Comparison of iron ore reduction in experimental blast furnace and laboratory scale simulation of blast furnace process

J. Sterneland, M. A. T. Andersson and P. G. Jönsson

The reduction of iron ore pellets in an experimental blast furnace has been surveyed by dissection of the blast furnace. Results of the dissection, as well as some results of measurements taken in the blast furnace interior during operation, have been compared with those of previously conducted laboratory reduction, softening and melting tests using the same type of pellets. The aim of the work was to compare laboratory testing with results from an experimental blast furnace. The high temperature phenomena occurring when reducing olivine iron ore pellets, with limited softening and a short temperature range of the melting process resulting in a thin cohesive zone, were found to be the same in laboratory tests and in the experimental blast furnace. The reduction process down through the burden of the experimental blast furnace, however, was not identical to that in the reduction, softening and melting experiments. The differences obtained were found to arise from different reducing conditions. Therefore, it was concluded that simulation of the reduction occurring in the blast furnace can be conducted on a laboratory scale, provided that the experimental conditions are carefully chosen for the specific blast furnace process to be simulated. Information about the internal state of the blast furnace can be obtained from the experimental blast furnace. I&S/1727

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INTRODUCTION

To improve the performance of the blast furnace, it is of interest to increase knowledge of iron oxide reduction in the furnace for various types of iron bearing materials. In blast furnaces in Sweden, only pellets are used as iron bearing materials. If knowledge of the behaviour of different types of pellets with respect to the reduction of iron oxide can be developed, it would be possible to optimise the properties of the pellets to result in optimum performance of the blast furnace.

There is little recent information reported with regard to the reduction degree of iron oxides within commercial blast furnaces. The reason is, of course, that this is difficult to measure during operation. Since the 1970s and early 1980s, when many blast furnaces were quenched and dissected (mostly in Japan, but also in the USA, former Soviet Union and Europe),1 the opportunity to examine the internal state of a commercial size blast furnace has been limited. The information from blast furnace dissections in the past can be difficult to interpret, since quenching in most cases was done using water. Water quenching may alter the oxidation state of the blast furnace burden, for instance by the reaction $\text{FeO} + \text{H}_2\text{O} = \text{FeO} + \text{H}_2$, and also a temperature increase in the shaft has been observed during water quenching.1 In addition, the blast furnace process has advanced considerably since the 1970s, and the dissection information is therefore not up to date.

Information regarding the reduction behaviour of iron oxide can also be obtained using an experimental pilot plant blast furnace. The size of an experimental blast furnace should be large enough to enable simulation of the operation of a commercial size blast furnace, and at the same time small enough to be economical for research purposes. The comparatively small size of the furnace provides opportunities for quenching and dissecting the furnace, so that up dated information about the reduction degree of iron oxide in various locations can be obtained. However, since experiments in an experimental blast furnace can still be fairly costly it would also be useful to carry out tests in a small laboratory furnace to determine the trials that are worthwhile conducting in the experimental blast furnace.

In the literature, a large number of researchers have studied the reduction behaviour of iron oxide in laboratory experiments.2–10 In a previous study at KTH (the Royal Institute of Technology, Stockholm, Sweden), a reduction, softening and melting, also called reduction under load, apparatus was used to characterise the behaviour of olivine iron ore pellets during reduction.11,12 Since then, trials have been conducted in the LKAB experimental blast furnace using the same type of material as burden feed, the olivine pellet MPBO (Malmberget Pellet Blast furnace Olivine, produced at the LKAB Malmberget mine). Part of the results from these trials are reported in the present work.

Earlier publications relating to the LKAB experimental blast furnace have dealt with the design, instrumentation and operation of the furnace, results from trials with various iron bearing materials (especially different pellet types, but also sinter and lump ores) and comparisons with commercial size blast furnaces.13–16 Some results from dissection of the experimental blast furnace have also been published.17 The aim of the present work was to compare results from the experimental blast furnace with results from laboratory testing, with the focus on reduction behaviour. To allow comparison, the operation of the experimental blast furnace and some of the measurements made should be explained. Therefore, the first part of the present paper describes how the experiments were carried out in the experimental blast furnace, and also the procedure of the laboratory scale tests. Thereafter, comparison of data from the experimental and laboratory furnaces is made and discussed, including the temperature and gas profiles obtained, the progress of reduction and phase distribution during reduction, and finally qualitative information on softening and melting.
Table 1 Experimental blast furnace specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working volume</td>
<td>8.2 m³</td>
</tr>
<tr>
<td>Hearth diameter</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Working height</td>
<td>5.9 m</td>
</tr>
<tr>
<td>Tuyeres</td>
<td>Diameter 54 mm (× 3)</td>
</tr>
<tr>
<td>Top pressure</td>
<td>Up to 1-1 bar</td>
</tr>
<tr>
<td>Charging</td>
<td>Modified bell type</td>
</tr>
<tr>
<td>Burden distribution</td>
<td>Movable armour</td>
</tr>
<tr>
<td>Injection</td>
<td>Coal, oil, slag formers</td>
</tr>
<tr>
<td>Blast</td>
<td>Up to 2000 Nm² h⁻¹</td>
</tr>
<tr>
<td>Blast heating</td>
<td>Pebble heaters</td>
</tr>
<tr>
<td>Max. blast temp.</td>
<td>1300 °C</td>
</tr>
<tr>
<td>Furnace crew</td>
<td>5-shift</td>
</tr>
<tr>
<td>Tapping volume¹</td>
<td>1-3–1.8 tHM² tap</td>
</tr>
<tr>
<td>Tap time</td>
<td>5-10 min</td>
</tr>
<tr>
<td>Tapping interval</td>
<td>60 min</td>
</tr>
<tr>
<td>Reducing agents¹</td>
<td>510–540 kg tHM</td>
</tr>
<tr>
<td>Quenching N₂ gas flow</td>
<td>300–400 m³ h⁻¹</td>
</tr>
</tbody>
</table>

¹tHM is tonne of hot metal.

*Excluding sampling research staff.

