the last 8 hours before quenching can be seen from Table 2 and Table 3.

<table>
<thead>
<tr>
<th>Prod (t/h)</th>
<th>Oxygen enrich (%)</th>
<th>Blast vol (Nm³/h)</th>
<th>Injection* kg/tHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>1.29</td>
<td>2.0</td>
<td>1640</td>
</tr>
<tr>
<td>D3</td>
<td>1.47</td>
<td>2.7</td>
<td>1640</td>
</tr>
<tr>
<td>D4</td>
<td>1.36</td>
<td>2.1</td>
<td>1590</td>
</tr>
<tr>
<td>D5</td>
<td>1.41</td>
<td>1.2</td>
<td>1690</td>
</tr>
<tr>
<td>D6</td>
<td>1.46</td>
<td>2.1</td>
<td>1760</td>
</tr>
</tbody>
</table>

*PC stands for Pulverised Coal

The EBF operated on slightly different production levels in the different campaigns. The lowest was in campaign 2 at 88% of the highest production rate in campaign 3. The oxygen enrichment was between
1.2 to 2.7%, the lowest in campaign 5 and the highest in campaign 3.

Four of the dissections were made with 100% pellet as ferrous burden material (dissections D2-D5) and the fifth with a mixed burden of sinter/pellets in the EBF. The auxiliary reductant injected, was pulverised coal (PC) in campaign 2–5, at rates of 84–95 kg/tHM and 55 kg/tHM oil in campaign 6.

The injection coal used, was the same in all cases: a high volatile coal with about 39% volatile, 6% ash and a fixed carbon content of 78%. The oil was a high sulphur diesel oil with a calorific value of 44.5 J/kg and 1.3% sulphur.

Table 3 Calculated operating parameters prior to quenching.

<table>
<thead>
<tr>
<th></th>
<th>Bosh gas CO (%)</th>
<th>Bosh gas H2 (%)</th>
<th>DRR (%)</th>
<th>Eta CO (%)</th>
<th>dP (kPa)</th>
<th>Flame Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>36</td>
<td>5.0</td>
<td>35</td>
<td>43.4</td>
<td>2.9</td>
<td>2170</td>
</tr>
<tr>
<td>D3</td>
<td>37</td>
<td>6.7</td>
<td>32</td>
<td>45.5</td>
<td>1.6</td>
<td>2120</td>
</tr>
<tr>
<td>D4</td>
<td>37</td>
<td>6.5</td>
<td>30</td>
<td>47.2</td>
<td>1.6</td>
<td>2116</td>
</tr>
<tr>
<td>D5</td>
<td>36</td>
<td>6.5</td>
<td>31</td>
<td>47.5</td>
<td>1.0</td>
<td>2133</td>
</tr>
<tr>
<td>D6</td>
<td>36</td>
<td>8.5</td>
<td>32</td>
<td>46.6</td>
<td>2.1</td>
<td>2144</td>
</tr>
</tbody>
</table>

The composition of the bosh gas was different in campaigns 2 and 6, where the hydrogen content was about 1.5% lower and in the other case 2% higher.

Calculated DRR, Direct Reduction Rate, was high in campaign 2, which also had the lowest gas utilisation. The differential pressure between the bosh and the lower shaft was highest in campaign 2, and lowest in campaign 5.

A few results from the operation during the last 8 hours are shown in Table 4.

Table 4 Operation results before quenching.

<table>
<thead>
<tr>
<th></th>
<th>Reductant (kg/tHM)</th>
<th>Slag rate kg/tHM</th>
<th>HM Temp (°C)</th>
<th>Top gas (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>535</td>
<td>140</td>
<td>1462</td>
<td>204</td>
</tr>
<tr>
<td>D3</td>
<td>543</td>
<td>146</td>
<td>1409</td>
<td>158</td>
</tr>
<tr>
<td>D4</td>
<td>530</td>
<td>76</td>
<td>1435</td>
<td>207</td>
</tr>
<tr>
<td>D5</td>
<td>547</td>
<td>139</td>
<td>1408</td>
<td>218</td>
</tr>
<tr>
<td>D6</td>
<td>519</td>
<td>177</td>
<td>1449</td>
<td>181</td>
</tr>
</tbody>
</table>

The reductant rate (coke + auxiliary injection) was low in campaign 6. The replacement ratio for the oil versus coke was about 1.26. The top gas temperature was normal in all cases except for campaign 3 with an unusually low top gas temperature.

