CHAPTER 1.5

Electric Furnace Steelmaking

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1.5.1. INTRODUCTION TO ELECTRIC STEELMAKING

The history of electric steelmaking is quite short—only little over 100 years from
the first trials to melt steel by utilizing electric power. During that period, great advances-
ments have been attained both in furnace equipment and technology, melting practice,
raw materials, and products. In this chapter, a short introduction to most significant pro-
gresses, features, and phenomena in electric steelmaking are presented.

1.5.1.1. Short History of Electric Steelmaking Until Today

The electric arc furnace applied in steelmaking was invented in 1889 by Paul Héroult [1].
Emerging new technology started in the beginning of the twentieth century when wide-
ranging generation of relatively cheap electric energy started at that time. First-generation
furnaces had a capacity in between 1 and 15 t. The EAF had Bessemer/Thomas converters
and Siemens Martin furnaces as strong competitors, initially. But its niche was the produc-
tion of special steels requiring high temperature, ferroalloy melting, and long refining times.

In the 1960s, with the advent of billet casting, the EAF occupied another niche: it was
the melting unit of choice for the so-called minimills, feeding billet casters for the pro-
duction of rebar and wire rod.

In the following two decades, to better support the short tap-to-tap time required by
the billet casters, the EAF reinvented itself as a melting-only unit. Steel refining was left
for the recently introduced ladle furnace. Large transformers were introduced; ultra-
high-power furnaces developed, which were made possible by adopting foaming slag
practice. This way, tap-to-tap time became close to casting time.

By 1985, a new niche for electric steelmaking began to be taken: flat products,
through thin slab casting and direct rolling. Also this process route has achieved a signif-
ificant role in world steel production.

Altogether, the basic argument is that most of the ferrous scrap worldwide is recycled
and refined to special steels just via electric furnaces. EAFs are versatile, charging every-
thing from all sorts of scrap to hot briquetted iron (HBI), direct reduced iron (DRI), pig
iron, hot metal. EAFs may produce all type of steels: long and flat, carbon and alloyed, for
continuous casting, ingot casting, and teeming of castings in molds. Currently, EAF produces 29% of the crude steel produced worldwide (see Figure 1.5.1).

China, the United States, and India are the world leaders in EAF production (Table 1.5.1).

The developments in the EAF technologies since 1965, promoting lower electric energy consumption, shorter tap-to-tap time, and less electrode consumption, are shown in Figure 1.5.2 [3]. Furnace size enlarged up to 350 t maximum, which together with the shortening of tap-to-tap time, made possible to have more than 1 Mtpy capacity with just

![Figure 1.5.1 Worldwide production of steel via EAF. (For color version of this figure, the reader is referred to the online version of this chapter.) Based on data taken from Ref. [2].](image)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>70,900,000</td>
</tr>
<tr>
<td>United States</td>
<td>52,107,000</td>
</tr>
<tr>
<td>India</td>
<td>43,100,000</td>
</tr>
<tr>
<td>South Korea</td>
<td>26,377,000</td>
</tr>
<tr>
<td>Turkey</td>
<td>25,275,000</td>
</tr>
<tr>
<td>Japan</td>
<td>24,858,000</td>
</tr>
<tr>
<td>Italy</td>
<td>18,843,000</td>
</tr>
<tr>
<td>Russia</td>
<td>18,500,000</td>
</tr>
<tr>
<td>Germany</td>
<td>14,204,000</td>
</tr>
<tr>
<td>Mexico</td>
<td>13,035,000</td>
</tr>
</tbody>
</table>

Based on data taken from Ref. [2].
one furnace. Electric energy consumption decreased down to 350 kWh/t for 100% scrap operations. Chemical energy increased at levels not far from those of Basic Oxygen Furnace (BOFs). Refractory consumption fell down due to the replacement by cooled roof and panels, slag foaming, and refractory quality improvement. Power-off time is now of <10 min for the best operated furnaces. For a large number of ArcelorMittal group meltshops, average electrode consumption was 1.43 kg/t.

### 1.5.1.2. Role of Recycling and Electric Steelmaking

The electric arc furnace is the most important scrap recycling process. In the developed world, 100% steel scrap is the most common charge. The situation is not the same in the emerging countries, where scrap is not always available in the required amount; alternative materials like DRI, HBI, pig iron, and hot metal take part in the charge. Worldwide, scrap covers around 75% of the metallics for EAFs, while DRI/HBI covers around 15% and the balance is covered by pig iron and hot metal.

Besides recycling scrap, electric furnaces are sometimes used for recovering internal wastes, like electric arc furnace dust, slags, and refractory materials. Also, social wastes like tires and plastics are utilized in EAFs in some countries.

### 1.5.1.3. AC and DC Furnaces

Most of the electric arc furnaces use alternate current (AC). Nevertheless, in the 1990s, active interest was targeted at development of direct current (DC) EAFs. The drivers were less electrode consumption, less energy consumption, and less flickering. There are different designs: one electrode and one anode in the furnace bottom (see Figure 1.5.3); two electrodes with four anodes (see Figure 1.5.4).
Figure 1.5.3 DC EAF with one electrode and bottom anode. (For color version of this figure, the reader is referred to the online version of this chapter.)

Figure 1.5.4 DC EAF with two electrodes and four bottom anodes [4].
In the beginning, there were expectations based on the rapid progress of thyristor rectifiers as power supply. At the same time, long life for the furnace bottom and refractories were expected. Then, new ideas for DC power conversion were promoted, such as the chopper technology (converter based on Insulated Gate Bipolar Transistor (IGBT) semiconductors), freewheeling (using a bypass diode), or split-alpha control (separate control of each of the half-bridge of a thyristor rectifier); all to reduce generated reactive power and flicker [5].

Not all the expectations of the DC EAFs were met. The benefit of lower electrode consumption is offset by the higher specific cost of large diameter electrodes. Some of the anode designs have had a short life. The chopper technology had higher losses, higher equipment costs, lower reliability, and excessive maintenance cost compared with thyristor rectifier [5].

It is said that the development of the fin-type anode, with small cooling requirements, could improve anode life, maintenance, and safety [6]. The advance in electronics could also impact in favor of DC furnaces in the future.

