Abstract
This paper will define the slag compositions required to obtain and control optimum foamy slag conditions in the Electric Furnace. In defining the optimal slags, consideration is given to the effects of scrap quality, carbon injection, slag basicity and MgO content. A computer model based on published phase-diagrams has been developed which graphically maps the chemistries for optimal foaming conditions. The model has been applied to steelmaking operations yielding excellent results between the predicted and actual outcomes.

1. INTRODUCTION

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 paper is to define the conditions required to obtain and control optimum foamy slags in the electric furnace (finding the proper slag). Readily available technical information and published phase diagrams have been utilized to present slag foaming principles in a practical and easy to understand fashion.

2. BACKGROUND ON SLAG FOAMING IN THE EAF

2.1 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 ($\text{Ca}_2\text{SiO}_4$) 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 (Σ) 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 foam stability (optimum slag). Once this point is exceeded the slag becomes too "crusty" (oversaturated) and the foaming index decreases.

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* The foaming index (Σ) is a parameter that relates the gas flow rate, foam height, and the foam life.
2.2 Slag composition and slag basicity

Table I shows typical slag components along with their respective melting points.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Melting Point (°C)</th>
<th>Melting Point (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>1720</td>
<td>3128</td>
</tr>
<tr>
<td>CaO</td>
<td>2600</td>
<td>4712</td>
</tr>
<tr>
<td>MgO</td>
<td>2800</td>
<td>5072</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2030</td>
<td>3686</td>
</tr>
<tr>
<td>FeO†</td>
<td>1370</td>
<td>2498</td>
</tr>
<tr>
<td>MnO</td>
<td>1850</td>
<td>3362</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>2260</td>
<td>4100</td>
</tr>
<tr>
<td>CaF₂</td>
<td>1420</td>
<td>2588</td>
</tr>
</tbody>
</table>

FeO† – in this paper iron oxide will be referred to as FeO, while in reality, iron is present in EAF slags predominantly as Fe²⁺ with minor amounts of Fe³⁺ ions.

From this table it can be seen that the melting points of most of the oxides fall above normal steelmaking temperatures. The exception to this is CaF₂ (Fluorspar) and FeO, which have melting points of 1420°C (2588°F) and 1370°C (2498°F), respectively.

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.

For the sake of simplicity, the components in Table I can be separated into two groups; refractory oxides and fluxing oxides. The refractory oxides are CaO and MgO, and the addition of these oxides beyond the liquidus composition results in an increase in the effective viscosity of the slag. The fluxing oxides consist of SiO₂, Al₂O₃, FeO, MnO and CaF₂. The addition of these components will increase the fluidity of the slag (for the slags typically encountered in EAF steelmaking). The most prevalent fluxing oxides in the EAF slag are FeO and SiO₂, with Al₂O₃ and MnO as the minor fluxing components.

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 SiO₂ with Al₂O₃ 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.
The concept of slag basicity is an attempt to define the balance between the refractory oxides and the fluxing oxides. The most commonly used expression of slag basicity is the $B_2$ (or $V_B$) ratio, which is the weight ratio of CaO and SiO$_2$ in the slag (% CaO /% SiO$_2$). Other indices used to express slag basicity are:

$$B_3 = \frac{\text{CaO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3}; \quad B_4 = \frac{(\text{CaO} + \text{MgO})}{(\text{SiO}_2 + \text{Al}_2\text{O}_3)}; \quad B_5 = \frac{(\text{CaO} + \text{MgO})}{\text{SiO}_2}$$

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.

In their paper on the electrical properties of EAF slags, Wunsche and Simcoe$^5$ recommended a $B_5$ ratio of 1.8 in order to obtain the optimum voltage gradient in the arc column. McAllister$^6$ recommended a $B_2$ ratio of 2.0 with MgO ranging from 8–12% and FeO from 10–20%. Selin and Co-workers$^{2,7,8}$ discouraged the use of basicity ratios, but utilized graphical methods and a model to calculate the MgO saturation levels in the slag as a function of the CaO and FeO content of the slag.

