**CONSTEEL® EVOLUTION: THE PROVEN TECHNOLOGY FOR MAXIMUM EAF CHARGING FLEXIBILITY**

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**ABSTRACT**

Steel is the primary construction material of modern societies; similarly to what has happened in old economies, after World War II, a growing availability of scrap is soon going to be experienced also in new economies making the recycle of scrap via electric arc furnace the most economically and ecologically convenient steel-making route.

The use of scrap in electric arc furnace steelmaking is often balanced with virgin iron units (usually DRI, HBI, pig iron and hot metal) according to local scenario of raw materials availability and cost; a practice which has also enabled electric steelmaking to challenge the traditional oxygen converter route for the production of high purity steel grades.

The electric arc furnace lends itself well to the processing of a variable raw material mix, especially when adopting the continuous charge approach, normally used only for the charge of large amounts of DRI.

The Consteel®, industrially applied first in 1989 in Gerdau-Ameristeel Charlotte (and still in operation since then), is the first and only truly continuous scrap feeding system for an electric arc furnace, which is also designed to reduce the energy consumption for the process through scrap heating by off-gas heat recovery.

To date there are more than 46 Consteel® installation worldwide and the paper describes the reasons behind the increasing industrial acceptance of this technology, such as energy efficiency, reliability and environmental friendliness, and why it maximizes the flexibility of electric arc furnace steelmaking in terms of charge materials, making it the most convenient technology for a changing raw material market

**KEY WORDS**

CONSTEEL, ELECTRIC ARC FURNACE, CONTINUOUS CHARGING, RAW MATERIALS FLEXIBILITY

1 **THE RATIONALE BEHIND SCRAP-BASED ELECTRIC STEELMAKING**

Steel is the primary construction material of modern societies and the production of steel from iron ore, either via the traditional Blast Furnace – Oxygen Converter (BF-BOF) route or the newer Direct Reduction – Electric Arc Furnace (DR-EAF) route, is a very energy demanding process, requiring about 14.9 GJ/t [1], and this energy demand can be related to the environmental footprint of these processes, for which has been estimated a specific emission around 1800 kg CO₂/t [8].

On the other hand, steelmaking based on the recycle of steel scrap via EAF requires about 5.7 GJ/t [1] and emits about 440 kg CO₂/t [8], therefore it is not just a way to avoid the accumulation of steel scrap coming from obsolete goods, but it is also the most cost convenient and environmentally friendly steelmaking route; this stands behind the steady increase in the share of steel being produced via the EAF route [14] (Figure 1.1).

Of course, a sufficient availability of steel scrap and electric power, at reasonable prices, are necessary conditions.

Similarly to what has happened in Europe, after World War II, with the birth of the Mini-Mill plants, new economies may not have these conditions at their beginning but the increased use of scrap-based electric arc steelmaking will eventually happen.
At a regional level, the most convenient balance between steelmaking from iron ore, which is producing the so-called “virgin iron”, and scrap-based steelmaking depends on the local energy and raw materials availability and cost scenario, and on market requirements in terms of acceptable level of residual elements in final steel products.

For an electric arc furnace steelmaker, this translates into the need to balance the charge of steel scrap with virgin iron units such as pig iron, hot metal, DRI and HBI; a practice that is enabling electric steelmaking to increasingly challenge the traditional oxygen converter route also in the production of low residuals (Cu, Sb, Sn etc.) steel grades.

2  THE FLEXIBILITY OF CONSTEEL® CONTINUOUS CHARGING

For the modern electric arc furnace steelmaker, the possibility to easily adapt the metallic charge of the furnace to follow the variations in raw material cost scenarios and market demands is, obviously, very important.

The electric arc furnace is intrinsically flexible in terms of charge materials but we will now see why the ultimate charge flexibility is achieved by electric arc furnaces operating according to the continuous charging process concept.

The continuous charging process is normally used by electric arc furnaces processing large amounts of DRI or HBI, since batch processing (top charging by buckets) of these material has proven to be unworkable\(^1\); this concept has been extended to the processing of scrap with the introduction of the Consteel® technology (Figure 2.1).