### 1.5.2. RAW MATERIALS, AVAILABILITY, SCRAP CLASSES, SCRAP TRADING

As mentioned before, most of the metallic needs of the EAFs are met with scrap. Scrap being charged to the EAF can be divided by origin roughly in three classes:

- Obsolete scrap (old cars, appliances, machinery)
- Industrial scrap (generated during processing of strip or bars)
- Internal scrap (quality rejections, tundish bottom, steel recovered from slag)

Obsolete scrap may be prepared for charging in different ways

- By fragmentation in a shredder
- By pressing, forming bales
- By cutting with oxygen

Shredding is the dominant scrap preparation process, for recycling cars and domestic appliances. Many scrap dealers and EAF steelmakers are installing such equipment because of the advantages regarding contamination with soil, density, and corresponding lower energy and lime consumption, and even less noise. Shredders may operate under humid (originating a liquid waste, but with less air pollution) or dry conditions. A typical installation is seen in Figure 1.5.5. Usually, they include a heavy rotor turning at high speed to reduce the scrap fed into the rotor housing, a dedusting system for air cleaning, equipment to separate the scrap, and a variety of systems to divide the shredded material into ferrous, nonferrous, and residues [8]. Classification is by size or drive power (small, medium, large, and very large (mega-shredder)). In Japan small ones are preferred, in Europe medium size is the choice, and in the United States the market is dominated...
by large and mega-shredders [7]. Regarding air cleanliness, there are dry, dump, and wet shredders.

More tools are being incorporated to shredders, either upstream or downstream, in order to separate elements like copper or materials like plastics.

In Table 1.5.2, an example of chemistry and density (an important factor for productivity) of different raw materials is presented.

No. 1 heavy melting steel (HMS 1) is defined as steel scrap ¼” and over in thickness. Individual pieces not over 60 × 24” prepared in a manner to ensure compact charging. No. 2 heavy melting steel (HMS 2) differs from No. 1 mainly in that the lower limit of thickness is 1/8”, and more coated steel is allowed. No. 1 bundles are tightly compacted bales of light gauge scrap produced in hydraulic balers. The material is collected from press shops, and it consists of clean sheet, strip, and trimming, which could have been sold as punching and plate scrap or a No. 1 busheling scrap.

No. 2 bundles contain significant amount of galvanized sheet [9].

Regarding international trade, scrap is exported usually by developed countries, like the United States and Japan, and imported by developing countries. Those countries or

Figure 1.5.5 Typical dump shredder design [7]. (For color version of this figure, the reader is referred to the online version of this chapter.)
Table 1.5.2 Example of Bulk Density and Chemistry Including Gangue and Residual Elements in Different Scrap Types and Other Ferrous Charge Materials

<table>
<thead>
<tr>
<th></th>
<th>HMS 1</th>
<th>HMS 2</th>
<th>Local Shred.</th>
<th>Bush Bundle #2</th>
<th>Auto Bundle</th>
<th>Rails Revert/Prompt</th>
<th>Internal Turning</th>
<th>Pig Iron</th>
<th>Liquid Iron</th>
<th>DRI Iron Carbide</th>
<th>Average Scrap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.60</td>
<td>0.70</td>
<td>0.70</td>
<td>0.75</td>
<td>0.65</td>
<td>0.85</td>
<td>1.10</td>
<td>0.80</td>
<td>1.30</td>
<td>2.50</td>
<td>3.80</td>
</tr>
<tr>
<td>C</td>
<td>0.22</td>
<td>0.22</td>
<td>0.98</td>
<td>0.60</td>
<td>0.30</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.15</td>
<td>0.58</td>
<td>3.50</td>
</tr>
<tr>
<td>Si</td>
<td>0.16</td>
<td>0.13</td>
<td>0.57</td>
<td>0.30</td>
<td>0.05</td>
<td>0.07</td>
<td>0.22</td>
<td>0.22</td>
<td>0.05</td>
<td>0.20</td>
<td>0.39</td>
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<td>Mn</td>
<td>0.66</td>
<td>0.60</td>
<td>0.57</td>
<td>0.43</td>
<td>0.30</td>
<td>0.27</td>
<td>0.43</td>
<td>0.38</td>
<td>0.30</td>
<td>0.65</td>
<td>0.79</td>
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<td>P</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>S</td>
<td>0.04</td>
<td>0.05</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
<td>0.08</td>
<td>0.01</td>
<td>0.10</td>
<td>0.02</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Fe</td>
<td>93.8</td>
<td>95.6</td>
<td>97.1</td>
<td>93.6</td>
<td>91.1</td>
<td>91.0</td>
<td>97.8</td>
<td>95.6</td>
<td>88.1</td>
<td>92.7</td>
<td>92.8</td>
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<tr>
<td>O</td>
<td>1.48</td>
<td>0.96</td>
<td>3.36</td>
<td>0.4</td>
<td>0.50</td>
<td>3.36</td>
<td>2.22</td>
<td>3.52</td>
<td>0.20</td>
<td>1.60</td>
<td>0.00</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.00</td>
<td>1.00</td>
<td>0.60</td>
<td>0.30</td>
<td>0.10</td>
<td>0.10</td>
<td>0.20</td>
<td>0.30</td>
<td>3.00</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>CaO</td>
<td>0.96</td>
<td>0.80</td>
<td>1.07</td>
<td>0.50</td>
<td>0.30</td>
<td>1.15</td>
<td>0.08</td>
<td>0.28</td>
<td>0.70</td>
<td>0.45</td>
<td>1.30</td>
</tr>
<tr>
<td>MgO</td>
<td>0.08</td>
<td>0.20</td>
<td>0.15</td>
<td>0.13</td>
<td>0.06</td>
<td>0.14</td>
<td>0.00</td>
<td>0.03</td>
<td>0.20</td>
<td>0.01</td>
<td>0.20</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.30</td>
<td>0.20</td>
<td>0.10</td>
<td>0.47</td>
<td>0.40</td>
<td>0.00</td>
<td>0.40</td>
<td>0.78</td>
<td>0.00</td>
<td>0.02</td>
<td>0.55</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1.00</td>
<td>0.80</td>
<td>0.89</td>
<td>0.87</td>
<td>0.65</td>
<td>0.70</td>
<td>1.30</td>
<td>0.70</td>
<td>0.35</td>
<td>0.60</td>
<td>0.50</td>
</tr>
<tr>
<td>Gangue</td>
<td>2.34</td>
<td>2.00</td>
<td>2.21</td>
<td>1.97</td>
<td>1.41</td>
<td>1.99</td>
<td>1.78</td>
<td>1.79</td>
<td>1.25</td>
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</tr>
<tr>
<td>Basic</td>
<td>0.96</td>
<td>1.00</td>
<td>1.20</td>
<td>0.57</td>
<td>0.46</td>
<td>1.64</td>
<td>0.06</td>
<td>0.40</td>
<td>2.00</td>
<td>0.75</td>
<td>2.60</td>
</tr>
<tr>
<td>Cu</td>
<td>0.160</td>
<td>0.110</td>
<td>0.400</td>
<td>0.250</td>
<td>0.100</td>
<td>0.030</td>
<td>0.030</td>
<td>0.230</td>
<td>0.100</td>
<td>0.080</td>
<td>0.173</td>
</tr>
<tr>
<td>Ni</td>
<td>0.070</td>
<td>0.050</td>
<td>0.150</td>
<td>0.060</td>
<td>0.060</td>
<td>0.030</td>
<td>0.030</td>
<td>0.030</td>
<td>0.060</td>
<td>0.080</td>
<td>0.111</td>
</tr>
<tr>
<td>Cr</td>
<td>0.110</td>
<td>0.150</td>
<td>0.180</td>
<td>0.190</td>
<td>0.110</td>
<td>0.170</td>
<td>0.040</td>
<td>0.090</td>
<td>0.110</td>
<td>0.080</td>
<td>0.050</td>
</tr>
<tr>
<td>Sn</td>
<td>0.010</td>
<td>0.017</td>
<td>0.025</td>
<td>0.015</td>
<td>0.012</td>
<td>0.025</td>
<td>0.000</td>
<td>0.013</td>
<td>0.012</td>
<td>0.015</td>
<td>0.011</td>
</tr>
<tr>
<td>Mo</td>
<td>0.030</td>
<td>0.010</td>
<td>0.010</td>
<td>0.005</td>
<td>0.011</td>
<td>0.010</td>
<td>0.040</td>
<td>0.000</td>
<td>0.011</td>
<td>0.020</td>
<td>0.062</td>
</tr>
<tr>
<td>% Used</td>
<td>27</td>
<td>10</td>
<td>5</td>
<td>15</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>16</td>
<td>0</td>
</tr>
</tbody>
</table>