### 2.3 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 add 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:

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

and

$$\text{FeO} + C = \text{Fe} + \text{CO} (g) \quad \text{................................................................. (3)}$$

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$^9$.

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:

$$C + \frac{1}{2} O_2 (g) = CO \quad \text{................................................................. (2)}$$

and

$$\text{Fe} + \frac{1}{2} O_2 (g) = \text{FeO} \quad \text{................................................................. (4)}$$
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 (4)), and the rate of FeO reduced by the injected carbon (reaction (3)). 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.

3. 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 SiO₂ and Al₂O₃ 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 SiO₂ and Al₂O₃)
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 (SiO₂, Al₂O₃, 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.

3.1 Conventional EAF Steelmaking

In conventional EAF steelmaking operations, the ability to add material through the roof of the furnace is not available, thereby necessitating that all material is added in scrap buckets. The lime and dolomite are normally added with the scrap, resulting in an initial slag that is "crusty". The oxidation of the Si and Al in the scrap is normally insufficient to fully flux the added refractory oxides. When all of the scrap is melted, the basicity of the slag is fairly constant, and is fixed by the amount of lime added and the amount of Si and Al that was present in the scrap. It is obviously very important to have a good idea of the Si and Al levels of the scrap, as these can dramatically affect the basicity ratio of the slag.

As oxygen is injected into the bath, the steel is decarburized, but FeO (the principal flux) is formed. The slag fluidity changes accordingly from crusty to fluffy and the slag starts to foam. The amount of FeO that is generated will obviously depend on the amount of oxygen and carbon injected. It is important to inject good quality coal/coke, i.e. low ash and volatile content. Coal ash consists primarily of fluxing oxides (SiO₂, Al₂O₃ and alkalis) so that the injection of coal with a high ash content could gradually decrease the basicity of the slag. This could adversely affect the foaming properties of the slag.

Optimizing and controlling the slag in Conventional EAF operations is the most difficult, since the opportunity to add fluxes to the furnace is limited to additions with the scrap. A good knowledge of the quality of the scrap is therefore required, i.e., the Si and Al levels, the rustiness, and the size distribution. Unfortunately, this information is rarely available. If the amount of lime and dolomite is not adjusted for scrap quality, then the foaming behavior of the furnace slags will be erratic and difficult to control. Some slags could be too basic and foam too late where other slags could be too acidic and foam too early. Essentially, control of the slag in conventional EAF operations can be compared to trying to hit a moving target. The only chance to adjust the slag chemistry in this type of operation is by carbon injection or injection of limited amounts of magnesia or dolomitic stone. This practice will only serve as a "band-aid" approach in order to prolong the foaminess in the furnace. The merits of these injections will be discussed later in the paper.

3.2 Conventional/DRI and Consteel Steelmaking processes

In these processes, an auxiliary flux feeding system is normally available. This greatly enhances the ability to control the slag in the furnace so that a more consistent slag foaming is generally observed. Another very important benefit of this type of process is that the chemistry of the feed materials is better known, resulting in a more accurate mass-balance calculation. For example, when the composition or metallization of the DRI changes slightly, an adjustment can
immediately be made to maintain an optimum practice. The biggest benefit of the auxiliary feeding system is that during the heat, the amount of material that is fed into the furnace can be adjusted to maintain consistent foaminess.

A mass-balance approach is an indispensable tool to calculate the composition of the slag. Even more important is the knowledge of what slag composition to aim for and what factors will negatively affect slag foaminess. The next part of the paper will address these issues.