The higher DRR and lower Eta CO in campaign 2 is probably caused by a disturbance, a small slip that occurred about 4 hours before quenching.

In terms of fluctuating gas utilisation and irregular burden descent, the operational stability in the test with lime/olivine fluxed pellets in campaign 3 was poor. The reason for this was most likely that the pellet had a low strength during reduction and had a tendency for swelling, which caused hangings and slips during the trial period.

In campaign 4 an extremely low slag rate was used (75–80 kg/tHM), as this was a trial with co-injection of fluxes with PC.

In campaign 5 and 6 the same pellet quality was used, but in campaign 6, 70% sinter was used in the mixed burden.

RESULTS FROM LABORATORY TESTS

Laboratory-based high temperature and reducibility data for actual pellets were used for identifying whether a specific property could be linked to the position and thickness of the cohesive zone as found in the different dissections.

Table 5 provides the main results from reduction/melt down tests performed at LKAB’s research laboratory in Malmberget. The test starts with a pre-reduction of the sample, normally to 65% degree of reduction. The sample, about 0.300 kg in weight is then transferred to a graphite crucible, Fig. 2, having a diameter of 0.049 m, and placed in an HF induction furnace. A load of 49 kPa is applied and the sample is heated under nitrogen gas flow of 180 Nl/h until complete meltdown. Heating rates in the HF induction furnace are 150°C/min up till 1100°C and then 10°C/min until meltdown. During the heat up, weight loss, bed contraction and weight of dripping material are recorded.

The definition for softening of the material has been chosen at the temperature where 50% bed
contraction occurs, TE50. The softening-melting interval is defined as the interval between TE50 and TE100, the latter is the temperature at 100% bed contraction. The temperature for the start of melting is recorded when the sample starts losing weight and dripping starts, Tm. The temperature where melting ends is recorded as Tmf.

**In the literature attempts have been made to correlate these critical temperatures for the ferrous burden materials to the position (melting temperature) and extension or thickness (temperature interval TE50 – TE100) of the cohesive zone.** Based on these assumptions and the results in **Table 5 and Table 6**, the position of the cohesive zone for the different burden materials should be:

1. highest in the blast furnace for KPBA and LFBF;
2. lower for LOBF and mixed KPBA/sinter burden; and
3. lowest for KPBO.

The extension/thickness of the cohesive zone should be:

1. largest for the mixed burden and KPBO
2. less for KPBA and LOBP burden
3. least for LFBP

To compare the reduction profile found at the different dissections, all pellets were tested in the RUL-test (Reduction Under Load) according to the ISO standard 7992. The results can be found in **Table 7**.

**Table 5** Main results from LKAB melt-down test.

<table>
<thead>
<tr>
<th>Pellet</th>
<th>TE50 (°C)</th>
<th>TE 50 - TE100 (°C)</th>
<th>Tm Start (°C)</th>
<th>dT Tm-Tmf (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPBO</td>
<td>1325</td>
<td>184</td>
<td>1490</td>
<td>22</td>
</tr>
<tr>
<td>LOBP</td>
<td>1359</td>
<td>112</td>
<td>1414</td>
<td>62</td>
</tr>
<tr>
<td>LFBP</td>
<td>1330</td>
<td>96</td>
<td>1384</td>
<td>57</td>
</tr>
<tr>
<td>KPBA</td>
<td>1264</td>
<td>171</td>
<td>1383</td>
<td>54</td>
</tr>
<tr>
<td>KPBA+S</td>
<td>1288</td>
<td>224</td>
<td>1489</td>
<td>27</td>
</tr>
</tbody>
</table>

In **Table 5** the lime/olivine-fluxed pellet, LOBP, has the highest softening temperature followed by the lime-fluxed pellet, LFBP, and olivine pellet, KPBO. Quartzite/lime pellets KPBA and KPBA mixed with sinter, have the lowest softening temperature. Conversely, KPBO and mixed KPBA/sinter have the highest melting point, followed by LOBP, LFBP and KPBA have the lowest meltdown temperatures.

