The successful piloting of CRISP, the innovative continuous steelmaking technology

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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

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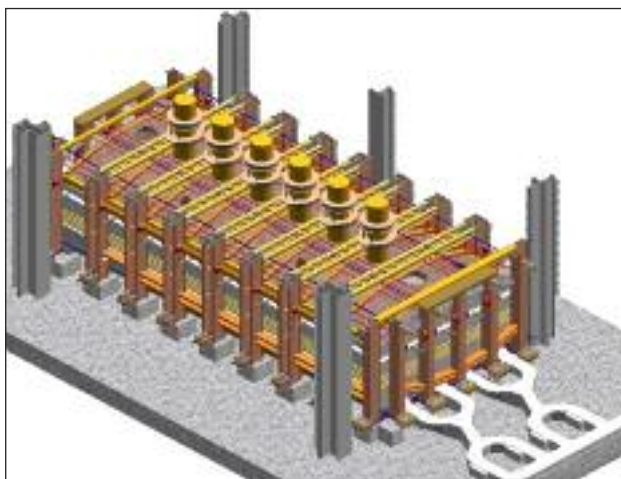
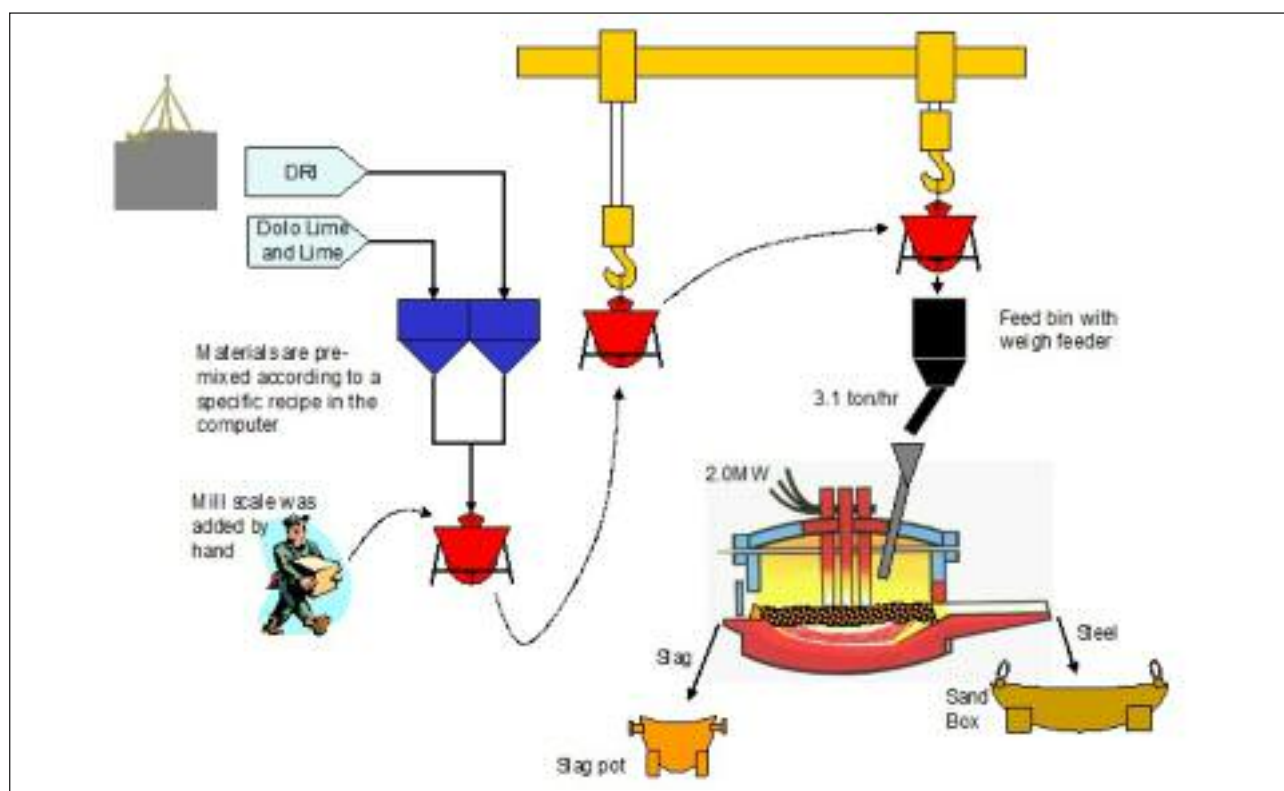**FIG. 1** *Schematic of CRISP stationary electric furnace.*

Schema del forno elettrico stazionario CRISP.

