Many steelmakers add charge and injection carbon for slag foaming concurrently with oxygen injection, but most often do not critically evaluate their current practices. Carbon and oxygen injection is viewed as a means to maintain a good carbon boil for hydrogen and nitrogen removal, as a means to sustain a foamy slag, and as a way to introduce chemical energy into the melting process. However, it can also have a significant effect on the metallic yield, slag composition, slag volume, as well as sulfur contents in both steel and in the furnace offgas. This paper discusses the historical development and theory of carbon and oxygen usage, and presents examples of practices in common use. Practices relating to the resurgent use of direct reduced iron and hot briquetted iron in North America are also described and evaluated. These practices are then discussed with respect to how they affect the overall steelmaking process with the intent of providing guidance to arc furnace steelmakers so that injection practices are cost-effectively and intelligently implemented.

Since the charge materials made to the furnace are the single largest component of the liquid steel cost, the importance of making a material and energy balance of the EAF process cannot be understated. While many steelmakers make a charge calculation solely to determine the necessary residual content to make a steel grade, there can be a multitude of solutions to make the same grade. Most often a least-cost charge calculation is made to determine the necessary residual content to make a steel grade, there can be a multitude of solutions to make the same grade. Most often a least-cost charge calculation is made to determine the charge mix based upon the materials available in the yard. However, it is also important to determine the “cost in use” or “value in use” as mentioned in other technical papers.1,2 This paper primarily focuses on only one aspect of this, carbon addition, but also considers how the choice of carbon source affects other aspects of the operation, such as tap sulfur content and slag volume.

Background

Steel production in electric arc furnaces (EAFs) has seen significant development since the advent of the mini-mill in the early 1980s. Prior to 1980, before the widespread use of ladle furnaces and ladle metallurgy, it was common for furnaces to utilize a two-slag practice. Furnaces were often refractory lined with tap-to-tap (TTT) times exceeding 3 or 4 hours. The EAF process consisted of bucket charging of ferrous materials and fluxes with melting occurring only by the input of electrical energy. Once meltdown was achieved, oxygen was then injected using lance inserted into the furnace door(s) concurrent with deslagging to remove the phosphorus-laden slag. In some shops, carbon was often shoveled into the furnace during the oxygen blowing, like the stoking of a steam engine. Operators noticed that this caused the slag to foam and resulted in a better “slag-off,” smoother furnace regulation, and even decreased electrical energy consumption. Little did these operators know at the time that they were making foamy slags and that this practice would become commonplace.
Once complete meltdown was achieved, the heat was often “blocked” with the addition of alloys and additional fluxes to build a reducing slag. After this, the heat was superheated to the aim tap temperature and tapped. While double-slag practices are still being used in some of the smaller foundries and specialty shops, this practice differs markedly from the vast majority of today’s EAF operations. This paper not only recounts the development of the equipment and practices that are universally recognized today, but also how they should be properly applied.

Development of Oxy-Fuel Burners and Oxygen Injection

Discussion of oxygen and carbon injection is not complete without mentioning the technology that led to its prolific use, which is the application of oxy-fuel burners. Burner use was first applied outside the U.S. because of higher electrical costs abroad. A paper in the 1976 Electric Furnace Proceedings describes one of the earliest applications of burner technology. Descriptions of the burner’s effects on the refractory walls raised concerns from EAF steelmakers. So, it was not until water-cooled panel and roof technology became widespread in EAFs in the 1980s that burner use became common. Water cooling and burner use were introduced somewhat concurrently, because in those instances where burners were added to refractory-lined furnaces without a fourth-hole fume evacuation system, it was quickly discovered that both intensive water cooling and adequate fume evacuation were necessary for burners to be successfully utilized. Burners were initially applied to supplement electrical energy in EAFs with lower specific energy input (<0.6 MVA/short ton). They were also found to be useful in providing energy into the “cold spots” of a furnace. As EAF powering increased to the current de facto standard for ultrahigh-power (UHP) furnaces with at least 1 MVA/short ton tap weight, burner operation played an integral role in making EAFs the melting machines that they have become.