EXPERIMENTAL BLAST FURNACE

General

When LKAB decided to build the experimental blast furnace in 1997, one of the goals was to provide the best tool for blast furnace research. All typical equipment required for a blast furnace has therefore been installed in the experimental blast furnace, and the monitoring and measuring facilities are even more extensive. The general specifications and operating parameters of the experimental blast furnace are given in Table 1. Compared with a commercial blast furnace, the experimental blast furnace has less compression of the burden, shorter gas and iron ore residence time, higher heat losses (per tonne of hot metal), lower hot metal temperature and higher hot metal silicon content.† Despite these differences, the experimental blast furnace incorporates a complete ironmaking process as in the commercial blast furnace. All operating functions, including reduction, softening, melting, desulphurising, alkali recirculation and so on, are the same. In addition, some abnormal events such as scaffolding, hanging, channelling and other typical disturbances may also occur in the experimental blast furnace, depending on operating conditions and burden quality. The main difference is perhaps a higher fuel rate for the smaller furnace owing to its high heat losses, thus feeding a higher rate of reducing gas to the iron ore. To obtain a fuel rate close to that reached in a commercial scale furnace, the experimental blast furnace uses a higher blast temperature and higher intensity of operation than that used in a normal commercial scale furnace. To decrease the heat losses further, ceramic refractory insulation of the furnace has been used where possible, and only the tuyeres and the lower bosh region immediately above the tuyeres are water cooled. Thereby the heat loss is minimised and, consequently, the rate is kept relatively low, 510–540 kg/THM (where THM is tonne of hot metal), which is comparable to that in production blast furnaces.

The experimental blast furnace is regularly operated in campaigns of 4–10 weeks, twice a year. So far there have been nine campaigns conducted in the furnace, in total over 430 days of operation. Over 40 different pellet types (commercial as well as trial pellets) and several sinter grades and lump ores have been tested, either constituting 100% of the iron bearing burden or in burden mixtures (different pellet mixtures, pellet–sinter mixtures, pellet–sinter–lump ore mixtures, etc.).

1 Probe positions in experimental blast furnace

Results from the experimental blast furnace presented below are all from trials using the standard grade olivine pellet MPBO. This pellet type is regularly used as a reference burden, since its behaviour is well recognised after over 20 years of operation in Swedish blast furnaces. The composition of the MPBO pellet is given in Table 2. Experimental conditions for the various trials are outlined in the ‘Results’ section.

Measurements and sampling during furnace operation

In the experimental blast furnace, horizontal probes have been installed at three different levels of the blast furnace shaft, as shown in Fig. 1, for removal of material samples and to measure temperature and gas composition. The vertical positions of these three probes, with respect to the burden stockline surface, are given in Table 3. When using the horizontal gas and temperature probes, measurements can be made at several positions of the furnace diameter. In general, measurements are conducted at five different radial positions: close to opposite walls, in the centre and on both sides of the centre (between the centre and the two opposite walls).

By using a vertical temperature probe, i.e. letting a thermocouple descend with the burden, an improved picture of the vertical temperature profile within the furnace can be obtained. When inserting the vertical thermocouple into the burden of the experimental blast furnace, the geometry of the furnace top is such that the thermocouple follows the burden close to the wall, thus giving the wall profile of the temperature in the burden column.

Excavation and material sampling

Shutdown and quenching of the experimental blast furnace is carried out by flushing the burden column with nitrogen.
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Table 4 Approximate characterisation of reducing conditions at given radial positions in blast furnace

<table>
<thead>
<tr>
<th>Rate of temperature increase</th>
<th>Wall</th>
<th>Midradius</th>
<th>Centre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reducing gas potential</th>
<th>Wall</th>
<th>Midradius</th>
<th>Centre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical load</th>
<th>Wall</th>
<th>Midradius</th>
<th>Centre</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>

and wustite, samples are etched in 5%HF in an H2O solution for 20 s, giving the wustite a darker (grey) appearance in the microscope. (Magnetite and wustite are difficult to separate under the microscope because they both comprise a cubic lattice. However, during etching the wustite is more readily dissolved, giving it a darker appearance in the optical microscope.) After manually defining zone boundaries for the different structures, automatic image analysis can be used to calculate the extent of each of the structures.

LABORATORY EXPERIMENTS

Reduction under load tests

In a previous work a reduction under load (RUL) equipment was developed at KTH. Several experiments were conducted using the MPBO olivine pellet. Some of the results from that work have been used in the present investigation for comparison with results from the experimental blast furnace. For a description of the reduction equipment and detailed results, the reader is therefore referred to previous papers.11,12 In this section, only a summary of test conditions is given. Results of the RUL experiments are presented in the ‘Results’ section. Experiments were actually of the reduction–softening–quenching is 300–400 Nm³h⁻¹ (i.e., 40–50 Nm³h⁻¹ m⁻³ of working volume), high enough to exchange the total gases and preventing heat from the lower part of the results, the reader is therefore referred to previous papers.11,12 In this section, only a summary of test conditions is given. Results of the RUL experiments are presented in the ‘Results’ section. Experiments were actually of the reduction–softening–melting type (non-isothermal), but are, for simplicity, referred to as reduction under load tests. Thus, the test method is not to be confused with the standardised RUL test (ISO 7992, isothermal at 1050 °C).18 Reducing conditions, with special attention to the parameters rate of temperature increase, reducing gas composition and mechanical stress, at various radial positions in a blast furnace can be approximately comprehended as given in Table 4. Based on literature data, six reducing programmes were established for three different temperature and load profiles, with two different gas composition profiles for each temperature profile.11 In the ‘Results’ section, averages of the two trials at each radial position are used for comparison with data from the experimental blast furnace. In Table 5, the rates of temperature increase and time for completion of the laboratory experiments are outlined. The gas composition was continuously changed as the temperature increased. Table 6 gives the carbon monoxide contents of the reducing gas at various temperatures during reduction. Hydrogen content of the reducing gas was coupled to carbon monoxide content by using a hydrogen content of one-tenth of the carbon monoxide content. These two reducing gases were then balanced by carbon dioxide up to 40% by volume, the rest of the reducing atmosphere being nitrogen. The load applied to

Table 5 Rate of temperature increase and time for completion of reduction under load (RUL) tests for given temperature profiles

<table>
<thead>
<tr>
<th>Temperature interval, °C</th>
<th>Wall profile</th>
<th>Midradius</th>
<th>Centre profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>400–800</td>
<td>4</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>800–1000</td>
<td>5</td>
<td>1.2</td>
<td>5</td>
</tr>
<tr>
<td>1000–1600</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Time for complete test, min</td>
<td>260</td>
<td>320</td>
<td>193</td>
</tr>
</tbody>
</table>

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Lower shaft probe (gas analysis and temperature) E
Middle shaft probe (gas analysis and temperature) D
Vertical probe (temperature) B, C, D, E
Upper shaft probe (gas analysis and temperature) D

RESULTS

The sample, also given in Table 6, was different for each of the temperature profiles, and continuously increased during testing to simulate the increasing load of the overlaying burden during its descent in the blast furnace.