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\(^1\) Is impossible to achieve a uniform meltdown of these charges, with formation of unmolten lumps (to so-called “ironbergs” or “ferrobergs”) due to the poor thermal conductivity and tendency to coalesce of these materials.
The Consteel® achieves the continuous feeding of scrap by means of an inertial conveyor, which moves the scrap from an open section, used for charging (usually by crane), to the furnace, passing through a closed section in which scrap is being heated by process off-gas travelling in the opposite direction, towards the fume extraction system (FES).

The first industrial application of the Consteel® technology took place in 1989, in Gerdau-Ameristeel Charlotte (USA) – where is still in operation – and since then there has been a steady industrial acceptance of this technology reaching a present installed base of 46+ units worldwide (Figure 2.2).
It is worth pointing out that the Consteel® has been the first industrially proven system for the continuous charging and heating of scrap, and, despite several attempts to imitate its operation, it remains the only truly continuous scrap charging and heating system even today and that not a single Consteel® installation has ever been substituted with another EAF technology.

The success of the Consteel® was particularly evident in China, around year 2000, because it was recognized to be the most convenient steelmaking process for the optimal use of the existing weak electric networks.

The scrap and power shortage that followed a few years later forced many Chinese steelmakers to combine the scrap charge with hot metal\(^2\) experiencing why Consteel® is also the best option for taking advantage of hot metal in electric steelmaking: it is basically because the Consteel® process allows to spread the decarburization of the melt across the entire power-on time, often without major changes in the primary off-gas systems and without incurring in decarburization delays that limit the productivity of a traditional top-charge EAF\(^3\) when the hot metal charge rises above \(\sim 30\%\) of the total\(^2\)[4].

The experiences with hot-metal in Consteel® furnaces have spanned from 20\% to about 86\%, reaching a point in which the furnace can be operated like an oxygen converter, without electric power, with power-on/oxygen blowing time around 32 minutes, yet still able to operate on a 100\% scrap charge when needed; the 100 t Consteel® EAF installed in Shaoguan Iron & Steel Co. (PRC) is a great example of this type of operation.

Nowadays, with the cost of steel scrap going down and the increased pressure to reduce CO\(_2\) emissions, there will be a drive to reduce the use of hot metal and increase the use of scrap; the Consteel® EAFs are just ready for that.

Another example of the Consteel® flexibility is the 140 t Consteel® EAF for Vallourec-Sumitomo Brazil (Brazil), commissioned in 2012, which has been designed to work with a charge mix made of scrap, up to 40\% pig iron and up to 40\% hot metal.

We also have a Consteel® EAF, installed in South Korea, in which the continuous charge of scrap has been combined with the continuous feeding of DRI and HBI\(^3\).

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\(^{2}\) Usually produced by mini-blast furnaces (MBF).

\(^{3}\) In a traditional top-charged EAF, bath decarburization by means of oxygen injection can be performed only in the second half of the process, when the charge meltdown is complete. Compensating the shorter time for decarburization with stronger oxygen injection is possible only up to a certain limit beyond which the process is not compatible with the furnace configuration nor with the need to operate with electric arc heating.
It is therefore evident (Figure 2.4) how the Consteel® system can seamlessly combine the continuous charging of scrap with any form of virgin iron charge: hot metal, pig iron, DRI or HBI.

Figure 2.4 Consteel® generalizes continuous charge steelmaking

As general rule, DRI and HBI shall be fed to the furnace in the traditional way4, that is directly through the furnace roof, while hot metal shall be poured into the furnace through a door or sidewall runner, pig iron, instead, can be mixed with scrap into the charging conveyor.

Like pig iron, also beach iron, in pieces of a few tons each, can be charged via Consteel®, together with scrap, as done by an Italian steelmaker.

The question now would be: the continuous charging process is indeed flexible in terms of metallic charge mix but how flexible is the Consteel® system versus the type of steel scrap to be charged to the furnace?

The answer is very simple: the Consteel® system can use any type of steel scrap; whatsoever metallic raw material that can be charged in a traditional electric arc furnace can be used in a Consteel® system as well.

In terms of maximum dimensions of scrap, the normal limits specified by the European Steel Scrap Specification[6] – 1.5x0.5x0.5m – are compatible with continuous charging via Consteel®.

