EAF Fundamentals

by

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The EAF operating cycle – Charging, melting and refining

1. INTRODUCTION

There have been many advances in EAF technology that have allowed the EAF to compete more successfully with the integrated mills. Most of these have dealt with increases in productivity leading to lower cost steel production. Gone are the days when electric power was the only source of energy for scrap melting. Tap to tap times decreases from a range of 3 to 8 hours to less than one hour with electric energy consumption in the range of 380 – 400 kWh/ton. The following innovations helped to achieve the higher production rates:

- Oxy-fuel burners
- Supersonic Oxygen lancing and Co-jet burners
- Foamy slag practice and carbon/lime injection
- Post combustion in the EAF freeboard
- EAF bath stirring
- Modified electrical supply (series reactors etc.)
- Current conducting electrode arms
- DC furnace technology
- Innovative process technologies (scrap preheat, continuous charging etc.)

Most of the productivity gain achieved over the past 10-15 years was related to the injection of gasses into the furnace, i.e. oxygen and natural gas. Exothermic reactions were used to replace a substantial portion of the electrical energy input in the EAF. Whereas oxygen utilization of 300 SCF/ton was considered the norm just 10 years ago, some operations now use more than 1500 SCF/ton. With post-combustion, total oxygen rates as high as 2500 SCF/ton have been implemented in the EAF. It is now common for between 30 and 40% of the total energy input to the EAF, to come from oxy-fuel burners and oxygen lancing. The following table gives some comparison of the energy input for the old EAF's and the modern EAF's.

Table 1.1. EAF Heat balance comparing Old and New EAF energy inputs and outputs

<table>
<thead>
<tr>
<th>Inputs:</th>
<th>Old EAF</th>
<th>New EAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>82%</td>
<td>65%</td>
</tr>
<tr>
<td>Burners</td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>Bath Reactions</td>
<td>18%</td>
<td>30%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>57%</td>
<td>57%</td>
</tr>
<tr>
<td>Slag</td>
<td>11%</td>
<td>10%</td>
</tr>
<tr>
<td>Cooling water losses</td>
<td>6%</td>
<td>10%</td>
</tr>
<tr>
<td>Off-gas losses</td>
<td>7%</td>
<td>20%</td>
</tr>
<tr>
<td>Miscellaneous losses</td>
<td>16%</td>
<td>3%</td>
</tr>
</tbody>
</table>
The EAF operates as a batch melting process producing batches of molten steel known as "heats". The EAF operating cycle is called the tap to tap cycle and is made up of the following operations:

- Furnace charging
- Melting
- Refining
- Deslagging
- Tapping
- Furnace turn-around

This technical document will focus primarily on furnace charging, melting, and refining, and will discuss these operations in detail in the sections that follows.

2. FURNACE CHARGING

2.1 Introduction

The first step in any tap-to-tap cycle is "charging" into the furnace. The roof and electrodes are raised and are swung to the side of the furnace to allow the scrap-charging crane to move a full bucket of scrap into place over the furnace. The bucket bottom is usually a clam shell design - i.e. the bucket opens up by retracting two segments on the bottom of the bucket. The scrap falls into the furnace and the scrap crane removes the scrap bucket. The roof and electrodes swing back into place over the furnace. The roof is lowered and then the electrodes are lowered to strike an arc on the scrap. This commences the melting portion of the cycle. The number of charge buckets of scrap required to produce a heat of steel is dependent primarily on the volume of the furnace and the scrap density. Most modern furnaces are designed to operate with a minimum of back-charges. This is advantageous because charging is a dead-time where the furnace does not have power on and therefore is not melting. Minimizing these dead-times helps to maximize the productivity of the furnace. In addition, energy is lost every time the furnace roof is opened. This can amount to 10 - 20 kWh/ton for each occurrence. Most operations aim for 2 to 3 buckets of scrap per heat and will attempt to blend their scrap to meet this requirement. Some operations achieve a single bucket charge. Continuous charging operations such as CONSTEEL and the Fuchs Shaft Furnace eliminate the charging cycle.

The scrap yard operator will prepare buckets of scrap according to the needs of the melter. Preparation of the charge bucket is an important operation, not only to ensure proper melt-in chemistry but also to ensure good melting conditions. The scrap must be layered in the bucket according to size and density to promote the rapid formation of a liquid pool of steel in the hearth while providing protection for the sidewalls and roof from electric arc radiation. Other considerations include minimization of scrap cave-ins which can break electrodes and ensuring that large heavy pieces of scrap do not lie directly in front of burner ports which would result in blow-back of the flame onto the water cooled panels. The charge can include lime, dolomitic lime, and carbon, or these can be injected into the furnace during the heat. Many operations add some lime and carbon in the scrap bucket and supplement this with injection.
2.2. Scrap Classification

The main raw material for EAF steelmaking is steel scrap. Scrap is an energy intensive and valuable commodity and comes primarily from three main sources:

1. Reclaimed or obsolete scrap – Scrap material arising from a vast range of materials beyond useful life including old cars, demolished buildings, discarded machinery and domestic objects.

2. Industrial or prompt scrap – Ferrous scrap material of all types arising from current manufacturing operations for immediate disposal. Normally of uniform characteristics and predictable quality

3. Revert or home scrap – Scrap generated during the steelmaking process, e.g. crop ends from rolling operations, metallic losses in slag, etc.

The latter two forms of scrap tend to be clean, i.e. they are close in chemical composition to the desired molten steel composition and thus are ideal for recycle. Reclaimed/obsolete scrap frequently has a quite variable composition and quite often contains contaminants that are undesirable for steelmaking. Reclaimed/obsolete scrap is much more available than industrial/prompt scrap and thus the use of clean iron units is expected to increase as shortages of prompt scrap continues to grow.

2.3. Scrap Chemistry

The typical "bulk" chemistry of a number scrap types is listed in Table 2.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>%C</th>
<th>%Mn</th>
<th>%Si</th>
<th>%S</th>
<th>%P</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 HMS</td>
<td>0.5</td>
<td>0.8</td>
<td></td>
<td>0.05</td>
<td>0.030</td>
</tr>
<tr>
<td>#2 HMS</td>
<td>0.35</td>
<td>0.8</td>
<td></td>
<td>0.05</td>
<td>0.060</td>
</tr>
<tr>
<td>Shredded</td>
<td>0.2</td>
<td>0.65</td>
<td></td>
<td>0.03</td>
<td>0.025</td>
</tr>
<tr>
<td>Plate &amp; structural</td>
<td>0.2</td>
<td>0.65</td>
<td></td>
<td>0.02</td>
<td>0.017</td>
</tr>
<tr>
<td>Revert scrap</td>
<td>0.2</td>
<td>0.5</td>
<td>0.1</td>
<td>0.02</td>
<td>0.015</td>
</tr>
<tr>
<td>Turnings</td>
<td>3</td>
<td>0.5</td>
<td>2.5</td>
<td>0.057</td>
<td>0.080</td>
</tr>
<tr>
<td>Obsolete scrap</td>
<td>0.35</td>
<td>0.6</td>
<td>0.12</td>
<td>0.037</td>
<td>0.018</td>
</tr>
</tbody>
</table>

The most important chemical aspect of scrap is the elements that are labeled residuals, which include Cu, Sn, Ni, Cr and Mo. The levels of these elements must be below specified limits for certain steel grades since they can affect product quality and casting operations. Table 2.3 shows residual levels for typical scrap types and compares these with residual levels for Midrex DRI. Table 2.4 shows residual level requirements for various steel product types.
Table 2.3. Typical scrap residual chemistries compared with Midrex DRI

<table>
<thead>
<tr>
<th>Typical scrap residuals</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Bundles</td>
<td>0.01</td>
<td>0.02</td>
<td>0.07</td>
<td>0.03</td>
<td>0.04</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>#1 HMS</td>
<td>0.02</td>
<td>0.04</td>
<td>0.25</td>
<td>0.09</td>
<td>0.10</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>#2 HMS</td>
<td>0.03</td>
<td>0.07</td>
<td>0.55</td>
<td>0.20</td>
<td>0.18</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Shredded</td>
<td>0.025</td>
<td>0.04</td>
<td>0.22</td>
<td>0.11</td>
<td>0.18</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>#2 Bundles</td>
<td>0.03</td>
<td>0.09</td>
<td>0.50</td>
<td>0.10</td>
<td>0.18</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Plate &amp; structural</td>
<td>0.017</td>
<td>0.020</td>
<td>0.365</td>
<td>0.07</td>
<td>0.09</td>
<td>0.025</td>
<td>0.01</td>
</tr>
<tr>
<td>Midrex DRI-min</td>
<td>0.02</td>
<td>0.005</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Midrex DRI-max</td>
<td>0.09</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 2.4. Residual levels for selected steel grade

<table>
<thead>
<tr>
<th>Residuals per grade</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Sn</th>
<th>As</th>
<th>N (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC fine wire</td>
<td>0.1</td>
<td>0.08</td>
<td>0.08</td>
<td>0.015</td>
<td>0.015</td>
<td>0.015</td>
<td>60</td>
</tr>
<tr>
<td>Cold heading</td>
<td>0.1</td>
<td>0.08</td>
<td>0.08</td>
<td>0.01</td>
<td>0.015</td>
<td>0.015</td>
<td>80</td>
</tr>
<tr>
<td>Forging grades</td>
<td>0.15</td>
<td>0.12</td>
<td>0.12</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>80</td>
</tr>
<tr>
<td>Plating quality</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>80</td>
</tr>
<tr>
<td>IQ</td>
<td>0.3</td>
<td>0.15</td>
<td>0.12</td>
<td>0.03</td>
<td>0.03</td>
<td>0.025</td>
<td>100</td>
</tr>
<tr>
<td>Structural</td>
<td>0.4</td>
<td>0.15</td>
<td>0.15</td>
<td>0.08</td>
<td>0.03</td>
<td>0.02</td>
<td>120</td>
</tr>
<tr>
<td>Re-bar</td>
<td>0.4</td>
<td>0.35</td>
<td>0.15</td>
<td>0.08</td>
<td>0.08</td>
<td>0.035</td>
<td>120</td>
</tr>
<tr>
<td>Deep drawing*</td>
<td>0.06</td>
<td>0.1</td>
<td>0.07</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Drawing quality*</td>
<td>0.1</td>
<td>0.1</td>
<td>0.07</td>
<td>0.03</td>
<td>0.015</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Tier 3 HR*</td>
<td>0.12</td>
<td>0.12</td>
<td>0.1</td>
<td>0.05</td>
<td>0.02</td>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

*Flat rolled products

The potential effects of residual elements on product properties are summarized below:

- Hot shortness (Cu, made worse in the presence of As, Sn, Sb)
- Seams, cracks, inter-granular weakness (S, P, H)
- Irregularity of mechanical properties on hot-rolled products (W, Mo, Mn, Cr, Ni, P, N)
- Poor cold forming ability of the hot-rolled material (N, S, P)
- Heat affected zone embrittlement (N, P, H)

A steelmaking facility that are making products with low residual levels will be forced to use higher quality prompt scrap but at a much higher cost. The alternative is to use a combination of the contaminated obsolete scrap along with what is generally referred to as clean iron units or alternate iron units. These are materials that contain little or no residual elements. Clean iron units are typically in the form of direct reduced iron (DRI), hot briquetted iron (HBI), iron carbide, pig iron, and hot metal (molten pig iron). It is possible to use lower grade scrap which contains residual elements, if this scrap is blended with clean iron units so that the resulting residual levels in the steel following melting meet the requirements for the specific steel grade. Obsolete scrap (high residuals) is much more readily available than prompt scrap and thus the use of clean iron units is expected to increase as shortages of prompt scrap continue to grow.
In addition to the residual elements contained in scrap, there are also several other undesirable components including oil, grease, paint coatings, zinc coatings, water, oxidized material and dirt. The lower the grade of scrap, the more likely it is to contain greater quantities of these materials. As a result this scrap may sell at a discount but the yield of liquid steel may be considerably lower than that obtained when using a higher grade scrap. In addition, these undesirable components may result in higher energy requirements and environmental problems. Thus the decision for the scrap mix to be used within a particular operation will depend frequently on several factors including availability, cost, yield, and the effect on operations (based on scrap density, oil and grease content, etc.). In practice, most operations buy several different kinds of scrap and blend them to yield the most desirable effects for the EAF operations.

### 2.4. Alternative Clean Iron Units

Table 2.5 shows the typical make-up of various alternative iron sources used in the EAF. It is important to recognize that the composition of the alternative iron source is critical in determining its value for use in the EAF. A detailed discussion on various types of alternative iron materials follows below.

**Table 2.5.** Typical composition of several types of alternative iron sources

<table>
<thead>
<tr>
<th>%</th>
<th>Midrex DRI</th>
<th>Hyl HBI</th>
<th>Iron Carbide</th>
<th>Pig Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fe</td>
<td>90 - 94</td>
<td>91 - 93</td>
<td>87</td>
<td>91.0 - 95.7</td>
</tr>
<tr>
<td>Metallic Fe</td>
<td>83 - 89</td>
<td>83 - 88</td>
<td>2.5</td>
<td>91.0 - 95.7</td>
</tr>
<tr>
<td>Fe₃C</td>
<td></td>
<td>69.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO/Fe₂O₄</td>
<td>6 - 14</td>
<td>6 –13</td>
<td>20.2</td>
<td></td>
</tr>
<tr>
<td>% Metallization</td>
<td>88 - 96</td>
<td>92 - 95</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Silica (SiO₂)</td>
<td>1.5 - 2.5</td>
<td>1.5 – 2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silican (Si)</td>
<td>0.4 - 1.5</td>
<td>0.4 – 1.5</td>
<td>1.5</td>
<td>0.3 - 3.0</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td></td>
<td></td>
<td>1.0</td>
<td>0.4 - 1.0</td>
</tr>
<tr>
<td>Mn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.02 - 0.09</td>
<td>0.02 – 0.05</td>
<td>0.033</td>
<td>0.08 - 0.5</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.005 - 0.03</td>
<td>0.002 - 0.02</td>
<td>&lt; 0.01</td>
<td>Max 0.04</td>
</tr>
<tr>
<td>CaO</td>
<td>1.5</td>
<td>0.3 – 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>0.45</td>
<td>0.5 – 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>1 - 2.5</td>
<td>1.2 – 2.2</td>
<td></td>
<td>3.5 - 4.5</td>
</tr>
</tbody>
</table>

#### 2.4.1 DRI/HBI

The following important factors should be considered when using DRI or HBI:
- % Metallization
- % Carbon in DRI (>1% preferred)
- % FeO (~ 1% C is required to balance out 6% FeO)
- DRI requires 100-200 additional kWh/ton to melt compared to scrap
- Up to 25% DRI can be added with the scrap – more can be added through the roof
• HBI is more dense than DRI. HBI sinks into the bath (melt similar to pig iron) and DRI floats at the slag/metal interface.
• HBI/DRI contain acid gangue components and the higher the gangue content the higher the lime/MgO addition requirements

The metallization of DRI/HBI is very important from the standpoint of melting cost and iron yield. The higher the % metallization, the greater the yield of metallic iron to the product.

\[
\% \text{Metallization} = \frac{\% \text{Fe Metallic}}{\% \text{Fe Total}} \times 100
\]

Metallization is a measure of efficiency of direct reduction – both the inherent efficiency of the process used and the efficiency by which the process is operated. Different processes have different upper limits of metallization that can be economically achieved. Typically steelmakers prefer a metallization of about 92% or higher. Any iron in the DRI/HBI that is not in the metallic form will be present as iron oxide and must be reduced in the bath to recover the iron units. This will require both energy input and a source of reductant, usually carbon. If there is sufficient carbon to balance the amount of FeO in the DRI, the total iron content can be recovered. Approximately 1 % carbon is required to balance out 6% FeO. However, in some cases only 50% of the non-metallic iron is recovered. The effect of metallization on energy requirements will be discussed in the detail in the melt-in section.