Average values calculated based on % used and chemistry. Density is the apparent density.
regions with low scrap availability tend to protect their steel industry by taxing scrap exports.

As shown in Table 1.5.2, some 25% of the metallics requested by the EAF industry are satisfied with DRI/HBI, pig iron, and hot metal. Gas-based direct reduction dominates the DRI captive plants, which are located in countries with availability of natural gas and electricity at low cost. India, Iran, Mexico, Saudi Arabia, and Russia have been the top DRI producers in 2011 [10]. As most of this DRI is produced in captive plants, it can be assumed that they are the top consumers too.

It is well known that DRI melting consumes more electric energy than scrap. This has to do with the presence of acid gangue in the iron ore, which follows to DRI and must then be neutralized by lime addition and increased amount of slag compared with conventional melting of scrap. A high percentage of metallization helps in keeping energy consumption under control (see Figure 1.5.6).

Coal-based direct reduction is strong in India. Inherent to the process is the low C content in DRI compared with gas-based DRI (0.1% coal-based versus around 2% for gas-based DRI). Carbon content in the DRI is important because some of this carbon means an external energy source that combined with the oxygen injection in the EAF promotes a natural slag foaming by the CO produced by the reaction of unreduced iron oxide and carbon in the DRI, which helps to decrease the electric energy consumption.

Other drawbacks of coal-based DRI are related to the conditions under which this process is carried out in India (high ash coal, high gangue iron ore, and environmental footprint).

Use of high proportion of pig iron in the EAF charge is common in Brazil due to the availability of relatively cheap material from charcoal-based blast furnaces. Hot metal charging is usual in Chinese EAFs due to the lack of scrap [12].

![Figure 1.5.6 Influence of DRI metallization on power consumption [11]. (For color version of this figure, the reader is referred to the online version of this chapter.)](image)
1.5.3. FURNACE CONSTRUCTION

As shown earlier in Figure 1.5.2, the increase in furnace electric power has been the key factor in the development of EAF technology during the past 50 years. As in the 1960s, a common EAF power was 250–300 kVA/t liquid steel; today standard ultra-high-power EAFs have 900–1000 kVA/t steel available in the transformers. These furnaces are equipped with water-cooled panels and EBT tapping. EBT stands for eccentric bottom tapping, a tapping system that yields a uniform steel jet falling into the ladle, with slag carry over controlled to a certain extent. In Figure 1.5.7, a scheme of such state-of-the-art EAF is presented.

1.5.3.1. Furnace Cooling

The current furnace includes three water-cooled parts: roof, panels, and off-gas duct (Figure 1.5.8). Although some heat is lost due to the heat extraction by the cooling water, this design makes possible less refractory consumption (because they replace refractory...
Figure 1.5.8 Cooled parts of the electric arc furnace. (a) Panels making the upper part of the shell, (b) roof, and (c) off-gas duct. (For color version of this figure, the reader is referred to the online version of this chapter.)
linings) and the use of high power. At the time the panels were first introduced, some
fears arose on safety risks, but after realizing the cost advantage, almost all EAF adopted
them. They may be made of steel or copper (much longer life) and with different designs
(conventional, flip and turn, etc.) [13].

Recently, more attention has been paid to safety with water cooling [14]. Firstly, to
detect, limit, and avoid the possibility of water leakage and secondly, to cut the need of
repairing work in the hot furnace. Off-gas analysis, when hydrogen is included, is a useful
tool to detect leakage. To limit leakage and maintenance work, solid cast or machined
water panes have been introduced. Split shell, with spray-cooled upper shell means less
risk as nonpressurized water tends to penetrate less in case of leakage.