Samples of 500 g of oxide material, corresponding to a bed height of ~55 mm, were reduced under load in an 80 mm diameter graphite crucible. Below and above the pellet bed, 30 mm layers of coke breeze were placed. The weight loss during reduction was continuously measured, and ingoing and outgoing reducing gas compositions were regularly recorded. From this information the reduction degree could be calculated. The following definition of Results from gas composition and temperature measurement was operated slightly centre working, reduction from the sample, also given in Table 6, was divided.

The reproducibility of this measurement can be observed in Fig. 4, which shows the results of vertical reduction programmes without an oxide sample. The gas temperature decreased down to 140–240 °C when leaving the furnace. and dioxide subtracted from outgoing oxygen in water vapour, carbon monoxide and carbon dioxide. All calculations above were corrected for carbon deposition (at low temperatures, i.e. below 750–800 °C) and carbon gasification (at higher temperatures), which had been registered in reduction programmes without an oxide sample. 11

Experimental blast furnace measurements

Temperature and gas distribution in blast furnace shaft

Results from gas composition and temperature measurements using the horizontal probes in campaigns D and E are shown in Fig. 3, which indicates the contents of CO and CO₂ in the gas and the horizontal temperature distribution across the furnace shaft at the three probe levels. As can be seen from Fig. 3, the blast furnace at the time of the measurements was operated slightly centre working, i.e. the measured temperature was higher in the centre than at the walls, indicating a higher gas flow in the centre. It can be noted that the CO content of the blast furnace gas decreased dramatically while the gas was ascending through the burden column, from 42–45% via 34–35% and 28–32% at the depths of 34, 24 and 10 m, respectively, down to approximately 24–26% at the gas offakes. Similarly, there was an increase in the gas CO₂ content up through the furnace, from approximately 0–2% via 13–14% and 17–20% at the depths of 34, 24 and 10 m, respectively, to 23–25% at the gas offakes. The gas temperature decreased at the same positions, from 860–980 °C via 850–900 °C and 690–820 °C down to 140–240 °C when leaving the furnace. The vertical probe, i.e. the in-burden thermocouple, was used to measure the wall profile of the temperature in the burden. The reproducibility of this measurement can be observed in Fig. 4a, which shows the results of vertical temperature probing on different days during experimental blast furnace campaign E. For the major part of the blast furnace shaft, depth from 1.5 to 4 m (800–1100 °C), the difference in temperature measured on various occasions was less than 50 K.

Figure 4b shows a comparison of the in-burden wall temperature profiles for various campaigns. The burden composition was almost the same, but different operating parameters were used in different campaigns, resulting in varying in burden temperature profiles. Differences in temperature between campaigns B and C and between campaigns D and E were small, ~50 K for most of the furnace shaft. However, the difference between campaigns B and C and campaigns D and E was more pronounced, 100–150 K, in a large part of the shaft, which again can be explained by the different operating conditions (see also Table 8).

Experimental blast furnace excavation

All data presented in this section are from the excavation of the experimental blast furnace after campaign A. Operating parameters before quenching of the furnace were shown in Table 8. During excavation of the experimental blast furnace...
 blast furnace samples were collected and afterwards investigated using optical microscopy and image analysis. The following iron oxide/iron structure types were identified:  
(i) coarse hematite  
(ii) medium coarse hematite  
(iii) fine hematite  
(iv) hematite lamellae  
(v) old (original) magnetite  
(vi) large grain magnetite  
(vii) mixed size magnetite  
(viii) magnetite matrix  
(ix) wustite  
(x) snowflake metallic iron  
(xi) sintered metallic iron  
(xii) melted metallic iron.  
The definition of the degree of reduction $R$ given above can be modified to include the analysed contents of oxygen in the samples (wt-%), according to  
\[
R = \frac{m_{\text{O,original}}}{m_{\text{O,removed}}} \times 100\% \quad (2)
\]

The reduction degree of the various iron oxide/iron phases can then be determined as  
(i) hematite, $\text{Fe}_3\text{O}_4$: $R_{\text{hematite}} = 0\%$  
(ii) magnetite, $\text{Fe}_7\text{O}_8$: $R_{\text{magnetite}} = 11.1\%$  
(iii) wustite, $\text{Fe}_5\text{O}_4$: $R_{\text{wustite}} = 29.6\%$  
(iv) iron, Fe: $R_{\text{iron}} = 100\%$.  
For the non-stoichiometric wustite phase, $\text{Fe}_5\text{O}_4$, the value of $x$ at the lowest temperature of stable existence, 570 °C, has been used, i.e. 0.947 (below this temperature $\text{FeO}$ decomposes to Fe and $\text{Fe}_2\text{O}_3$, but $\text{FeO}$ can readily be undercooled, whereby the decomposition is prevented). The difference in reduction degree calculated with the two investigated in a separate paper. The furnace cross-section was divided into three circular di 

\[
\text{iron structure types were identified: (i) coarse hematite, (ii) medium coarse hematite, (iii) fine hematite, (iv) hematite lamellae, (v) old (original) magnetite, (vi) large grain magnetite, (vii) mixed size magnetite, (viii) magnetite matrix, (ix) wustite, (x) snowflake metallic iron, (xi) sintered metallic iron, (xii) melted metallic iron.}
\]