4. UTILIZING CaO-MgO-SiO$_2$-FeO SYSTEM TO DETERMINE MgO SATURATION LEVELS.

The CaO-MgO-SiO$_2$-FeO system was 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 this reference system. The isothermal section through the ternary systems of the quaternary CaO-MgO-SiO$_2$-FeO system in contact with metallic iron at 1600°C (2912°F), is shown in Figure 2.$^{10,11}$

![Figure 2. Isothermal Section through the ternary systems of the quaternary CaO-MgO-SiO$_2$-FeO system in contact with metallic iron at 1600°C (2912°F)$^{10,11}$]
The CaO-FeO-SiO₂ system is characterized by an extensive all-liquid field and a large Ca₂SiO₄ stability area extending into this field. In this system, the fluidizing oxides are SiO₂ and FeO resulting in the large liquid area. In contrast, the CaO-FeO-MgO system is characterized by a very small all-liquid area at the FeO apex, and extensive solid solution between FeO and MgO. This solid solution phase ((Mg,Fe)O₃₅) is called magnesio-wustite (MW). In the CaO-FeO-MgO system, CaO and MgO are the refractory oxides while FeO is the only fluxing oxide.

The CaO-MgO-SiO₂-FeO system represents the major components in EAF slags and is therefore a good reference system to define these slags. The position of the saturation lines of CaO and MgO in this system are therefore very important, as they will delimit the boundaries at which point second phase particles will be present in the slag. The saturation lines of MgO-based solid solution phases ((Fe,Mg)O and (Fe,Mg)₂SiO₄) in the CaO-FeO-MgO-SiO₂ system in contact with metallic iron have been projected on the CaO-SiO₂-FeO system as shown in Figure 3.

Figure 3. The saturation lines of MgO-based solid solution phases ((Fe,Mg)O and (Fe,Mg)₂SiO₄) in the CaO-FeO-MgO-SiO₂ system in contact with metallic iron as projected on the CaO-SiO₂-FeO system at 1600°C(2912°F).
Important to note in Figure 3 is the increase in the solubility of MgO as the SiO\textsubscript{2} content of the slag increases. The data from these diagrams also shows that at a constant basicity, the solubility of MgO decreases with increasing FeO for slags that are not CaO-Saturated. This decrease in MgO solubility with increasing FeO is significantly more substantial for slags with low basicity ratios than for more basic slags (consider slopes of the MgO saturation curves in Figure 3.).

In a similar fashion, the saturation lines of the CaO-based phases (Ca\textsubscript{2}SiO\textsubscript{4} and Ca\textsubscript{3}SiO\textsubscript{5}) in this system have been projected in Figure 4. The saturation level of CaO in these slags at 1600°C (2912°F) ranges from 42% to about 45%. Most EAF slags contain CaO below these levels indicating that they are CaO unsaturated. Also of interest in Figure 4 is the shrinking of the stability field of Ca\textsubscript{2}SiO\textsubscript{4} as the MgO content of the slag increases.

![Figure 4. The saturation lines of CaO-based phases in the CaO-FeO-MgO-SiO\textsubscript{2} system in contact with metallic iron as projected on the CaO-SiO\textsubscript{2}-FeO system at 1600°C(2912°F)\textsuperscript{10}.](image-url)
From Figures 3 and 4 and the limiting ternary systems CaO-MgO-SiO$_2$ and CaO-MgO-FeO, the points of dual saturation (Ca$_2$SiO$_4$ and (Fe,Mg)O) can be determined. The MgO content at dual saturation is shown graphically in Figure 5 as a function of slag basicity ($B_2 = \%\text{CaO}/\%\text{SiO}_2$) 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 5 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.

![Figure 5. The solubility of MgO for slags that are dual saturated with respect to CaO and MgO at 1600°C (2912°F).](image)

For slags with a basicity ratio ($B_2$) > 3.5, the solubility limit levels off to about 6 to 5.5% MgO where it remains constant into the CaO-MgO-FeO system ($B_2 = \infty$). The MgO solubility at dual saturation in this system is about 5.5% at 1600°C (2912°F).