1.5.3.2. Electrodes

Artificial graphite electrodes are currently a standard in EAF operations. Raw materials
are petroleum coke (needle type is preferred) and coal tar pitch. They are mixed and
processed at high temperature in several steps. Milestones of electrode technology are
shown in Table 1.5.3.

Electrode water cooling was first adopted by Nippon Steel Corporation, and then
most companies followed. Main advantage is to decrease side consumption. Large DC
furnaces with only one electrode obliged to the development of very large electrodes,
800 mm diameter. Some development work has been carried out recently to avoid some
drawbacks of the nipple system joining two electrodes.

Table 1.5.3 Milestones in the Development of Artificial Graphite Electrodes [15]

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1898</td>
<td>Invention of amorphous carbon electrodes for the Hérault EAF</td>
</tr>
<tr>
<td>1900</td>
<td>Acheson furnace for electrode graphitization</td>
</tr>
<tr>
<td>1931</td>
<td>Introduction of connection nipple</td>
</tr>
<tr>
<td>1963</td>
<td>Massive use of conical connection nipple</td>
</tr>
<tr>
<td>1963</td>
<td>Massive use of impregnation with coal tar pitch</td>
</tr>
<tr>
<td>1980</td>
<td>Massive use of needle coke for electrode production</td>
</tr>
<tr>
<td>1990</td>
<td>Massive use of digital electrode regulation systems</td>
</tr>
<tr>
<td>1990</td>
<td>Introduction of robot for automatic joining of electrodes</td>
</tr>
<tr>
<td>1998</td>
<td>Patenting of electrode cooling with water ring</td>
</tr>
<tr>
<td>2004</td>
<td>First commercial use of electrodes with male–female union</td>
</tr>
<tr>
<td>2009</td>
<td>Patenting of the use of carbon fibers for electrode reinforcement</td>
</tr>
</tbody>
</table>
1.5.4. MELTING PRACTICE AND METALLURGY

The basic principle of electric steelmaking today is that the furnace is a “melting machine” that produces liquid steel with required chemistry, temperature, and mass in time to feed steel to successive ladle treatments and continuous caster, which finally determines the production rhythm. Typical tap-to-tap times are in the range of 40–60 min, which is also the total furnace time per heat.

1.5.4.1. Melting Practice and Foaming Slag

Although Ultra High Power (UHP) furnaces are used, fast melting by using only electric power is difficult and not the most economic practice either. Importing extra energy and assisting melting technique can greatly accelerate scrap melting and bring economic benefits. Accordingly, the current state of the art in EAF steelmaking is to use as much as possible chemical energy, besides electric energy, to accommodate tap-to-tap times to the pace of the downstream continuous caster.

Regarding the application of electric energy, at the start of melting, after basket charge, not all the available power can be applied, as the electrodes may be still in a high position, too close to the roof. Then, when the melting operation has advanced further, changing to the tap maximum power may be applied. This is not the case for 100% flat-bath operations like in Consteel EAFs or 100% DRI/HBI charging through the fifth hole.

Chemical energy is introduced by oxygen, carbonaceous materials, and natural gas, more and more through injectors rather than lances. The energy-generating reactions are:

\[
\begin{align*}
C + \frac{1}{2}O_2 &= \text{CO} \quad 2.55 \text{ kWh/kg C} \\
C + O_2 &= \text{CO}_2 \quad 9.1 \text{ kWh/kg C} \\
\text{CO} + \frac{1}{2}O_2 &= \text{CO}_2 \quad 2.81 \text{ kWh/kg C} \\
\text{Fe} + \frac{1}{2}O_2 &= \text{FeO} \quad 1.32 \text{ kWh/kg Fe}
\end{align*}
\]

The refining step usually does not require full power, which with already flat bath could be dangerous for the lining. At that time, the foaming of the slag is a must. For the slag to foam, the production of CO gas is necessary, by means of the injection of carbon and oxygen through lances or burners. For foaming purposes, several carbonaceous materials are useful, depending on local cost and availability: anthracite, petroleum coke, coke breeze.
Another requirement for good slag foaming has to do with slag chemistry. Basicity should be more than 1.5 and FeO content should be neither very low nor very high.

In Figure 1.5.9, the view of foaming and nonfoaming slag during EAF operation is presented as observed through the slag door.

As in other metallurgical reactors, slag plays a very important role in EAF operations. Protection of cooling panels and refractories, arc stability, dephosphorization, thermal insulation, and heat transfer are some of the expected tasks.

The main slag formers in the EAF are lime, dolomitic lime, oxides in scrap, gangue in DRI, oxidation products from metallic charge, ash of carbonaceous additions, MgO picked-up from refractories as well as the slag remaining from the previous heat. Some plants recycle scale or other wastes, thus adding to the slag. The main EAF slag components are CaO, SiO$_2$, FeO, and MgO; other components are Al$_2$O$_3$, MnO, and P$_2$O$_5$.

A mass balance, based on the chemistry and weight of those slag formers, is helpful for the comparison with measured chemistry, for a better understanding of attack on refractory linings, lime fines lost to the off-gas, incidence of changes in weight, chemistry of additions, etc.

For foaming purposes, as already mentioned, a slag basicity of at least 1.5 is recommended. To decrease the need of MgO for slag saturation, slag basicity should be 2. In the ternary diagram of Figure 1.5.10, including MgO saturation lines, it is possible to evaluate MgO required for saturation of a slag of a given basicity and FeO content.

Control of foaming slag remains a matter of continuous development. More and more EAFs are incorporating tools to evaluate slag foaming, based on noise, vibration, and harmonics. In most cases, this is used as an off-line help for the furnace operator. But some EAFs have recently introduced online control of the carbon and oxygen injection for slag forming, based on the mentioned measurements [17,18].

1.5.4.2. Refining in EAF

For most steelmaking operations, refining in the EAF is limited to dephosphorization, decarburization, and temperature adjustment. Phosphorus in the charge could be at
higher than usual levels for DRI, HBI, pig iron, and hot metal, depending on the iron ore source. Some steels require particularly low P levels to avoid too high ductile/brittle transition temperature or tempering brittleness. From the equilibrium point of view, lower temperatures, high slag basicity, and high oxidation of the bath favor dephosphorization. Slag/metal interaction is important from a kinetic point of view but is not always attainable in the EAF.