Table 8 Blast furnace operating parameters* before shutdown of campaign (Camp.) A, and during campaigns B, C, D and E, respectively: averages of 24 h stable (representative) operation

<table>
<thead>
<tr>
<th>Burden</th>
<th>Productivity, tHM m⁻² · 24 h⁻¹</th>
<th>Productivity, tHM m⁻² · 24 h⁻¹</th>
<th>Oxygen enrichment, %</th>
<th>Moisture, g Nm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPBO pellets, kg/tHM</td>
<td>1396</td>
<td>1381</td>
<td>1389</td>
<td>1384</td>
</tr>
<tr>
<td>Quartzite, kg/tHM</td>
<td>10</td>
<td>7</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Limestone, kg/tHM</td>
<td>60</td>
<td>33</td>
<td>42</td>
<td>53</td>
</tr>
<tr>
<td>BOF slag, kg/tHM</td>
<td>51</td>
<td>52</td>
<td>54</td>
<td>36</td>
</tr>
<tr>
<td>Coke, kg/tHM</td>
<td>515</td>
<td>442</td>
<td>439</td>
<td>407</td>
</tr>
<tr>
<td>Top gases</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>1208</td>
<td>1178</td>
<td>1171</td>
<td>1189</td>
</tr>
<tr>
<td>Pressure, bar (gauge)</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>CO₂, %</td>
<td>24.0</td>
<td>21.8</td>
<td>20.7</td>
<td>22.5</td>
</tr>
<tr>
<td>H₂O, %</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.6</td>
</tr>
<tr>
<td>Hot metal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>1416</td>
<td>1460</td>
<td>1435</td>
<td>1468</td>
</tr>
<tr>
<td>C, %</td>
<td>4.5</td>
<td>4.6</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Si, %</td>
<td>0.66</td>
<td>1.17</td>
<td>1.54</td>
<td>1.71</td>
</tr>
<tr>
<td>S, %</td>
<td>0.065</td>
<td>0.032</td>
<td>0.030</td>
<td>0.032</td>
</tr>
<tr>
<td>Slag</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate, kg/tHM</td>
<td>146</td>
<td>136</td>
<td>137</td>
<td>140</td>
</tr>
<tr>
<td>CaO, %</td>
<td>30.5</td>
<td>30.9</td>
<td>34.1</td>
<td>32.6</td>
</tr>
<tr>
<td>SiO₂, %</td>
<td>34.5</td>
<td>34.0</td>
<td>32.8</td>
<td>32.9</td>
</tr>
<tr>
<td>MgO, %</td>
<td>17.0</td>
<td>18.7</td>
<td>17.3</td>
<td>18.2</td>
</tr>
<tr>
<td>Al₂O₃, %</td>
<td>12.8</td>
<td>14.6</td>
<td>14.5</td>
<td>15.2</td>
</tr>
</tbody>
</table>

* MPBO is Malmberget pellet blast furnace olivine, BOF is basic oxygen furnace, PCI is pulsed coal injection, $\eta_{CO}$ is gas utilisation.

1 Utilisation of furnace volume (working volume from stockline to tuyere level).
2 Output per unit hearth area.

\[
R_i(\%) = \frac{v_{\text{iron}} \times R_{\text{iron}}}{v_{\text{iron}} \times R_{\text{iron}} + v_{\text{wustite}} \times R_{\text{wustite}}} \quad (3)
\]

where $v_i$ is the volume fraction of iron oxide/iron phase $i$. The accuracy of this method was verified by comparing calculated reduction degree values with results from the standard procedure of identifying reduction degree, i.e. from chemical analysis, for samples collected at the same position. The comparison can be seen in Fig. 5, which shows the degree of reduction in various layers of the furnace and at different radial positions. The values presented in Fig. 5 show that the deviation between the methods of calculating the degree of reduction is generally less than 8 percentage units.

Depending on how the cross-sections of individual pellets are chosen in microscopic analysis, there will be some internal variation in phase composition. From experience, it is known that most variations within a pellet particle are found in the radial direction, between the surface and the interior of the particle. This is because of reduction proceeding topochemically from the pellet surface to the centre. Effort is, therefore, put into cutting and polishing the pellet at the largest possible cross-section, ensuring that the pellet centre is included in the microscopic examination. By mounting seven pellet particles together and using the average of the calculated reduction degree, the natural fluctuation in attained reduction degree between different pellet particles from the same sample point is reduced. Variations within a collected sample are to be further investigated in a separate paper.

The furnace cross-section was divided into three circular segments with equal surface area, as denoted by the broken lines in Fig. 2. Thereby the sample points were classified into radial positions, representing wall, midradius and centre.
Figure 6a shows the reduction degree as a function of depth in the blast furnace, measured from the stockline downwards, for the three radial positions of wall, midradius and centre. As can be seen in Fig. 6a, the samples from the wall position gained a higher reduction degree compared with the centre and midradius samples from a depth of 1·5 m (or from the wustite stage) down to 3·5 m depth, where all samples were close to complete reduction. The reason for this is that the blast furnace at that time was wall working, which influences the reduction behaviour in the lower shaft of the furnace. The wall working blast furnace process is discussed further below.

It can also be seen from Fig. 6a that reduction was rapid at the beginning and up to a reduction degree of ~25%. Here, most of the original hematite had turned into wustite, leaving only small amounts of magnetite in the core of the pellet particles. After that there was little reduction during about one-third of the total reduction process, until the reduction rate again increased, reducing the wustite to iron at a rate similar to, or even higher than, the initial hematite and magnetite reduction.

