The successful piloting of CRISP, the innovative continuous steelmaking technology

F. Wheeler, Y. Gordon, S. Broek, I. Cameron

Since inception, the Continuous Reduced Iron Steelmaking Process (CRISP), an innovative, patented technology for continuous steelmaking from pre-reduced iron ore, has undergone significant development. Most recently, pilot testing at the Swerea MEFOS AB in Luleå, Sweden successfully confirmed the viability of the underlying metallurgical principles as well as the practicality of continuous operation, setting the stage for the commercialization of this technology. The CRISP technology builds on existing practices and equipment, and thus represents a logical step in the on-going development of electric steelmaking. The innovative use of a stationary electric furnace, common in other metals industries such as nickel or copper smelting, for continuous steelmaking is, however, a departure from the current trends and forms the basis of this new steelmaking technology. The unique features of the CRISP technology lead to important operational benefits. The paper will illustrate these benefits and the related capital and operating cost savings, and describe the current status and on-going development of the CRISP technology. The factors leading to a reduced environmental footprint are also outlined.

KEYWORDS: CRISP, Continuous steelmaking, stationary electric furnace, DRI-based steelmaking, slag control, steel decarburization, piloting steel technology

INTRODUCTION
Since the Continuous Reduced Iron Steelmaking Process (CRISP) was first presented in 2002 at the 7th European Electric Steelmaking Conference in Venice [1], this innovative patented technology pioneered by Hatch has undergone significant development. During this period the following was accomplished:

• Conceptual process parameters including slag engineering were developed;
• Preliminary design of the stationary electric furnace has been completed;
• Plant layouts including the critical interface with the DR furnace were prepared;
• Plant logistics were examined and computer-simulated;
• Preliminary capital and operating costs have been established;
• The economic viability of the technology was confirmed;
• A US and other patents covering the technology have been awarded [2].

Following this earlier conceptual development at Hatch [3, 4, and 5], fundamental research including laboratory tests was carried out at the Department of Materials Science and Engineering of the University of Toronto. This work confirmed the principles of the process and identified viable slag chemistries that would meet the demanding - and often conflicting - metallurgical requirements of the CRISP concept and set the stage for the next step: the pilot testing of the CRISP technology. The details of this slag engineering research and the analysis of the slag performance in the pilot trials have been described in an earlier paper [6].

Recent pilot testing at the research facilities of Swerea MEFOS in Luleå, Sweden successfully confirmed the viability of the underlying metallurgical principles as well as the practicality of continuous operation, setting the stage for the commercialization of this technology.

THE CRISP TECHNOLOGY
The CRISP process is not a radical departure from current steelmaking practices but rather a logical step in the ongoing evolution of steel technology from a batch process to continuous operations.

The essence of the CRISP process is the use of a large stationary refractory-lined electric furnace for the continuous melting of direct reduced iron (DRI). This type of furnace, shown schematically in Fig. 1, while novel to the steel industry, is well established in other metals industries and is found, for example, in nickel, copper, or ilmenite smelters.

In a CRISP plant, the charge material is fed continuously through the furnace roof from an overhead feed system. The feed rate is adjusted to maintain the target bath temperature. The furnace remains under power during electrode make-up and slipping, and tapping as well as during most refractory and tap hole repairs. The furnace is equipped with multiple tap holes for steel and slag. Steel is tapped periodically into ladles and processed in conventional downstream facilities: ladle metallurgical and continuous casting. Slag is tapped into slag pots and transported for processing in the yard.

PILOT TESTING OBJECTIVES AND TEST FACILITIES
The pilot testing was carried out in two separate campaigns on the 8-tonne AC electric arc furnace at Swerea MEFOS[7]. This
facility was selected, after an extensive world-wide search, in view of its staff of experienced researchers and technicians with internationally recognized expertise in the field of metallurgy and heavy pilot plant activities, as well as the well-equipped pilot plant facilities.

The Phase I trials in August 2007 were devoted to testing the interaction of slags of a selected composition with the steel bath, with the aim of identifying a window of appropriate operating parameters for the CRISP technology. A prime objective was to identify a slag composition that would provide the decarburization of the steel to below 0.10 %C and good foaming slag, while at the same time not erode the slag line refractories. In all, nine different slag compositions were tested on 14 heats over a period of four days. Varying levels of basicity and FeO contents were examined.