Reversion of phosphorus from slag to steel may take place when heating to the aimed temperature, close to the end of the process. Then, if there is some slag carry over to the ladle, and steel and slag have a low oxidation level, P reversion is again possible. Therefore, in such phosphorus critical cases slag carry over to the ladle should be carefully prevented. That can be done by slag detection—slag stopping system or by EBT, which is stopped before the end of the steel. In such a “hot heel” practice, a significant fraction of liquid steel is left in the furnace for the next heat. Hot heel practice not only prevents steel from rephosphorization, but also speeds up the melting process; however, it has a smaller charge weight in the ladle as a drawback.

A summary of some of the models developed for dephosphorization is presented in Table 1.5.4.

Different equations were tested by calculating final P contents using plant data [19] and comparing with analyzed P contents in Figure 1.5.11. It was found that the
Table 1.5.4 Different Dephosphorization Models Based on Thermodynamics, Experimental Data, and “Basicity” Concept [19]

<table>
<thead>
<tr>
<th>Author and Model</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balajiva and Vajlagupta [20]</td>
<td>( \log K_p = 10.78 \log(\text{CaO}) - 0.00894 T (\degree \text{C}) - 6.245 )</td>
</tr>
<tr>
<td>Healy [21]</td>
<td>( \log \left( \frac{[P]}{[P]_0} \right) = \frac{22,350}{T} - 16 + 0.08(\text{CaO}) + 2.5 \log(\text{Fe}) \pm 0.4 )</td>
</tr>
<tr>
<td>Turkdogan and Pearson [22]</td>
<td>( \log K_{\text{PO}} = 21,740 - 9.87 + 0.071 \text{BO} )</td>
</tr>
<tr>
<td>Suito and Inoue [23]</td>
<td>( \log \left( \frac{[P_2O_5]}{[P]_0^2} \right) = 0.145((\text{CaO}) + 0.3(\text{MgO}) - 0.5(\text{P}_2\text{O}_5) \ + 0.3(\text{MnO}) + 1.2(\text{CaF}_2) - 0.2(\text{Al}_2\text{O}_3)) + \frac{22,810}{T} - 20.51 )</td>
</tr>
<tr>
<td>Suito and Inoue [23]</td>
<td>( \log \left( \frac{[P_2O_5]}{[P]_0^2} \right) = 7.87 \log((\text{CaO}) + 0.3(\text{MgO}) - 0.05(\text{Fe}_2\text{O}_3) \ - 0.5(\text{P}_2\text{O}_5) + 0.6(\text{MnO})) + \frac{22,340}{T} - 27.124 )</td>
</tr>
<tr>
<td>Bergman and Gustafsson [24]</td>
<td>( \log C_{\text{Pu}} = 21.55\lambda + \frac{32.912}{T} - 27.9 ) where ( C_{\text{Pu}} = \frac{(% \text{Pu})}{(% \text{P}) (% \text{O})^{1/2}} )</td>
</tr>
</tbody>
</table>

Figure 1.5.11 Differences between analyzed phosphorus contents and calculated phosphorus contents according to different models. Experimental data based on 1725 heats [19]. (For color version of this figure, the reader is referred to the online version of this chapter.)
distribution by Turkdogan equation was closest to the mean value, but showed somewhat bigger scatter than both Suito’s and Healy’s models.

Decarburization is carried out as a refining task. If the charge is 100% scrap, carbon in the metallic charge should be relatively low. This is not the case when charging a high percentage of DRI (if produced in a gas-based unit), HBI, pig iron, or hot metal, with carbon contents between 1.6 and 4.5.

Usually, due to productivity reasons, steelmakers prefer to achieve a carbon content of around 0.05 before tapping. Lower contents may imply a too high oxidation level. In Figure 1.5.12, the theoretical C–O equilibrium is compared with plant values. The equilibrium calculation was performed by using FactSage 6.2 Program Package and FToxide and FactSage databases.

An alternative strategy is “catch-carbon” practice in which carbon content is targeted at somewhat under the final value, to be reached with alloys addition. This practice can bring material savings in alloying and deoxidation, but needs strict individual process control for each heat. For this reason, it is not so good for productivity, and if final carbon is maintained high, dephosphorization could be problematic.

Desulphurization is usually carried out at tapping and during ladle metallurgy, as in those stages the steel is deoxidized and the slag has high basicity and low oxygen potential (low content of oxidizing components, “FeO,” MnO, etc.). Nowadays, all other refining operations, except decarburization and dephosphorization, are performed in ladles and the electric arc furnace can act as a fast “melting machine.”

**Figure 1.5.12** Calculated [C]–[O] equilibrium at 1600 °C (1873 K) compared with typical region of plant values [25].
1.5.4.3. Carbon Steel Melting Versus Stainless and High-Alloyed Steel Melting

As already mentioned, for carbon steel melting, most steelmakers make only one kind of crude steel in the furnace, independently of the steel grade to be made. Due to productivity reasons, they prefer to produce a low carbon steel with the temperature required for further processing in the ladle furnace, and the residual impurity contents low enough to fulfill the final product specification. Phosphorus, as discussed earlier, can be removed in the electric furnace process. Metallic impurities Cu, Sn, Cr, Ni, etc., are higher in scrap-based electric steel than in ore-based converter steel, in general. When steel grades with strictly limited contents of these impurities are produced, the charge materials must be carefully selected. The charge is designed and prepared consisting of mixture of different scrap classes and further diluting with pure “virgin” iron materials like pig iron, DR1, or HBI. Thus the charge can be optimized to fulfill metallurgical quality demands and the material costs.

A small fraction of the steel produced is special steel like stainless and tool steel. Their production is in the order of magnitude 40 Mtpy. Practices for the production of these high-value products differ from those for carbon steels. Recycled steel is of utmost importance as raw material for melting and recovery of expensive metals. Scrap cost justifies portable spectrometers to separate specific grades. High-carbon FeCr takes part in the EAF charge, too.

As expensive alloying elements like chromium may partially report to the slag, here EBT tapping is not usually the choice, but a spout which favors slag carry over to the ladle for further downstream alloy recovery. For the same purpose, tilting angle may be large, up to 40°. Ladle metallurgy facilities may include Argon Oxygen Decarburization (AOD) (dominant) or Vacuum Oxygen Decarburization (VOD) for decarburization without incurring in Cr oxidation.