The temperature difference between TE50 and TE100 is lowest for LOBF and LFBF (about 100°C), larger for KPBO and KPBA (about 175°C), while the largest temperature difference is found for the mixed KPBA and sinter sample (about 220°C).

**Table 6** gives the corresponding results for samples of KPBO and KPBA from reduction/melt down tests (REAS-test) performed by Studien-Gesellschaft für Eisenerz-Aufbereitung (SGA) in Othfresen, Germany. This test is described in detail in other papers.

In the REAS test the sample is placed between graphite layers and a load of 98 kPa is applied. The sample is heated while reducing gas is flowing through the sample until 65% degree of reduction (in this case) and then proceeds under inert atmosphere, (100% N₂) until meltdown of the sample. Shrinkage, pressure drop, weight loss, incoming and outgoing gas composition and weight of dripping material are recorded.

**Table 6** Results from REAS test KPBO and KPBA.

<table>
<thead>
<tr>
<th>Pellet</th>
<th>TE50 (°C)</th>
<th>TE50 - TE100 (°C)</th>
<th>Tm S (°C)</th>
<th>dT Tm-Tmf (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPBO</td>
<td>1290</td>
<td>60</td>
<td>1350</td>
<td>50</td>
</tr>
<tr>
<td>KPBA</td>
<td>1260</td>
<td>45</td>
<td>1305</td>
<td>30</td>
</tr>
</tbody>
</table>

**Table 6** shows that there are similar relativities although smaller in the critical temperatures, between the two types of pellets as in the LKAB test. The temperatures are also lower, especially for the start of meltdown.

Table 6 shows that there are similar relativities although smaller in the critical temperatures, between the two types of pellets as in the LKAB test. The temperatures are also lower, especially for the start of meltdown.

A sample of 1.200 kg in weight is placed in the furnace and the sample is heated to 500°C under nitrogen flow of 25 Nl/min for 45 minutes. This temperature is kept constant for 15 minutes and the nitrogen flow is increased to 50 Nl/min. A load of 44 kPa is imposed on the sample, with further heating to 850°C for 70 minutes and with a gas composition of 20% CO/21% CO₂/6% H₂/53% N₂ at 50 Nl/min.

After that time the gas composition is changed to 38% CO, 3% CO₂, 6% H₂ and 53% N₂ at the same gas flow. The load is increased to 98 kPa and heated to 950 °C for 90 minutes. The test proceeds with a
gas composition of 41% CO, 0% CO₂, 6% H₂ and 53% N₂, heated to 1100°C for 55 minutes under the same load. The test is stopped when the desired reduction degree is reached, normally 65%. The reduction time, R₄₀, pressure drop and bed height shrinkage is reported.

The results in Table 7 show differences expressed as the R₄₀, reduction rate at 40% reduction degree. The highest reduction rate is for the lime-fluxed pellet, LFBP, and the lowest for the quartzite/lime fluxed pellet, KPBA. The difference is 0.17 in absolute value, corresponding to 13% higher reduction rate. The difference in reduction time to reach 80% reduction degree is 7 minutes and this means that KPBA takes about 10% longer time to reach that reduction degree.

The maximum differential pressure over the bed during reduction is very different for the pellets in the test, ranging from 4 to 28 mm water gauge. The high value means that there may be a risk of a high pressure drop in the lower part of the blast furnace.