The Phase II trials in April 2008 then built on the positive results of the first round with the objective of demonstrating one of the key aspects of the CRISP process: the viability of continuous melting over an extended period. The target slag compositions identified in the Phase I trials, shown in Table 1, was used in the Phase II trials. The MgO content was maintained at 1 - 2% above saturation.

To facilitate the CRISP trials, Swerea MEFOS installed an overhead feed system, designed specifically to allow the controlled continuous feed of DRI along with oxide and flux materials. Batches of these materials were preweighed into hoppers which were then bottom-discharged into the overhead feed bin equipped with a weigh feeder.

The furnace operating parameters were selected to approximate the operations proposed for a CRISP furnace:

- The furnace power was set at 2 MW which equates to approximately 500 kW/m² of hearth area, the anticipated power density of the CRISP furnace;
- The target bath temperature of 1,600°C was maintained by adjusting the feed rate of materials (DRI / flux mixture).

For the Phase II continuous pilot trials, Swerea MEFOS fabricated four sandboxes to replace the steel ladles used in the Phase II trials.

![FIG. 1 Schematic of CRISP stationary electric furnace.](image1)

**FIG. 1 Schematic of CRISP stationary electric furnace.**

*Schema del forno elettrico stazionario CRISP.*

![FIG. 2 Logistics of the Phase II trials.](image2)

**FIG. 2 Logistics of the Phase II trials.**

*Logistica delle prove della Fase II.*

<table>
<thead>
<tr>
<th>Test #</th>
<th>Day</th>
<th>FeO wt%</th>
<th>B₂O₃</th>
<th>C wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>As low as possible</td>
<td>2.0</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>As low as possible</td>
<td>2.0</td>
<td>0.04 and 0.06</td>
</tr>
</tbody>
</table>

**TAB. 1 Target starting slag compositions; Phase II (continuous) pilot trials.**

Prescrizioni di composizione iniziale delle scorie, prove con impianto pilota Fase II.
I trials. This eliminated the need to superheat the steel prior to tapping and enabled the near-continuous mode of operation. The logistics of the Phase II pilot trials are shown schematically in Fig. 2. The 8-tonne furnace is shown in Fig. 3.

PILOT TEST RESULTS AND DISCUSSION

In the Phase I trials a total of 14 heats were made in a four-day period with an overall consumption of 70 tonnes of DRI. The longest trial, consisting of five continuous heats, lasted approximately twelve hours.

The key findings from the Phase I pilot trials were:
- It is possible to produce low-carbon steel (below 0.10 wt% C) with a good foaming slag and low FeO (below 18 – 20 wt%);
- The relationship between FeO and C is closer to equilibrium than that experienced in conventional EAF steelmaking (Fig. 4);
- This can be achieved without the use of gaseous oxygen;
- No major refractory erosion was experienced under these conditions;
- Stable and reproducible operating conditions can be achieved;

The relationship between bath carbon and slag FeO and basicity for a non-O2 scenario is established for conditions projected for a CRISP operation. These findings allowed a window of operating parameters to be defined that would enable sustained and reproducible continuous steelmaking using the CRISP technology. They served as the basis for the Phase II pilot trials.

The total campaign time of the Phase II pilot trials carried out in April 2008 was 115 hours, in which time 254 tonnes of DRI were melted to make 52 ‘heats’ in a continuous mode.

As seen from Fig. 5, the trial heats were carried out in four distinct phases (1-4). The bath temperature was maintained close to the target 1,600 °C throughout the trial heats (Fig. 6) while the slag FeO content varied according to the target bath carbon in the trial phase.

- In Phase 1 the objective was to establish the steady state melt-in carbon without the addition of iron oxides (millscale or iron ore). This was reached in approximately 14 hours when the carbon plateaued at 0.5 – 0.6 wt% C, close to the stoichiometric value calculated from the carbon and residual oxide content in the DRI. At this point, gradual additions of mill scale were made with the intent of bringing the bath carbon down to 0.10 wt% C, the target level set for Phase 2.