As burner use proliferated and TTT times became shorter through the 1980s, operators began to look for ways to shorten and combine the various EAF process steps. Because the overall process was changing, a better understanding of the material and energy balance of an EAF was required. Where and how the energy was generated in the EAF was a subject of disagreement even within organizations filled with recognized experts in the industry, such as Lectromelt. Accordingly, one of the authors of this paper was tasked with developing a material and energy balance including a Sankey diagram based upon detailed information gathered from a furnace at ARMCO Kansas City. The calculations had to account for all materials added and removed from the furnace, including scrap, fluxes, steel, slag, dust, offgas and even in-draft air. Plus, the heat generated by all chemical reactions and the energy required to melt all materials had to be tallied. In performing this energy balance, it was found that the oxidation of carbon and metallics contributed about 15% of all the energy input, but it became readily apparent that a significant amount of energy input (approximately 9%) and yield loss (about 1%) could not be accounted for. It was only by assuming that the scrap contained 1% combustibles and about 0.5% moisture that the calculations finally balanced. This discovery provides important insight for those performing similar calculations for EAFs. It was these early handwritten calculations that have led to the sophisticated EAF process models that are now used by equipment suppliers and steel producers alike. Current process models can now perform a thorough and accurate material and energy balance of an EAF and can even account for chemical reactions and equilibria between metal, slag and gas phases. The results obtained can provide valuable insight as to whether a given EAF practice is performing properly.

As burner use became more common, it was soon discovered that operating burners at the stoichiometric 2:1 ratio of oxygen to natural gas was not optimal. Fume exiting the furnace, especially during the early phases of melting, had high CO contents. Energy that could be introduced inside of the furnace shell was being lost to the water-cooled duct leading to the baghouse. Accordingly it became more typical to operate sidewall burners super-stoichiometric with up to 20–25% excess oxygen. Thus, accounting for, and exploiting, CO generated by combustibles in the scrap, bath and injected carbon has become an important factor as TTT times of less than an hour are now commonplace, and steelmakers are trying to make best use of all the energy sources being introduced into the furnace.

Burner use must be properly accounted for, since their gas consumption, as well as maintenance, must be considered as part of the total EAF operating cost. During the meltdown of a furnace shell filled with scrap, burner heat transfer efficiency to the charge can be as high as 90%, but at flat bath this efficiency can drop to 20% or even lower. However, the burner must continue to fire throughout the heat to prevent plugging of the gas ports with the firing rate of a common oxy-fuel type burner being 20 to 30% of its maximum rate. Unfortunately, the majority of the hot gases pass directly into the fume system, providing little contribution to heating the charge. An alternative method to keep the burner ports open is to substitute compressed air for burner oxygen. This provides a larger gas volume and higher flow through the burner ports compared to using pure oxygen, which can result in reduced oxygen consumption and overall operating costs. The most extreme case for poor burner efficiency is a furnace that always operates under...
flat bath conditions where scrap (e.g., CONSteel™) and/or direct reduced iron (DRI) is continuously fed. In such cases, the burner function of a sidewall injector can, and has been, successfully turned off.

In addition to acting as a burner, the vast majority of sidewall burner installations now incorporate oxygen injectors with the burner providing shrouding gas to support a coherent oxygen jet, originally introduced as the Praxair CoJet™. These injectors have replaced most water-cooled lances that used to be inserted through the furnace sidewall, because they are inherently safer by reducing water leaks and potential explosions. Sidewall injectors typically impact the bath at an angle of 43° and can be mounted in burner boxes that protrude into the furnace sidewall. This arrangement places the oxygen jet closer to the bath for increased efficiencies and avoids washing of the sidewall refractory under the burner. When the injector is close to the steel bath and slag, it has been shown to produce a marked increase in furnace performance and decrease in conversion costs in some trials. In EAFs with good slag foaming practices, this type of equipment places the oxygen injector itself (and also any co-located carbon injectors) under the surface of the foamed slag. There are substantial advantages in this arrangement: primarily, a shorter oxygen jet means a more coherent jet impacting the surface of the steel bath, increasing the likelihood that it penetrates the surface and reacts efficiently with the steel. Another major benefit is that submerging carbon injectors in slag effectively prevents carbon fines from being picked up by the offgas being extracted from the EAF. Any injected carbon comes into contact with slag and is immediately available to react with FeO in the slag.

The oxygen injection in an EAF needs to be balanced with the requirements of the process to combust the carbon and various metallic elements contained in the charge to achieve the desired tap carbon and oxygen content. Too often steelmakers set a goal for the amount of oxygen they want to inject instead of calculating the amount required by the process. The question steelmakers must ask is, “What will I be oxidizing in the furnace?” because if carbon is not the target, then metallics will be oxidized. The result will then be a decrease in overall metallic yield, which is the single largest cost in electric steelmaking.

Post-Combustion in the EAF — Post-combustion (PC), which is the complete combustion of CO to CO2 in an arc furnace, was seen as one of the ways to increase overall energy efficiency and reduce electrical energy consumption. Complete combustion within the furnace is sought because the reaction 2CO + O2 → CO2 releases 1.46 kWh/Nm3 O2. This is explained by the authors of one of the earliest papers that discussed PC in the EAF in 1993, and in a follow-up paper the next year.