The results for LKAB RUL-test in Table 8 are similar and in this case the highest reduction rate R₄₀ is measured for the sinter. The difference in pressure drop is much smaller in this test but the lowest pressure drop is still for the lime-fluxed pellet, LFBP.

**RESULTS FROM DISSECTIONS**

The results from 5 different dissections of the EBF are given as:

- macrostructure of the burden column with characterisation of the cohesive zone;
- Reduction degree Rg %, of the ferrous burden close to the cohesive zone as calculated from chemical assays and characterisation with optical microscopy; and
- The potassium, zinc and sulphur assays for the samples close to the cohesive zone

The cohesive zone is characterised using 4 key parameters, 3 measured distances and one ratio:

1. Distance from stockline to the top of the cohesive zone, dS-T;
2. Distance from the top to the end of the “root” of the cohesive zone, dT-Re;
3. Distance from the top of the cohesive zone to the start of the “root”, dT-Rs; and
4. The height of the “root” as percentage of the total height of the cohesive zone, %Rh

All distances are given in mm. The reduction degree, Rg %, is defined as the proportion of oxygen removed in relation to the original oxygen content of the iron oxide:

\[
Rg (\%) = \frac{m_{\text{acc,rem}}}{m_{\text{ori}}} \times 100 \tag{1}
\]

where \( m_{\text{acc,rem}} \) is the accumulated mass of oxygen removed from the specimen, and \( m_{\text{ori}} \) is the original content of oxygen present as iron oxides.

The reduction degree from microscopy characterisation, Rgo %, is calculated from the volume % of identified iron oxides in the sample, calculated with help of image analysis. The assumed oxygen percentages for each type of iron oxide is summarised and the reduction degree is calculated according to (1).

The results from dissections D2, D4, D5, D6 are discussed based on the results from the various analysis and chemical assays made. Dissection D3 is not discussed in detail because of the poor operational characteristics at quenching.

**MACROSTRUCTURE OF THE BURDEN COLUMN**

In Fig. 3 the general macrostructure of the burden column in D6 is shown.

The definition of the cohesive zone chosen in this study is as follows:

1. Cohesive zone, CZ, starts when ferrous burden materials shows agglomeration and deformation and/or has a reduction degree of 65% or more; and
2. The “root” is the part of the cohesive zone that extends to the furnace wall.

It is not always straightforward to give the exact location of and the extent of the CZ. This is due to the fact that it often difficult to follow the layer structure in the furnace especially when the ferrous burden layers consist of one part that is compressed/agglomerated (cohesive) and the other part remains uncompressed over rest of the radius.

Another source of error is that even if each layer is removed as complete as possible by using high capacity vacuum suction, there is always a risk that pellets or pieces of sinter will percolate down to
lower layers; this is sometimes seen in the samples removed from the furnace.

Over all, it is the documentation of each layer that gives the major input for the analysis of the macrostructure of the burden. This information is then checked against the results from chemical assays and characterisation by microscopy of the samples taken at the different dissections.

In D3 a large cavity was found just below the top of the CZ. This cavity was about 1.0 m high, with a diameter of 0.25 m at the top and 0.45 m at the bottom taking up about 20% of the EBF volume in that area.

The presence of cavities, channels and scaffolds in the burden and at the furnace wall has also been recorded in other dissections. Also recorded were “fused” layers, where most of the pellets are welded together, forming a grid. There has been little deformation of the pellets in these layers and it is not a “true” cohesive layer because there are voids in the grid that make it possible for the gas to pass. It seems to be easier for these to form if the ferrous burden materials have high reducibility, or rather are lime-fluxed.

The cavities and channels seem to be very stable structures as the inner surface usually have a high degree of metallisation higher up than the rest of the burden. In Fig. 4 an example of a cavity about 0.1 × 0.15 m in the cohesive zone – is shown. The picture is from D4. In the case of dissections D2, D4, D5 and D6 the operation was regarded as normal, despite the various structures in the burden column. These are probably quite common during operation.