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4 If the HBI amount to be charged is not exceeding ~20% of the total charge, it can be mixed with scrap, in the conveyor.
The main rule to be obeyed is that the maximum scrap piece length must not exceed the distance between the tip of the Consteel® conveyor and the electrodes, in order to avoid the chances of an electrical bridge between these parts; this may limit the maximum acceptable piece length on small furnaces whilst large furnaces can be more tolerant; in practice, steel scrap normally available on the market is already compatible with the smallest Consteel® installation.

In the Consteel® process the charge of scrap is continuous, thus scrap density is not affecting the operations as much as it does in a conventional top-charge furnace, where a too light scrap may require more bucket charges, reducing efficiency and productivity, and where too much heavy scrap produces delays in the charge meltdown, if not frequent electrode breakages due to massive scrap cave-ins during the initial melting.

The Consteel® process is carried out balancing the power input to the furnace with the mass flow rate of charge materials (similarly to the control logic applied in DRI fed furnaces) and the required mass flow rate is achieved automatically by the system’s control logic, adjusting the feeding rate of the conveyor: faster for light scrap and slower for heavy scrap; the mass flow rate is controlled by a furnace weighing system and/or by a charge tracking system (in newer installations).

The scrap discharged by the conveyor melts by immersion in a large pool of molten metal (the hot heel) providing the most favorable conditions for the melting of heavy scrap pieces, like bundles, which are notoriously troublesome for conventional EAFs; the only requirement is to distribute uniformly the heavy pieces along the charge.

In general, it is much easier to melt heavy scrap pieces in a Consteel® EAF than in a conventional EAF of the same size, and the furnace performance will benefit if the hot heel is correctly sized and the process is combined with bottom stirring with Nitrogen or Argon.
Usually the hot heel is sized as 42÷50% of the tap weight; this mass of molten metal is maintained across the various heats and acts as a stabilizing “thermal flywheel” for the process. On the very first heat of the furnace campaign, the hot heel is created with the meltdown of a bucket charge. When the furnace needs to be drained, the charge is reduced and the hot heel used to tap a full heat.

3 OTHER BENEFITS OF THE CONSTEEL® SYSTEM

At the beginning of the Consteel® history, this technology for charging scrap and pig iron to the furnace was seen essentially a way for reducing the electric energy demand for the process, heating the charge with the process off-gas.

Its great operational flexibility, discussed in the first part of this paper, was one of the benefits of this system which became apparent only years after its widespread industrial application; there are other benefits worth mentioning that can be grouped in three categories: process, equipment & maintenance and environmental benefits.

3.1 Process benefits

3.1.1 Continuous charging: the best combination for efficiency and flexibility

In traditional furnaces, the charge of scrap is done by buckets and is melted by direct action of the electric arcs, often with the help of oxy-fuel burners, to achieve a faster and more uniform charge meltdown\(^5\).

This operation is characterized by strong disturbances of the electric arcs (and on the electrical network) for several minutes, minutes in which is not possible to harness all the active power available. The arcs eventually stabilize but by then the heat transfer efficiency has dropped since the charge will be semi-molten thus unable to completely shield the furnace from arc radiation. In this type of operation, any major DRI or HBI addition to the charge is done continuously, starting from the point in which the scrap charge is almost completely molten.

With the adoption of the Consteel® system, the processing of scrap becomes similar to that of DRI or HBI, and those can be combined in any possible way, and thanks to the operation on a flat bath, under foaming slag, the electric arcs will be always able to take advantage of the available active power, with the least possible disturbances on the electrical network.

The scrap heating achieved inside the Consteel® system is an important plus to this type of operation, allowing a significant reduction in electric energy consumption: old Consteel® systems where able to achieve average temperatures in the range 250÷300 °C, allowing electric energy savings around 40 kWh/tls, with the new Consteel® Evolution™ the average temperature will rise to 400÷450 °C, boosting the electric energy savings up to 70 kWh/tls.

The Consteel® Evolution™ is not a definite furnace setup but rather a set of improvements and new solutions, starting from a different tunnel geometry up to the possibility to use burners inside the heating section of the tunnel\(^{[15]}\), that are coming out of several years of field experience and extensive CFD studies on the heat exchange between scrap and the off-gas, inside the Consteel® heating tunnel.