By using vertical probing in the furnace it was possible, in addition to measuring the gas temperature as shown in
Comparison of reduction degree calculated from phase identification (id.) and calculated from chemical analysis for three given radial positions: campaign A

Fig. 4b, to measure the burden descent rate at different heights of the burden column. The vertical probe consisted of a thermocouple to which a weight with a barblike construction was attached. When assessing the probe data, it is of course important to know the furnace profile to be able to calculate the vertical distance in the furnace (the probe path is assumed to be somewhat inclined, i.e. to follow the furnace wall, an assumption considered reasonable from observations of material movements during dissections of blast furnaces). This procedure assumes that the descent of the burden was not disturbed. By applying the descent rate measured in campaigns B–E to data from campaign A (since this measurement was not available at that time), the data in Fig. 6a can be transformed into that shown in Fig. 6b. Figure 6b indicates the reduction degree as a function of elapsed time since charging into the blast furnace. The fast initial reduction can again be seen: the first 25% of reduction took less than 40 min. The pellets then travelled down through the reserve zone, with little reduction, for up to almost 1 h (shorter for the samples close to the wall). Then the reduction rate increased again, from ~30% reduction up to 90% reduction degree during the next 30 min. Finally, the reduction rate was lowered during the period where complete reduction was obtained.

In Fig. 7, the extent of the various iron oxides/iron phases down through the furnace is shown for the different radial positions of the experimental blast furnace. It can be seen that the hematite was quickly reduced in the upper part of the blast furnace. However, the reduction of magnetite to wustite was found to start before complete reduction of hematite to magnetite. Similarly, iron started to form long before all magnetite was reduced to wustite. Thus, in the major part of the blast furnace shaft, three different iron oxide/iron phases coexisted.

Comparison between laboratory tests and experimental blast furnace

Owing to the relatively small volume of the experimental blast furnace, the throughput time is normally about 4–5 h, which is shorter than in large scale production blast furnaces where a throughput time of 6–8 h is usual. The throughput time of iron bearing materials in a blast furnace is mainly a function of the furnace size, the productivity (defined as hot metal produced per time increment) and the volume of the burden per tonne of hot metal charged from the top. For a specific blast furnace, the throughput time is therefore given by the blast volume, amounts of injected reducing agents, oxygen enrichment, top pressure, raw material properties, etc. For most commercial blast furnaces the strategy applied is to maximise productivity, giving the best overall economy of iron production (lowest cost per tonne of hot metal produced). In practice, this means blowing as much blast as possible (limited only by the capacity of the blower or the permeability of the blast furnace burden). In the case of the experimental blast furnace, the strategy is somewhat different, since maximum production and lowering the hot metal cost is not a primary goal, and therefore not demanded. In fact, the productivity can be chosen to be in a fairly broad range, from 25 to 41 t/day (3·0–5·0 t/m³/24 h or 22·1–36·2 t/m²/24 h), depending on the goals of the trial. However, there is a practical lower limit of productivity, given by the amount of blast which can still create a raceway penetration of...
7 Extent of given iron oxide/iron phases through furnace in campaign A for three positions

a wall; b midradius; c centre
suitable size and far enough into the furnace burden to promote a centre working blast furnace process. Because of the limitation in minimum blast volume, the throughput time of the experimental blast furnace cannot be increased much beyond 5 h. Therefore, the throughput time of iron bearing materials in the experimental blast furnace, and thus the iron oxide reduction rate, is one of the parameters that deviates from operation in a large scale production blast furnace (as mentioned above).

Parameters for laboratory reduction under load experiments, also called RUL tests, are chosen to simulate the process in a specific blast furnace. In previous work, RUL experiments were conducted to simulate a commercial blast furnace, thus incorporating a reducing programme with a longer reduction time, compared with the experimental blast furnace. In Fig. 8, where reduction temperature versus time is compared for the experimental blast furnace and the RUL trials, the differences in temperature–time cycles can be seen.

Because of different reduction times, a comparison of reduction behaviours between the experimental blast furnace and the laboratory RUL experiments based on a timescale is not suitable, but is better done by comparing reduction degrees as a function of a dimensionless distance, representing the vertical position in the blast furnace. Figure 9 shows comparisons between reduction degrees as a function of dimensionless distance originating from distance from the stockline in the experimental blast furnace or originating from reduction time in RUL experiments, for the wall, midradius and centre positions, respectively. The dimensionless distance \( D \) is thus based on burden movement in the blast furnace and calculated from

\[
D = \frac{\text{vertical distance from stockline}}{\text{stockline–dripping zone distance}} \quad (4)
\]

For the RUL laboratory experiments, equation (4) is modified and the dimensionless distance calculated as a time fraction of the experiment, according to

\[
D = \frac{\text{elapsed time of experiment}}{\text{total time of experiment}} \quad (5)
\]

The distances for the RUL results have thus been calculated as a fraction of reduction time in the midradius experiment.
However, as the RUL experiments were separately conducted, the dimensionless distance could also be individually calculated, on the time basis of each of the experiments. The difference between these procedures is schematically explained in Fig. 10, i.e. reduction results are compared for a certain vertical level of the furnace (left), or for a certain temperature isotherm of the furnace (right). In Fig. 11, the alternative procedure has been used. The dimensionless distance is here based on the timescale of the individual experiments, and shown for the wall and centre profiles (the midradius profile results are the same as Fig. 9b, since this experiment constituted the time basis in the first calculation).

As can be seen in Figs 9a and 11a, the shape of the reduction curve for the wall position down through the burden of the experimental blast furnace is similar to the results of RUL laboratory tests. The main difference is that reduction was somewhat faster in the experimental blast furnace owing to the wall working process. The deviation most of the time, is in the region of a maximum of 10 percentage units. However, there is also a principal difference in the shape of the reduction curves. In the reduction values from the experimental blast furnace, a reduction plateau can be noted at \(~25\%\) reduction degree, a result of restricted reduction in the reserve zone, and above \(40\%\) degree of reduction the reduction rate is much higher than for the laboratory results.

Also for the midradius position, Fig. 9b, the plateau-like shape of the reduction curve from the experimental blast furnace can be observed, at \(25–30\%\) reduction degree, as can the higher reduction rate at high degrees of reduction. Apart from these deviations, the reduction pattern is similar between the experimental blast furnace and the laboratory results, most of the time with less than 15 percentage units difference.

The biggest difference between the experimental blast furnace and the RUL experimental results is for the centre radial position, Figs. 9c and 11b. In the experimental blast furnace the reduction values at almost all levels are lower than in the laboratory test. This is an effect of the laboratory tests being set up to simulate a centre working blast furnace, while the experimental blast furnace was wall working. Therefore, reduction in the centre was very fast in the first case, while in the latter it was considerably slower, and the difference is up to 30 percentage units comparing temperature isotherms, Fig. 11b, and even greater when comparing for the vertical level in the furnace, Fig. 9c. Also in this case there was restricted reduction in the reserve zone of the experimental blast furnace, while this did not occur in the laboratory reduction test.