Gangue content in DRI/HBI is probably the reason cited most often for steelmakers reluctance to use the materials in the EAF. Gangue consists of both acidic and basic components. Acidic components are silica, alumina and TiO\(_2\) and originates from the ore and binders used in pelletizing. Basic components include CaO and MgO, which are normally added to the ore before/during reduction. The biggest concern with gangue materials is that they may require additional lime and doloma additions in order to maintain a specific target basicity in the slag. The additional flux additions consume energy within the steelmaking process. Furthermore, failure to the basic oxides or sufficient basic oxides could result in poor foaming and excessive refractory erosion.

Consider the following example:
41 tons of DRI is replacing 37 tons of scrap (0.2 %Si and 0.01% Al) on a 165 ton charge.
The DRI chemistry is the following: 90% Metallization, 1.6% SiO\(_2\), 1.3% Al\(_2\)O\(_3\), 1.5% CaO, 0.47% MgO.
In order to maintain a B\(_3\) basicity (CaO/[SiO\(_2\) +Al\(_2\)O\(_3\)]) of 2.0, an additional 2700 lb. lime (96% CaO) will be required.
Silica and alumina levels in the DRI are in large part dependent on the selection of iron ore for the process. Selection of appropriate iron ores is essential for acceptable quality DRI. For most gas based DRI processes, SiO\(_2\) levels 1-3% in the DRI are typical. Al\(_2\)O\(_3\) levels of 0.5 – 1.5 is also typical. However, for coal based DRI processes, SiO\(_2\) and Al\(_2\)O\(_3\) levels in the DRI tend to be much higher as the coal ash will also contribute acidic components to the final product. As a result, coal based DRI will tend to be developed in those areas with low scrap availability, no access to cheap natural gas and access to cheap coal. Table 2.6 gives a comparison of DRI/HBI metallization and compositions from different operations worldwide.
Table 2.6. DRI/HBI compositions for several facilities worldwide

<table>
<thead>
<tr>
<th>Process</th>
<th>Midrex</th>
<th>Midrex</th>
<th>Midrex</th>
<th>Midrex</th>
<th>Midrex</th>
<th>Hyll</th>
<th>HyllIII</th>
<th>Fior</th>
<th>Fastmet</th>
<th>Fastmet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot Fe</td>
<td>89.50</td>
<td>90.90</td>
<td>91.00</td>
<td>94.32</td>
<td>94.10</td>
<td>88.87</td>
<td>87.87</td>
<td>91.00</td>
<td>88.09</td>
<td>92.72</td>
</tr>
<tr>
<td>Fe met</td>
<td>85.74</td>
<td>85.47</td>
<td>83.72</td>
<td>88.36</td>
<td>88.00</td>
<td>78.68</td>
<td>79.04</td>
<td>82.81</td>
<td>83.69</td>
<td>88.08</td>
</tr>
<tr>
<td>%Metal</td>
<td>95.80</td>
<td>94.03</td>
<td>92.00</td>
<td>93.68</td>
<td>93.52</td>
<td>88.53</td>
<td>89.95</td>
<td>91.00</td>
<td>95.00</td>
<td>95.00</td>
</tr>
<tr>
<td>C</td>
<td>1.29</td>
<td>1.87</td>
<td>1.2</td>
<td>0.2</td>
<td>0.2</td>
<td>2.24</td>
<td>1.7</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>P</td>
<td>0.05</td>
<td>0.005</td>
<td>0.05</td>
<td>0.03</td>
<td>0.085</td>
<td>0.03</td>
<td>0.05</td>
<td>0.09</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>SiO₂</td>
<td>3.84</td>
<td>4.32</td>
<td>2.08</td>
<td>1.1</td>
<td>1.58</td>
<td>1.3</td>
<td>2.04</td>
<td>2.77</td>
<td>6.09</td>
<td>3.33</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.63</td>
<td>0.47</td>
<td>1.93</td>
<td>0.62</td>
<td>0.81</td>
<td>0.51</td>
<td>1.07</td>
<td>1.2</td>
<td>1.29</td>
<td>0.4</td>
</tr>
<tr>
<td>CaO</td>
<td>2.51</td>
<td>0.38</td>
<td>0.95</td>
<td>0.65</td>
<td>0.81</td>
<td>1.95</td>
<td>2.67</td>
<td>0.04</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td>MgO</td>
<td>0.06</td>
<td>0.27</td>
<td>0.41</td>
<td>0.33</td>
<td>0.53</td>
<td>1.16</td>
<td>0.4</td>
<td>0.84</td>
<td>0.85</td>
<td>0.71</td>
</tr>
<tr>
<td>FeO</td>
<td>4.9</td>
<td>7.07</td>
<td>9.48</td>
<td>7.77</td>
<td>7.94</td>
<td>13.28</td>
<td>11.51</td>
<td>10.67</td>
<td>5.74</td>
<td>6.04</td>
</tr>
<tr>
<td>Acid</td>
<td>4.5</td>
<td>4.8</td>
<td>4</td>
<td>1.7</td>
<td>2.4</td>
<td>1.8</td>
<td>3.1</td>
<td>4</td>
<td>7.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Basic</td>
<td>2.6</td>
<td>0.7</td>
<td>1.4</td>
<td>1</td>
<td>1.3</td>
<td>3.1</td>
<td>3.1</td>
<td>0.9</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td>kWh/tls</td>
<td>644</td>
<td>680</td>
<td>679</td>
<td>590</td>
<td>603</td>
<td>676</td>
<td>690</td>
<td>694</td>
<td>736</td>
<td>628</td>
</tr>
<tr>
<td>Company</td>
<td>Delta</td>
<td>OEMK</td>
<td>Ispat</td>
<td>Sabah</td>
<td>Opco</td>
<td>Krakatau</td>
<td>Hylsa</td>
<td>Fior</td>
<td>sub-but</td>
<td>pet-coke</td>
</tr>
<tr>
<td>Country</td>
<td>Nigeria</td>
<td>Russia</td>
<td>Trinidad</td>
<td>Malaysia</td>
<td>Venezuela</td>
<td>Indonesia</td>
<td>Mexico</td>
<td>Venezuela</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The carbon content of the DRI/HBI is receiving a lot attention at the present time. If excess carbon is present, it can be used as an energy source in conjunction with oxygen injection in order to reduce electrical power requirements. As mentioned previously, approximately 1% carbon is required in the DRI/HBI to offset every 6% FeO in the material. The following is a listing of the important factors regarding carbon in DRI/HBI:

- Carbon can be increased in natural gas base DRI processes up to 5%. However, these higher carbon DRI's increase the gas consumption of the reduction process and decrease the productivity of the process.
- The upper carbon limit is lower for HBI – below 2 percent.
- Some of this carbon is available as a fuel which can be combusted with oxygen in the arc furnace to reduce electrical energy requirements.
- However, as the carbon is increased it displaces other constituents. 2% more carbon will mean 2% less iron and the yield of iron recovered per unit charged will be lower.

Table 2.7 shows typical characteristics of DRI and HBI. Note that the bulk density of DRI is much higher than most scrap and the density of HBI is even higher. HBI is a modern charge material to be a substitute for, or used in combination with scrap. HBI is used as if it were a clean, consistent, sized, high quality ferrous scrap material. There are no special problems or hazards that are unique to HBI. It handles faster, easier, and takes less space than scrap. When wet the same precautions that would be taken charging wet scrap should be followed.
Table 2.7. Typical physical characteristics of DRI and HBI

<table>
<thead>
<tr>
<th></th>
<th>DRI</th>
<th>HBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Form</td>
<td>Pellets/lump</td>
<td>Briquette</td>
</tr>
<tr>
<td>Apparent Density (g/cm³)</td>
<td>3.5</td>
<td>5.0 – 5.5</td>
</tr>
<tr>
<td>Bulk Density (T/m)</td>
<td>1.6 – 1.9</td>
<td>2.4 – 2.8</td>
</tr>
<tr>
<td>Size (mm)</td>
<td>4 - 20</td>
<td>30 x 50 x 110</td>
</tr>
</tbody>
</table>

The gangue in the DRI/HBI may cause the material to become "gummy" as it approaches melting temperature which may cause sticking to cooler furnace areas such as water cooled panels if large concentrations are charged high and on the periphery of the charge. It is recommended that HBI be charged into the scrap bucket so that it mixes with other scrap.

2.4.2. Pig Iron and Hot metal

The world average use of pig iron (PI) in the EAF is approximately 5%. However, in some part of the world where scrap is scarce, pig iron may be used in quantities up to 60%. Typically, when using pig iron, furnace operators prefer small "pigs" which will melt in along with the scrap in the charge. Usually, a maximum of 20% cold pig iron is used in the EAF because it takes longer to melt in than scrap. If the pig iron consists of very large pieces, it will take longer to melt and may result in large swings in bath chemistry. The late melting of PI will significantly increase the carbon content of the steel and result in expectedly high tap-carbons. Some operations have witnessed large un-melted pieces of PI when tapping. Pig iron should be placed in the bottom half of the first bucket so that it will melt into the bath early in the heat. This allows for adequate decarburization time (thus avoiding the possibility of an extended tap-tap time), and allows for maximum recovery of energy from CO post-combustion to cold scrap in the furnace.

The high apparent density (S.G. = 3.3) of pig iron makes it quite suitable for bucket charging. However, granulated PI has the added advantage in that it can be charged continuously through the roof in a manner similar to DRI. This is beneficial in reducing power off times and maximizing furnace productivity.

Pig iron is another group of materials in which the chemical composition can vary quite considerably. As can be seen from Table 2.8, the silicon content can vary from as low as 0.3% up to 2.5 wt%. The manganese content is typically around 0.4% but can be as high as 1.0%. Carbon varies between 3.5 and 4.5 and is usually greater than 4% in most operations. This contrasts sharply with scrap which typically contains 0.1% silicon, 0.1-0.3% carbon and 0.3-0.6% manganese.

Table 2.8. Pig iron compositions

<table>
<thead>
<tr>
<th>Type</th>
<th>%C</th>
<th>%Si</th>
<th>%S</th>
<th>%P</th>
<th>%Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steelmaking PI</td>
<td>3.5-4.5</td>
<td>&lt;1.0</td>
<td>&lt;0.04</td>
<td>0.08-0.25</td>
<td>0.4-1.0</td>
</tr>
<tr>
<td>Foundry PI</td>
<td>3.6-4.1</td>
<td>2.0-2.5</td>
<td>&lt;0.04</td>
<td>0.5-0.7</td>
<td>0.6-0.9</td>
</tr>
<tr>
<td>Corex PI</td>
<td>4.3</td>
<td>0.3</td>
<td>0.04</td>
<td>0.09</td>
<td>0.1</td>
</tr>
<tr>
<td>Brazilian PI</td>
<td>4.1-4.4</td>
<td>0.3-0.4</td>
<td>0.003-0.015</td>
<td>0.07-0.11</td>
<td>0.10-0.50</td>
</tr>
<tr>
<td>Brazilian Foundry I</td>
<td>3.8-4.2</td>
<td>1.5-3.0</td>
<td>0.01</td>
<td>0.08-0.12</td>
<td>0.40-0.80</td>
</tr>
</tbody>
</table>
In the case of pig iron, a power savings could result from using 10-15% PI in the charge. This is due to the silicon, manganese, and carbon contained in the pig iron. These act as a source of chemical heat in the bath when oxygen is injected. Pig iron typically contains silicon which reacts with oxygen to produce SiO$_2$ which reports to the slag. This might require some additional lime addition in order to maintain the slag basicity. Table 2.9 shows the value of the silicon, manganese and carbon in the pig iron.

<table>
<thead>
<tr>
<th></th>
<th>wt%</th>
<th>Slag Kg</th>
<th>O$_2$ M$^3$</th>
<th>kWh</th>
<th>$$/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.1</td>
<td>11.5</td>
<td>0.80</td>
<td>4.81</td>
<td>0.083</td>
</tr>
<tr>
<td>Mn</td>
<td>0.1</td>
<td>1.8</td>
<td>0.20</td>
<td>1.57</td>
<td>0.050</td>
</tr>
<tr>
<td>C</td>
<td>0.1</td>
<td></td>
<td>0.93</td>
<td>1.81</td>
<td>0.025</td>
</tr>
</tbody>
</table>

**Assumptions:** Slag C/S ratio = 2.5, 25% FeO in slag, 10% MgO in slag. Cost accounts for lost iron units ($160/tonne) and oxygen ($0.05/cubic meter) requirements only. Energy contribution is net (i.e. after heating to 1600°C and melting additional flux requirements).

While the silicon in the pig iron generated the largest chemical energy contribution it also greatly increased the slag quantity in the furnace. For the same FeO content, a greater slag volume will result in higher iron yield losses (Shown in example later).

Hot metal production is a standard part of operations in integrated steelmaking. Hot metal is produced in the blast furnace from iron ore pellets. This hot metal is then refined in BOF's to produce steel. However, several integrated facilities have installed EAF's and are now charging hot metal to the EAF. The charging of hot metal to the EAF is quite complex because care must be taken that the charged hot metal does not react with the highly oxidized slag which is still in the EAF.

Some operations charge hot metal to the EAF by swinging the roof and pouring it into the furnace. This causes very rapid mixing of the hot heel and highly oxidized slag in the EAF with the hot metal and sometimes explosions occur. For this mode of operation it is recommended that a slag deoxidizer be added prior to hot metal addition. Typical de-oxidizers are silicon fines, aluminum tines and/or calcium carbide. An alternative method of charging the hot metal to the EAF is to pour it down a launder which is inserted into the side of the EAF. This method requires more time for charging of the hot metal but results in a much safer operation.

Paul Wurth has recently developed a side charging system whereby the hot metal can be charged while power is on. Charging time is not an issue for this system because hot metal addition is continuous throughout the heat. This provides several process benefits:

1. Bath chemical composition remains essentially constant because oxygen injection rate can be matched to the hot metal feed rate to oxidize carbon and silicon at the rate at which they are added to the furnace.
2. Control of silicon oxidation rate can be matched with dolo-lime addition to ensure that large excursions in slag chemistry do not occur.
3. CO generation rates are controlled and thus the off-gas treatment system sizing can be optimized.
4. Bath and slag chemistries are more consistent and thus a closer approach to equilibrium is achieved.
5. Short tap-to-tap times can be achieved due to the fact that decarburization can begin very early in the heat.