The goal of PC is to recover the 4.5 to 4.7 kWh that are available for each Nm3 of PC O2 depending upon whether the PC occurs in the foamy slag or in the free space above the melt and within the scrap, respectively. By monitoring the offgas composition at Nucor Steel–Utah, they were able to monitor and quantify the PC ratio defined as the ratio of CO2/(CO + CO2) in the offgas. The benefits gained at this facility are shown in Table 1. Similar PC results were reported by others. However, it is important to note the author’s comments related to the problems that may or do occur with improper oxygen use in an EAF. Among these are increased electrode consumption (or panel/roof damage), refractory wear and increased yield loss. This is similar to the experiences at Nucor Steel–Decatur LLC that are described in a paper written decades later by one of the authors of this paper. The conclusion is that a thorough knowledge of the arc furnace process is required in order to properly configure operating profiles, offgas analysis is useful, and accurate instrumentation is imperative. Without all these, an intelligent, informed decision cannot be made.

Despite all the efforts to achieve post-combustion and recover this energy in an arc furnace, it is important to note that as temperatures increase, the amount of carbon monoxide created also increases, as illustrated in Fig. 1. Praxair originally presented this information when they were investigating EAF burner operation and post-combustion. The original author supplied this information again for inclusion in this paper. The difference is that information on the reaction kinetics supplied by Praxair was provided as molar fractions, but this is plotted as volume percent in this paper, considering ideal gases.

Table 1

<table>
<thead>
<tr>
<th>Furnace Operating Statistics Before and After Post-Combustion Implementation</th>
<th>Conventional</th>
<th>Post-combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (kWh)</td>
<td>365</td>
<td>327</td>
</tr>
<tr>
<td>Lance O2 (ft³)</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Post-combusted O2 (ft³)</td>
<td>0</td>
<td>280</td>
</tr>
<tr>
<td>Burner O2 (ft³)</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Burner gas O2 (ft³)</td>
<td>275</td>
<td>275</td>
</tr>
<tr>
<td>Charge carbon (lbs.)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Injection carbon (lbs.)</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Electrodes (lbs.)</td>
<td>5.7</td>
<td>5.7</td>
</tr>
</tbody>
</table>
Because this information is based upon theoretical, ideal conditions, some insight must be used to apply this to the actual operation and reactions that occur inside the EAF. During the early stages of scrap melting, volatiles are evolved that will shift the equilibria, resulting in incomplete combustion without sufficient oxygen being available. Also, if the residence time of the gases in the furnace is very short, complete combustion will not occur in the furnace. Accordingly, it is difficult to recover this energy into the charge, or slag, with the situation becoming increasingly worse once the furnace has achieved meltdown — not to mention the difficulties of efficiently transferring heat from a gas to a solid or liquid. The best opportunity to recover post-combustion energy is during the initial melting of the charge materials while they are still cold.

Carbon Additions in the EAF

Carbon added to the EAF is required to provide the carbon boil to flush the hydrogen and nitrogen from the bath before tap. The total carbon in the charge can be calculated by making a summation of the carbon contained in everything added to the furnace including the different types of scrap, pig iron, DRI/hot briquetted iron (HBI), charge carbon and injection carbon. The following sections discuss the various methods and forms by which carbon can be introduced to the EAF.

Evaluation of Charge Carbon Additions — Few steelmakers have the time available to critically evaluate their carbon addition practices, but doing so provides insight into the overall process. Following is an explanation of what happens in the furnace during charging.

Equilibrium and kinetics for methane and CO combustion: equilibrium $\text{CH}_4 - \text{O}_2$ (a), kinetics of stoichiometric $\text{CO} - \text{O}_2 - 0.4$ second (b), kinetics of $\text{CH}_4 - \text{O}_2$ (c), and equilibrium $\text{CO} - \text{O}_2$ (d).

Figure 1
Everyone that has ever observed an arc furnace has looked in awe at the fireball that erupts from the furnace whenever a charge is dropped. This fireball is caused by the sudden deoxidation of the heel caused by its rapid cooling by the scrap addition as well as the burning of combustibles contained in the charge. These combustibles are organic materials that cover the scrap, such as paint, grease, oil, soil, etc., as well as any charge carbon added to the bucket. Plus, since the most common form of charge carbon is low-sulfur anthracite coal, one must consider that it typically contains only about 82% fixed carbon with the remainder being ash and volatile organic compounds. When anthracite is heated, the volatiles are driven off. Therefore, essentially, only the fixed carbon is available to dissolve in the heel and participate in the carbon-oxygen reaction that contributes to the boil in the furnace. One must also take into account that during the early stages of melting, the carbon content of the heel will not be in equilibrium with the high FeO in the remaining tap slag. So, additional charge carbon will be also lost during deoxidation of the remaining slag.