### DISCUSSION

**Experimental blast furnace measurements**

**Horizontal gas and temperature measurements**

Horizontal gas composition and temperature profiles measured in the experimental blast furnace (Fig. 3) correspond well to gas profiles in commercial blast furnaces reported in the literature.\(^1\)\(^2\) To some extent the horizontal variations in blast furnace gas composition distinguish the experimental blast furnace from commercial blast furnaces.
vertical measurement. In the experimental blast furnace, vertical measurements of the temperature profile were made close to the furnace wall. The results shown in Fig. 4 illustrate that if the vertical temperature is measured in the same position at different times but for the same operating conditions, the maximum temperature difference is 50 K, or less than 5%, in the temperature interval 800–1100 °C. However, as seen in Fig. 4b, the vertical temperature profiles in the experimental blast furnace had different appearances in different campaigns. The reason for the varying levels of temperature in the shaft can be found in the different operating conditions of the furnace.

Comparing temperature measurements taken by horizontal and vertical probes, Figs. 3 and 4b (curves for campaigns D and E), it can be noted that at the level of the upper shaft probe the two measurements are in close agreement. At the middle and lower shaft probes, however, there is a deviation between horizontal and vertical probe temperature measurements. The temperatures measured by the horizontal probes are lower than the corresponding values from the vertical probe measurement, by 80 K and 140 K for the middle and lower shaft probes, respectively. The following errors have been identified as possible reasons for the difference:

(i) the measurements were, for practical reasons, conducted with a time delay of a few hours

(ii) the angular position of the vertical probe measurement was 90° displaced compared with the position of the entrance of the shaft probes into the shaft, i.e. 90° also from the inner and the outer ends of the horizontal shaft probe measurement across the furnace radius

(iii) measurement error.

The influence of time delay, (i) above, is considered minor, as the measurements were conducted during stable blast furnace operation. With regard to error (ii), there is of course some temperature difference at different angular positions of the furnace shaft, but these are believed to be much less than the observed temperature deviation. The remaining, and most likely, possible reason for the difference in measured temperatures in the lower shaft is a measurement error, (iii). The probable cause for this is water cooling of the horizontal shaft probes, influencing the temperature measurements especially at higher temperatures, i.e. above 800 °C. In contrast, the vertical probe temperature measurement, which is not influenced by any cooling system, is believed to supply more reliable data. Consequently the actual temperature in the lower shaft should then be higher than that measured by the middle and lower horizontal shaft probes. However, if the effect of probe cooling is a result of heat conduction from the measuring point to the probe, the error in temperature measurement should become proportional to the temperature difference between the measuring point and the probe. If so, it could be argued that, even though the level of temperature measurements at the middle and lower shaft probes is too low, the observed temperature distribution across the furnace diameter should be reliable.

**Vertical temperature measurements**

In general, the shape of the temperature profile in most cases followed the pattern given in the literature, i.e. fast heating immediately after charging followed by a slower heating rate through the thermal reserve zone, and finally fast heating again in the lower part of the blast furnace. However, the vertical temperature profile within a blast furnace can vary greatly depending on operating practice, and of course also depending on the burden materials used. Naturally, the results of temperature measurements are also very much dependent on the radial position of measurement. In the experimental blast furnace, vertical measurements of the temperature profile were made close to the furnace wall.
gas flow, and potentially also faster heating of the burden, the material close to the wall should start to melt earlier than the central portion. Indications of this were also seen during excavation of the blast furnace, where the cohesive zone was found to be almost flat, but inclining somewhat upwards to the wall. From the lower part of the shaft (from pellet layer 15 of a total of 24 layers of iron ore, from stockline to hearth), the pellet particles close to the wall had started to sinter to large aggregates. Further down the furnace the sintering was even more pronounced, but the original spherical shape of the individual pellet particles was not changed. The melting of the metallised pellets was found to be rapid, occurring in only two consecutive layers of the burden, i.e. only two layers contained semimelted material, or what is normally referred to as cohesive zone formation.

Comparison between laboratory tests and experimental blast furnace

The main purpose of the present work was to study how well laboratory data compare with data from an experimental blast furnace. The findings from the study are discussed below.

Temperature and gas composition

The heating rate of the centre position of the reduction under load tests resembles the vertical temperature profiles at the wall of the experimental blast furnace. This is an effect of the comparatively fast reduction process in the experimental blast furnace as opposed to the conditions used in the reduction under load experiments. Also, the temperature and gas composition profiles chosen for the RUL experiments resemble the horizontal temperature and gas composition profiles measured in the experimental blast furnace.

Reduction degree

As shown in Fig. 6a, initial fast reduction in the experimental blast furnace can be observed, followed by a very low reduction rate and finally again a high reduction rate (disregarding minor reduction probably occurring in the liquid phase). The same observation is often cited in literature describing the reduction mechanisms in the blast furnace. It is stated that the initial reduction of hematite and magnetite to wustite in the blast furnace shaft is fastening the reducing gas composition far above the equilibrium of those reduction reactions. In combination with a comparatively small amount of oxygen to remove (compared with wustite reduction), i.e. the lower part of the blast furnace produces excessive amounts of gas for the primary reduction steps, the initial reduction becomes fast. For the next reduction step, from wustite to iron, gas with a lower oxygen potential is required (compare the equilibrium phase diagram of Fe–O–C). Therefore, considerable reduction of FeO does not take place until the wustite enters the middle or lower part of the blast furnace shaft, where the reducing gas is strong enough for further reduction. Consequently, the region including very little reduction is referred to as the chemical reserve zone. The extent of the chemical reserve zone is dependent on the geometry of the blast furnace, i.e. the height of the internal burden column for a specific blast furnace. From the dissection after campaign A, the chemical reserve zone could be defined as reaching from ~1 to 2 m below the stockline (compare Fig. 6a).