Hot metal provides benefits similar to pig iron with the added benefit that all material is already at a temperature of approximately 1430°C. Thus the major portion of the energy requirement in the EAF, (that required for melting the Fe) is already provided. Obviously there are limitations as to how much hot metal can be used in the EAF. Generally, the maximum oxygen injection rate will limit the amount of hot metal use if optimum tap-to-tap times are to be achieved. A study conducted by Paul Wurth indicates that the optimal proportion of hot metal in the EAF charge lies between 25 and 50%. Table 2.10, shows the value of silicon, manganese and carbon in the hot metal. Note that the energy supplied is somewhat greater than that for pig iron which reflects the additional sensible heat content. In addition one tonne of hot metal at 1430°C supplies approximately 250 kWh in the form of sensible heat, based on Fe content alone. For 100% scrap operation, the power consumption increases by 25 kWh/tonne liquid over the pig iron case. It can be seen that the use of both pig iron and hot metal are extremely beneficial to the EAF productivity and energy consumption.

<table>
<thead>
<tr>
<th></th>
<th>wt%</th>
<th>Slag Kg</th>
<th>O₂ M³</th>
<th>kWh</th>
<th>$/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.1</td>
<td>11.5</td>
<td>0.80</td>
<td>4.81</td>
<td>$0.083</td>
</tr>
<tr>
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<td>0.20</td>
<td>1.57</td>
<td>$0.050</td>
</tr>
<tr>
<td>C</td>
<td>0.1</td>
<td>0.93</td>
<td>0.93</td>
<td>1.81</td>
<td>$0.025</td>
</tr>
</tbody>
</table>

**Assumptions:** Slag C/S ratio = 2.5, 25% FeO in slag, 10% MgO in slag. Cost accounts for lost iron units ($160/tonne) and oxygen ($0.05/cubic meter) requirements only. Energy contribution is net (i.e. after heating to 1600°C and melting additional flux requirements).

### 2.4.3. Iron Carbide

Iron Carbide is a chemical compound consisting of 3 parts iron with one part carbon and having the chemical formula Fe₃C. Iron carbide is a relatively hard, brittle material which resemble coarse iron filings or black sand. Iron carbide has a melting point of 1800°C. Iron carbide can be charged into the furnace in sacks or can be injected. Injection is the preferred method of introducing the material into the bath as recovery is maximized. This however creates some practical limitations on the amount of iron carbide that can be used because limitations on the injection rate exist. At Nucor Crawfordsville, the maximum effective injection rate achieved so far is 5500 pounds per minute (i.e. higher rates have been attempted but have has negative effects on iron carbide recovery). Iron carbide dissolves into the steel bath and as the carbon goes into solution, it reacts with FeO or dissolved oxygen in the bath producing a very tine dispersion of carbon monoxide bubbles. Depending on the degree of reduction, some unreduced iron oxide will also be present, integral to the particles of iron carbide.

The solution of iron carbide into the bath is very rapid and as a result, CO gas evolution rates are very high. The rapid CO evolution in the bath is very beneficial because it helps to strip nitrogen.
from the bath. However, large concentration spikes of CO in the off gas are a problem for the off gas system.

Under the current operating conditions, iron carbide can only be added once a flat bath is achieved. This limits the iron carbide to a maximum of about 20-30% of the furnace charge due to injection rate limitations and decarburization considerations. Extending the injection period would impact negatively on furnace productivity. Ideally, it would be better if the iron carbide injection could be spread out over a longer period of time. Thus furnace designs such as CONSTEEL or twin shell furnaces maybe more appropriate for use of large quantities of iron carbide.

In terms of energy contribution, hot metal is the clear front-runner, but iron carbide ranks second and when compared to cold scrap shows that considerably less melting energy is required even for cold iron carbide. This is key to reducing the energy requirement in the EAF and minimizing the tap-to-tap time. Generally speaking, at the rates of use currently achieved (20 –30% of charge), an average energy reduction of approximately 55-90 kWh/tonne liquid steel can be achieved if the iron carbide is highly reduced with greater than 6 % carbon in the product. The only negative side to iron carbide is that the iron yield per tonne is relatively low due to the high carbon content. However previous trials indicated that all iron units in the iron carbide are recovered (i.e. those present as iron oxides and the iron present as carbide).

2.4.4. Combining Alternative Iron Feedstocks

Several steelmaking operations have begun to consider mixing alternative iron feedstocks in order to balance out some of the disadvantages associated with some feed materials. It has been recognized that charging hot metal reduces overall power requirements and also significantly reduces tap-to-tap time. On the other hand, DRI increases power requirements and extends tap-to-tap times. By combining these two materials in the charge it is possible to offset the detrimental energy consumption effects of DRI and achieve cycle times similar to or lower than conventional EAF scrap based operations.

It is important to note that though the oxygen requirement increases with the use of the alternative iron mixture in the furnace, the electrical power requirement remains constant indicating that the furnace tap-to-tap should not change as long as the operation is capable of supplying the oxygen. The slag volume increases considerably as the use of PI/HBI increases. This will increase melting costs and will also result in slightly lower iron yield. It is apparent from the fore-going discussion that alternative iron sources can be combined effectively to give high tonnage operations with short tap-to-tap times. This is especially important for operations producing flat products because typical casting speeds dictate a demand for short furnace cycle times and large heat sizes.

2.5. Carbon in Charge Mix

Carbon is important in EAF refining operations and can contribute a sizable quantity of the energy required in steelmaking operations. In electric furnace steelmaking, some carbon will be contained in the scrap feed, in DRI, HBI or other alternative iron furnace feeds. The amount of
carbon contained in these EAF feeds will generally be considerably lower than that contained in hot metal and typically, some additional carbon is charged to the EAF. In the past carbon was charged to the furnace to ensure that the melt-in carbon level was above that desired in the final product. As higher oxygen utilization has developed as standard EAF practice, more carbon is required in EAF operations as a fuel.

The reaction of carbon with oxygen within the bath to produce carbon monoxide results in a significant energy input to the process and has lead to substantial reductions in electrical power consumption in EAF operations. The generation of CO within the bath is also key to achieving low concentrations of dissolved gases (nitrogen and hydrogen) in the steel as these are flushed out with the carbon monoxide. In addition, oxide inclusions are flushed from the steel into the slag.

Typically a specific carbon level in the bath is targeted at melt-in and the charge mixture adjusted to achieve this value. Most EAF operations are aiming for a melt-in carbon level of approximately 0.2 to 0.4% C. A combination of different carbon containing raw materials such as different scrap mixtures, pig iron, and charge carbon are typically utilized to obtain the target carbon melt-in value. Failure to ensure adequate carbon levels in the steel at melt-in could result in "over-blowing" off the heat and significant yield losses.

2.5.1 Carbon in Pig iron and hot metal

The "recovery" of carbon from pig iron and hot metal into the bath is very high (>90%) and it is a very effective way to attain specific target carbon levels in the steel at melt-in. The carbon content of pig iron varies between 3.5 and 4.5 and is usually greater than 4% in most operations. This contrast sharply with scrap which contains 0.1 to 0.3% carbon.

2.5.2 Carbon in DRI and HBI

If excess carbon is present in the DRI it could be recovered in the bath. Approximately 1% carbon is required in the DRI to offset every 6% FeO in the DRI. MIDREX has carried out an extensive study with several of its' clients and has concluded that high carbon levels in the DRI are not beneficial to the EAF steelmaker. MIDREX found that increasing carbon levels up to 1.8 % aided in creating and sustaining a good foamy slag. However, above 1.8% carbon, there is no economic benefit, as the carbon does not supply any technical need. MIDREX claims that additional carbon requirements in the furnace are most economically achieved through the injection of carbon into the bath (at 80 % recovery). Production of high carbon DRI will negatively impact the productivity of the MIDREX reduction furnace and will displace iron units. Carburization potential is related to iron oxide type. If carburization is increased, the percent metalization will decrease unless the production rate is reduced. Typical carbon levels in MIDREX DRI range from 0.2 % to approximately 2 %.

HYL has presented a different view of carbon levels in DRI. HYL claims that high carbon levels can be very effective in supplying energy to the EAF. In the case of HYL DRI, it is claimed that 95 % of the carbon is present as iron carbide. HYL feel that their process is capable of achieving carbon levels ranging from 1.5 to 4.5 % in the DRI. At 1.5 % carbon, the iron carbide content
would be 25%. At 4.5% carbon, the iron carbide content in the DRI would be 55%. HYL have coupled high carbon DR1 production with hot charging of the DRI to the EAF. This may be related to the fact that at carbon levels above 2% in the DRI, the material becomes very difficult to briquette. Thus for the merchant DRI market, high carbon DRI might not be as readily available as conventional DRI. HYL indicates a cost saving of approximately $US 5 per tonne liquid steel for the case where DRI makes up 50% of the charge weight and is hot charged at 650°C with a carbon content of 4%.

2.5.3. Carbon added as Charge carbon

The addition of charge carbon with the scrap to achieve the target carbon levels in the bath is by far the most cost effective way to obtain the required carbon units. Unfortunately the recovery of carbon from charge carbon is not always consistent and can vary from 30 to 80% depending on the coal size and method of addition to the furnace. CO-Steel Raritan, who replaced the pig iron in their charge with low residual scrap and charge carbon, found that the sizing and quality of the charge carbon is very important to achieve good and consistent recoveries of carbon in the steel. After numerous trials it was found that charge carbon with the sizing of 3/4" x 5/16" gave the best results. The most significant issue in the improvement of the charge carbon practice was the control of the percent of fines in the material. There were two factors contributing to a high fine content: 1) Poor vendor quality control; and 2) pneumatic delivery piping system with numerous 90-degree bends. Vendors corrected the quality problem with pressure from the mill. The piping system was reconfigured to eliminate the 90-degree bends and minimize the 45-degree bends.

Typical charge carbon rates for medium carbon steel production lie in the range of 5 – 25 pounds per ton liquid steel. The amount of charge carbon used will be dependent on several factors including:

- Carbon content of scrap feed
- Projected oxygen consumption
- Desired tap carbon
- The economics of iron yield versus carbon cost

In general, the amount of charge carbon used will correspond to a carbon/oxygen balance, as the steelmaker will try to maximize his iron yield.

3. MELTING

3.1. Introduction

The melting period is the heart of EAF operations. The EAF has evolved into a highly efficient melting apparatus and modern designs are focused on maximizing the melting capacity of the EAF. Melting is accomplished by supplying energy to the furnace interior. This energy can be electrical or chemical. Electrical energy is supplied via the graphite electrodes and is usually the largest contributor in melting operations. Initially, an intermediate voltage tap is selected until the electrodes bore into the scrap. Usually, light scrap is placed on top of the charge to
accelerate bore-in. Approximately 15% of the scrap is melted during the initial bore-in period. After a few minutes, the electrodes will have penetrated the scrap sufficiently so that a long arc (high voltage) tap can be used without fear of radiation damage to the roof. The long arc maximizes the transfer of power to the scrap and a liquid pool of metal will form in the furnace hearth. At the start of melting the arc is erratic and unstable. Wide swings in current are observed accompanied by rapid movement of the electrodes. As the furnace atmosphere heats up the arc stabilizes and once the molten pool is formed, the arc becomes quite stable and the average power input increases.

Chemical energy can be supplied via several sources including oxy-fuel burners and oxygen lances. Oxy-fuel burners burn natural gas using oxygen or a blend of oxygen and air. Heat is transferred to the scrap by flame radiation and convection by the hot products of combustion. Heat is transferred within the scrap by conduction. Large pieces of scrap take longer to melt into the bath than smaller pieces. In some operations, oxygen is injected via a consumable pipe lance to "cut" the scrap. The oxygen reacts with the hot scrap and burns iron to produce intense heat for cutting the scrap. Once a molten pool of steel is generated in the furnace, oxygen can be lanced directly into the bath. This oxygen will react with several components in the bath including, aluminum, silicon, manganese, phosphorus, carbon and iron. All of these reactions are exothermic (i.e. they generate heat) and supply additional energy to aid in the melting of the scrap. The metallic oxides that are formed will end up in the slag. The reaction of oxygen with carbon in the bath produces carbon monoxide, which either burns in the furnace if there is sufficient oxygen, and/or is exhausted through the direct evacuation system where it is burned and conveyed to the pollution control system.

Once enough scrap has been melted to accommodate the second charge, the charging process is repeated. Once the final scrap charge is melted, the furnace sidewalls are exposed to intense radiation from the arc. As a result, the voltage must be reduced. Alternatively, creation of a foamy slag will allow the arc to be buried and will protect the furnace shell. In addition, a greater amount of energy will be retained in the slag and is transferred to the bath resulting in greater energy efficiency.

Once the final scrap charge is fully melted, flat bath conditions are reached. At this point, a bath temperature and sample will be taken. The analysis of the bath chemistry will allow the melter to determine the amount of oxygen to be blown during refining. At this point, the melter can also start to arrange for the bulk tap alloy additions to be made. These quantities are finalized after the refining period.

3.2 Chemical Reactions and Energy Requirements

The EAF requires heat for the melting and refining of steel. The main source of heat is electrical energy administered through the electrodes. The remainder of this heat is provided through chemical energy (chemical reactions). The heat balance of an EAF can be described by breaking the process down into those sub-processes that consume heat and those, which produce heat. If the sum of the heats provided by the process is added to the sum of the heats consumed by the furnace, there is a difference, which must be made up by electrical energy from the transformer.
The following processes consume heat in the EAF:

- Melting of the scrap, DRI, Fe₃C, pig iron, etc. and providing the superheat required for tapping
- Melting of slag materials and bringing them into the tap temperature
- Heat of the air drawn into the furnace through the slag door, spaces in shell, etc. by the bag house fans.
- Electrical losses
- Water cooled panel and ducts
- Radiation losses during opening and closing the roof.
- Flue gas sensible heat

The following processes provide heat in the EAF:

- Electrical energy
- Oxidation of C, Si, Mn, Fe, and other elements dissolved in the steel by lancing
- Electrode oxidation
- Charge carbon oxidation
- Slag formation reactions
- Burners
- Post-combustion (via air ingress or by injecting O₂)

### 3.2.1 Heating and melting of the metallic charge in the EAF (Scrap, DRI/HBI, pig iron & hot metal)

The principal reaction of melting in the EAF is:

\[ \text{Fe (in scrap, DRI...)} @ T_1 = \text{Fe (liq)} @ T_2 \]  

(3.1)

For most operations, \( T_1 = 25°C \) and \( T_2 \) between 1600 and 1650°C

The following equation can be used to calculate the heat required (enthalpy) to heat the iron from room temperature (25°C) to a temperature \( T \) where it is molten (Equation applicable in the range 1500° – 1700°C).

\[ \text{Energy (kWh/Kg Fe)} = (2.27 \times 10^{-4} \times T) + 0.0142 \]  

(3.2)

From this equation it can be calculated that the energy required to heat and melt 1 kg of pure Fe from 25°C to 1650°C (3002°F) is 0.389 kWh.