While thermodynamic equilibria are used to make calculations related to what is occurring in an arc furnace, the materials in the arc furnace are seldom, if ever, in equilibrium because the melting and refining process is dynamic. Instead the furnace is in a constant state of quasi-equilibrium with metallics and fluxes being melted and oxygen and carbon being continuously added. Nevertheless, after tap, the composition of the heel and slag remaining in the furnace can be estimated with fairly good accuracy based on the temperature and oxygen measurement made just before tap. Also, by keeping an accurate inventory of the remaining heel, flux additions made and slag removed from the furnace, a material balance can be made to determine the efficiency of a charge carbon addition. The following information is needed to do this:

- Charge carbon composition (primarily the fixed C content).
- Amount of carbon added.
- An estimate of the slag retained in the furnace after tap.
- Tap carbon content.
- Tap temperature.

Using this information, as well as an estimation of how far the process deviates from the carbon-oxygen and oxygen-FeO equilibria, a calculation can be made to determine the efficiency of a charge carbon addition. Fig. 2 shows a typical example of a calculation made for an actual operating furnace wherein it can be noted that only about 50% of the total charge carbon addition actually contributes to raising the carbon content of the heel. This is typical for most furnace operations.

Considering the calculation discussed earlier, some interesting comments can be made as related to practices that are common in some of the larger DC furnaces operating in Compact Strip Production (CSP) shops — in particular, the fact that they operate with very large heels, and they typically retain a significant amount of slag from the previous heat in order to provide sufficient foamy slag to bury the comparatively longer DC arc. For a typical 150-ton tap weight, it is not unusual for a DC furnace to have a heel exceeding 100 tons, or for that furnace to retain the total slag generated during the melting of the previous heat, or even two heats. Accordingly, there is a significant amount of free oxygen available in the heel as well as a large amount of FeO available in the slag. When a furnace is operated in this manner, it was observed that the complete charge carbon addition seemed to “disappear.” In other words, it did not result in an increase in the carbon content of the heel remaining.

### Figure 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heel Size</td>
<td>t</td>
<td>109</td>
<td></td>
</tr>
<tr>
<td>Heel Size</td>
<td>t</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Slag Amount</td>
<td>kg/ t</td>
<td>40.6</td>
<td></td>
</tr>
<tr>
<td>% Slag retained in EAF</td>
<td>%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Tap C</td>
<td>%</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>Dev from Equil for Tap O</td>
<td>ppm</td>
<td>1.1</td>
<td>(1 = equilibrium)</td>
</tr>
<tr>
<td>Dev from Equil for Slag FeO</td>
<td>%</td>
<td>5.0</td>
<td>(1 = equilibrium)</td>
</tr>
<tr>
<td>Tap temp</td>
<td>C</td>
<td>1660</td>
<td></td>
</tr>
<tr>
<td>Charge C</td>
<td>kg/ t</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>Fixed C in Chg C</td>
<td>%</td>
<td>85%</td>
<td>Model assumes only fixed C contributes; Volatiles and ash do not.</td>
</tr>
<tr>
<td>Tap O</td>
<td>ppm</td>
<td>731</td>
<td><strong>Adjust Dev from Equil if this value does not reflect actual practice</strong></td>
</tr>
<tr>
<td>Slag FeO</td>
<td>%</td>
<td>31.9</td>
<td><strong>Adjust Dev from Equil if this value does not reflect actual practice</strong></td>
</tr>
<tr>
<td>Slag FeO</td>
<td>kg</td>
<td>1412</td>
<td></td>
</tr>
<tr>
<td>Slag</td>
<td>kg</td>
<td>314.4</td>
<td></td>
</tr>
<tr>
<td>Heel</td>
<td>kg</td>
<td>270.3</td>
<td></td>
</tr>
<tr>
<td>Total Chg C</td>
<td>kg</td>
<td>1584.7</td>
<td></td>
</tr>
<tr>
<td>Total Fixed C</td>
<td>kg</td>
<td>1324.9</td>
<td></td>
</tr>
<tr>
<td>C lost to reaction w/ O</td>
<td>kg</td>
<td>438.5</td>
<td></td>
</tr>
<tr>
<td>Effective Chg C</td>
<td>%</td>
<td>56.9%</td>
<td></td>
</tr>
</tbody>
</table>

Charge carbon efficiency calculation.
in the furnace. Therefore, it was decided, and it is now common practice, to not add any charge carbon in the bucket. Instead, many of these shops utilize pig iron as a source of carbon for the heel.