Another important feature of this diagram is the significant increase in MgO solubility (with decreasing basicity) for slags with basicity levels less than 2.0. In some cases, the initial slag that is formed in the EAF might have a low basicity, resulting in a higher MgO solubility. The addition of dolomite with the first scrap bucket will provide the necessary MgO units for saturation, minimizing refractory wear on the bottom and lower banks of the furnace.

### 4.1 The effects of Al$_2$O$_3$, TiO$_2$, VO$_2$ and MnO on the solubility of MgO in the slag

The effects of Al$_2$O$_3$, TiO$_2$, and VO$_2$ on the solubility of MgO have been evaluated in prior research where it was found that replacing SiO$_2$ with Al$_2$O$_3$, TiO$_2$ and VO$_2$, decreased the solubility of MgO. The decrease was somewhat greater for VO$_2$ and TiO$_2$ than for Al$_2$O$_3$. 
The majority of EAF slags consists primarily of the components CaO, MgO, SiO₂, Al₂O₃, MnO, and FeO. The sum of the remaining components in the slag (TiO₂, VO₂, and Cr₂O₃) generally totals less than 2% (excluding stainless steel EAF slags). Therefore, in this paper the effects of TiO₂, VO₂ and Cr₂O₃ on the solubility of MgO were considered small enough to be ignored.

In this paper, the effect of Al₂O₃ on the solubility of MgO was incorporated as follows:

1) The B₃ basicity ratio was used instead of the simple B₂ ratio to express slag basicity.
2) The MgO solubility using the data from Figure 5 was calculated as a function of the B₃ ratio.
3) The decrease in MgO solubility as Al₂O₃ replaces SiO₂ is incorporated by a correction factor. This is demonstrated by considering the two MgO-Saturated slags in Table II:

Table II. MgO saturated slags at 1600°C (2912°F)

<table>
<thead>
<tr>
<th></th>
<th>Slag A</th>
<th>Slag B</th>
</tr>
</thead>
<tbody>
<tr>
<td>% MgO</td>
<td>9.3</td>
<td>8.3</td>
</tr>
<tr>
<td>% CaO</td>
<td>43.1</td>
<td>43.2</td>
</tr>
<tr>
<td>% SiO₂</td>
<td>21.5</td>
<td>11.5</td>
</tr>
<tr>
<td>% Al₂O₃</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>% FeO</td>
<td>26.1</td>
<td>27.0</td>
</tr>
<tr>
<td>B₂ (CaO/SiO₂)</td>
<td>2.0</td>
<td>3.8</td>
</tr>
<tr>
<td>B₃ (CaO/(SiO₂+Al₂O₃))</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

In Slag B, 10% of the SiO₂ was replaced by an equivalent amount of Al₂O₃. This resulted in a decrease in the solubility of MgO from 9.3% (Slag A) to 8.3% (Slag B). If the simple B₂ ratio rather than the B₃ ratio had been used to determine the MgO solubility from Figure 5, a significant underestimation of the solubility of MgO would have resulted. The effect of Al₂O₃ on the solubility of MgO using the B₃ ratio and the correction factor can be calculated as follows:

\[
\% \text{ MgO}_{\text{sat}} = \% \text{ MgO}_{\text{ref}} \times (B_3 \text{ ratio}) - \text{Al}_2\text{O}_3 \text{ correction factor}
\]

where

\[
\% \text{ MgO}_{\text{ref}} = \text{Obtained from Figure 5.}
\]

\[
\text{Al}_2\text{O}_3 \text{ correction factor} = 0.615 \times \left( \frac{\% \text{Al}_2\text{O}_3}{(\text{SiO}_2+\text{Al}_2\text{O}_3)} \right) \times (\% \text{MgO}_{\text{ref}} - 6)
\]

So that for Slag B,

\[
\% \text{ MgO}_{\text{sat}} = 9.3 - [0.615 \times \left( \frac{10}{21.5} \right) \times (9.3 - 6)]
\]

\[
= 8.3
\]
In this paper, it was assumed that MnO is approximately equivalent to FeO in strength and would act as a fluxing oxide. The phase relations in the equivalent ternary systems are very similar, since these two components have similar molecular weights and ionic radii. For the balance of this paper, FeO and MnO will be considered equivalent so that "FeO" will represent the sum of FeO and MnO, i.e., $\text{FeO} = \text{FeO} + \text{MnO}$.