Foaming of the slag is not easily accomplished due to the adverse effects of Cr oxidation and inadequate slag properties. Interesting results have been achieved by using waste-based briquettes, with oxygen and carbon carriers [26].

1.5.5. ENERGY BALANCE OF EAF PROCESS, ELECTRIC ENERGY, CHEMICAL HEATING, PREHEATING, POSTCOMBUSTION

A typical energy balance of a scrap-based modern electric furnace is seen in Figure 1.5.13. Major energy input is electric energy, followed by chemical energy. Other energy inputs are combustion of natural gas, metal oxidation, burning of volatiles from the scrap, and burning of electrodes.

The main part of energy output is included in liquid steel. Then the second largest energy output is the heat loss and chemical energy (unreacted gases) in the off-gas, which is of the order of 35–38%. This is valid for furnaces with intensive combustion. If a major part of melting energy were from electricity, the losses by off-gas would be low. Other
losses are heat loss to the furnace walls, water cooling, electrical losses, and slag losses. In the example, there was no energy recovery from the off-gas. The role played by chemical heating had become more and more important with time. First, it was used as a tool for cutting the scrap and to accelerate decarburization. But now an important part of the energy needed for melting is supported by oxygen injection due to improved economy (high price of electricity).

The way oxygen is introduced in the furnace has changed with time. First, hand-held consumable pipes were used for injection. Then, lance manipulators made this work easier. Later, supersonic lances were introduced. Finally, injectors through the wall were the choice, due to easy automation and possibility of working with the closed door (Figure 1.5.14). Besides oxygen, they may be designed to inject natural gas, carbon, and lime injection.

Postcombustion over the bath is a complicated issue due to the difficulty in bringing back to the bath the energy liberated by CO combustion in the free board. The two preferred ways to recover latent and sensible heat in the off-gas are scrap preheating and heat recovery.

The energy balance is interesting as an exercise for steelmakers. It can be carried out based on theoretical considerations or statistical values. Ref. [28] provides a complete basis for a theoretical energy balance.

A popular way to calculate energy consumption is the formula developed by Köhle, updated in 2002 on the basis of an extensive work taking data from five furnaces [29].

\[
\frac{W_R}{\text{kWh/t}} = 375 + 400 \left( \frac{G_E}{G_A} - 1 \right) + 80 \frac{G_{\text{DR1/HBI}}}{G_A} - 50 \frac{G_{\text{Shr}}}{G_A} - 350 \frac{G_{\text{HM}}}{G_A} + 1000 \frac{G_Z}{G_A} + 0.3 \left( \frac{T_A}{\degree C} - 1600 \right) + 1 \frac{t_S + t_N}{\text{min}} - 8 \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \frac{M_N}{\text{m}^3/\text{t}} + N_V \frac{W_V - W_{V_{\text{m}}}}{\text{kWh/t}}
\]
$W_{R}$ is the specific electric energy consumption, $G_E$ is the weight of ferrous materials, $G_A$ is the furnace tapping weight, $G_Z$ is the tapping temperature, $G_{DRI}$ is the weight of DRI, $G_{HBI}$ is the weight of HBI, $G_{HM}$ is the weight of hot metal, $t_S$ is the power-on time, $t_N$ is the power-off time, $M_G$ is the specific burner gas, $M_L$ is the specific lance oxygen, $W_V$ is the energy losses (if measured), $W_{V_m}$ is the mean value of $W_V$, and $N_V$ is the furnace specific factor (0.2–0.4).

A comparison of results obtained with the two Köhle’s formulas is presented in Figure 1.5.15.
1.5.6. SPECIAL FURNACE CONSTRUCTIONS

Some steelmakers select particular EAF designs suited for specific tasks. For instance, integrated DRI plants use continuous cold or hot DRI charging through so-called fifth hole. Those interested in heat recovery from off-gas may use Consteel continuous scrap heating and charging, with recovery of off-gas energy to a certain extent; others may select so-called shaft furnace, another way to recover heat off-gas energy.

1.5.6.1. Continuous Charging with Preheating

In Consteel EAFs, preheating is carried out continuously with the off-gas exiting the furnace over a conveyor feeding the scrap to the EAF (Figure 1.5.16). The upper part of the scrap enters the furnace hotter than the lower part, which is not so much exposed to the heat. Most advantages of the furnace type come from the full flat-bath operation, although energy recovery through preheating is even significant. A current trend in these furnaces is to have a large hot heel, even 50% of the heat weight, thus favoring heat transfer from liquid to solid steel, as long as there is bottom stirring. Here the mechanism of radiation from the electrodes to the scrap around the electrodes does not exist.

By the writing of this chapter, 41 Consteel EAFs have been built and 35 are in operation, with some more under construction. The emphasis in the latest decade has been more on high productivity, large EAFs installed in Asia, rather than in the

![Figure 1.5.16 Continuous scrap charging and off-gas energy recovery with Consteel EAF [51]. (For color version of this figure, the reader is referred to the online version of this chapter.)](image-url)
energy-recovery feature. Here there is potential for more efficiency. In Figure 1.5.17, results of temperature measurement testing are shown.

As previously mentioned, continuous charging lets us use maximum power from the start of the heat, as a difference with batch charging, where lower tap is applied after charging of each bucket to avoid damage to the roof. Obviously, power-off time for bucket charging is avoided.

Recently, the Consteel Evolution concept has been proposed, including natural gas burners for charge preheating before entering the off-gas preheated tunnel, and off-gas analysis to improve postcombustion in the tunnel [31].

1.5.6.2. Preheating in Shaft

The other industrially applied way of preheating the scrap is the shaft furnace. They are often DC EAFs with one central electrode and some of them operating in twin mode. Currently, 23 such furnaces are in operation (19 of Fuchs type and 4 of Eco-arc type). In Figure 1.5.18, a scheme of a Fuchs shaft furnace is shown, together with the typical charging/melting cycle.

Formation of dioxine has been reported for some of these operations. Main reasons for dioxine formation are (a) plastics in the scrap and (b) critical temperature range.