For 1 tonne of Fe (1000 kg) the energy requirement is: 389 kWh/tonne
For 1 ton of Fe (2000 lb) the energy requirement is: 353 kWh/ton
3.2.2. Energy from Chemical Reactions

Chemical energy in the EAF is derived by burning elements or compounds in an exothermic manner. Oxygen is reacted with carbon, hydrocarbon compounds, silicon, manganese, and iron. Sources that provide chemical energy include:

- Oxy-fuel burners
- Charge carbon
- Foaming Carbon
- Exothermic constituents in scrap
- Exothermic constituents in alternate iron sources

The latter two sources are of particular interest as they both can significantly influence the performance of the furnace. The reason is that the efficiency of the combustion of Si and Mn can be significant (90 – 100%), whereas, the efficiency realized from combustion of foamy coal is relatively low (30 to 50%).

The important exothermic reactions and the heats of reaction (\(\Delta H\)) are listed in Table 3.1.

### Table 3.1. Important EAF Reactions at 1650°C (3000°F)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>(\Delta H) (kWh/kg of first specie)</th>
<th>(\Delta H) (kWh/lb of first specie)</th>
<th>(\Delta H) (kWh/SCF oxygen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe + ½ (O_2)(g) = FeO</td>
<td>-1.275</td>
<td>-0.578</td>
<td>-0.167</td>
</tr>
<tr>
<td>Si + (O_2)(g) = SiO(_2)</td>
<td>-9.348</td>
<td>-4.240</td>
<td>-0.308</td>
</tr>
<tr>
<td>4Al + 3(O_2)(g) = 2Al(_2)O(_3)</td>
<td>-8.650</td>
<td>-3.924</td>
<td>-0.365</td>
</tr>
<tr>
<td>C + ½ (O_2)(g) = CO(g)</td>
<td>-2.739</td>
<td>-1.242</td>
<td>-0.077</td>
</tr>
<tr>
<td>CO(g) + ½ (O_2) = CO(_2)(g)</td>
<td>-2.763</td>
<td>-1.253</td>
<td>-0.182</td>
</tr>
<tr>
<td>C + (O_2)(g) = CO(_2)</td>
<td>-9.184</td>
<td>-4.166</td>
<td>-0.129</td>
</tr>
<tr>
<td>Mn + ½ (O_2)(g) = MnO</td>
<td>-2.044</td>
<td>-0.927</td>
<td>-0.264</td>
</tr>
<tr>
<td>H(_2)(g) + ½ (O_2)(g) = H(_2)O(g)</td>
<td>-34.614</td>
<td>-15.701</td>
<td>-0.164</td>
</tr>
<tr>
<td>CH(_4)(g) + 2(O_2)(g) = CO(_2)(g) + 2H(_2)O(g)</td>
<td>-13.994</td>
<td>-6.347</td>
<td>-0.132</td>
</tr>
</tbody>
</table>

The data in Table 3.1 is somewhat simplified since it excludes the enthalpy of fusion (endothermic) of the oxides and the enthalpy of solution (mixing) of the oxide in a slag phase (exothermic). However, some of these enthalpy effects almost cancel each other out so that the data can be used on a comparative basis. Table 3.1 clearly shows that Si, Al, Mn and C in the scrap can contribute a significant amount of chemical heat to the furnace. It is especially the elements Si and Al that have very high enthalpy values. Unfortunately, the oxidation of these two elements results in the acidic components SiO\(_2\) and Al\(_2\)O\(_3\) reporting to the slag. In order to maintain the basicity of the slag (CaO/[SiO\(_2\) + Al\(_2\)O\(_3\)]), increasing amounts of lime and dolomite will have to be added to the furnace, which, require more heat (endothermic).

Another very important source of chemical energy that does not increase the flux and slag amounts in the furnace very much, is carbon. From Table 3.1 it is clear that the combustion of carbon to CO is exothermic, and the complete combustion to CO\(_2\) even more exothermic. From
the stoichiometry of the following reactions, the minimum amount of oxygen required to react with the carbon can be determined (Table 3.2).

### Table 3.2. Amounts of oxygen required to combust carbon and CO gas

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Amount of specie reacting</th>
<th>Amount of O(_2) required (kg)</th>
<th>Amount of O(_2) required (SCF)</th>
<th>Amount of CO/CO(_2) formed</th>
</tr>
</thead>
<tbody>
<tr>
<td>C + ½ O(_2)(g) = CO(g)</td>
<td>1 Kg C</td>
<td>1.333 kg O(_2)</td>
<td>35.5</td>
<td>2.33 Kg CO</td>
</tr>
<tr>
<td>C + O(_2)(g) = CO(_2)(g)</td>
<td>1 Kg C</td>
<td>2.66 Kg O(_2)</td>
<td>70.8</td>
<td>3.66 kg CO(_2)</td>
</tr>
<tr>
<td>CO + ½ O(_2)(g) = CO(_2)(g)</td>
<td>1 Kg CO (g)</td>
<td>0.57 kg O(_2)</td>
<td>15.2</td>
<td>1.57 Kg CO(_2)</td>
</tr>
</tbody>
</table>

The following conversion factor was used: 1 Kg O\(_2\) = 26.632 SCF O\(_2\)

A large part of the attractiveness of the carbon is the fact that no detrimental slag materials are formed. However, it should be noted that high CO levels in the EAF offgas can greatly increase the required size of the offgas system and with these the overall cost of the gas treatment system. One approach is to apply a post combustion program in the EAF. Furthermore, at extremely high levels of carbon in the bath, the oxygen lancing system capacity may limit the decarburization capability and extended tap-to-tap times may result. In addition, prior to implementing high levels of carbon and oxygen use in the furnace, the furnace offgas system capabilities should be evaluated to ensure that they are sufficient for the modified operating practice. Regardless EAF operators are cautioned against raising carbon levels in the furnace above 2% due to the extended decarburization times that result.

If using high levels of carbon in the EAF, certain modifications must be made to the operating practices. Notably, oxygen injection must be spread out over the entire heat. Otherwise, the extremely high CO generation rates over a short period of time make it difficult to use post-combustion to recover a significant quantity of the energy generated. In addition, large peak flows of CO are detrimental to offgas system performance and much larger gas cooling requirements will be required.

In operations utilizing a large amount of charge carbon or high carbon feed materials, up to 60% of the energy contained in the offgas may be calorific due to large quantities of un-combusted carbon monoxide and Hydrogen. Recovery of all of this energy in the EAF could decrease energy input by 8 to 10%, though in reality, most attempts at recovering this energy have resulted in energy savings of 2 - 3%. Thus it is important to consider such factors when evaluating the energy balance for a given furnace operation.

In a previous section the various methods and efficiencies of adding carbon to the charge was discussed. However, a source of carbon and energy in EAF operations that is inherent in the process is the carbon from the electrodes. Electrode consumption rates range from 1.5 to 3 kg/t and could contribute 15 –25 kWh per ton of the total energy input into the furnace.

### 3.2.3. Energy from Burners

Oxy-fuel burners are now almost standard equipment on electric arc furnaces around the world. The first use of burners was for melting in many parts of scrap at the slag door where arc heating was fairly inefficient. As furnace power was increased, burners were installed to help melt at the
cold spots common to UHP operation. This resulted in more uniform melting and decreased the melting time necessary to reach a flat bath. It was quickly realized that productivity increases could be achieved by installing more burner power. Typical productivity increases reported in the literature have been in the range of 5 - 20%. In recent years oxy-fuel burners have been of greater interest due to the increase in the cost of electrodes and electricity. Thus natural gas potentially provides a cheaper source of energy for melting. The primary function of burners in a high-powered EAF is to ensure even scrap melting thus decreasing the potential of scrap cave-ins and broken electrodes.

The EAF has natural cold areas where the radiative heat of the arc has a lower efficiency. Typically, the cold areas of the AC furnace are situated between the phases (electrodes). For eccentric bottom tapping (EBT) furnaces, the area around the tap hole is usually difficult to heat as well. For this reason, sump burners are commonly being employed. The sump burner output is usually smaller than sidewall burners. For example, if a furnace is equipped with three 4 MW sidewall burners, the sump burner will typically have a power output of 2 MW.

Many furnaces also use a burner mounted to the slag door. The slag door burner is used to melt the scrap that falls in front of the door during charging. With a slag door burner, the scrap in front of the door is melted down quickly which provides access to the furnace for the oxygen lance. Decarburization can therefore begin earlier with a door burner, which is important for shops requiring short heat times. Furnaces that are not equipped with slag door burners are forced to wait until the scrap in front of the door gets hot enough that it can be cut away using the oxygen lance. This may mean waiting until late into the first bucket before the scrap is hot enough to cut using oxygen.

EAF oxy-fuel burners produce a high velocity flame that is pointed downward into the scrap. The high velocity enables the hot gases from the flame to penetrate the spaces between scrap pieces to heat the scrap by convection. This heat transfer takes place via three modes:

1. Forced convection from the combustion products to the scrap
2. Radiation from the combustion products to the scrap
3. Conduction from carbon or metal oxidation and from scrap to other scrap

Primarily heat transfer is via the first two modes except when the burners are run with excess oxygen. Heat transfer by convection and radiation is highly dependent on the temperature difference between the scrap and the flame and on the surface area of the scrap exposed for heat transfer. As a result oxy-fuel burners are most efficient at the start of a melt-in period when the scrap is cold. As scrap surface in contact with the flame decreases and due to the fact that the scrap temperature also increases. It is generally recommended that burners be discontinued after 50% of the meltdown period is completed so that reasonable efficiencies are achieved. An added complication is that once the scrap heats up it is possible for iron to react with the water formed by combustion to produce iron oxide and hydrogen. This results in yield loss and the hydrogen must be combusted downstream in the offgas system. Usually the point at which burner use should be discontinued is marked by a rise in offgas temperature (indicating that more heat is being retained in the offgas). In some operations the temperature of the furnace side panels adjacent to the burner is used to track burner efficiency. Once the efficiency drops below a set-point the burners are shut off. In most cases it is advantageous to maintain at least a low
burner-firing rate throughout the heat to prevent plugging of the burners by splashing metal and slag. It is also good practice to place the burners on high fire just before the bucket is dropped into the furnace to prevent metal and slag from splashing back onto the burners causing them to plug.

Typical industry practice indicates that 0.133 MW of burner rating should be supplied per ton of furnace capacity (Figure 3.1). Other references recommend a minimum of 32 kWh/ton of burner power to eliminate cold spots in a UHP furnace and 50 – 100 kWh/ton of burner power for low powered furnaces.

![Figure 3.1 Recommended Burner Power as a function furnace capacity](image)

Heat transfer efficiencies reported in the literature vary greatly in the range of 50 - 75 %. Burner efficiency as a function of operating time based on actual furnace offgas measurements has been determined. A typical efficiency curve is shown in Figure 3.2.

![Figure 3.2 Oxy-fuel burner efficiency as a function of operating time](image)
These trials show that burner efficiency drops off rapidly after 40 - 50 % of the melting time. By 60 % into the melting time burner efficiency has dropped off to below 30 %. It is apparent that a cumulative efficiency of 50-60 % is achieved over the first half of the meltdown period and drops off rapidly afterwards. As a result, typical operating practice for a 3 bucket charge is to run the burners for 2/3 of first meltdown, 1/2 of second meltdown and 1/3 of third meltdown. For operations with only one backcharge, burners are typically run for 50 % of each meltdown phase.

Many burner systems are now equipped with the ability to inject oxygen into the furnace. Typically burners will cycle between “burner mode” and “oxygen injection mode” throughout the meltdown cycle. In some cases this will result in instantaneous oxygen injection rates to the EAF in excess of 6000 cfm. This will result in rapid scrap meltdown but if sufficient carbon is not provided to recover the iron units, high yield loss will result. High FeO levels in the slag at meltdown may also impede slag foaming and result in excessive refractory wear. Similar conditions can arise during refining if burners are used to provide supersonic oxygen injection to the bath.

Most burners must be mounted high in the side-wall in order to minimize damage and plugging caused by slag and metal splashing. Typically, the furnace water-cooled shell extends 8 to 12 inches beyond the refractory furnace bottom. As a result, burners must be installed so that the flame does not impinge on the refractory because this would cause accelerated refractory erosion. Thus the lower in the furnace shell that the burner is installed, the shallower the angle of impingement on the bath must be in order to clear the refractory. The more shallow this angle is, the more difficult it becomes to achieve good bath penetration. Injectors installed higher in the furnace shell can achieve a better penetration angle but the gas momentum is much lower at the bath surface due to the greater distance that the gas jet must travel. The result is, that the slag will tend to become highly oxidized in the vicinity of the oxygen injector. Additional carbon should be injected in order to balance FeO generation and ensure that good slag foaming is achieved.

The amount of power input to the furnace has a small effect on the increase in heatload and offgas volume. The major factor is the rate at which the power is put into the furnace. Thus for a low powered furnace (high tap-to-tap time), the total burner input to the EAF may be in the range of 80 -100 kWh/Ton but the net effect on the offgas evacuation requirements may not change much because the burners are run for a long period of time. Likewise for a high-powered furnace, due to the short tap-to-tap time the burner input rate may be quite high even though the burners supply only 30 kWh/Ton to the furnace.

Recently, several vendors have developed stationary wall mounted lances that can deliver oxygen at supersonic rates to the molten bath. The motivation for using these lances in an EAF is as follows:

- Wall mounted lances allow decarburization to occur with the slag door closed. This reduces air ingress into the furnace.
- Injection is possible in several locations, which can speed up the decarburization process.
- Lower maintenance cost are recognized because there are fewer or no moving parts with the wall-mounted injector.
Significant savings in electrical energy from using wall-mounted lances can be realized by keeping the slag door closed during refining. Benefits will be less pronounced if significant amounts of carbon are used in the furnace. As more carbon and oxygen are injected into the furnace, less air is drawn into the furnace. Therefore, closing the door will have less benefit.

3.3. Oxygen Utilization in the EAF

Over the past 20 years oxygen lancing has become an integral part of EAF melting operations. It has been recognized in the past that productivity improvements in the open hearth furnace and in the BOF were possible through the use of oxygen to supply fuel for exothermic reactions. Whereas previously oxygen was used primarily only for decarburization in the EAF at levels of 96 – 250 SCF per ton in modern operations anywhere from 10 - 30 % of the total energy input is supplied via exothermic bath reactions.

Oxygen injection can provide a substantial power input - a lance rate of 2000 SCFM is equivalent to a power input of 12 MW based on the theoretical reaction heat from combustion of carbon to CO and associated bath reactions. Oxygen injection can be applied in two ways. Early in the heat, oxygen can be injected to cut the scrap, thus speeding up the meltdown process. Once a sufficient liquid pool is formed, oxygen is injected into the liquid steel where it reacts with carbon, silicon, aluminum and manganese.