4.2 The effect of temperature on the solubility of MgO

From the various ternary diagrams of the quaternary CaO-MgO-Al$_2$O$_3$-SiO$_2$ system, the effect of temperature on the solubility of MgO has been approximated. In the CaO-MgO-FeO system, the MgO solubility is the least temperature sensitive and the dependence is about 1.75 % MgO per 100 ° (using 1600°C as midpoint temperature). However, in the other systems, the MgO solubility change per 100° is approximately 2 - 3% MgO. In this paper, a temperature dependence of 1.75 % MgO per 100° was used as follows:

$$\% \text{MgO}_T = \% \text{MgO}_\text{ref} + (0.0175 \times (T-1600))$$

Where,

$\% \text{MgO}_T = \% \text{MgO}$ at temperature $T$ in °C

$\% \text{MgO}_\text{ref} = \% \text{MgO}$ at 1600°C from Figure 5

5. Isothermal Saturation Diagrams (ISD)

5.1 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 5 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 5 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 5 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 6 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$_3$. 

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Figure 6. Isothermal Solubility Diagram (ISD) for a basicity ($B_3$) of 1.5.
(Where $C_2S = \text{Ca}_2\text{SiO}_4$, $MW = \text{Magnesio-wustite}$, and $L = \text{Liquid}$)

Point (a) on this diagram is the point of dual saturation with respect to MgO ($MW$) and CaO ($C_2S$) on the liquidus surface, and has been determined from Figure 5. 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$^{10}$ 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 6 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 6 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 $X_1$ to $X_2$), 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 6 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 6. 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 6 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.

5.2 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 6), can be used to generate ISD's for other basicities. Figures 7 to 9 represent the 1600°C (2912°F) Isothermal Stability Diagrams at basicities of 2.0, 2.5 and 3.0, respectively.
Figure 7. Isothermal Solubility Diagram (ISD) for a basicity (B₃) of 2.0.

Figure 8. Isothermal Solubility Diagram (ISD) for a basicity (B₃) of 2.5.

Figure 9. 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:

a) The shrinking of the all-liquid area as the basicity of the slag increases.
b) The subsequently higher levels of FeO that are required to reach the liquidus boundary.
c) The decrease in MgO solubility as the basicity of the slag increases.
d) 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 6 to 9.)
e) 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 10 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 10. Inferred Effective foaminess as a function of basicity and FeO content (time)

In the examples presented earlier (Figures 6 to 10), the Al₂O₃ content of the slag was 0%. Replacing SiO₂ with Al₂O₃ will not change the basicity of the slag since the B₃ 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.
6. DEVELOPMENT OF A FOAMY SLAG MODEL USING A MASS BALANCE APPROACH

6.1 Background

Earlier, the effect of the various fluxing oxides on MgO solubility was discussed. In order to consider the impact of these oxides on phase relations (ISD's) and the change of the slag composition during the heat, a foamy slag model was developed. In the model a mass balance approach is used to calculate the composition of the slag at various intervals throughout the heat. This approach incorporates the impact of all contributions (added and generated during the heat) on the composition of the slag.

The path of the calculated slag at the various intervals is then superimposed on a calculated Isothermal Stability Diagram. At the various intervals, the model shows the corresponding shift in the saturation curves of the ISD due to changes in both slag basicity and temperature.