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\(^5\) Burners are located to avoid “cold-spots” in the furnace, usually in correspondence with the inter-phase zones for a 3AC furnace.
Some of the Consteel® Evolution™ solutions have been applied in the switch to Consteel® technology for the EAF installed in IRM (Canada), and in the new Consteel® for the EAF installed in ORI Martin (Italy), and performance improvements are in line with the expectations.

Figure 3.1 The charging section of ORI Martin’s new Consteel® Evolution™ used for the production of CHQ and automotive steel grades

To compete against Consteel®, nowadays we can see new furnace configurations that are trying to combine the recognized benefits of the Consteel® charging method with a more intense scrap heating, and this is achieved charging and heating the charge with process off-gas through a vertical shaft.

First, let’s remark that that none of these new shaft furnaces can operate with a truly continuous process (the best some of these can do is approximating a continuous process reducing the charge batch size), therefore some of the benefits of the continuous process are lost.

In general shaft furnaces do have a strong potential in terms of charge heating via furnace off-gas but, as industrial experience has demonstrated in the last decade, they are very demanding in terms of maintenance and consistency of scrap charge characteristics (e.g. sizing and density); these furnaces are also unable to charge significant amounts of pig iron and, overall, they represent a very specialized class of melting machines.

Considering the fact that drawing the off-gas through the scrap inside the shaft causes a strong head loss to be compensated by the fumes extraction system, and that shaft furnaces often need re-heating burners to bring the off-gas temperature at the shaft exit back up to the level required for the thermo-destruction of any pollutant released by the charge, it is yet be demonstrated whether a stronger scrap heating really pays off in terms of energy efficiency, if one considers the fume system and the furnace system as a whole.
3.1.2 Improved charge yield

A better metallic charge yield is one of the unexpected Consteel® benefits that became apparent only after its wide industrial application: it has been found[16] that switching from a classic bucket charged furnace to Consteel® furnace usually results in about 1% yield improvement.

The reasons behind this phenomenon are basically two: dust recovery and lower charge oxidation.

Dust recovery takes place due to the system’s configuration: the heaviest, iron-rich, dust particles emitted by the process deposit onto the scrap present inside the heating tunnel and then they are brought back to the furnace along with scrap[10].

A similar effect could be experienced also when the charge of scrap is combined with DRI feeding, recovering part of the DRI fines which would otherwise be carried out with the off-gas and lost in the fumes extraction plant.

Regarding the lower charge oxidation, the phenomenon is mostly evident when comparing a fast traditional furnace with its Consteel® equivalent: the conventional bucket-charged furnace can perform the required bath decarburization in about half of the active time whilst the Consteel® can use it entirely.

Therefore, the Consteel® process needs a lower decarburization rate than the conventional EAF, achieving bath/slag conditions closer to equilibrium; this translates into lower oxygen activity and lower iron oxidation for the same carbon and temperature, improving the charge yield and reducing the cost of reducing additions (Al, FeSi, FeSiMn etc.) in the tapping ladle.

The lower decarburization rate can also explain why the fume extraction system for a Consteel® EAF can be significantly smaller than that for the corresponding bucket-charged EAF.

3.1.3 Lower nitrogen pickup

It has been found that the charge of scrap via Consteel® EAF allows to tap the furnace with a nitrogen content that is about 15 ppm lower that of the corresponding process carried out with a conventional bucket-charged EAF[16].

This phenomenon is essentially due to the different operation of the electric arc in the two processes: in Consteel® the arc burns always under foaming slag thus reducing the interaction with air and the breakup of the atmospheric nitrogen molecules in close proximity of the molten steel; this atomic nitrogen is the most reactive and the most easily picked up by molten steel.

3.2 Equipment & maintenance benefits

3.2.1 Optimization of fume extraction system

Since the Consteel® system allows the continuous processing of scrap and pig iron, the off-gas emission profile is the most stable that can be realized by a steelmaking furnace and this allows the optimal sizing of the primary fume extraction system: the oversizing required to deal with the emission peaks of a discontinuous process can be avoided.