In a typical steelmaking operation tens of thousands of SCF of pure oxygen are utilized to make a heat of steel. Ten of thousands of SCF oxygen that is drawn in by air also contribute to some of these reactions. However, pure oxygen is preferred over air and used in the EAF for three main reasons:

- It's high reactivity and high concentration of O₂ allows for rapid decarburization and greater utilization of the heat of reaction due to:
  1. Little or no nitrogen to absorb valuable heat.
  2. Oxygen does not introduce nitrogen into the steel. Nitrogen dissolved in the steel can harm the quality of most grades.
- Burners using pure oxygen with natural gas produce higher flame temperatures than air/natural gas burners. This enables higher energy transfer rates from the burner flame to the scrap. Productivity is improved with oxy-fuel burners.
- Post combustion using pure oxygen is more efficient than natural post combustion from the air drawn into the furnace. Nitrogen absorbs much of the heat of post combustion.

All three of the above points enable the operator to make high quality steel at a higher rate of production.

3.3.2. Scrap cutting operations

Scrap cutting operations are usually commenced once the scrap has been heated enough so that the oxygen jet will ignite when it impinges on the scrap. Many operations start scrap cutting oxygen too early and as a result, the oxygen is not used efficiently. As discussed previously, many burners are now equipped to alternate between a scrap heating mode and an oxygen
injection mode. If scrap is not sufficiently melted back, prior to starting scrap cutting, the oxygen jet can deflect back on the furnace side-wall causing damage. If the stream of oxygen penetrates well into the scrap, any heat generated through the oxidation of Fe to FeO will be radiated to the surrounding scrap and heat transfer efficiency will be close to 100%. If the oxygen cannot penetrate the scrap, heat will be radiated back to the furnace side-wall and much lower net heat transfer efficiency will result. If only part of the oxygen reacts with iron, the remainder will remove some heat as it leaves the furnace again reducing the net heat transfer. In actuality, all of these mechanisms occur resulting in varying degrees of efficiency in scrap cutting operations. When the furnace freeboard begins to open up, heat may also be radiated to the furnace roof resulting in damage to the delta. Therefore, scrap cutting operations should not proceed much more than 50% - 60% into meltdown operations. Additional carbon must be supplied to ensure that FeO generated during scrap cutting operations is recovered during refining.

3.3.2. Oxygen Injection

Oxygen lances can be of two forms. Water-cooled lances are generally used for decarburization though in some cases they are now used for scrap cutting as well. The conventional water-cooled lance was mounted on the furnace platform and penetrated into the side of the furnace through a cut-out in the water-cooled panel. Water-cooled lances are not intended to penetrate the steel bath though they sometimes penetrate into the slag layer. Consumable lances are designed to penetrate into the bath or the slag layer. They consist of consumable pipe which is adjusted as it burns away to give sufficient working length. The first consumable lances were operated manually through the slag door. Badische Stahl Engineering developed a robotic manipulator to automate the process. This manipulator is used to control two lances automatically. Various other manipulators have been developed recently and now have the capability to inject carbon and lime for slag foaming simultaneously with oxygen lancing. One major disadvantage of lancing through the slag door is that it can increase air infiltration into the furnace by 100 – 200%. This not only has a negative impact on furnace productivity but also increases offgas system evacuation requirements substantially. As a result, not all of the fume is captured and a significant amount escapes from the furnace to the shop. This can be even a more significant problem if substantial quantities of CO escape to the shop because this gas cools rapidly and as a result not all of the CO burns to CO\textsubscript{2}. Thus background levels of CO in the work environment may become an issue. To reduce the amount of air infiltration to the EAF, some operations insert the lance through the furnace side-wall.

Energy savings due to oxygen lancing arise from both exothermic reactions (oxidation of carbon and iron) and due to stirring of the bath with leads to temperature and composition homogeneity of the bath. The product of scrap cutting is liquid iron and iron oxide. From Table 3.4 it is apparent that much more energy is available if iron is “burned” to produce FeO. Naturally though, this will impact negatively on productivity. Studies have shown that the optimum use of oxygen for conventional lancing operations is in the range of 1000 – 1250 SCF/ton. Above this level yield losses are excessive and it is no longer economical to add oxygen. Typical operating results have given energy replacement values for oxygen in the range of 0.056 – 0.125 kWh/SCF oxygen, with an average of 0.1 kWh/SCF oxygen. These values show that it is likely that both carbon and iron are reacting. In addition some studies have shown that the oxygen yield (i.e. the
amount reacting with carbon) is in the range of 70 – 80 %. This would support the theory that both carbon and iron are reacting. During “scrap cutting” operations the oxygen reacts primarily with the iron. Later when a molten pool has formed the FeO is reduced out of the slag by carbon in the bath. Thus the net effect is to produce CO gas from the oxygen that is lanced.

Based on the information cited in the preceding section, it can be expected that for every SCF of oxygen lanced, 0.75 SCF will react with carbon to produce 1.5 SCF of CO (based on the average energy replacement value of 0.1 kWh/SCF oxygen). If in addition the stirring effect of the lancing brings bath carbon or injected carbon into contact with FeO in the slag, an even greater quantity of CO may result. That this occurs is supported by offgas chemical analysis data that indicates a decarburization efficiency of greater than 100 %. Thus during the decarburization period up to 2.5 SCF of CO may result for every SCF of oxygen injected. Typical oxygen lance rates are in the range of 1000 – 3500 SCFM per lance and are usually limited by the ability of the fourth hole system to evacuate the furnace fume. Recommended lance rates for various furnace sizes indicate a rate of approximately 25-30 SCFM/tonne of furnace capacity. In some newer processes where feed materials are very high in carbon content, an oxygen lance rate equivalent to 0.1 % decarburization per minute is required. In such cases the lance rate may be between 6000 and 10000 SCFM which is similar to BOF lance rates.

For bath carbon levels above 0.3 %, essentially all of the oxygen reacts to produce CO. Though FeO is produced locally at the point of injection, the FeO circulates within the furnace and reacts with carbon to form CO. Below 0.3 % carbon the efficiency of oxygen reacting to form CO drops off and more and more FeO is generated in the slag. For tap carbon levels below 0.1 % C, FeO levels in the slag can be quite high and represent an unavoidable yield loss. Increased carbon injection becomes necessary to control slag FeO levels prevent excessive refractory erosion.

The efficiency of heat transfer from oxidation reactions is extremely high due to the fact that the reactions are taking place in the bath. The only energy removed is the sensible heat in the CO leaving the bath. However, good bath penetration is necessary to ensure that the reactions are taking place in the steel. Bath penetration is a function the angle of gas impingement on the bath surface. If angle is too shallow, the oxygen will push back the slag cover and allowing more nitrogen in the steel. Slag splashing can cause damage to the furnace shell and may increase electrode wear. If the oxygen reacts on the steel surface, a large amount of the heat generated will radiate to the furnace shell and roof because the slag cover has been pushed back. This will result in low heat transfer efficiency to the steel as well as increased furnace wear and potentially higher heat loads to the offgas.

Too steep an injection angle can cause steel and slag to slop back onto the lance tip which ultimately will cause lance failure. Though the instantaneous heat transfer efficiency is not effected, the loss of oxygen lance operation will affect steelmaking efficiency once the lance fails.

The major drawback to high oxygen lance rates is the effect on fume system control. Offgas volumes are greatly increased and the amount of CO generated is much greater. This must be
taken into account when contemplating increased oxygen use. The following factors can also have an effect on lancing operations:

- The use of oxygen lancing throughout the heat can be achieved in operations using a hot heel in the furnace. Oxygen is lanced at a lower rate throughout the heat to foam the slag. This gives better shielding of the arc leading to better electrical efficiency. It also gives lower, more continuous flow rates of CO to the offgas leading to lower peak offgas rates. Thus reduces the extraction requirement of the offgas system.

- High generation rates of CO may necessitate a post-combustion chamber in the DES system. If substantial amounts of CO are not captured by the DES system, ambient levels in the work environment may not be acceptable. Typically up to 10% of the CO unburned in the furnace reports to the secondary fume capture system during meltdown.

- Operating with the slag door open increases the overall offgas evacuation requirements substantially. If possible oxygen lances should penetrate the furnace higher up in the shell. Another factor to consider is that the increased amount of nitrogen in the furnace will likely lead to increased NO\textsubscript{x}. Potentially the use of a furnace enclosure might become attractive for operations using high lance rates.

3.4. CO Post-Combustion

Generically, post-combustion refers to the burning of any partially combusted compounds. In EAF operations both CO and H\textsubscript{2} are present. A high degree of CO post-combustion corresponds high H\textsubscript{2} post-combustion. CO gas is produced in large quantities in the EAF both from oxygen lancing and slag foaming activities. Since it is not possible for CO to burn to CO\textsubscript{2} in the bath, CO will be the predominate gas in the freeboard during these operations. Large amounts of CO and H\textsubscript{2} are generated at the start of meltdown as oil, grease and other combustible materials evolve from the surface of the scrap. If there is sufficient oxygen present, these compounds will burn to completion. In most cases there is insufficient oxygen for complete combustion and high levels of CO result.

Earlier Table 3.1 showed that the heat of combustion of C to CO\textsubscript{2} is three times greater than the heat of combustion of C to CO. Thus this represents a very large potential energy source for the EAF. If the CO is burned in the furnace it is possible to recover heat within the steelmaking process, thus reducing the heatload that the offgas system must handle. Studies have shown that the potential energy saving is significant and could be a much as 80 kWh/tonne. Tests also showed that the offgas from the furnace could contain considerable amounts of non-combusted CO and that these occurred when there was insufficient oxygen present in the furnace freeboard.

3.4.1. Post-Combustion In Electric Arc Furnaces

Several trials have been run using post combustion (PC) in the EAF. In some of the current processes, oxygen is injected into the furnace above the slag to post-combust CO. Some processes involve injection of oxygen into the slag to post-combust the CO before it enters the furnace freeboard. Most of these trials were inspired by an offgas analysis which showed large
quantities of CO leaving the EAF. Combustion products directly contact the cold scrap. PC can also be carried out low in the furnace or in the slag itself. Heat transfer is accomplished via the circulation of slag and metal droplets within the slag. PC oxygen is introduced at very low velocities into the slag. Some other systems have incorporated bottom blown oxygen (via tuyeres in the furnace hearth) along with injection of oxygen low in the furnace. It is claimed that PC low in the furnace can give efficiencies averaging 4.5 kWh/ Nm$^3$ oxygen whereas PC high in the furnace gives only 3 kWh/ Nm$^3$ oxygen. The theoretical limit for PC of CO at bath temperatures (1600°C) is 5.8 kWh/Nm$^3$ of oxygen. Post-combustion in the slag typically aims at combustion of 20-30% of the CO generated. Post-combustion in the free-board aims at 80% combustion of the CO. Introduction of PC oxygen through burners was only 60% efficient.

For PC oxygen levels greater than 15 Nm$^3$/tonne, yield losses were excessive. In addition other methods of introducing the oxygen were attempted. Oxygen introduced through the delta increased productivity but increased electrode consumption by a factor of three. The usefulness of the heat generated by post-combustion will be highly dependent on the effective heat transfer to the steel scrap and the bath. Trials have shown that the increased heat load to the water cooled furnace panels was 6 – 7 kWh/tonne. Oxyfuel burner use can lead to yield losses and increased electrode consumption as some combustion products react with iron to form FeO. Trials run on the preheating of scrap with oxy-fuel burners showed that above scrap temperatures of 1400°F, 2-3% yield loss occurred. If additional carbon is not supplied a yield loss will occur. This is likely to be the case for PC. An iron yield loss of 1% equates to a power input of 13.2 kWh/tonne. This can have a significant effect on the overall PC heat balance resulting in a fictitiously high THE for PC. As Fe is oxidized to FeO, a protective layer can form on the scrap. Once the FeO layer is formed, oxygen must diffuse through the layer in order to react with the iron underneath. This will help to protect the scrap from further oxidation if this layer does not peel off exposing the iron. At temperatures above 2400°F the FeO will tend to melt and this protective layer will no longer exist.

3.5. The energy balance in the EAF

Many EAF operations have recently developed heat balances for their furnaces. These balances are based on the total energy inputs and outputs to the furnace over the whole tap-to-tap cycle. Analysis of such balances indicates that there are wide variations in energy requirements and in the efficiency of energy transfer in the EAF. The form of energy inputs vary widely and these will tend to have an effect on energy losses from the process.

To melt steel scrap, it takes a theoretical minimum of 300 kWh/ton. To provide superheat above the melting point of 2768°F requires additional energy and for typical tap temperature requirements, the total theoretical energy required usually lies in the range of 350 to 370 kWh/ton. However, EAF steelmaking is only 55 to 65% efficient and as a result the total equivalent energy input is usually in the range of 560 to 680 kWh/ton for most modern operations. This energy can be supplied from a variety of sources as shown in the table below. The energy distribution is highly dependent on local material and consumable costs and is unique to the specific meltshop operation. A typical balance for both older and more modern EAF’s is given in Table 3.3.
Table 3.4. Energy balance comparison of High power to medium and lower power furnaces

<table>
<thead>
<tr>
<th></th>
<th>UHP FURNACE</th>
<th>Low to Medium Power Furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Energy</td>
<td>50 - 60 %</td>
<td>75 - 85 %</td>
</tr>
<tr>
<td>Burners</td>
<td>5 - 10 %</td>
<td></td>
</tr>
<tr>
<td>Chemical Reactions</td>
<td>30 - 40 %</td>
<td>15 - 25 %</td>
</tr>
<tr>
<td><strong>TOTAL INPUT</strong></td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>OUTPUTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>55 - 60 %</td>
<td>50 - 55 %</td>
</tr>
<tr>
<td>Slag</td>
<td>8 - 10 %</td>
<td>8 - 12 %</td>
</tr>
<tr>
<td>Cooling Water</td>
<td>8 - 10 %</td>
<td>5 - 6 %</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>1 - 3 %</td>
<td>17 - 30 %</td>
</tr>
<tr>
<td>Offgas</td>
<td>17 - 28 %</td>
<td>7 - 10 %</td>
</tr>
</tbody>
</table>

The figures above are highly dependent on the individual operation and vary considerably from one facility to another. Factors such as raw material composition, power input rates and operating practices (e.g. post-combustion, scrap preheating) can greatly alter the above balance. In operations utilizing a large amount of charge carbon or high carbon feed materials, up to 60 % of the energy contained in the offgas may be calorific due to large quantities of un-combusted carbon monoxide. Recovery of this energy in the EAF could increase energy input by 8 to 10 %. Thus it is important to consider such factors when evaluating the energy balance for a given furnace operation. An example of such a balance is shown in Table 3.4.

Typical electrical energy input varies from 340 - 500 kWh per ton. The combustion of organic compounds associated with the scrap typically accounts for 40 - 80 kWh/ton. Electrode consumption accounts for 15 - 25 kWh per ton of the total energy input. The largest variations are for energy input related to oxygen injection and the amount of burner power input used. Oxygen/carbon reactions typically account for 100 - 250 kWh per ton of energy input. Burners account for an energy input of 25 - 80 kWh per ton. In the case of these latter two types of energy input, large gas volumes are generated and these will tend to remove energy from the EAF in the offgas stream. In the case of oxygen carbon reactions, CO is generated which if not burned in the EAF will contribute to much higher total offgas heat-load.