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

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,

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

Logistica delle prove della Fase II.

Test #	Day	FeO wt%	B$_4$	C wt%
1	1	As low as possible	2.0	0.10
2	3	As low as possible	2.0	0.04 and 0.06

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

Prescrizioni di composizione iniziale delle scorie, prove con impianto pilota Fase II

FIG. 3   *The Swerea MEFOS 8-tonne AC electric arc furnace.*
Forno elettrico ad arco AC MEFOS da 8 t.
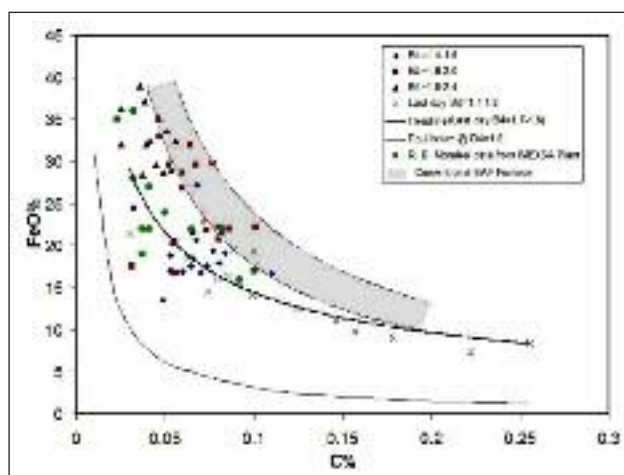
FIG. 4   *Comparison of the bath carbon/FeO relationship from the Phase I CRISP pilot trials (2007) with conventional EAF operation.*

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.
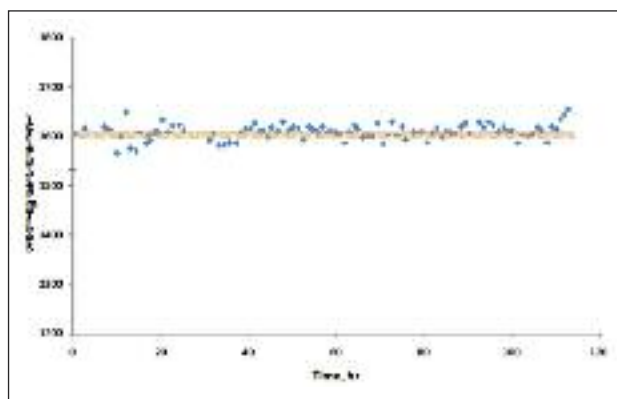
FIG. 6   *Bath temperature in the course of the Phase II trials.*

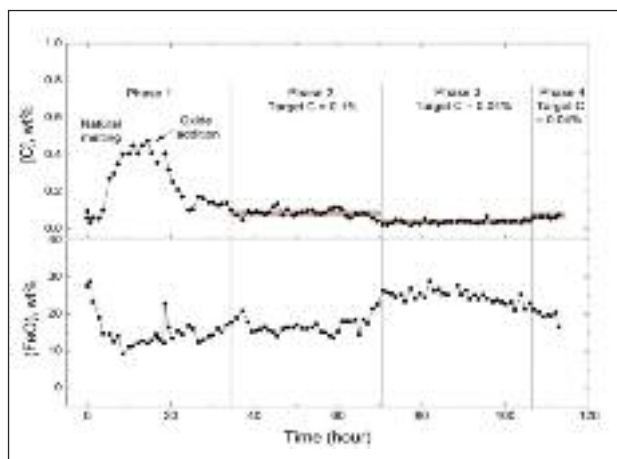*Temperatura del bagno nel corso delle prove della Fase II.*