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6 Corresponding furnace means a furnace that has the same heat size, the same charge and the same productivity.
A stable off-gas emission profile is, also, ideally suited for the application of a wasted heat recovery system, like the ECS from Tenova Re-Energy, which is used for the production of steam from the available off-gas energy, the reason being that the more stable is the emission profile of the furnace the smaller is the steam accumulator required to stabilize the steam output.

3.2.2 Minimum electrical disturbances and electrode consumption

The Consteel® allows continuous process of scrap and pig iron, melting them by immersion not by direct arc action; in this process the electric arc works always on a flat bath, were foaming slag is constantly being promoted, and this reduces greatly the disturbances on the electrical network (less harmonics and flicker) and this has allowed to avoid the installation of a SVC unit in several cases.

This this way of operating the electric arcs also reduces the tip consumption of the electrodes and, since it allows a better exploitation of the available electrical power, it allows the selection of a transformer rated for about 13÷15% less MVA than the transformer required for the corresponding bucket-charged furnace.

3.2.3 Reduced maintenance cost and increased operational safety

The Consteel® is a simple and reliable system but like any other piece of equipment needs some maintenance, albeit small.

In 2008 we did a study[9] in order to better understand what Consteel® users where claiming that this type of EAF operation was allowing them to get maintenance savings over the conventional bucket-charge EAF.

Among the overall savings - that were estimated to be around 13 €/tls at that time - it was found a reduction of about 1€/tls in expenses for mechanical maintenance, essentially for the furnace charging crane7 and of the furnace sidewall panels.

The experience made by the first Consteel® user in Italy, ORI Martin, is a well-known example.

ORI Martin moved from a conventional furnace to Consteel® in august 1996. Before the switch, it was necessary to change more than one furnace panel per month; ten years after the switch to Consteel® the total number of panels changed was just four, and none of these due to damages suffered during normal operation.

This dramatic reduction in panels damage in Consteel® operation translates into a significantly lower chances of water leakages into the furnace (an event unfortunately not uncommon in bucket charged furnaces) thus decreasing the risks of explosions due to water in the furnace and increasing operational safety.

The need to perform bucket charging in Consteel® is minimum and this reduces the mechanical stress of the furnace structure and of the furnace charging crane, whose workload is drastically reduced up to the point that the crane crew can be eliminated altogether: normal operations, such as the electrode slipping, can be managed directly by the furnace operator, via remote control of the crane.

3.2.4 Reduced refractory wear

The mechanism of refractory erosion of the furnace is complex as it is influenced by many operational parameters, however the continuous processing of scrap and pig iron provide conditions to mitigate the

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7 The cost of operation, maintenance and manning for the cranes used to charge the Consteel® is practically equivalent to that required for the filling of charge buckets in a conventional furnace; moreover, it should be considered that Consteel® technology reduces the number of scrap buckets to just one or two, with a further reduction of the relevant handling and maintenance costs.
phenomenon thanks to the reduced thermal-cycling and mechanical stresses coming from the substantial elimination of bucket charges; avoiding this stresses results in less micro-spalling of the exposed refractory lining. Because of this it is possible to find Consteel® furnaces with a refractory consumption around 1 kg/tls (excluding the tap-hole sealing sand).

Including the refractory of the heating tunnel\(^8\), our estimate for the refractory consumption of a Consteel® furnace is about 80% of that of the corresponding conventional furnace.

### 3.3 Environmental benefits

#### 3.3.1 Reduced dust production

A traditional bucket-charged EAF produces about 20 kg/tls of dust, the dust production in the equivalent Consteel® EAF is about 30\%-40\% lower.

This can be explained as another positive side effect of the natural recycle of the dust deposit on the scrap inside the heating tunnel and of the lower decarburization rate (lower projections) allowed by this process technology.

Lower dust production means lower cost for its disposal, which is increasingly expensive due to the more stringent environmental regulations.

#### 3.3.2 Reduction of PCCD/F and NOx

Scrap can contain oil, paints, plastic and other substances that are or may turn into pollutants during the steelmaking process; some of these substances may become precursors of polychlorinated dibenzo-p-dioxins (PCDD), polychlorinated dibenzo-p-furans (PCDF) and polychlorinated biphenyls (PCD), a class of substances whose emission has been severely restricted by new environmental regulations.