For the most part, the energy retained is approximately 350 - 380 kWh per in the steel ton, dependent on tap temperature. Energy retained in the slag varies from 30 - 50 kWh per ton and is dependent both on steel tap temperature and the amount of slag generated per ton of steel. Thus these energy requirements are pretty much set by steelmaking requirements.
Table 3.4. Energy balance in the EAF

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>kWh/ton</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Energy</td>
<td>410.9</td>
<td>62.7</td>
</tr>
<tr>
<td>Chemical Energy from bath reactions</td>
<td>73.3</td>
<td>11.2</td>
</tr>
<tr>
<td>Chemical energy from charge/injection carbon</td>
<td>25.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Chemical energy from electrode oxidation</td>
<td>7.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Post combustion energy</td>
<td>78.0</td>
<td>11.9</td>
</tr>
<tr>
<td>Energy from burners and lances</td>
<td>59.5</td>
<td>9.1</td>
</tr>
<tr>
<td>Total Energy Input</td>
<td>655.5</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUTPUTS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy to heat/melt the steel</td>
<td>366</td>
<td>55.8</td>
</tr>
<tr>
<td>Energy to heat/melt the slag</td>
<td>32.1</td>
<td>4.9</td>
</tr>
<tr>
<td>Energy to heat the air</td>
<td>78.8</td>
<td>12</td>
</tr>
<tr>
<td>Energy loss to off gas</td>
<td>53.6</td>
<td>8.2</td>
</tr>
<tr>
<td>Energy loss to cooling water</td>
<td>107.1</td>
<td>16.3</td>
</tr>
<tr>
<td>Miscellaneous energy losses</td>
<td>17.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Total Energy Output</td>
<td>655.5</td>
<td>100</td>
</tr>
</tbody>
</table>

The other energy outputs include losses to water cooled components at 60 - 100 kWh per ton, miscellaneous and electrical losses at 20 - 80 kWh per ton and losses to the offgas at 140 - 180 kWh per ton. All of these losses are related to the manner in which the furnace is operated and the efficiency of energy transfer to the steel in the furnace.

Electrical and miscellaneous losses are related to equipment properties and the number of furnace back-charges respectively (approximately 8 –10 kWh/ton for every scrap bucket charged). Thus miscellaneous losses can be reduced by using denser scrap or by reviewing charge bucket practices to reduce the number of back-charges. Losses to the water-cooled furnace components are a function of the rate of energy input and the efficiency of this energy transfer to the steel. Thus for a furnace with high power input rates, every effort must be made to ensure that high energy transfer efficiencies are achieved. Losses to the off gases are a major concern for two reasons. Firstly, these represent lost energy from the process, which could otherwise be put to use in scrap melting operations. Secondly, high offgas heat loads require more costly offgas system components to cool these gases before they are cleaned in the bag house. Losses to the system arise from two sources – calorific offgas heat and sensible heat. Sensible heat is the heat contained in the gases leaving the EAF based on gas temperatures. Thus if hot gases are unable to transfer heat to the scrap and the steel, the sensible heat load in the gases leaving the EAF will increase. Calorific heat is potential energy based on the ability of the furnace off gases to oxidize further resulting in a release of energy. Typically the gases that have high calorific heat content include hydrogen and carbon monoxide. However, vaporized or partially combusted organic compounds sometimes leave the furnace in the offgas and these too can contain a significant amount of calorific energy. It becomes apparent that the key to minimizing offgas heat-load is to ensure that high energy transfer efficiencies are achieved for any forms of energy input which result in additional offgas generation in the furnace. One attempt at ensuring better energy transfer efficiency has been to use offgas to heat scrap either
external to the EAF or part of an integrated furnace scrap pre-heat operation. This is not always a feasible solution for existing furnace operations and as a result a better method for monitoring energy efficiency in the EAF is required. If better heat transfer efficiency can be achieved in the EAF, less heat will be lost to the offgas. As a result, offgas system requirements will be reduced.

It is important that operators are made aware of heat transfer limitations for auxiliary energy inputs. For example, operation of individual burners above the 4 - 5 MW range, usually results in conditions where any additional energy input is difficult to transfer to the scrap. Elevated offgas temperature and damage to the furnace shell usually result. Oxygen injection rates through a single port nozzle are limited to the 2500 - 3000 SCF range for injection at a single location. Higher injection rates at a single point typically result in localized depletion of bath carbon and higher slag FeO levels. In some cases slag foaming is adversely affected.

A number of energy balance models are available to calculate the energy requirements in the EAF. Using a model to describe the contribution of chemical energy in the steelmaking process allows changes in the operation to be presented while all other conditions remain constant. Therefore, the effects of a single operational change can be estimated. In actual operation where production is the main priority, it is extremely difficult to control all parameters while varying only one parameter. Therefore, it is difficult to estimate process improvements unless lengthy trials are conducted where conditions remain constant enough to gather statistically significant results. A model can demonstrate these principles more easily.
4. REFINING IN THE ELECTRIC ARC FURNACE

4.1 Introduction

Refining operations in the electric arc furnace have traditionally involved the removal of phosphorus, sulfur, aluminum, silicon, manganese and carbon from the steel. In recent times, dissolved gases, especially hydrogen and nitrogen, have been recognized as a concern. The refining stage used to be more clearly separated from the Melting stage in the EAF process in older low powered furnaces with low oxygen injection usage. Scrap was first molten down to flat bath conditions and then oxygen was injected to lower the carbon content and the metal superheated during the refining stage. There was thus a true concept of melt-in carbon content and subsequent refining. In modern EAF operation, the melting and refining stage overlap more and oxygen injection is initiated early in the heat, for operations with a significant metal heel from very early during melting. While the discussion will be based on the concept of a particular melt-in condition, it is also valid for modern overlapping practices and can be viewed as the melting stage extending into the refining stage. As some scrap is still melting during the overlapping period, it can contribute carbon, silicon, aluminum and of course iron to the molten bath.

Most of the compounds which are to be removed during refining have a higher affinity for oxygen than the carbon. Thus the oxygen will preferentially react with these elements to form oxides which float out of the steel and into the slag. Control of the metallic constituents in the bath is important as it determines the properties of the final product. Usually, the melter will aim at lower levels in the bath than are specified for the final product. Oxygen reacts with aluminum, silicon and manganese to form metallic oxides, which are slag components. These metallics tend to react with oxygen before the carbon. They will also react with FeO resulting in a recovery of iron units to the bath.

For example consider the reaction between Mn and FeO:

\[ \text{Mn} + \text{FeO} = \text{MnO} + \text{Fe} \]  

(M4.1)

Manganese will typically be lowered to about 0.06 % in the bath.

The objectives of the EAF process and specifically the refining stage, can be summarized as

- Produce a metal of desired %C (P&S)
- At temperature (aim tap temperature)
- Low %FeO in slag - high yield
- From the available raw materials (scrap, DRI, Pig iron)
- At cost balance between electrical and chemical energy
- In a reasonable time (productivity)

These factors are interrelated to a large extent and others are a direct result of the balance between the parameters. An important aspect required to achieve these objectives is a good foaming slag as it affects all these aspects.
4.2. The C-O-CO equilibrium

The C-O-CO reaction is probably the most important reaction in steelmaking and controls the refining process, together with the balance of mass and concentrations. The equilibrium constant for the reaction is shown in equation (4.3):

\[
[C] + [O] = CO_{\text{g}} \quad (4.2)
\]

\[
K = \frac{p_{\text{CO}}}{a_{\text{C}} a_{\text{O}}} = \frac{X_{\text{CO}} p_{\text{total}}}{f_{\text{C}} [\%C] f_{\text{O}} [\%O]} \quad (4.3)
\]

This reaction will not be discussed in great detail at this stage and only a few comments are important. The total pressure \(p_{\text{total}}\) of the site where this reaction occurs affects the equilibrium, as does the fraction of CO in the gas phase \(X_{\text{CO}}\). This principle is used to lower the carbon content to very low levels in vacuum processes. The most important observation for this reaction is that for a fixed \(p_{\text{CO}}\) and temperature, the activity of oxygen and carbon are inversely related – that is if \(O\) increases, then \(C\) decreases. For the steelmaker, this implies that to achieve a low carbon content the activity of oxygen must be high. The activity of \(O\) in the metal depends on how much oxygen is added/injected into the metal and is also related to the activity of \(\text{FeO}\) in the slag – a high \(O\) content in the metal implies a high \(\%\text{FeO}\) in the slag. While this general relation is true, quantification of the numbers is more difficult and depend on the dynamics of the process. Different operational strategies can lead to different \(\%\text{FeO}\) in the slag for the same low \(\%C\) in the metal.

4.3. Dynamic equilibrium in the EAF

The basic processes occurring during refinement are related to oxidation reactions. The following reactions are of importance (also for Al and Si in solution):

\[
[C] + [O] = CO_{\text{g}} \quad (4.2)
\]

\[
\text{Fe} + [O] = (\text{FeO}) \quad (4.4)
\]

\[
[\text{Mn}] + [O] = (\text{MnO}) \quad (4.5)
\]

Consider the conceptual three phase equilibrium between metal, slag and gas. At equilibrium all these reactions are related and for a certain oxygen activity there is a certain equilibrium between \([C]\) in metal and partial pressure of CO gas, \(\text{Fe}\) and activity of \(\text{FeO}\) in solution in the slag and \([\text{Mn}]\) and \(\text{MnO}\) activity in the slag. With knowledge of the activity behaviour of the oxides in the slag, we can thus determine what the equilibrium composition of the metal, slag and gas are.

Unfortunately the equilibrium approach does not help us to describe the EAF operation, as it is rarely in equilibrium. The EAF is in a dynamic equilibrium or a combination of consideration of the equilibrium, the mass balance and rate of the reactions. As material is continuously added to the furnace (at the very least \(O_{2}\) and C injection) the process is dynamic in nature and cannot reach equilibrium, because the concentrations are continuously changed by outside influences.
The thermodynamics are still valid, but only useful to determine the limits of the process and driving force for certain reactions to occur.

The EAF is also very much non-uniform – gradients in composition and temperature exist. The conditions in different parts of the furnace are vastly different and thus the thermodynamic equilibrium relations are different in different parts. There is constant exchange of material between different areas of the furnace and composition is affected by reactions, as well as mass transfer and mixing of materials of different compositions. For example, the temperature variation from the arc to the front of melting scrap is huge. The oxygen potential varies from 100% O$_2$ in the jet to a few parts per million in the deep areas of the bath at high carbon content.

For these reasons it is very difficult to model the EAF and true dynamic models are few and far between, due to the complexity and large variations between different shops. It is more common to evaluate the EAF operation by an overall mass and energy balance, by considering the initial charge and total consumption of materials and final composition and mass produced. Only the initial conditions and final conditions are required to evaluate the process, regardless of how the compositions change with time. This is a very useful approach to compare different EAF operations, but is limited as the dynamic nature of the process is ignored. (A dynamic simulation of the EAF refining stage is currently being developed by the Process Technology Group of Baker Refractories. The aim is not to provide a complete model of the EAF, but to quantify and simulate relative changes in operational condition.)

On a micro scale certain areas of the furnace can be very close to equilibrium, but bulk compositions of metal and slag (as are sampled) can be very far removed. The correlation between %C in the metal at tap and %FeO in the slag has often been used as a description of the EAF, however, this is not a true, but rather a dynamic equilibrium and is influenced by operating conditions, see Figure 4.1.

Certain correlations will be closer to the theoretical equilibrium, mainly because a simpler mechanism is involved and an averaged condition closely describes the relation. An example is the relationship between dissolved C and O in the bath according to reaction (4.2). If the metal is well mixed the main variable is the total pressure in the bath – increasing with depth of metal. For pure CO gas in equilibrium, the product of [%C]*[%O] is higher deeper in the bath. Using 1.3 times atmospheric pressure as the average pressure in the bath, the relation becomes [%C]*[%O] = 0.025 and can be used as a good ‘rule of thumb’ for most EAF operations (Figure 4.1). This is of course for the bulk metal composition as sampled and the composition at the slag-metal interface can be vastly different as it is affected by the %FeO in the slag. For this reason the correlation of %FeO to %C is not consistent for different EAF operations, in fact being highly variable.
4.4. Decarburization

The reduction of the carbon content of the metal from melt-in or flat bath to the desired tap carbon is achieved by injection of oxygen. The equipment used to inject oxygen can range from a consumable lance, to water-cooled lance to coherent jet burners or injectors in the side-walls. The carbon content at flat bath will depend on the recovery of the various forms of carbon in the charge (C in scrap, pig iron or charge carbon). The decarburization reaction forms mainly carbon monoxide (CO), which escapes as gas bubbles through the slag. Carbon is thus removed effectively as it escapes the system and cannot be reverted from the slag like other species (e.g. Mn or Fe.)

Initially the rate of decarburization depends on the rate of oxygen injection and how this reacts with other elements and Fe. The rate at which carbon is transferred from the bulk metal to the decarburization reaction sites is rapid enough to avoid carbon depletion. As the bulk carbon content is lowered, however, the rate of supply to the reaction site reduces. The rate of carbon removal is now controlled by the rate of mass transfer, as the carbon concentration at the reaction site is lower. If the rate of oxygen supply remains constant, this implies that more Fe will be oxidized due to the depletion of carbon (all O₂ reacts). While the critical bulk %C at which this occurs depends on relative rates of oxygen supply and stirring in the metal, it is thought to be in
the order of 0.3%C. After this critical carbon content is reached little is gained by increasing oxygen injection rate, as it first results in increased Fe oxidation to FeO. The rate of carbon removal also decreases as the carbon content of the bulk decreased. The rate of change in %C with time can be expressed according to:

\[
\frac{d\%C}{dt} = \frac{m_C \times (%C_{\text{bath}} - %C_{\text{equil}})}{h}
\]  

(4.6)

Where \(m_C\) is the mass transfer coefficient that is determined by diffusion and mixing of the bath and \(h\) is a dimension related to the depth of the metal bath. The rate at any time is proportional to the difference between the current \(%C_{\text{bath}}\) in the bulk and the equilibrium \%C as determined by the oxygen activity (O in bath or \%FeO in slag). The principle is demonstrated by the result of the EAF Refining Simulation for constant oxygen injection rate in Figure 4.2. For the base case the rate of decarburization starts decreasing at around 0.2%C and the \%FeO in the slag increases dramatically.

![Simulation of the effect of C injection increase on the %FeO over time](image)

In the mass transfer controlled region, the oxygen injection is not controlling the decarburization and excess oxygen only results in increased oxidation of FeO and loss of yield. It follows that the oxygen injection can be reduced to decrease the excess oxygen and decrease FeO formation,
while maintaining de-C rate. The oxygen injection and de-C or “carbon boil” strongly influence the stirring in the metal and thus the mass transfer coefficient ($m_C$). The relative magnitude of the effect of reducing oxygen injection on the resulting mass transfer rate will determine to what extent it affects the de-C rate. Alternatively, the excess O can be compensated for by increased injection of C (foamy carbon). This should maintain the stirring effect of the impinging oxygen jet, while providing more carbon in the slag to balance the increased FeO formation. This concept of balancing the O and C supply to the bath is considered a very important aspect of EAF operation. The effect is demonstrated in Figure 4.2 where the injection of C from the 5th minute (60 lb/min) and increasing it at the 11th minute (90 lb/min) prevents the increase in FeO content by balancing with the excess oxygen.