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-O_2 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 (mill scale 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.
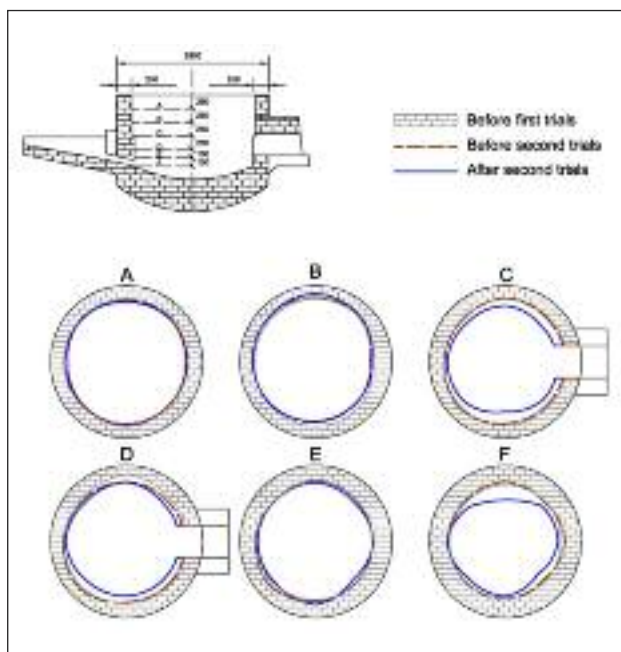
FIG. 7 *Furnace refractory profile before and after Phase I and Phase II trials.*

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 arcing 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.

BENEFITS OF THE CRISP TECHNOLOGY

The dramatic development of EAF steelmaking technology in recent decades has been well documented. Ever-increasing furnace power levels together with the introduction of large amounts of chemical energy and innovative practices, such as the foamy slag practice and eccentric bottom tapping, have lead to unprecedented advances in EAF productivity. Not only are heats churned out in tap-to-tap times routinely under one hour; power and electrode consumption have dropped to a fraction of previous levels.

These trends are not, however, without their limitations, and ongoing innovation requires a fresh approach rather than incremental improvements. CRISP represents such a departure from the current trends. This is illustrated in Table 2, in which the key differences of a CRISP furnace as compared to a conventional steelmaking electric arc furnace (EAF) are highlighted, using a nominal 1.5 million t/yr plant as an example.

The essence of the unique features of the CRISP technology is:
- 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 foaming 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 NO_x 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-

	Hot DRI Charged EAF	CRISP
Net Operating Time (hours/year)	7,200	8,000
Power-on Time / Occupancy (hours/year)	5,414	7,440
Production rate (tonnes liq steel/hour)	285	207
Hearth area (m^2)	38	329
Heat size (tonnes)	160	160
Hot heel (tonnes) (average)	50	1,000 to 1,500 (1,317)
Approximate residence time (hours)	0.75	7.15
Total energy consumption (ekWh/tonne)	756	610
Electrical power consumption (kWh/tonne liq steel)	428	510
Electrical power average/peak (MW)	113/137	106/127
Power density (kW/m^2)	3,840	385

TAB. 2 *Key operating parameters of a CRISP furnace as compared with a conventional EAF for a 1.5 million tonne/year plant.*

Parametri operativi principali del processo con forno CRISP confrontati con quelli di un forno EAF convenzionale in un impianto da 1,5 milioni di t/anno.

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:

NO$_x$.
Since the CRISP furnace has minimal air ingress, the NO$_x$ concentrations are well below 50ppm. This is in contrast to a conventional EAF, where the large ingress of air combined with the arc action lead to much higher NO$_x$ 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 post combustion of the gas in the fume duct and no furnace doors opened during operation. By contrast, in conventional EAF operations, typically 200 g/t NO$_x$ 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
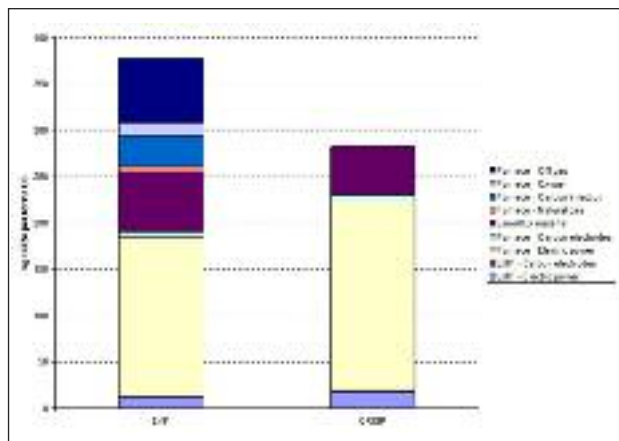
FIG. 8 *Comparison of GHG emissions from steelmaking and ladle metallurgy operations of an EAF and CRISP plant.*

Confronto fra le emissioni GHG da operazioni siderurgiche e di siviera di un impianto EAF e CRISP.