As can be seen from Table 9, there are differences between the dissections. The most important are:

1. The lowest position of the CZ is found in D2 with olivine pellets KPBO as ferrous burden material.
2. The lowest root position is found in D6 where 70% sinter and 30% KPBA pellet were used as ferrous burden materials.
3. The olivine pellet KPBO gives the shortest CZ D2 and the shortest root part (33% of the total CZ height).
4. The largest difference in CZ height is between D2 and D4 (D3 is excluded because of

### Table 9 Key parameters for the CZ in D2 – D6.

<table>
<thead>
<tr>
<th>Layer</th>
<th>dS-T (mm)</th>
<th>dT-Re (mm)</th>
<th>DT-Rs (mm)</th>
<th>%Rh (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>3920</td>
<td>1050</td>
<td>700</td>
<td>33</td>
</tr>
<tr>
<td>D3</td>
<td>3220</td>
<td>1950</td>
<td>750</td>
<td>62</td>
</tr>
<tr>
<td>D4</td>
<td>3410</td>
<td>1720</td>
<td>650</td>
<td>62</td>
</tr>
<tr>
<td>D5</td>
<td>3560</td>
<td>1320</td>
<td>600</td>
<td>55</td>
</tr>
<tr>
<td>D6</td>
<td>3750</td>
<td>1480</td>
<td>920</td>
<td>38</td>
</tr>
</tbody>
</table>

In general the CZ occupy about one fourth of the working height (the distance between the stockline and tuyere level) in the EBF, but the variations are quite large, from 18 to 34%.
operational problems); the CZ in D2 is about 60% of that in D4.

5. The cohesive zone is extended much more in horizontal direction (root part) for lime-fluxed pellets, LFBF, in D4.

Other observations that are consistent for the different dissections are the presence of slag formers all the way down to the tuyere level. The only fluxes that seem to melt in the shaft and bosh are different slag products like BOF slag that are sometimes used as burden flux material. Limestone and quartzite remain as discrete particles or as discrete masses (limestone after calcination). On the quartzite particles, an outer rim is formed consisting of alkali-silicate compounds.

RESULTS FROM BURDEN SAMPLING

Table 10 gives the calculated reduction degree from chemical assays together with results from characterisation of polished sections in optical microscopy as an average for the sampled layers at four different levels. The polished sections are from D4 (D4 Mic) and D5 (D5 Mic) and are sampled from the same layers as the chemical samples. The heights given in Table 8 are mean values and the true values for the different campaigns vary ±0.1 m. The first level at 3.0 m is located above the top of the CZ in all cases. The second to fourth level is inside the CZ for all dissections except D2 where the level 4.0 m is just at the top of the CZ.

<table>
<thead>
<tr>
<th></th>
<th>Rg % At 3.0 m</th>
<th>Rg % At 3.5 m</th>
<th>Rg % At 4.0 m</th>
<th>Rg % At 4.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>22</td>
<td>31</td>
<td>48</td>
<td>64</td>
</tr>
<tr>
<td>D4</td>
<td>32</td>
<td>50</td>
<td>69</td>
<td>95</td>
</tr>
<tr>
<td>D4 Mic</td>
<td>32</td>
<td>61</td>
<td>76</td>
<td>100</td>
</tr>
<tr>
<td>D5</td>
<td>38</td>
<td>54</td>
<td>66</td>
<td>83</td>
</tr>
<tr>
<td>D5 Mic</td>
<td>35</td>
<td>75</td>
<td>97</td>
<td>100</td>
</tr>
<tr>
<td>D6 P</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>D6 S</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>95</td>
</tr>
</tbody>
</table>

The calculated reduction degree does not vary significantly between the different dissections except for D2, where the KPBO pellet has a significantly lower Rg % compared with the results from the other dissections (but, at the same time, these samples are outside the cohesive zone). It is notable that the Rgo % from microscopy characterisation in D4 and D5, are higher than the calculated Rg % for samples taken in the cohesive zone based on chemical assays.