Similarly, there is also a thermal reserve zone, where there is little heat transfer from the ascending blast furnace gas to the descending burden. The thermal reserve zone often includes the chemical reserve zone, but also a part of the region of initial reduction above the chemical reserve zone and the region of indirect reduction, i.e. the gaseous reduction of wustite starting below the chemical reserve zone and reaching down to the end of the thermal reserve zone. At the end of the thermal reserve zone the temperature of the ascending gas is higher, and consequently the descending material is heated further. In the high temperature region in the lower part of the blast furnace, above 1000°C, the highly endothermic Boudouard reaction prevails, leading to direct reduction of FeO. The thermal reserve zone of the experimental blast furnace can be studied in Fig. 4b, where it typically reached from 1 to 4 m below the stockline for the wall position of campaigns B–E.

For the wall and midradius positions, the deviation in reduction between laboratory experiments and the experimental blast furnace was not considerably large. However, the shape of the reduction curves was different. In the experimental blast furnace, reduction was restricted in the middle part of the furnace, corresponding to the chemical reserve zone as described above. Although a thermal reserve zone was applied in the midradius reduction under load experiments, a chemical reserve zone behaviour was not observed, as shown in Fig. 4b. This was a result of the reducing gas potential used in the experiments, which was somewhat too high to restrict reduction in the thermal reserve zone. The effect of the limited gas flow in the centre of the experimental blast furnace, restricting the reduction rate, in combination with the experimental setup of RUL experiments with extremely strong reducing gas and a high heating rate, was a strong deviation in reduction after the wustite reduction stage for the centre sample.

The differences described above are a result of differences in reducing conditions. The gas compositions varied somewhat, when comparing levels of the different gas components between laboratory tests and results of the experimental blast furnace gas measurements (campaigns D and E). In the laboratory tests the contents of CO in the gas used were lower than that found in the experimental blast furnace. However, the CO2 contents were also lower, resulting in a higher CO/CO2 ratio. This is demonstrated in Fig. 13, where the gas ratios (CO/(CO + CO2) × 100) in the laboratory tests and experimental blast furnace have been superimposed on the Fe–O–C equilibrium diagram. It can be seen that the gas ratios below 900°C were all higher for the laboratory tests, compared with conditions of experimental blast furnace campaigns D and E.

The lower gas ratios below 900°C in the experimental blast furnace were caused by the equilibrium between iron and wustite, governing the gas ratio at low temperatures. At higher temperatures CO gas is much more stable than CO2, and almost all CO2 produced is converted to CO.
resulting in a gas ratio of ~100. The effect of lower gas ratios at low temperatures was found in the restricted reduction in the middle part of the experimental blast furnace. Similarly, the fast increase in gas ratio at 900–1000°C, for experimental blast furnace conditions compared with laboratory tests, was reflected in faster reduction in the long period.

The difference in reduction time for the laboratory tests compared with the experimental blast furnace is partly compensated when comparing degree of reduction as a function of distance in the furnace, as shown in Figs. 9 and 11. The similar gas ratios thereby result in similar reductions for the wall and midradius positions, when comparing according to distance in the furnace, except for the absence of a chemical reserve zone in the laboratory tests owing to relatively strong reducing gas compositions used. For the centre position, on the other hand, the conditions were quite opposite between laboratory tests and experimental blast furnace, resulting in large differences in observed reduction degree.

However, from examination of the microstructures of iron oxides during reduction, another difference has been found between the experimental blast furnace and the laboratory test results. In the previous investigation of reduction under load samples, the reduction was found to take place in stages, i.e. reduction to a lower oxygen containing iron oxide phase did not occur until the previous reduction step was completed. Therefore, at no time did more than two iron oxide (or iron) phases coexist. In Fig. 7 it can be seen that this was not the case for materials collected in the experimental blast furnace. There was a clear overlap in the reduction process resulting in three coexisting phases (i.e. hematite-magnetite-wustite or magnetite-wustite-iron) for longer periods. This was probably due to the faster reduction in the experimental blast furnace. However, the stepwise reduction observed in RUL experiments was found to occur in spite of a reducing gas potential high enough for further reduction to a lower iron oxide phase. This phenomenon was explained by an assumed locally high carbon dioxide potential. Because the driving force for reduction is higher for the less stable phases (i.e. the highest oxides), these were reduced first. When the gaseous product of the reduction reactions of higher oxides in the pellet core (i.e. carbon dioxide) diffused out through the particle, there was the potential for a local partial pressure of carbon dioxide high enough to prevent temporarily further reduction of the outer part of the particle. In the experimental blast furnace, on the other hand, this 'reduction preventing' layer was probably not as significant, owing to the higher heating rate and the excessive amounts of strongly reducing gas, which forced the reduction of the outer pellet layers to continue.

Softening

In the reduction under load experiments it was found that the pellet particles studied retained their original spherical shape until melting started, and even after that. During heating the metallised iron in the particles of the pellet bed was noted to pick up carbon in contact with coke, and thereby eventually melt because of the lowered melting temperature of the iron phase. There was increasing, and especially at very high temperatures extensive, sintering between the particles, lowering the void fraction of the pellet bed. There was also sintering within particles, causing shrinkage of the individual particles and thereby a contraction of the bed. What is normally referred to in the literature as softening, however, was not found to occur.

As described above, even though reduction was found to be considerably faster in the experimental blast furnace, the mechanism of contraction of the pellet bed owing to sintering and the meltdown process, without considerable deformation, was found to be the same. This is because MgO (originating from the olivine addition) forms a solid solution with wustite during reduction, which increases the melting point far above the melting point of wustite, or fayalite (2FeO·SiO₂). This circumstance contributes to the advantageous high temperature properties of the olivine pellet. The absence of significant softening during reduction—meltdown is believed to be a special feature of this type of olivine pellet, since in later experimental blast furnace excavations other burden materials have been found to behave differently during reduction and meltdown. In many cases, using other pellet types, there has been extensive softening of pellets in the high temperature region of the furnace, resulting in several (in extreme cases up to 7–8) layers of what is defined as the cohesive zone.