4.5. Slag foaming

It is important to maintain the foaming slag throughout refining period to ensure efficient electrical energy input and protect the side-walls and roof from intense heat of the arc. Figures 4.3. and 4.4 demonstrate the benefits of achieving good slag foaming in terms of stability of power supply and for minimization of heat losses to the furnace shell.

![Figure 4.3 Effect of foamy slag on heat losses](image)
The foam height depends primarily on the slag volume, composition and rate of gas evolution. Maintaining the foam requires control over the slag composition and continued production of CO gas. The main change in slag composition during refine is a change in FeO (&MnO) content. At melt-in or flat bath, the fluxes are all dissolved in the slag and the Si and Al is already oxidized to the oxides in the slag. By controlling the FeO content of the slag, the foaming properties of the slag are thus controlled. The composition of the slag at melt-in must of course first be good for foaming.

The generation of gas is two fold – both from the decarburization of the metal bath and due to reaction of injected carbon and FeO in the slag. It is believed that bubbles generated from the decarburization reaction in the metal are fine and well dispersed, which is ideal for foaming. The bubbles formed by reaction of FeO and injected C in the slag on the other hand are not as effective in foaming the slag, but nevertheless important. As the carbon content of the bath is continually reduced during refine, the evolution of gas from the bath also declines and the bubbles generated in the slag become more important to maintain foaming.
In the mass transfer controlled region of decarb urization, not only does the gas evolution from the metal decline, but the FeO content of the slag can also increase. This increase in FeO content will lead to a more fluid slag and the potential decrease in foam stability by decreasing slag viscosity (severity will depend on conditions on ISD). In addition the temperature usually increases during refine – super heating from relatively scrap melting temperature to tap temperature. This temperature increase also results in more fluid slag and less stable foaming slag. Here, the principles of balancing the oxygen and carbon injection also find application. By matching the carbon injection to the excess oxygen and thus FeO generation, the FeO content is maintained and gas generation increased. The reduction of FeO by injected C is thus important to maintain the foaming slag, both by controlling slag composition and generating the required gas bubbles.

### 4.6. Injection carbon efficiency

The efficiency of the injected carbon can depend on a number of operational parameters. The ideal case is when all the carbon injected reacts with O or FeO and none is lost to the freeboard to react with gases and be extracted with the off gas. The injection position can thus be important, it should be injected into the slag and not high in the furnace. (This is also important for other injection materials like lime – it of no use if it just reports in the bag-house dust). Injection deep into the slag should also improve efficiency as it increases the residence time in the slag and thus potential for reaction. Remember that due to its lower density, the natural tendency of carbon is to float on top of the slag – where it is not efficient and reacts with free board gases or floats out with tapped slag. For the same reason a good foaming slag is important as it increases the time for reaction. If the foam is lost at any stage it is very difficult to foam again by injection carbon alone. Injection closer to the oxygen jet or intentionally on the same line of flight to allow the oxygen to draw it into the slag would improve penetration. In the last case, however, direct combustion of the carbon with the injected oxygen can significantly alter its effectiveness. This is not necessarily detrimental, but the decarb urisation mechanism and efficiency can be affected.

Last but not least, the quality and sizing of the injected material is important. Too fine particles do not have enough momentum to penetrate the slag and are easier to loose to the off gas. Quality, in terms of fixed carbon or char content, volatile content and ash content are also important. Coke or graphite are mostly fixed carbon and thus preferred, however, reactivity of the carbon can be lower. For coal (anthracite) high fixed carbon (FC) and low ash is preferred, as FC is the effective reacting specie and coal ash is acidic and will affect the slag basicity and thus foaming properties. It is not sure how high volatile content will affect the performance. It is also possible to inject alternative materials to control FeO content and produce gas bubbles. One such example is CaC$_2$ (calcium carbide), which forms CaO and CO by reaction with 3 units of FeO. It does not have a benefit over C when evaluated by mass (52 lb of CaC$_2$ can reduce as much FeO as 36 lb of C), but because of higher density it can have an advantage when volume restrictions apply (size of delivery bunkers). Also it is a potentially a more hazardous material than carbon to handle. Another possible alternative material would be FeSi, but the acidic oxide (SiO$_2$) will again affect the foaming properties of the slag, on a mass basis worse than the ash in coal.
4.7. Behaviour of other elements (Mn, P, Si)

4.7.1. Introduction
Phosphorus and sulfur occur normally in the furnace charge in higher concentrations than are generally permitted in steel and must be removed. Unfortunately the conditions favorable for removing phosphorus are the opposite of those promoting the removal of sulfur. Therefore once these materials are pushed into the slag phase they may revert back into the steel.

Phosphorus retention in the slag is a function of the bath temperature, the slag basicity and FeO levels in the slag. At higher temperature or low FeO levels, the phosphorus will revert from the slag back into the bath. Phosphorus removal is usually carried out as early as possible in the heat. Hot heel practice is very beneficial for phosphorus removal because oxygen can be lanced into the bath while its temperature is quite low. Early in the heat the slag will contain high FeO levels carried over from the previous heat thus aiding in phosphorus removal. High slag basicity (i.e. high lime content) is also beneficial for phosphorus removal but care must be taken not to saturate the slag with lime. This will lead to an increase in slag viscosity, which will make the slag less effective. Sometimes fluorspar is added to help fluidize the slag. Stirring the bath with inert gas is also beneficial because it renews the slag/metal interface thus improving the reaction kinetics.

In general, if low phosphorus levels are a requirement for a particular steel grade, the scrap is selected to give a low level at melt-in. The partition of phosphorus in the slag to phosphorus in the bath ranges from 5 to 15. Usually the phosphorus is reduced by 20 to 50% in the EAF.

Sulfur is removed mainly as a sulfide dissolved in the slag. The sulfur partition between the slag and metal is dependent on slag chemistry and is favored at low steel oxidation levels. Removal of sulfur in the EAF is difficult especially given modern practices where the oxidation level of the bath is quite high. Generally the partition ratio is between 3 and 5 for EAF operations. Most operations find it more effective to carry out desulfurization during the reducing phase of steelmaking. This means that desulfurization is performed during tapping (where a calcium aluminate slag is built) and during ladle furnace operations. For reducing conditions where the bath has a much lower oxygen activity, distribution ratios for sulfur of between 20 and 100 can be achieved.

4.7.2. Mn distribution
The final distribution of Mn between the metal and the slag depends on the relative importance or rates of the oxidation and reduction reactions. The basic reaction is:

\[ [\text{Mn}] + [\text{O}] = (\text{MnO}) \]  \hspace{1cm} (4.7)

In different parts of the furnace, the reigning oxygen potential and activity of MnO in the slag will determine at what rate and to what extent the Mn is either oxidised or reduced. The final Mn content is thus determined by the equilibrium, kinetic and mass balance parameters in the furnace. The behavior of Mn is expected to be similar to that of Fe. Thus the Mn distribution ratio (\%MnO in slag / \%Mn in metal) will increase with increasing oxygen potential or \%FeO in the slag and decreasing \%C in the metal. The total mass of Mn in the slag-metal system (total in charged materials) and final slag to metal ratio will the final \%Mn in the metal. Improvement of the Mn distribution, that is more Mn in the metal and less in the slag, can result in significant savings as less ferromanganese would be required to reach the metal specification of \%Mn.
4.7.2. Phosphorous distribution

The removal of phosphorous from the metal to the slag is an important function of the EAF as primary steelmaking process. This is because phosphorous can be removed under oxidizing conditions and not in subsequent secondary metallurgy processes like ladle refining, for which the conditions are reducing. The equilibrium reaction is shown below, where $O^{2-}$ represents the oxygen ion in a basic slag (from CaO and MgO).

$$[P] + \frac{5}{2}[O] + \frac{3}{2}(O^{2-}) = (PO_4^{3-})$$  \hspace{1cm} (4.8)

The phosphorous distribution ratio is increased by a basic slag and oxidising conditions as represented by $[%O]$. The term $k_{PO}$ is a measure of the phosphorous capacity of the slag and increases with ($%CaO + 0.3%MgO$) and CaO is more effective than MgO. Turkdogan evaluated the results of a number of studies and derived the following equation to describe the effects of temperature and slag composition on the phosphate capacity of steelmaking type slags.

$$\log k_{PO} = \frac{21740}{T} - 9.87 + 0.071*BO$$  \hspace{1cm} (4.10)

where

$$BO = %CaO + %CaF_2 + %MgO$$

The $k_{PO}$ values at 1600°C of widely different slags are plotted in Figure 4.6.

![Figure 4.6. Diagram showing the effect of "basicity" on phosphate capacity](image)
The effect of temperature is the result of two opposing effects. Lower temperature is beneficial for the phosphorous reaction, but also decreases the lime solubility in the slag (Figure 4.7).

Figure 4.7. The effect of temperature on phosphate capacity

Phosphorous is one of the potential limiting factors for operation of an EAF at very low FeO levels in the slag. If FeO levels in the slag are low to improve yield, the phosphorous removal will decrease and the final phosphorous content of the metal might exceed specifications. The range of slag basicities required to obtain a good foaming slag is also lower at lower FeO content (see ISD’s) and will also be detrimental to P removal. Just like for Mn, the total P load in the charge materials, distribution ratio and slag to metal ratio will determine the final %P in the metal. Because of the lower concentration of P (relative to Mn) in the slag and especially the metal, it also possible that kinetic limitations play an important role and that P removal can become mass transfer controlled similar to C. Equilibrium is thus not necessarily achieved in the EAF and transient effects of intermediate periods of higher oxygen potential might be beneficial for removal of P.
4.7.3. Sulfur distribution

As sulfur removal is more effective under reducing conditions, like in the blast furnace hot metal or during secondary metallurgy in the ladle, the EAF is not ideal for S removal. Distribution ratios (%S)/[%S] are in the range of 2 to 5, compared to 50 to over 1000 in the ladle. The relatively large slag volume in the EAF is an advantage however and some sulfur can be removed. Slag basicity is probably the most important factor affecting S removal in the EAF, but S should not be used as a criterion to choose slag operating regimes as the benefit is very small compared to the impact on the rest of the process (foaming, yield etc.). The sulfur load in the charge materials is important to consider, especially as carbon sources can contain a lot of sulfur. Figure 4.8 shows the effect of the SiO$_2$ and P$_2$O$_5$ content of the slag on sulfur removal ($k_{SO}$)

![Figure 4.8. The effect of slag composition on sulfur removal in steelmaking slags](image)

4.8. Removal N$_2$ and H$_2$ in the EAF

The reaction of carbon with oxygen in the bath to produce CO is important as it supplies a less expensive form of energy to the bath, and performs several important refining reactions. In modern EAF operations, the combination of oxygen with carbon can supply between 30 and 40 % of the net heat input to the furnace. Evolution of carbon monoxide is very important for slag foaming. Coupled with a basic slag, CO bubbles are tapped in the slag causing it to "foam" and helping to bury the arc. This gives greatly improved thermal efficiency and allows the furnace to operate at high arc voltages even after a flat bath has been achieved. Burying the arc also helps to prevent nitrogen from being exposed to the arc where it can dissociate and enter into the steel.
If the CO is evolved within the steel bath, it helps to strip nitrogen and hydrogen from the steel. Nitrogen levels in steel as low as 50 ppm can be achieved in the furnace prior to tap. Bottom tapping is beneficial for maintaining low nitrogen levels because tapping is fast and a tight tap stream is maintained. High oxygen potential in the steel is beneficial for low nitrogen levels and the heat should be tapped open as opposed to blocking the heat.

The nitrogen content of steels produced in the EAF is generally higher than in oxygen steelmaking primarily because there is considerably less CO evolution, which removes nitrogen from the steel. The usual methods of controlling nitrogen are by carbon oxidation and the use of DRI/HBI or pig iron. Nitrogen removal decreases once the carbon content falls below approximately 0.3%C, as most of the oxygen is then reacting with Fe and is therefore not producing CO. Starting with a higher initial carbon allows for more CO evolution and reduces the activity of oxygen, which retards the rate of the nitrogen reaction. The effect meltdown carbon on nitrogen removal is shown in Figure 4.9.

![Figure 4.9. Change in bulk nitrogen concentrations during EAF steelmaking](image)

The other method of reducing nitrogen is the use of DRI or HBI. These materials reduce nitrogen primarily through dilution. The nitrogen removal using 25% and 50% DRI/HBI is shown in Figure 4.10.
Figure 4.10. Effect of DRI on nitrogen content during EAF steelmaking

At 1600°C, the maximum solubility of nitrogen in pure iron is 450 ppm. Typically, the nitrogen levels in the steel following tapping are 80 - 100 ppm.

Decarburization is also beneficial for the removal of hydrogen. It has been demonstrated that decarburizing at a rate of 1 % per hour can lower hydrogen levels in the steel from 8 ppm down to 2 ppm in 10 minutes.
FOAMING IN THE EAF

1. Introduction to foaming

In recent years, better refractory performance has been achieved by utilizing slag engineering principles. The most widely documented improvement has been the effect of slag splashing in the BOF. In a similar fashion, slag foaming in the electric arc furnace (EAF) has not only lowered refractory and electrode consumption, but has also had a significant impact on improving thermal efficiency and decreasing melting time. Unfortunately, maintaining a predictable and consistent foamy slag for every heat has eluded many steelmakers for a long time. Often times adequate slag foaming occurs at the beginning of refining, but then decreases towards the end of the heat. This variability in foaming behavior has “forced” many steelmakers to melt to a “generic” low-C heat for every grade of steel, regardless of final carbon specifications. The loss in iron yield that results from this practice is somewhat offset by a more predictable arc-furnace foaming practice and melt down time.

The process of slag foaming can be simply stated as: Reactions that generate gas bubbles are required along with the proper slag to sustain these bubbles. The goal of this section is to define the conditions required to obtain and control optimum foamy slags in the electric furnace (finding the proper slag).

2. Slag Viscosity and Surface Tension

Previous research has shown that foaming characteristics improve with decreasing surface tension and increasing viscosity of the slag. However, it was also shown that the presence of suspended second phase particles in the slag had a much greater impact on foaming than surface tension and slag viscosity. In laymen’s terms, the slags that achieve the best foaming properties have a consistency (fluidity) that falls between "creamy" and "fluffy", with "watery" and "crusty" on the extreme ends of the spectrum. This means that these "optimum" slags are not completely liquid ("watery") but are saturated with respect to CaO (Ca$_2$SiO$_4$) and/or MgO (Magnesia - wustite solid solution). These second phase particles serve as gas nucleation sites, which lead to a high amount of favorable small gas bubbles in the foaming slag.