In a Japanese version of shaft furnace (Eco-arc by J. P. Plantech), charging is performed by means of a skip car instead of a bucket. The shaft has no device for keeping the scrap inside. The off-gas treatment includes a postcombustion chamber to decompose dioxines and a fast cooling chamber to avoid de novo synthesis.
1.5.6.3. Hot Charging of DRI

For EAF operations supported by a captive direct reduction plant, hot charging is an option to decrease energy consumption. After an early experience in Companhia Sidérgica de Guanabara, Brazil, of transport of hot DRI in cast iron “bottles” to the EAF, in the late 1990s hot DRI charging has been adopted at Ternium Guerrero, Mexico; Ternium Puebla, Mexico; and Hadeed, Saudi Arabia (see Figure 1.5.19).

![Figure 1.5.18](image1)  
Electric furnace with off-gas energy recovery by preheating scrap in a shaft. Left: scheme for a DC shaft furnace, with one electrode [32]. Right: Operating cycle for a shaft furnace charging two scrap baskets [33].

Figure 1.5.19  
Scheme of an EAF continuously fed with hot DRI [34]. (For color version of this figure, the reader is referred to the online version of this chapter.)
1.5.6.4. Hybrid Process for Steelmaking of Scrap and Hot Metal

Another particular furnace design comes from the interest in enlarging the flexibility in raw materials, particularly hot metal. In a conventional EAF, as hot metal charge increases, the need for oxygen injection is bigger. So, for plants prepared for a high percentage of hot metal, a kind of hybrid furnace, with BOF-style oxygen lancing and scrap (+DRI) melting with electrodes in a separate stand has been developed. The commercial name is CONARC and it has been adopted by a few plants in India and South Africa (Figure 1.5.20) [35].

In other cases, particularly in China, hot metal pretreatment is carried out before EAF charging. This procedure allows for some dephosphorization, decarburization, and temperature increase of the hot metal. This way, shorter tap to tap is achieved [36].

1.5.7. ENVIRONMENTAL AND SAFETY ISSUES

The electric arc furnaces bring about some special environmental concerns, namely:
- Disposal/recycling of electric arc furnace dust, slag, and refractories
- Noise

1.5.7.1. EAF Dust

Dust is formed during the melting process typically around 10 kg/t liquid steel. Dust contains mainly iron oxides, CaO, and ZnO. The first two are “common and natural consequences” having their origins in Fe-based charge and lime additions into the furnace and slag. The amount of ZnO in dust is related to the amount of galvanized steel in the scrap. During the melting process, zinc is vaporized as Zn\(_{\text{(g)}}\) and leaves the metal bath but is then oxidized to form ZnO when transported with the off-gas and meeting more
oxidizing conditions. The EAF dust is typically collected to bag filters in the off-gas treatment installation. Disposal of EAF dust is not allowed in most countries because of the risk of lixiviation of metals like Zn, Cd, and Pb, which are considered dangerous. One way is to treat the dust in order to stabilize metals, as per, for instance, the Super Detox technology. This process involves a series of complex physical and chemical reactions, including oxidation/reduction, insolubilization of metals, polymerization of silicates, puzzolanic bonding, and solidification. Metals change to their less soluble state and are physically immobilized. Stabilized material has low permeability and high strength. The treated residue is not considered dangerous and the disposal as land filling is less expensive [37].

Another possibility, explored mainly in Europe, is the recycling of the dust in the EAF itself. This procedure has two advantages: total dust generation in a year and per ton steel is less and the Zn content is increasing cycle by cycle, and the dust removed from the circuit has 20% ZnO or more making it more attractive to zinc producers [38].

The most popular process for zinc recovery is the so-called Waelz kiln, located usually outside the steel plant boundaries. These furnaces have been developed in the early twentieth century by zinc producers to enrich low Zn ore (Figure 1.5.21). They have

Figure 1.5.21 Scheme of the Waelz kiln and auxiliary equipment, the most usual tool for the recycling of the EAF dust to enrich it in ZnO for the production of ZnO or Zn metal [39]. (For color version of this figure, the reader is referred to the online version of this chapter.)
been adopted in the 1950s for EAF dust treatment. Currently, BEFESA is the leading company in Europe, coming from the waste treatment sector, and Horsehead, a zinc producer, is the leader in North America [40].

Recently, due to the increase in iron ore cost, some interest arises in the recovery of the Fe units contained in the EAF dust, along with the Zn units. This way, processes based in rotating hearth furnace or channel induction furnace like PRIMUS or PIZO have been developed and installed in a few locations [41,42].

1.5.7.2. EAF Slag
This slag contains typically high CaO, SiO$_2$, FeO, and MgO, as well as smaller amount of other oxides. Supposing a slag generation of 100 kg/t of crude steel, worldwide EAF slag production would amount to 45 Mtpy. As oxygen steelmaking slag, the recycling of this by-product has been focused in construction use, as inert material in pavement. To this purpose, some kind of stabilization is required. Other less explored possibility is the recycling in the EAF process itself.

1.5.7.3. EAF Refractories
One of the most successful experiences of recycling of spent refractories in EAF steelmaking is that of the Chita plant of Daido Steel, in Japan, which by the year 2000 recycled internally 58% of the spent refractories [43]. This plant produces 1.7 Mt of special steels. MgO–C and MgO bricks of some zones of the EAF are recycled as refractories in the EAF itself, after eliminating slag and metal adhesions. Others are crushed and used as slag conditioner for Ladle Furnace (LF) and EAF.

1.5.7.4. Noise
Typical noise levels for EAFs given by sound power level are between 125 and 139 dB. Relevant parameters for total noise resulting from electric steelmaking plants are the installed transformer capacity, the size of the furnace, existing enclosures of the EAF and the melting shop, operating conditions, etc. [14]. From the equipment and process point of view, factors that diminish arc noise are related to good foaming practice, use of shredded scrap, continuous charging, etc. Other measures taken in EAF plants installed in an urban environment include the so-called dog house or elephant house, special isolation measures in the building walls, and tunnels to communicate noisy buildings, high walls.