**Injection Carbon Additions and Foamy Slags** — The benefit of injecting carbon to develop and sustain a foamy slag is a well-established practice recognized by steelmakers. Foamy slags are important to capture and focus the energy of the electric arc and to shield the furnace sidewalls and roof. Their formation is dependent on the reaction of CO in the bath as well as in the slag via the reaction of metallic oxides with carbon. Pretorius and Carlisle wrote the pre-eminent guide on foamy slags, which is followed by many steelmakers, wherein they define the chemical composition of slags that result in the best foamy slags for various basicities and FeO contents.\(^{15}\) These slags are created and constantly replenished by the simultaneous injection of oxygen and carbon into the bath. In the U.S., the most common form of injection carbon, like charge carbon, is low-sulfur anthracite coal due to cost and availability, but nearly any carbon source can be used. The actual practices are discussed in more detail below.

Since injecting carbon is desirable, many believe that, if some is good, more must be better and, when taken to the absolute extreme, as much as can possibly be injected certainly must be the epitome. However, the injection of excessive amounts of carbon is not without side effects, particularly if the slag conditions cannot support it. The oxidation of carbon increases the amount of offgas that must be handled by the fume system, and if it is not captured by the slag, fine carbon can be carried over into the fume system duct where it will burn, resulting in high baghouse temperatures. In addition, the carbon injection must be at least balanced by the oxygen injection rate. High oxygen rates can result in splashing of slag and/or metal on the furnace walls and roof. This can lead to delta flashovers to the walls and roof, metal accumulations on the electrodes, a.k.a. “skins” and buildup on the walls, which can decrease the furnace volume available to hold the charge. Because of this fact, EAF literature abounds with papers citing reductions in power consumption, even when the amount of injection carbon is reduced. To the trained observer, the potential for injection carbon savings is obvious when flame is emitting from every opening on a furnace. The last consideration that is often ignored when injecting carbon is that anthracite coal contains siliceous ash that contributes to slag volume. This silica must also be fluxed, creating a cycle of increasing slag mass, energy consumption and metallic losses.

Of great importance in understanding how to optimize carbon injection rates is comprehending how slag and steel chemistries change over time in the EAF operating cycle. As the bath carbon levels reach 0.1% and lower, the generation of FeO is increasingly favored over the generation of CO in the steel bath. This has a substantial effect on the need for injection carbon in the EAF. Earlier in the heat, when the majority of injected oxygen is consumed by carbon in the steel bath, slag FeO levels remain low, so the need for injection carbon is limited. Later in the heat, as FeO levels increase, more and more carbon is needed to control FeO.

**Carbon Injection — What Is Typical? What Is Excessive?**

Since the primary goal of carbon injection is for slag foaming, what would be considered a typical addition rate? Based upon the authors’ experiences, the injection carbon consumption normally averages between 8 and 12 kg/t, but there certainly are exceptions, which the authors do not necessarily support.

If increasing the amount of injection carbon resulted in increased energy input into an EAF, there should be data to support this. SMS had collected operating data from a multitude of EAF shops back in 2007. Fig. 3 shows a plot of power consumption as a function of injected carbon and total oxygen consumptions with trend lines and R² evaluations noted for the two data sets. As it can clearly be seen, there is no correlation between increased injected carbon and reduced electrical consumption, but increasing oxygen injection does appear to provide some benefit (most likely at the expense of oxidizing metallics). Likewise, Fig. 3 shows data from a single shop where one of four carbon injectors became plugged, thus reducing the injection carbon by 22.3% with an
insignificant effect on the power consumption (1.5% increase).

The data shown in Figs. 3 and 4 indicate that in terms of energy consumption for the EAFs in question, the amount of injection carbon is less of a factor than many believe. It seems that once some adequate level of slag foaming is achieved, the effect on electrical energy consumption from additional injection carbon is minimal. After this point, it seems that the most effective use for injection carbon is for FeO control in the furnace slag. This is an important function, since it has a major impact on metallic yield. Many operations set the level of carbon injection based on whether they feel the furnace is foaming “good,” “bad,” or just “ok” and whether slag FeOs are reasonable. A good rule of thumb is, “If slag FeOs are a little high, turn the carbon up. If they look ok, leave it where it is.”

If asked, most EAF operators can tell of many occasions where they have seen furnace slag rolling out the slag door with small flames, sparks and fumes coming off of it. Many shops have installed water sprays over their slag pots for the occasions where the pot begins to boil over. These symptoms are usually the result of unreacted carbon in the slag. It does the EAF little good to inject so much carbon that substantial amounts of it are lost to the slag pot. While these practices appear to work, they are not ideal and can be improved. A simple and straightforward option is for the operator to experiment with different injection rates and amounts with any given scrap mix to determine the point for optimal furnace performance and FeO control. For this to work, a relatively stable scrap mix must be maintained. If bath carbon levels vary erratically and unpredictably, it will be almost impossible to arrive at a good, consistent injection practice through experimentation alone.