The term effective viscosity was defined to relate the amount of second phase particles in the slag and viscosity as follows:

\[ \eta_e = \eta (1 - 1.35 \Theta)^{5/2} \]  

where

- $\eta_e$ - effective viscosity of the slag
- $\eta$ - viscosity of the molten slag
- $\Theta$ - fraction of precipitated solid phases

Figure 1 shows the relationship between the foaming index ($\Sigma^*$) and the relative effective viscosity. As the relative effective viscosity is increased, the residence time of the gas bubbles in the slag is prolonged, extending the stability and subsequently the life of the foam. However, as indicated in Figure 1, there is a maximum amount of second-phase particles that is beneficial for

* The foaming index ($\Sigma$) is a parameter that relates the gas flow rate, foam height, and the foam life.
foam stability (optimum slag). Once this point is exceeded the slag becomes too "crusty" (oversaturated) and the foaming index decreases.

![Graph showing the relationship between foaming index and effective viscosity.](image)

**Figure 1.** The Relationship between the Foaming Index and Effective Viscosity.

### 3. Slag composition and slag basicity

With respect to slags, consideration must be given to the desired components. Since most electric furnace slagline refractories are basic, then MgO and/or CaO saturation is required to minimize chemical attack of the refractories. Additionally, saturation of the slag with these oxides (the presence of second phase particles) is an essential requirement for good foaming. Therefore, based on required foaming properties and the desire to protect the refractories, dual saturation (CaO and MgO), or at least MgO saturation would be required.

The "secret" to slag engineering for the EAF is therefore to achieve a balance between the refractory oxides and fluxing oxides. This balance will ultimately yield slags that are both compatible with basic refractories and capable of attaining the desired foaming requirements. The complexity in achieving this balance is that the fluxing oxides are not equal in “strength” and will have different effects on the solubility of CaO and MgO in the slag. For example, replacing the SiO$_2$ with Al$_2$O$_3$ in the slag increases the solubility of CaO but decreases the solubility of MgO. Increasing the FeO content in the slag results in decreased MgO solubility, but has little affect on the CaO solubility.

In this paper the B$_3$ ratio is used to express the solubility of MgO in the slag and the phase compositions of the slag.
4. Gas Generation

In the previous section, the importance of slag properties on foaming behavior was discussed. The second essential factor for foaming is gas generation (bubbles) and the sustaining of these gas bubbles in the slag. The predominant species in the gas phase is CO, with smaller amounts of CO$_2$ present.

The CO$_2$ is usually formed from the calcination of residual carbonate in the lime or dolomite that is added to the furnace. Since the calcination reaction is endothermic, unburned limestone or dolomitic stone is rarely used as a bulk addition in the furnace. However, towards the end of the heat, small additions of raw stone can be beneficial as will be discussed later in this paper.

The CO is generally produced according to the following two chemical reactions:

\[ C \text{ (in the bath or injection)} + \frac{1}{2} O_2 \text{ (g)} = CO \text{ (g)} \]  

(3)

\[ \text{FeO} + C = \text{Fe} + \text{CO (g)} \]  

(4)

The CO generated at the liquid bath level is generally more conducive to good slag foaming than CO formed in the slag itself. This is because the CO coming from the bath consists of small bubbles that are almost uniformly distributed.

The injection of oxygen alone (without carbon) gives poor slag foaming despite good gas presence. This is due to the temperature increase and the FeO generated from the following exothermic reactions, which dramatically decreases the viscosity of the slag:

\[ C + \frac{1}{2} O_2 \text{ (g)} = CO \]  

(5)

\[ \text{Fe} + \frac{1}{2} O_2 \text{ (g)} = \text{FeO} \]  

(6)

From the above, it is clear that controlling the FeO content of the slag is a key factor to predictable foaming behavior. FeO is the major fluxing component in the slag and strongly influences the effective viscosity and hence the foaming properties of the slag. The amount of FeO that will form is essentially a race (competition) between the rate of FeO generated due to oxygen injection (reaction (6)), and the rate of FeO reduced by the injected carbon (reaction (4)). If the injected oxygen is balanced by a sufficient amount of carbon injection, and the slag is foaming well, the FeO content in the slag will stay fairly constant. However, if the fluidity of the slag increases due to either an increase in temperature or FeO content, a decrease in the foaming height could result. In this case, the effectiveness of FeO reduction by carbon is diminished because the retention time of the carbon (CO) in the slag is decreased. This is a typical phenomenon in many shops. As the fluidity of the slag increases, such that the foam height significantly drops, it is very difficult for the slag to foam again, even if the rate of carbon injection is significantly increased.

5. A mass-balance approach to calculating the composition of the EAF slag

Understanding and control of the parameters affecting the efficiency of the EAF process empowers the steelmaker to make the essential decisions for optimization. A mass-balance
approach, using simple spreadsheets, is a fundamental tool that can be employed to evaluate the critical operational (and cost) parameters in the EAF.

A mass-balance calculation can be used to approximate the slag composition in the EAF from typical heat data: metal and slag heel in the furnace, scrap composition, fluxes, and the extent of blow and carbon injection. With the use of historical slag analyses, the assumptions and "boundary conditions" of the mass balance can be adjusted to give a fairly reliable prediction of the EAF slag composition. This will enable the steelmaker to adjust his flux addition and carbon and oxygen injection for optimum energy consumption, good foaming practice, and minimum refractory wear.

In setting up the mass-balance, it is important to consider all contributions to the furnace slag:

a) Residual slag in the furnace  
b) The Si and Al content of the scrap  
c) The amount of dirt (sand) coming in with the scrap  
d) The SiO$_2$ and Al$_2$O$_3$ from the DRI and pig iron  
e) The extent to which the scrap is rusted (increases the FeO content in the slag)  
f) The compositions of all the oxides (lime and dolomite) added to the furnace  
g) The size of the scrap (fine scrap tends to oxidize more readily than large pieces of scrap)  
h) The amount of ash in the coal and the chemistry of the ash (normally SiO$_2$ and Al$_2$O$_3$)  
i) The amount of slag that is lost during the foaming process

A mass-balance approach is essentially an attempt to balance the added refractory oxides (lime and dolomite) with the fluxing oxides (SiO$_2$, Al$_2$O$_3$, FeO and MnO) that are generated from the scrap. Slagmaking in the EAF is very dynamic in that the slag composition is changing throughout the heat. The extent the composition of the slag will change is dependent on the type of EAF operation. There are essentially three types of EAF operations:

a) Conventional – Scrap and fluxes (lime and dolomite) are charged by bucket into the furnace. In some cases the lime is pneumatically injected into the furnace.  
b) Conventional/DRI – A large part of the iron units is added as DRI. The DRI and fluxes are continuously fed through the roof of the furnace.  
c) Consteel – Scrap and flux is continuously fed into the furnace via conveyor belt.

6. Utilizing CaO-MgO-SiO$_2$-FeO system to determine MgO saturation levels.

The CaO-MgO-SiO$_2$-FeO system and the limiting ternary systems CaO-MgO-SiO$_2$ and CaO-MgO-FeO were used as a reference to determine the saturation levels of CaO and MgO. The effect of Al$_2$O$_3$ on the solubility of CaO and MgO was determined relative to these reference systems. The MgO content at dual saturation is shown graphically in Figure 2 as a function of slag basicity ($B_2 = \%$CaO/$\%$SiO$_2$) at 1600°C (2912°F). This figure shows that the saturation limit of MgO decreases as the basicity of the slag increases. The data in Figure 2 is therefore very important as it defines the minimum amount of MgO required in the slag to be compatible with basic refractories, for a specific basicity ratio.
7. Generation and features of Isothermal Stability Diagrams at constant basicity

The data on the solubility of MgO as a function of slag basicity in Figure 2 is very important as it defines the minimum amount of MgO required in the slag for refractory compatibility. However, in its current format, it is difficult to relate the data in this figure to foaming properties in the EAF. It was mentioned previously that FeO is the major fluxing component in the slag and has a distinct impact on foaming properties. The effect of FeO on the solubility of MgO is not shown in Figure 2 although it is possible to back-calculate the amount of FeO that would be present in a slag at any basicity ratio. In most conventional EAF operations, the basicity of the slag remains fairly constant throughout the heat and is determined by the Si and Al levels in the scrap and the amount of refractory oxides added with the scrap. For this reason, the phase relations at constant basicity would be of great interest as they probably best represent the slag conditions throughout the heat.

The solubility data from Figure 2 and the CaO-MgO-SiO$_2$-FeO system were used to construct maps of the phase relations as a function of MgO and FeO content at a constant basicity and temperature. The "maps" of these phase relations are called Isothermal Stability Diagrams (ISD). Figure 3 is the ISD for slags with a basicity ($B_3$) of 1.5 and shows the stability regions of the various phases at 1600°C (2912°F) and for slags with 0% Al$_2$O$_3$. 

Figure 2. The solubility of MgO for slags that are dual saturated with respect to CaO and MgO at 1600°C (2912°F).
Figure 3. Isothermal Solubility Diagram (ISD) for a basicity \(B_3\) of 1.5.  
(Where \(C_2S = Ca_2SiO_4\), MW = Magnesio-wustite, and L = Liquid)

Point (a) on this diagram is the point of dual saturation with respect to MgO (MW) and CaO (C\(_2\)S) on the liquidus surface, and has been determined from Figure 2. The liquidus lines (saturation curves) originate from point (a) and are defined as (a)-(b) and (a)-(c) for MgO and CaO saturation respectively. The saturation curves and the phase stability lines were generated from the CaO-MgO-SiO\(_2\)-FeO system and its lower-order ternaries. The dashed line tracing the liquidus region, is an inferred line for slags with peak foaming characteristics, i.e. optimum effective viscosity due to the presence of second phase particles (Point [G] in Figure 1).

Figure 3 is characterized by a fairly large all-liquid area. Slags that fall in this area will have poor foaming properties due to the low viscosity of the slag and the lack of second phase particles \((\Theta = 0)\). The position of the liquidus curves is very important as they show the maximum amount of FeO that can be tolerated before the slag will be fully liquid. Also clearly shown in this diagram is the relationship between the FeO level and the amount of liquid in the slag. As the FeO level increases, so too does the liquid fraction, clearly demonstrating the fluxing effect of FeO. Another important feature displayed in this diagram is the decrease in MgO solubility (on the MgO saturation curve [a] –[b]) with increasing FeO content for slags that are not saturated with CaO.

Consider slag X in Figure 3 and the path the composition of slag X will take as the FeO content increases. At position X, the slag consists of \(C_2S\), MW and liquid and is probably too crusty to foam very well at this stage. As the FeO content of the slag increases (due to the injection of oxygen), the MgO content of the slag is diluted and the slag follows the path X to X'. As the composition of the slag moves from X to X\(_1\), the fluidity of the slag changes from "crusty" to "fluffy" and the foaming properties of the slag improve. However, as the composition of the slag
continues to move towards the liquidus boundary (point X₁ to X₂), the effective viscosity of the slag decreases as the amount of liquid in the slag increases. This results in a decrease in foaming. At point X₂ the slag is fully liquid and remains liquid as the FeO content increases to point X'.

The initial slag composition (X) is MgO saturated but as the FeO content increases, the slag becomes unsaturated with respect to MgO making it aggressive to the furnace refractories.

Consider slag Y in Figure 3 and the path of the liquid composition as the FeO content of the slag increases. The initial FeO content of slag Y is identical to slag X, yielding the same crustiness and poor foaming properties. As the FeO content of the slag increases and the liquid composition follows the path Y to Y₁, the foaming characteristics of the slag improve. However, as the slag composition moves from Y₁ towards Y', the good foaming properties of the slag are maintained due to the presence of second phase MW particles. This is in contrast to slags X₂ and X₁, which are fully liquid at this FeO level. Not only is slag Y fully compatible with the refractories over the entire composition interval (MgO saturated), but the foaming properties are much less sensitive to FeO content. The foaming "window" for slag Y is significantly larger (8 – 20% FeO) than for slag X (8 – 17% FeO). Also, since slag Y has the ability to foam over a larger composition range, the injection of carbon to reduce FeO could be more effective in this slag, than in slag X.

Consider slag Z in Figure 3. The initial MgO content of this slag is too high resulting in a slag that will have poor foaming properties and remain fairly crusty, even if its FeO content is increased significantly.

The ISD presented in Figure 3 clearly demonstrates the effects of FeO and MgO on the phase relations and hence the foaming properties of slags. Not only is the MgO content of the slag important in terms of refractory compatibility, but it is also very important for foaming properties. The ISD also shows the difference between research on foaming and actual steelmaking conditions. In the former, solid particles are added to a liquid slag, gradually increasing the effective viscosity of the slag, whereas in real steelmaking conditions the reverse is true. In steelmaking, the slag is initially crusty because of the addition of refractory oxides with the charge, and then gradually becomes more liquid as the fluxes (SiO₂, Al₂O₃ and FeO) are generated by the oxygen blow.

8. The generation of Isothermal Stability Diagrams at other slag basicities

The same principles that were used to develop the example ISD at a basicity of 1.5 (Figure 3), can be used to generate ISD's for other basicities. Figures 4 to 6 represent the 1600°C (2912°F) Isothermal Stability Diagrams at basicities of 2.0, 2.5 and 3.0, respectively.
Figure 4. Isothermal Solubility Diagram (ISD) for a basicity (B₃) of 2.0.

Figure 5. Isothermal Solubility Diagram (ISD) for a basicity (B₃) of 2.5.

Figure 6. Isothermal Solubility Diagram (ISD) for a basicity (B₃) of 3.0.
The most significant features of these Isothermal Stability Diagrams (ISD's) are the following:

1. The shrinking of the all-liquid area as the basicity of the slag increases.
2. The subsequently higher levels of FeO that are required to reach the liquidus boundary.
3. The decrease in MgO solubility as the basicity of the slag increases.
4. The smaller effect of FeO on the MgO saturation curve as the basicity of the slag increases. (Note slope of the MgO saturation line [a]-[b] in Figures 4 to 6.)
5. The effect of MgO content on the CaO saturation curve

These Isothermal Stability Diagrams show the importance of the initial MgO content of the slag. If the initial MgO level is too low, the window of effective foaming (as a function of FeO content) is small. Conversely, if the initial MgO content is too high, the slag could be too crusty and potentially not achieve optimum foaming conditions. From the diagrams it can be concluded that the "ideal" aim MgO content for foaming and refractory compatibility is about 1 – 1.5 % higher than the MgO value at dual saturation.

The diagrams also show that there are an infinite number of slag composition possibilities that can yield good foaming properties. This is supported by EAF slag practices throughout the industry where slag basicities can vary from less than 1.5 to more than 3.0 with FeO levels from 10 to 50%, while achieving good slag foaming behavior. Figure 7 graphically depicts the effective foaminess as a function of slag basicity and FeO content. Note the decrease in MgO solubility as the slag basicity increases.

Figure 7. Inferred Effective foaminess as a function of basicity and FeO content (time)
In the examples presented earlier (Figures 4 to 6), the Al$_2$O$_3$ content of the slag was 0%. Replacing SiO$_2$ with Al$_2$O$_3$ will not change the basicity of the slag since the B$_3$ ratio is used but it will decrease the solubility of MgO which will shift the position of the dual saturation point ([a]) in these diagrams. Increasing temperature will increase the MgO and CaO solubility of the slag, but decrease the FeO content at dual saturation and shift the CaO-saturation liquidus curves accordingly.

9. References