An interesting result is that the Rg % for the KPBA pellet and the sinter in D6 are almost identical, despite the big difference in reducibility measured in laboratory tests.

In Fig. 5 the Rg % from D2, D4 to D6 is graphed for samples taken at mid-radius in the dissection. The Rg % in Fig. 5 gives the same trends as found in Table 10.

The samples taken from the dissections were analysed for potassium, zinc and sulphur. The loads for K₂O and sulphur are given in Table 11.

<table>
<thead>
<tr>
<th></th>
<th>K₂O (kg/tHM)</th>
<th>Sulphur (kg/HM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>1.2</td>
<td>3.7</td>
</tr>
<tr>
<td>D4</td>
<td>1.0</td>
<td>4.1</td>
</tr>
<tr>
<td>D5</td>
<td>1.7</td>
<td>3.3</td>
</tr>
<tr>
<td>D6</td>
<td>1.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>

The results from the sampling are given in Table 12 and Fig. 6–8.

Generally there are gradients in the concentration of these elements along the height of the EBF.
- $K_2O$ concentration increases with the depth of the cohesive zone;
- $Zn$ has an maximum in the middle shaft; and
- Sulphur has the same trend as $K_2O$, with concentration increasing with increasing depth.

Potassium, zinc and sulphur assays at the root of the CZ, level 4.5 m below stockline are listed in Table 12. Note that only the pellet analysis for D6 is given.

<table>
<thead>
<tr>
<th></th>
<th>$K_2O$ (%)</th>
<th>Zinc (ppm)</th>
<th>Sulphur (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>0.77</td>
<td>171</td>
<td>729</td>
</tr>
<tr>
<td>D4</td>
<td>0.72</td>
<td>120</td>
<td>1211</td>
</tr>
<tr>
<td>D5</td>
<td>0.61</td>
<td>18</td>
<td>--</td>
</tr>
<tr>
<td>D6 P</td>
<td>1.21</td>
<td>14</td>
<td>65</td>
</tr>
</tbody>
</table>

The potassium assays in Table 12 have a variation of about 30% with the highest value for pellet KPBA in D6, but the assay for the same pellet in D5 has the lowest value. It is possible that this difference can be explained by the presence of sinter in D6, where the pellet amount is about 30%. Otherwise there seems to be no differences between the different burden materials from the point of $K_2O$ uptake.

Even though the $K_2O$ load in D5 and D6 are higher, the mechanisms of alkaline circulation are not directly connected to the input.

The graphs in Fig. 6 also indicate that the slag phase composition in the pellet does not affect the alkaline uptake in any major way. There are however indications from Fig. 6 that the most “acid” pellet KPBA also have the highest $K_2O$ assays.

Sulphur concentration in the lower part of the cohesive zone shows large variations between the different dissections, as can be seen in Table 12 and Fig. 8. This is most likely an effect of the slag.
composition in the ferrous burden. The pellets with the lowest basicity have also the lowest sulphur content. The difference is very large for the quartzite/lime pellet, KPBA, compared to the lime-fluxed pellet, LFBF.

![Graph showing sulphur assays from dissection samples.]

**Fig. 8** Sulphur assays from dissection samples.

**DISCUSSION**

The results from the different dissections provide a general picture about the internal state of the EBF at the time of quenching. Among the interesting observations is the presence of different structures in the burden column that creates a non-homogenous burden. This type of structure normally starts around the cohesive zone and often takes the form of cavities, channels, sintered/fused aggregates and scaffolds at the wall. The amount and extension of these varies between each dissection but can be found in all dissections analysed. The presence of these structures are probably common also in commercial size blast furnaces and are the likely cause for variations in gas utilisation, burden descent and heat level for the hot metal. The operational characteristics of the EBF, prior to quenching, were regarded as normal in all cases, except for D3.

There are few indications that the ferrous burden properties can be correlated to these structures. As an example, they are more common for burden materials that form a porous iron shell during reduction, which is typical for lime-fluxed pellets.