As mentioned earlier, in a situation where the tap oxygen is relatively high (>600 ppm), the steel bath carbon at the end of the heat is very low, leading to a decrease in CO generation from the bath and a marked increase in FeO generation. In this critical period at the end of the heat, large amounts of iron can be oxidized to FeO in very short time periods (refer to Table 2).

Injection carbon is critical in controlling this final FeO buildup in the slag at the end of the heat. Because of this situation, the methodology for carbon injection should really be considered as two separate stages: one for the bulk of oxygen injection where the aim is to maintain adequate foam, and a second for the end of the heat where the aim is to both maintain adequate foam and to control FeO content. This is somewhat different from most EAF operations where carbon is typically set at one level and then maintained for the entire heat. The authors’ contention is that most plants probably over-use injection carbon early in the oxygen injection process and then greatly under-use it at the end of the heat. A more ideal solution would be to ramp up carbon injection at the end of the heat in proportion to the amount of FeO being generated. As notable in Table 2, the amount of injection carbon must increase quickly and
substantially to adequately control FeO generation. Even with very capable carbon injection equipment and a good understanding of FeO generation, it is likely that in many cases the amount of FeO generated will simply overwhelm the ability to deliver carbon effectively to the EAF. However, there is opportunity to improve current processes and make a substantial positive impact toward metallic yields.

If a steelmaker is interested in doing trials to determine the effect of injection carbon on power consumption, this may require resetting of pressures and conveying gas rates on injection vessels. If the injection system is designed to operate at a fixed rate, another technique is to simply increase the carbon particle size. Larger-sized particles inherently inject at lower rates. The authors suggest this technique because it is often found that plants use carbon that contains excess fines. If too fine, carbon particles can easily be carried out the fourth hole. Over a decade ago, a colleague did in-plant trials using “barley-sized” carbon in which all the fines had been screened out. This material was found to be just as effective in foaming as the unscreened material, and at much lower addition rates.

So, how does the ash content of the carbon affect the overall EAF operation? Table 3 shows a typical seller specification for injection carbon. Problems with this specification include:

- “Barley” anthracite is defined as 3/16 to 3/8 inch size. (There is no limit on the amount of undersized material.)
- The total sum of all constituents well exceeds 100%. (What is the actual analysis?)
- The ash analysis is not provided. (Ash varies widely depending on the source.)

Also included in Table 3 is an ash analysis available from the U.S. Geological Survey. Based on this information, estimates can be made based upon a 5 kg/t addition of injection carbon containing 11% ash. By assuming that all ash reports to the slag and silica and alumina must be neutralized for a B3 basicity of 1.6, then it is estimated that 1.6 kg/t of slag will be created assuming 30% FeO in the slag. While this amount of slag provides only a modest increase in the metallic losses as FeO in the slag (estimated at 0.04%), increasing the slag amount does increase the opportunity for losses due to metallics trapped in and carried out by the slag.

Carbon Contained in Pig Iron or Hot Metal Additions — When used, pig iron typically comprises 10–30% of the total charge, but it has been used for up to 50% of the total charge in extreme cases. The reasons for pig iron vary, but it is primarily used to lower the steel’s residual content. It also has side benefits. Steelmakers have discovered that pig iron is a desirable charge material because it:

- Can be used to dilute residuals.
- Provides a source of carbon to the bath to create a boil and flush hydrogen and nitrogen from the bath.
- Contains excess carbon that is already in solid solution, so it easily alloys with the heel.
- Has a low melting point, so it melts quickly.
- Has a high density, so it can be used to decrease total scrap volumes often resulting in a single bucket charge.

On the other hand, pig iron can contain high amounts of silicon. While this can generate a significant amount of chemical energy, this high silicon content requires increased lime additions. This increases slag volumes as well as metallic losses. All of this must be taken into account when evaluating the value-in-use of high-silicon pig iron.

Unlike pig iron, hot metal additions have the added benefit of providing sensible heat to the charge. Numerous papers extol the benefits of hot metal. When hot metal is used, the electrical consumption in an EAF can be reduced approximately 50 kWh/t for each 10% addition of hot metal, but this often depends on how and when the hot metal is added. The benefit is also that the tap-to-tap time can be reduced, but not without limitations. The rate of decarburization limits the addition rate to about of