1.5.7.5. Safety
The furnace area has some inherent risks for operators’ safety (see Figure 1.5.22). In recent times, innovations have been introduced to avoid manned operations in the platform and close to the hot furnace. Previously, the special construction of panels to avoid
water leakage was mentioned, as well as the spray-cooled upper shell, and hydrogen con-
trol in the off-gas to detect leakage. Robots for handling electrodes, taking samples, and
measuring temperature and oxygen activity are used in several plants. For refractory
demolition, gunning, fettling, and bricklaying robots become utilized, too. Devices
for taphole cleansing, for nonspontaneous opening, and for automatic sand filling
are offered.

1.5.8. FUTURE ASPECTS

As China and other emerging countries start having more scrap availability, and
within the frame of restrictions in CO₂ emissions of these countries, it makes sense to
expect an increase of EAF share in steel production. The International Energy Agency
has issued a forecast on process route and metallics consumption till the year 2050,
predicting an increase in EAF share to around 50% [45]. This is based on three scenarios
of global average temperature increase: 6, 4, and 2 °C. The scenario of 6 °C is an exten-
sion of current trends; that of 4 °C takes into account the commitments regarding emis-
sions limitation and energy efficiency improvement. The 2 °C is a very restrictive
scenario of CO₂ emissions.

Those scenarios are presented in Table 1.5.5, in relation with their incidence on pro-
cess route and utilization of metallics, in comparison with the situation in the year 2010.
Although this forecast has been controversial [46], it reflects the expectations in the future of this process route.

As discussed earlier, the EAF has remained as a tool for steel production over 100 years, changing its design, technology, and operation to keep up with changes upstream and downstream. While other furnaces competing with EAF in the first half of the twentieth century disappeared (i.e., Bessemer, Thomas, open hearth), the EAF has reinvented itself and invaded new niches, taking advantage of its flexibility.

Still, the EAF technology has to overcome several hurdles. Just to mention two of them, the increasing content of copper in the scrap and the energy efficiency.

As regards copper content in the scrap, new ways to deal with it from the very beginning are coming into the market. From car dismantling before shredder fragmentation to different ways to pick up copper of copper-rich parts after shredding are finding increased interest [2]. Different systems have been developed. One of them uses prompt gamma neutron activation analysis technology [47]. As the material passes through the tunnel of the analyzer, it is bombarded with neutrons from radioactive isotopes. The neutrons are captured by the atoms of the material and produce a secondary reaction in the form of gamma rays. This secondary gamma-ray spectrum is decompiled and analyzed to produce the composite elemental analysis of the material (Figure 1.5.23).

Another method is based on high-speed X-ray fluorescence, which makes it possible to analyze elements in milliseconds. More than 100 t/h of shredded scrap can be processed, through a 2-m wide conveyor, delivering a product with <0.2% Cu [48].

Usually 34–38% of the energy is lost in the off-gas as sensible heat and combustion heat. In a previous paragraph, scrap preheating in conveyor and shaft has been described.

### Table 1.5.5

<table>
<thead>
<tr>
<th>Process route</th>
<th>Year 2010</th>
<th>Year 2050: Low Demand</th>
<th>Year 2050: High Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAF (%)</td>
<td>28.5</td>
<td>50.2  51.6  50.6  50.4  51.7  51.0</td>
<td></td>
</tr>
<tr>
<td>BOF (%)</td>
<td>71.5</td>
<td>49.8  48.4  49.4  49.6  48.3  49.0</td>
<td></td>
</tr>
<tr>
<td>Metallics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot metal/pig iron (%)</td>
<td>68.6</td>
<td>45.6  44.3  40.8  45.5  44.2  37.9</td>
<td></td>
</tr>
<tr>
<td>Gas-based DRI (%)</td>
<td>3.5</td>
<td>7.0  7.0  9.5  7.0  7.0  9.7</td>
<td></td>
</tr>
<tr>
<td>Coal-based DRI (%)</td>
<td>1.3</td>
<td>4.8  4.8  0.0  4.7  4.7  0.0</td>
<td></td>
</tr>
<tr>
<td>Smelting reduction (%)</td>
<td>0.0</td>
<td>0.5  0.5  4.8  0.4  0.4  7.4</td>
<td></td>
</tr>
<tr>
<td>Scrap (%)</td>
<td>26.6</td>
<td>42.1  43.4  44.8  42.4  43.7  45.0</td>
<td></td>
</tr>
</tbody>
</table>
Recovery for steam only or for steam and power generation is a matter of recent studies [49]. This is more complex than at oxygen steelmaking plants. The off-gas varies in chemistry, temperature, and volume along the heat, which makes the heat recovery complicated. Nevertheless, some technological schemes have been proposed and are being analyzed by several steelmakers. As an example, in Figure 1.5.24, one of these schemes based on the organic Rankine cycle is presented.

Figure 1.5.23 Sketch of prompt gamma neutron activation analysis (PGNAA) equipment for online scrap analysis after shredding [47]. (For color version of this figure, the reader is referred to the online version of this chapter.)

Figure 1.5.24 Proposal for EAF off-gas recovery and power generation, based on organic Rankine cycle [50]. (For color version of this figure, the reader is referred to the online version of this chapter.)
Up to the writing of this chapter, four plants adopted off-gas recovery for steam production (see Table 1.5.6).

### Table 1.5.6 Plants Adopting EAF Off-Gas Recovery for Steam Production

<table>
<thead>
<tr>
<th>Plant</th>
<th>Country</th>
<th>Production (t/h)</th>
<th>Recovery Efficiency (%)</th>
<th>Steam (t/h)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgsmarienhütte</td>
<td>Germany</td>
<td>140</td>
<td>42</td>
<td>21 (216 °C: 13–20.5 bar)</td>
<td>2007</td>
</tr>
<tr>
<td>Elbe Stahlwerke Feralpi</td>
<td>Germany</td>
<td>133</td>
<td>84</td>
<td>40.8 (250–228 °C: 27–35 bar)</td>
<td>2013</td>
</tr>
<tr>
<td>Hyundai Steel Incheon</td>
<td>Korea</td>
<td></td>
<td></td>
<td>60</td>
<td>2014</td>
</tr>
<tr>
<td>TISCO Taiyuan</td>
<td>China</td>
<td></td>
<td></td>
<td>60</td>
<td>2014</td>
</tr>
</tbody>
</table>

*a*CONARC EAF.

REFERENCES