When analysing the different zones or levels in the blast furnace it becomes clear that the formation of a cohesive zone and the properties of that zone are essential for the overall process results.

It is not only the cohesive mass formed, but also phenomena such as fusing of ferrous burden material and forming a “grid” in the blast furnace before softening and melting starts. The question arises if these kind of grids give an improved operation by preserving the layer structure before softening and melting, or if it impairs the descent of material at the beginning of the cohesive zone because of the differential burden descent rates over the radius in that part of the blast furnace.

Based on the samples from the dissections, it is possible to follow the way the reduction proceeds in the EBF. It can be observed that there are only small differences in reduction profile between the different materials tested. It is also worth noting that the reduction degrees for the separate components in the mixed burden of sinter and quartzite/lime pellets are almost the same at corresponding levels, despite the large difference in $R_{40}$ in the LKAB RUL-test.

The reduction pattern seems to be more dependent on the interaction between the reducing gas and the ferrous burden materials, than the measured reducibility under laboratory conditions. The balance between gas demand and heat demand in the process also controls the reduction of the ferrous burden and the direct reduction rate in the process.

The position of the cohesive zone can be linked to the melting point of the ferrous burden materials. In this study, it has not been possible to correlate the thickness of the cohesive zone with the softening/melting interval from high temperature tests.

The circulation and uptake of trace elements like K$_2$O, zinc and sulphur show the same pattern in the different dissections. The concentration of potassium is rapidly increasing in the materials below the start of the cohesive zone, probably because part of the potassium in the furnace is combined with the gangue and forms more stable phases like alkali silicates.

Zinc concentration is high at levels above the cohesive zone. The highest zinc concentrations can be found in top layers of the burden.

Sulphur behaviour is linked to the concentration and amount of CaO in the burden materials and the
highest concentration is found in the lime-fluxed pellets.

CONCLUSIONS

Based on the analysis of the dissections made in the LKAB Experimental Blast Furnace the following can be concluded:

1. The burden column does not keep the same undisturbed layer structure throughout the furnace height, as structures such as cavities and channels are formed during operation. These are most frequent in the area where the cohesive zone exists.
2. The different high temperature test can be used to predict the position of the cohesive zone, but not the thickness.
3. The reduction of the different ferrous burden materials examined proceeds in the same way, with very little difference between materials.
4. Despite very large differences in reducibility for two different burden materials, the reduction degrees at the same level in the furnace are nearly the same.
5. The alkali concentration in the ferrous burden increases in the cohesive zone.
6. The zinc accumulates in the upper/middle shaft.
7. The uptake of sulphur is linked to the amount of CaO in the ferrous burden materials.

The main conclusions from the analysis of the different dissections are that the behaviour of the burden column during operation is influenced by irregularities which results in an inhomogeneous burden column which is most pronounced in the area where the cohesive zone exists. This phenomenon is probably common in blast furnaces and explains the presence of operational disturbances such as hangings, slips and variation in heat level for the hot metal.

It is however difficult to find properties of the burden materials that can be linked to the formation of these structures.

One way to predict the risk for disturbances can be to follow the process by on-line measurements of size distribution, calculated scaffolding, cohesive zone calculations and so on.

There is a great deal more information to be assessed in the samples from the different dissections and this needs to be evaluated to broaden the knowledge of ferrous burden materials behaviour in the EBF. This work will continue with the objective to understand the mechanisms for reduction, the influence of various process conditions and to identify material properties important for the formation of structures in the cohesive zone.

ACKNOWLEDGEMENT

The author would like to thank all colleagues and research staff at LKAB, MEFOS and contractors that contributed in planning and conducting the campaigns in the EBF. A special thanks to the different “dissection teams”, consisting of students and LKAB technicians, but always under the supervision of Per-Ola Eriksson.

Finally I like to thank the LKAB research team at the EBF and professors Bo Björkman and Jan-Olof Wikström for fruitful discussions.

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