<table>
<thead>
<tr>
<th>Product</th>
<th>Barley-sized anthracite</th>
<th>Oxide or element</th>
<th>This study (%)</th>
<th>333 Appalachian coal samples (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>3/16 inch</td>
<td>Ash</td>
<td>6.8</td>
<td>13.3</td>
</tr>
<tr>
<td>Typical analysis</td>
<td></td>
<td>SiO₂</td>
<td>41.2</td>
<td>41</td>
</tr>
<tr>
<td>Total moisture</td>
<td>&lt;4%</td>
<td>A₁₂O₃</td>
<td>26.8</td>
<td>23</td>
</tr>
<tr>
<td>Ash (dry)</td>
<td>&lt;12%</td>
<td>CaO</td>
<td>3.57</td>
<td>1.9</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>&lt;6%</td>
<td>MgO</td>
<td>1.47</td>
<td>0.90</td>
</tr>
<tr>
<td>Total sulfur</td>
<td>&lt;1%</td>
<td>Na₂O</td>
<td>0.56</td>
<td>0.36</td>
</tr>
<tr>
<td>Total fixed carbon</td>
<td>&gt;82%</td>
<td>K₂O</td>
<td>1.07</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fe₃O₄</td>
<td>10.40</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MnO</td>
<td>0.02</td>
<td>0.073</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TiO₂</td>
<td>1.40</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SiO₂</td>
<td>2.70</td>
<td>2.4</td>
</tr>
</tbody>
</table>
40% of the total charge to achieve the minimum tap-to-tap time. Hot metal additions beyond 40% will still continue to decrease power consumption, but the tap-to-tap time will increase. The effect of hot metal on power consumption and heat times is shown in Fig. 5.

Carbon Contained in DRI/HBI Additions — In the early 1980s, it was not uncommon for DRI to contain 1.2 to 1.5% carbon with approximately 92% metallization. The intent was to provide sufficient carbon to reduce the unmetallized iron with enough remaining to support a good carbon boil. For the “early adopter” DRI producers that were coupled with steel plants, it was not uncommon for the DRI production facility to be a separate cost center from the steel production facility. Where a steel plant desires high metallization, high carbon and low gangue, the DRI plant can have conflicting goals. It has been stated that a DRI facility has a 2.5% decrease in production for every 1% increase in metallization, and increasing metallization corresponds to an increase in natural gas consumption. If the iron pellets are sourced from the lowest-cost producer, excessive gangue contents, particularly silica, can also be high, leading to excessive amounts of slag and larger metallic iron losses in the steelmaking process. If the DRI facility also supplies merchant DRI, the situation could often become worse. Finally, when shipped long distances, a steelmaker must always consider losses due to reoxidation and fines generation. The current market is much different from those early years.

It was the widespread purchase and consumption of merchant DRI by steelmakers over the last few decades that prompted them to determine each charge material’s value in use, which has subsequently led purchasing managers to adopt quality standards and impose contract penalties for substandard DRI with low metallization and carbon contents. Numerous authors such as J.A.T. Jones have developed tools to better determine each material’s value. The question is: What are the most recent trends in DRI quality? To answer this, one only needs to look at DRI producer/consumers such as ArcelorMittal Lázaro Cárdenas and Nucor to determine what characteristics that have been found to be most desirable. The overwhelming current trend is to use DRI with high metallization and carbon content.

Numerous papers and studies have been published discussing the benefits and challenges with consuming DRI or HBI in the EAF. Although many of these contain extensive discussions on the carbon contained in the material, they rarely go into detail on the impact of DRI/HBI use to balancing carbon injection. DRI and HBI have an interesting impact on the EAF when they are consumed continuously via a roof feed system. Unlike highly dense pig iron, which sinks in the bath and melts into the bulk of the heat, DRI and HBI are less dense than the steel but more dense than the slag. This results in both DRI and HBI floating at or near the slag-metal interface after being fed to the EAF.

As the pellets or briquettes fall through the EAF slag, they are coated with a layer of solidified slag that likely slows the dissolution of these particles in the steel bath. As DRI and HBI have some amount of FeO remaining and also have carbon available, they will begin to produce CO gas as they heat up. Some interesting work was performed at the University of Toronto using x-ray video of DRI pellets submerged in liquid slag and the images clearly show the creation of a “halo” of CO gas around the pellets as they begin to heat up. This first stage of decarburization proceeds rapidly, and in experiments with individual pellets, it was complete 10–20 seconds after the start of gas evolution. As illustrated in Table 4, this CO generation is small compared to the total amount of carbon available in the merchant DRI and HBI used in the U.S. today, but is still useful in generating a foamy slag.

Once the initial decarburization step is complete, research at Carnegie Mellon University indicates that DRI pellets begin to melt and coalesce, eventually sinking to join the bulk steel bath. These results also revealed that in some cases the CO generation from the DRI pellet can create a bubble of iron surrounding a pocket of CO, reducing the density of the molten pellet and thus suspending it in the slag for some time. Whether this could happen in an industrial situation where there is extensive and sometimes violent mixing at the slag-metal interface is unclear, but it is an important aspect to consider when discussing the metallic yield impact of consuming high amounts of DRI.