FIG. 3 The Swerea MEFOS 8-tonne AC electric arc furnace.
*Forno elettrico ad arco AC MEFOS da 8 t.*

FIG. 4 Comparison of the bath carbon/FeO relationship from the Phase I CRISP pilot trials (2007) with conventional EAF operation.
*Rapporto carbonio/FeO nel bagno: confronto fra le prove nell’impianto pilota CRISP della Fase I e il processo EAF convenzionale.*

FIG. 5 Variation of bath carbon and slag FeO in the course of the Phase II trials.
*Variazione di carbonio e FeO nel bagno durante le prove della Fase II.*

FIG. 6 Bath temperature in the course of the Phase II trials.
*Temperatura del bagno nel corso delle prove della Fase II.*
can be produced on a CRISP furnace. The bath has a positive impact on the range of steel qualities with continuous feed of DRI. This low nitrogen content of the EAF steelmaking process where arcs together with air ingress usually results in significantly high nitrogen levels, even below 40 ppm, and often less than 20 ppm. This is very low for pilot trials showing an excellent refractory endurance. These differences lead to significant operational benefits, the most important being:

- Continuous melting without downtime for charging, tapping or fettling;
- Large liquid heel with the attendant long residence of metal in the furnace;
- Power density in the range of 300 to 500 kW/m² of hearth, a fraction of the level on a conventional EAF, typically 2,500 kW/m² to 3,000 kW/m²;
- The ability to decarburize to low levels of carbon (> 0.04 wt% C) without the use of gaseous oxygen.

These differences lead to significant operational benefits, the most important being:

- Decarburization is accomplished at slag FeO levels closer to equilibrium;
- The related improved yield provides meaningful savings in the cost of metallics;
- Furnace refractory life is measured in years rather than weeks or months;
- The high furnace availability, approaching 8,000 hours/year, leads to improved plant logistics (matching) with upstream and downstream facilities;
- The shielding of the arcs is accomplished by utilizing the foamy slag inherent to the continuous melting of DRI;
- The low gas velocity in the furnace freeboard significantly reduces the amount of dust carried over from the furnace. This not only reduces the dust disposal costs but also allows the charging of fine materials to the furnace, a cost-effective measure;
- The total specific energy requirement – power, oxygen, natural gas and carbon – is lower than on a conventional EAF; in the comparison case: 610 kWh/tonne liquid steel versus 756 kWh/tonne liquid steel;
- The continuous nature of the CRISP operation together with the furnace design allows the furnace off gas to be captured and utilized as a fuel gas;
- The steady even furnace power load of the continuous CRISP operation reduces the demands on the electrical utility grid. It also enhances the feasibility of connecting to a captive power plant;
- The GHG (green house gas) footprint and especially the NOx emissions are significantly lower.

These benefits translate into an operating cost advantage of the CRISP process as compared to conventional EAF steelmaking in terms of cost per tonne of liquid steel. The savings stem primarily from lower overall energy costs and improved yields, as well as lower costs for refractory, oxygen and electrodes. These are quantified in Section 6. It was also found that about 85% phosphorus reported to slag. This improvement in de-phosphorization capability of the steel.

**FIG. 7** Furnace refractory profile before and after Phase I and Phase II trials.

Profilo del refrattario del forno prima e dopo le prove della Fase I e II.

- In Phase 2 the carbon level was held in the vicinity of the targeted value for 33 hours of continuous operation, after which time it was decided to reduce the bath carbon to 0.04 wt% C.
- The Phase 3 carbon level was reached after a transition period of three hours and held for 38 hours of continuous operation.
- For Phase 4, the final phase of the trials, the target carbon level was set between that of Phase 2 and 3, at 0.06 wt% C. One of the most important findings of the trials was the confirmation that the process conditions of the CRISP technology allow the bath carbon to be controlled in a consistent and repeatable manner, solely by adjusting the slag FeO and without the use of gaseous oxygen. Another factor important for the economic viability of the CRISP technology is the ability to sustain the furnace refractories over an extended period without erosion. As seen from the measurements of the furnace refractory profiles made before and after the trials (Fig. 7), after two campaigns lasting in total approximately 200 hours of operation and without refractory repairs, there is, with the exception of minor erosion opposite the hot (B) phase, no loss of refractory. In fact, there is actually a net deposit of 66 mm. This was accomplished on an electric arc furnace without water-cooled sidewall panels or roof.

This is regarded as one of the most promising outcomes of the pilot trials showing an excellent refractory endurance. These encouraging results can be attributed primarily to the properties of the slag: good foaming action with low FeO levels and MgO saturation.