The emission of these pollutants is a complex phenomenon that is influenced by several concurrent factors: the amount of precursors in the scrap charge, the type of process carried out in the furnace and, ultimately, on the fume extraction system, which plays a key role, since the emissions are measured at the stack.

It has been demonstrated\(^{11}[12]\) that given a scrap charge with the same contents of PCDD/F precursors (e.g. polyvinyl chloride plastic) the Consteel® process releases a significantly lower amount of PCDD/F in the off-gas in comparison with the equivalent discontinuous process, with batch charges.

Besides the complexity of the phenomenon the explanation is simple: with a batch-charged furnace the release of precursors are concentrated in the first minutes of the processing of the scrap batch into the furnace and such concentration favors the formation of PCDD/F due to the well-known “law of mass action” stating that the rate of a reaction is proportional to the concentration of the reactants. On the contrary, with the Consteel® system the scrap charge is treated progressively and the eventual emissions are uniformly distributed in the primary off-gas flow.

For the abatement of PCDD/F is necessary to achieve: off-gas temperature $\geq 800^\circ$C, oxygen content $\geq 6\%$, good turbulence and to maintain these conditions for roughly 2s; in the Consteel® furnace, and especially in the newer Consteel® Evolution™ furnaces, these conditions are achieved normally, along the entire charging process.

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\(^8\) The refractory lining of the Consteel® heating tunnel is cheap and with a very limited wear that can be estimated around 0.1 kg/tls.
For bucket-charged furnaces, which concentrate the release of pollutants at low temperatures, and shaft furnaces, that heat a lot the charge but cool down excessively the off-gas, it becomes mandatory do provide the fume extraction system with gas reheating burners, increasing the overall energy consumption. The problem may be circumvented by the injection of pulverized activated carbon (PAC) in the off-gas stream but at the expense of a larger production of dust and higher risks of fire in the filter baghouse.

The thermo-destruction process of PCDD/F should be followed by a fast cooling, at not less than \(-300^\circ\text{C/s}\), to reach below 200°C; this is required to avoid the “de novo synthesis” of PCDD/F, and it is usually achieved with a quenching tower.

The above reasons brings us to the conclusion that the Consteel® system represents the best option to treat scrap with the minimum possible emission of PCDD/F and with a very conventional fumes extraction plant, without the need of any reheating burners.

There is a growing attention also to the emission of NOx and it has been found that the electric arc is the major responsible for these emissions in the EAF process\(^{[13]}\).

The amount of NOx emitted per ton of liquid steel produced via a conventional bucket-charged EAF is about 250 g/tls, whilst for a continuous charge this value is just 120 g/tls. This is due to the operation of the electric arcs under forming slag, which reduces the interaction of these electric arcs with the atmospheric oxygen and nitrogen.

### 3.3.3 Acoustic emissions

Using the EAF to melt scrap charged by bucket is notoriously much noisier that melting a continuous charge of DRI, this because the arcs are burning on flat bath and under a foaming slag; Consteel® extends this type of operation to the processing of scrap, significantly reducing the acoustic emissions of the plant.

Noise emissions can become a problem when there is a residential area in the close neighborhoods of the plant and emblematic example of such case is ORI Martin steel-works, located in Brescia (Italy), where the growth of the city to the boundaries of the plant, and the consequent mandatory request to limit noise emissions, was one of the major factors driving the switch from bucket-charging to Consteel® EAF.

ORI Martin performed several sound intensity measurements before and after the switch to Consteel® and to give an idea of the change, during normal Consteel® operations, the sound intensity level in proximity of the furnace was around 85 dBA whilst with the previous bucket-charged EAF the sound intensity level was above 90 dBA.

### 4 CONCLUSIONS

Due to cost and environmental reasons, scrap based steelmaking is inevitably going to grow.

The industry-proven Consteel® technology is extending the several benefits of the continuous process to scrap based steelmaking, with the benefit of scrap heating via process off-gas and allowing the maximum flexibility in the selection of charge materials.

The new Consteel® Evolution™ technology is able to further reduce the electrical consumption, thanks to improvement in scrap heating, without compromises in terms of operational ease and flexibility, thus offering an even better balance of efficiency, reliability and charge flexibility for present and future steelmaking needs.
5 REFERENCES