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.

Electric Furnace	Units	$US/unit	EAF Units/t LS	EAF $US/t	CRISP units/t LS	CRISP $US/t LS
MATERIALS						
DRI	tonne	242.8	1.15	278.39	1.08	262.21
Mill Scale	tonne	-			0.01	0.00
Pellets (mill scale subsidy)	tonne	121.00			0.03	3.29
Total burnt lime	tonne	113.61	0.032	3.62	0.019	2.21
Burnt dolomite	tonne	113.61	0.037	4.18	0.035	3.96
Carbon	tonne	133.00	0.01	1.20		
Subtotal materials				287.39		271.67
CONVERSION COST						
Labour	$/ hr	45.00	0.11	4.95	0.11	4.95
Repairs and maintenance				6.00		3.00
Refractory				3.00		1.00
Total electricity	kWh	0.06	428	25.68	510	30.60
Oxygen	Nm³	0.10	32.00	3.04		
CRISP gas production	GJ	0.00			0.31	0.00
Soft / demin. water	m³	0.22	0.01	0.001	0.30	0.06
Cold water	m³	-			6.73	0.00
Natural Gas	GJ	5.00	0.11	0.54		
Graphite electrodes (EAF)	tonne	4,233.00	0.002	6.77		
Soderberg electrodes (CRISP)	tonne	640.00			0.002	1.22
Contingency, 10%				5.00		4.08
Subtotal conversion cost				54.98		44.91
Total electric furnace costs				342.37		316.58
LADLE METALLURGY						
Conversion Cost 1				3.69		4.68
Total cost				346.07		321.27

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

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).

Item	Hot DRI Charged EAF	Hot DRI Charged CRISP
Raw material handling / stockyard	64	64
Ironmaking (DRI unit)	398	398
Steelmaking (Electric furnace)	208	200
Steel refining (LMF)*	23	38
Steel finishing (CSP)	463	463
Utilities and auxiliaries	25	25
Infrastructure & civil works	78	78
Administration facilities	14	14
Sub-total	1,274	1,282
EPCM	76	77
Contingency	203	204
Total project costs	1,553	1,562

* Note that the CRISP LMF capital cost estimate is larger than the EAF due to the need for two twin-position LMFs in the CRISP process route.

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

Sommario 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% DRI; 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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Abstract

L'impianto pilota del processo CRISP, tecnologia innovativa per la fabbricazione dell'acciaio in continuo

Parole chiave: impianti e processi, siderurgia

Il processo CRISP (Continuous Reduced Iron Steelmaking Process), una tecnologia innovativa brevettata per la produzione dell'acciaio in continuo da pre-riduzione del minerale di ferro, ha subito uno sviluppo significativo rispetto allo stadio iniziale. Recentemente, le prove pilota effettuate presso il MEFOS AB di Luleå, Svezia, hanno confermato in modo soddisfacente la validità dei principi metallurgici di base, nonché la praticabilità del funzionamento in continuo, creando quindi le condizioni per la commercializzazione di questa tecnologia.

Il processo CRISP si basa su pratiche e attrezzature esistenti, e rappresenta quindi un passo logico nello sviluppo dell'acciaieria elettrica. L'uso innovativo di un forno elettrico stazionario - comune in altre industrie dei metalli come per la fusione di nichel o di rame -, rispetto alle attuali tendenze nella produzione dell'acciaio in continuo, rappresenta tuttavia una svolta e costituisce la base di questa nuova tecnologia di fabbricazione dell'acciaio.

Le caratteristiche uniche della tecnologia CRISP sono in grado di portare notevoli vantaggi operativi.

Il documento illustra tali vantaggi e i relativi risparmi di capitale e costi operativi, e descrive lo stato attuale e gli sviluppi in corso della tecnologia CRISP.

Vengono anche riportati i fattori che determinano una riduzione dell'impatto ambientale.