The nitrogen content found in the steel was another important finding in the pilot trials. The dissolved nitrogen was consistently below 40 ppm, and often less than 20 ppm. This is very low for an EAF steelmaking process where arcs together with air ingress usually results in significantly higher nitrogen levels, even with continuous feed of DRI. This lower nitrogen content of the bath has a positive impact on the range of steel qualities that can be produced on a CRISP furnace.
making process is mainly attributed to the lower process temperature. Additional theoretical and experimental study will be required to better understand the mechanism of phosphorus partition between steel and slag in the CRISP furnace environment.

REDUCED ENVIRONMENTAL FOOTPRINT

The features of the CRISP process described above translate into a meaningful reduction in the environmental footprint. The specific areas impacted are discussed below:

NOX.

Since the CRISP furnace has minimal air ingress, the NOX concentrations are well below 50 ppm. This is in contrast to a conventional EAF, where the large ingress of air combined with the arc action lead to much higher NOX concentrations. Measurements made during the pilot trials at MEFOS support these projections. During the MEFOS trials, an average of 47 g/t and a maximum of 118 g/t were recorded, with the higher numbers being experienced when the slag door was opened. The emissions expected from a CRISP demonstration furnace are even lower, as the furnace will be operated under positive pressure, with no postcombustion of the gas in the fume duct and no furnace doors opened during operation. By contrast, in conventional EAF operations, typically 200 g/t NOX is generated.

Dust.

The low gas velocity in the furnace freeboard significantly reduces the amount of dust carried over from the furnace. This not only reduces the dust disposal costs but also allows the charging of fine materials to the furnace, a cost-effective measure.

GHG gases.

The GHG related to the steelmaking and ladle metallurgy operations of a CRISP plant are approximately 25% lower than those of an EAF plant, despite the higher electrical power consumption projected for the CRISP operations (Fig. 8). This is primarily due to the reuse of the off gas of the CRISP furnace as well as the fact that carbon materials and oxygen are not used as auxiliary energy in the CRISP furnace. This represents a distinct environmental advantage of the CRISP technology.

ONGOING DEVELOPMENT

The two campaigns of pilot testing at Swerea MEFOS were critical to the development of the CRISP technology. The test results validated the underlying metallurgical concepts, thus allowing the process design to be advanced. Some of the specific areas involved were:

- slag design and process control strategy;
- calculation of material and energy requirements;
- stationary furnace design;
- refinement of plant layouts;
- definition of auxiliary equipment;
- assessment of plant logistics;
- update of operating and capital costs.

This information was incorporated into a comparative feasibility study aimed at benchmarking the CRISP technology with the current EAF technology. A CSP plant producing 1.5 million tonnes/year of hot band was selected as a type of plant that would lend itself to a readily recognizable ‘apples-to-apples’ comparison. The main process facilities of the plant are:

- Direct reduction plant;
- Electric arc furnace (Stationary electric furnace);
- Ladle metallurgy furnace;
- Thin slab caster;
- Tunnel furnace;
- Compact hot strip mill.

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hot DRI Charged EAF</th>
<th>CRISP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Operating Time (hours/year)</td>
<td>7,200</td>
<td>8,000</td>
</tr>
<tr>
<td>Power-on Time / Occupancy (hours/year)</td>
<td>5,414</td>
<td>7,440</td>
</tr>
<tr>
<td>Production rate (tonnes liq steel/hour)</td>
<td>285</td>
<td>207</td>
</tr>
<tr>
<td>Hearth area (m²)</td>
<td>38</td>
<td>329</td>
</tr>
<tr>
<td>Heat size (tonnes)</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Hot heel (tonnes) (average)</td>
<td>50</td>
<td>1,000 to 1,500 (1,317)</td>
</tr>
<tr>
<td>Approximate residence time (hours)</td>
<td>0.75</td>
<td>7.15</td>
</tr>
<tr>
<td>Total energy consumption (ekWh/tonne)</td>
<td>756</td>
<td>610</td>
</tr>
<tr>
<td>Electrical power consumption (kWh/tonne liq steel)</td>
<td>428</td>
<td>510</td>
</tr>
<tr>
<td>Electrical power average/peak (MW)</td>
<td>113/137</td>
<td>106/127</td>
</tr>
<tr>
<td>Power density (kW/m²)</td>
<td>3,840</td>
<td>385</td>
</tr>
</tbody>
</table>