This research raises an interesting question as to the methods of FeO reduction out of the foaming
slag in an EAF consuming DRI or HBI continuously. The traditional model is that of a two-zone reaction, as detailed in a paper from ArcelorMittal Lázaro Cárdenas, where decarburization is accomplished in the liquid steel by injected oxygen and reduction of FeO is accomplished in the slag layer and in close proximity to the slag-metal interface. In the case of top-fed DRI or HBI, the material will be suspended near the slag-metal interface and in the slag itself while it heats and begins to melt and coalesce. Given the existence of aggressive mixing at the slag-metal interface and the tendency of smaller particles to become suspended in the slag, it seems likely that high-carbon metallic particles could be suspended in the slag and be available to react with liquid FeO. In this case, it would seem that at least some decarburization occurs within the slag layer between suspended iron droplets and the foamed slag, something very akin to the behavior seen in an emulsified BOF slag.

As the DRI pellet (or HBI briquette) begins to melt and join the bulk steel bath, a substantial amount of carbon is made available. Table 4 shows calculations of the “surplus” carbon available in DRI/HBI after a stoichiometric amount is consumed by the reduction of FeO. Even in the case of 2% carbon DRI/HBI, as much as 1.2% carbon can still be present in high metallization material, far higher than any scrap type besides cast iron or pig iron. When continuously charged to the furnace, the DRI/HBI provides for a substantial reservoir of carbon to react with injected oxygen or to reduce slag FeO. Table 5 details calculations on “surplus” carbon addition rates for varying DRI feed rates and the corresponding consumption of injection oxygen.

The considerable amounts of carbon made available through continuous charging have a marked impact on the need for injection carbon. At even moderate feed rates of DRI or HBI, it is possible for an EAF to operate with low injection carbon rates and still have very high foam height (assuming proper slag chemistry is maintained). At ArcelorMittal Lázaro Cárdenas, it has been shown that no injection carbon at all is needed in the heat until the very end of the process when the steel bath carbon is depleted and FeO generation rates rise. While this example is an EAF operation with 100% DRI feed, there is great potential to optimize the amount of injection carbon based on the particular scrap mix and operational parameters of the furnace.

**Summary**

It is too often found that EAF chemical energy practices have developed over weeks, months and years where the operators have strayed away from sound metallurgical practices. Sometimes this is out of convenience, such as starting the injection carbon at a set rate and continuing unchanged throughout the heat. Sometimes a process change is the result of unintended consequence. An example might be the purchase of substandard or lower-cost carbon injection material that is finer than originally used. This could unintentionally cause increased injection rates that provide no actual benefit.

Changes in the availability or quality of raw materials like pig iron, DRI or HBI can have massive impacts on the need for lancing oxygen and injection carbon. Sometimes the changes are the product of ignorance. An example might be an untrained operator believing that more is always better. It is the duty of managers and metallurgists that oversee the EAF operation to constantly and critically evaluate the operation with the goal of constant process improvement. It was the goal of the authors to better educate operators by providing a different way of viewing and evaluating EAF practices.
Did You Know?

**Gerdau and SKF in Agreement to Improve Productivity at Brazilian Steel Mills**

Brazilian steelmaker Gerdau and rotating equipment solutions provider SKF have signed a fee-based agreement aimed at increasing productivity and reducing unplanned downtime at Gerdau’s Charqueadas and Araçariguama steel mills in Brazil.

The agreement will see SKF provide a full range of products, including bearings, remanufacturing, lubrication systems and connected condition monitoring units. Data from critical machinery at the two steel mills will be analyzed at SKF's Rotating Equipment Performance Center in Brazil. Based on this analysis, SKF and Gerdau can plan maintenance and corrective actions, improving machine reliability and performance.

Fladimir Gauto, executive director at Gerdau Special Steel Brazil, said, “We are focused on generating value and increasing competitiveness in our operations, as well as on advancing with the implementation of innovative solutions in the steel industry. Our partnership with SKF will certainly be an important support in this regard.”

Claudinei Reche, president, SKF Latin America, said, “By offering customers in the steel industry the opportunity to work with us on a fee basis, we give them access to our full competence around the rotating shaft, in order to improve productivity. For an industry which has a very high cost for unplanned downtime, this is crucial. We will be able to help Gerdau improve their output and reduce their consumption of bearings, grease and energy, reducing the impact of their operations on the environment.”

References

14. Personal communication with Pravin Mathur, Praxair Inc.
16. Conversation with Mark Trapp, CIX LLC partner.

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