Summary

The very narrow range of the melting process in the experimental blast furnace is in agreement with what was found in the laboratory experiment, and is generally considered an important advantage of the olivine pellet type, together with the start of melting occurring at a high temperature. The narrow melting range results in a narrow cohesive zone in the blast furnace, which in turn gives a low pressure drop. The high melting temperature results in a cohesive zone low in the blast furnace, which provides more space for gaseous reduction. Thus, the high temperature phenomena of softening and melting were found to be correctly simulated in the laboratory reduction under load tests.

Comparing the progress of reduction on a laboratory scale with blast furnace reduction can be appropriately made as long as the reduction parameters for laboratory scale testing are correctly chosen. The deviation in reduction behaviour observed in the present work was mostly a result of the experimental parameters chosen for laboratory testing deviating from the conditions of the experimental blast furnace. Therefore, if laboratory reduction under load tests are considered for simulation of the blast furnace process, these could certainly be adequately conducted by adjusting the laboratory reduction parameters, i.e. temperature–gas composition–time programmes, for the blast furnace process in question.

To simulate the blast furnace operation on a laboratory scale, it is, of course, important to know the conditions in the blast furnace process. Although information regarding temperature and gas composition at various levels in commercial blast furnaces can be found in the literature, this information may only be valid for these furnaces measured under their conditions, such as raw materials used, operational parameters and strategies applied. Problings, excavations and dissections of the experimental blast furnace can provide more useful information of the state inside the blast furnace. Using such information to adjust the parameters used in laboratory tests, much better simulation of the blast furnace process can be conducted on a laboratory scale.

CONCLUSIONS

The high temperature phenomena occurring when reducing the MPBO pellet, including softening and melting, were found to be the same in laboratory tests and in the experimental blast furnace. The progress of reduction down through the burden of the experimental blast furnace was similar, but not identical, to the results of the RUL experiments. The differences obtained were found to arise from different reducing conditions. Using the same experimental conditions in laboratory scale reduction under load experiments as those obtained in the experimental blast furnace, better simulation of the reduction in the blast furnace can be conducted on a laboratory scale, as far as reduction
extent is concerned. Thereby it is concluded that laboratory reduction under load, or reduction, softening and melting, tests can be appropriately used to simulate the blast furnace process. However, to carry out such a simulation it is very important to know the internal state of the blast furnace. Since the blast furnace process has advanced a great deal in recent decades (concerning injection of reductants, lowering of coke rates, different charging strategies, increasing productivity, etc.) updated and accurate information regarding the blast furnace interior is needed to carry out appropriate simulations of the blast furnace process on a laboratory scale. Such information can be provided by the experimental blast furnace.

The more specific conclusions from the present study are summarised below.

Experimental blast furnace results

1. The reduction degree can be as accurately determined based on identification of iron oxide/iron phases in excavated material studied under the microscope as from chemical analysis.

2. Vertical probes can be used to measure the burden descent rate in the blast furnace shaft, and thereby an assessment of excavation data from vertical level to treatment time can be made, i.e. the reduction degree in an experimental blast furnace can be determined as a function of both depth and time from charging.

3. The reduction profile in the experimental blast furnace is similar to that described in the literature, i.e. fast initial reduction to wustite followed by slow reduction through the chemical reserve zone and again fast reduction of wustite in the lower part of the furnace.

4. Vertical temperature probe measurements are found to be very reproducible, and the results of temperature measurements agree with data from commercial furnaces given in the literature.

5. Temperature measurements taken using horizontal shaft probes can be unreliable at temperatures above 800°C, where cooling of the probe influences the results.

6. Horizontal temperature probe measurements in the upper shaft or top gas temperature profile measurements can be used to determine the gas distribution along the radial direction, and whether the blast furnace is centre working or wall working.

7. To get to the process is wall or centre working can be determined from the degree of reduction of the excavated material.

8. The gas profiles measured in the experimental blast furnace show that below 900°C, gas composition is governed by the equilibrium between iron and wustite (which means that the olivine pellet is very reducible).

Comparison of data from experimental blast furnace and reduction under load tests

1. The reduction time in the experimental blast furnace is shorter than that used in the RUL experiments (and that given in the literature). By applying a dimensionless vertical distance, based either on vertical level or on temperature isotherms, it is possible to compare results from the experimental blast furnace with RUL results (or results from commercial furnaces).

2. Reduction down through the burden of the experimental blast furnace is similar to results of the RUL experiments for the wall and midradius profiles, when comparing different levels of the furnace and disregarding the difference in experimental time. The biggest difference is found for the centre profile, caused by the wall working operation of the experimental blast furnace, while the RUL experiments were set up to simulate a centre working operation.

3. The deviation in shape of the reduction curves between laboratory tests and the experimental blast furnace results from the absence of a chemical reserve zone in the laboratory experiments, in turn caused by the choice of reducing parameters for the tests.

4. In the RUL experiments, at all time during reduction only two phases (iron oxides or iron) coexist and reduction is found to take place in stages. In the experimental blast furnace, most of the time during reduction three phases coexist. The reason given is faster reduction in the experimental furnace in comparison with the laboratory furnace.

5. Softening of the MPBO pellets is not found to take place either in the experimental blast furnace or in the RUL furnace.

6. Cohesive zone formation (low permeable, semimelted material) is found to be very restricted when using the MPBO pellet in the experimental blast furnace. Only two layers of semimelted material indicate fast melting of the metallised pellets, which was also observed in the RUL experiments.

FUTURE WORK

Future work should include the design of new RUL experiments to imitate the operation of the experimental blast furnace. The results can again verify the conclusion that it is possible to simulate blast furnace reduction on a laboratory scale.

By adding temperature indicators (so called tracers, or markers) to the burden before quenching of the experimental blast furnace, it should be possible to establish the temperature profile of the complete cohesive zone region. Thereby, in future work, further comparisons between laboratory tests and the experimental blast furnace can be carried out, with more emphasis on temperatures of cohesive mass formation, start of melting and final melting, which are valuable results from reduction under load (or reduction, softening and melting) tests.

The gas composition profile along the height of the experimental blast furnace should be monitored by vertical gas probes, to provide increased knowledge of the blast furnace interior, and to establish appropriate experimental conditions for laboratory simulations of the process.

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