**FIG. 8** Comparison of GHG emissions from steelmaking and ladle metallurgy operations of an EAF and CRISP plant.

**Confronto fra le emissioni GHG da operazioni siderurgiche e di stiviera di un impianto EAF e CRISP.**
**MATERIALS**

<table>
<thead>
<tr>
<th>Item</th>
<th>EAF</th>
<th>CRISP</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRI tonne</td>
<td>242.8</td>
<td>224.8</td>
</tr>
<tr>
<td>Mill Scale tonne</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>Pellets (mill scale subsidy) tonne</td>
<td>121.00</td>
<td>108.39</td>
</tr>
<tr>
<td>Total burnt lime tonne</td>
<td>113.61</td>
<td>108.39</td>
</tr>
<tr>
<td>Burnt dolomite tonne</td>
<td>133.00</td>
<td>127.39</td>
</tr>
<tr>
<td>Carbon tonne</td>
<td>133.00</td>
<td>127.39</td>
</tr>
<tr>
<td>Subtotal materials tonne</td>
<td>287.39</td>
<td>278.39</td>
</tr>
</tbody>
</table>

**CONVERSION COST**

<table>
<thead>
<tr>
<th>Item</th>
<th>EAF</th>
<th>CRISP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour $/ hr</td>
<td>45.00</td>
<td>45.00</td>
</tr>
<tr>
<td>Repairs and maintenance</td>
<td>6.00</td>
<td>5.95</td>
</tr>
<tr>
<td>Refractory</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Total electricity kWh</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Oxygen Nm³</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>CRISP gas production GJ</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Soft / demin. water m³</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Cold water m³</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Natural Gas GJ</td>
<td>5.00</td>
<td>4.95</td>
</tr>
<tr>
<td>Graphite electrodes (EAF) tonne</td>
<td>4,233.00</td>
<td>3,983.00</td>
</tr>
<tr>
<td>Soderberg electrodes (CRISP) tonne</td>
<td>640.00</td>
<td>640.00</td>
</tr>
<tr>
<td>Contingency, 10%</td>
<td>5.00</td>
<td>4.95</td>
</tr>
<tr>
<td>Subtotal conversion cost</td>
<td>54.98</td>
<td>54.98</td>
</tr>
<tr>
<td>Total electric furnace costs</td>
<td>342.37</td>
<td>337.37</td>
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</table>

**LADLE METALLURGY**

<table>
<thead>
<tr>
<th>Conversion Cost</th>
<th>EAF</th>
<th>CRISP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.69</td>
<td>4.68</td>
</tr>
<tr>
<td>Total cost</td>
<td>346.07</td>
<td>321.27</td>
</tr>
</tbody>
</table>

1) The LMF conversion cost is marginally more expensive for the CRISP process route since the liquid steel will require more time (and hence use more electricity) in the LMF due to its lower tapping temperature.

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**TAB. 3** Operating costs of steelmaking and ladle metallurgy, comparative feasibility study ($/tonne liquid steel).

Costi operative relativi a siderurgia e colata di siviera, studio di fattibilità comparativo ($/t di acciaio liquido).

**TAB. 4** Summary of capital costs used in the comparative feasibility study ($US million).

Sommaio dei costi di capitale usato nello studio di fattibilità comparativo (milioni di $US).
In the study it was assumed that the metallic charge is 100% DRIL; 90% hot/10% cold. A comparison of the furnace parameters is found in Table 2 above.

The operating and capital costs developed in the comparative feasibility study are shown in Table 3 and Table 4 respectively. While the capital costs of the plant are essentially identical, the estimated operating costs show a meaningful advantage of the CRISP plant – approximately $25/tonne. This, together with the operating advantages described above make a compelling case to consider the CRISP technology.

The comparative feasibility study is an essential summary benchmark document and an integral part of the ongoing commercialization program.

Acknowledgement

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REFERENCES
5) G. TRAQUAIR, F.M. WHEELER, and Y.M. GORDON, Proc. METEC In-SteelCon2007, Düsseldorf, Germany (June 2007).
6) M. BARATI et al., Proc. VIII Int. Conf. on Molten Slags, Fluxes & Salts, Santiago, Chile (Jan. 2009).