6.2 Application of the Foamy slag model to EAF steelmaking

The foamy slag model can be applied to EAF steelmaking in two ways:
(a) The design and simulation of slag conditions in the EAF.
(b) The evaluation of existing EAF slag compositions

Since the model and ISD can give an estimation of the slag and phase composition at any point throughout the heat, adjustments to maintain foaming conditions can be ascertained. For example, the timing and duration of foaming can be manipulated by the steelmaker through changes in target slag basicity and the amount of MgO added to the heat. The slag conditions simulated by the model can be readily verified by visual observation of the foaminess in the furnace and the collection of slag samples for analysis. The model is especially useful in considering "what if" scenarios, helping to determine the amounts of lime and dolomite needed to compensate for changes in chemistry of the charge materials.

It should be noted that the model in its existing form is applicable for the following composition and temperature ranges:

- Basicity ($B_3$) 1.2 to 3.5
- FeO content ($\%FeO + \%MnO$) < 55%
- The sum of Cr$_2$O$_3$, TiO$_2$, VO$_x$ less than 3%
- Temperature: 1500°C (2732°F) to 1750°C (3182°F)

The model calculates the MgO saturation point of any slag at any temperature and is therefore especially useful for evaluating slag compositions in terms of refractory compatibility. The MgO saturation values predicted by the model were verified by comparing the calculated values to experimentally determined values. Table III shows the average differences between calculated MgO values relative to a large number of experimentally determined values.
Table III. Comparison between experimental MgO solubility values and corresponding values calculated by the model.

<table>
<thead>
<tr>
<th></th>
<th>Number of Values (n)</th>
<th>Δ % MgO (Mean)</th>
<th>Δ % MgO (Std. Dev.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ishii and Freuhan12</td>
<td>14</td>
<td>-0.27</td>
<td>0.45</td>
</tr>
<tr>
<td>Inoue and Suito13</td>
<td>22</td>
<td>0.33</td>
<td>0.84</td>
</tr>
<tr>
<td>Suito et.al.14</td>
<td>29</td>
<td>-0.11</td>
<td>1.04</td>
</tr>
<tr>
<td>Selin7</td>
<td>21</td>
<td>2.22</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The data in Table III shows that there is good agreement between the calculated values and the data from studies by Ishii and Freuhan12, Inoue and Suito13 and Suito et. al.14 However, the MgO values reported by Selin7 were consistently lower than those calculated, as shown by the average difference of 2.2 % MgO.

In an experimental study, Ito and Fruehan1 observed that optimum foamy conditions were achieved at a B2 basicity ratio of 2.0 and a FeO content of about 20%. They also reported that the slags contained about 3-5 % Al2O3 due to contamination from the use of Al2O3 crucibles. The basicity of this optimum slag was recalculated in terms of the B3 basicity ratio and was found to be 1.75. The Isothermal Stability Diagram at B3 = 1.75 is shown in Figure 11 with the 20 % FeO line superimposed on this diagram. The inferred optimum foamy line in this ISD is consistent with the results that were observed in the study.

![Figure 11. Isothermal Stability Diagram at B3 = 1.75.](image)

The model was also applied to an actual steelmaking operation. Nucor Darlington, which produces steel via the Consteel process, agreed to the evaluation of their EAF practice using the model and agreed to incorporate some of the conditions recommended by the model.
The following were the EAF target slag conditions prior to the evaluation:

Slag Basicity ($B_2$) = 2.0
% MgO ≈ 8 - 9
% FeO ≈ 20

At Nucor Darlington, slag samples are routinely analyzed every heat, and flux adjustments are made on a heat to heat basis to maintain target conditions in the furnace. The initial target slag parameters as listed above were plotted on the corresponding ISD, which showed the slag to be MgO unsaturated and on the edge of becoming too liquid. This was confirmed by plant observations. The slag foaming decreased and significant wear in the banks of the furnace occurred when the slag became less basic (or the FeO content increased), due to changes in scrap type and quality.

Using the model calculations (recommendations), Nucor Darlington switched from a 20% to a 25% MgO lime, changed their basicity calculation to include $\text{Al}_2\text{O}_3$, and adjusted their aim chemistry to 1.8 - 2.2 basicity ($B_3$) and 10% minimum MgO in the slag. This new target would result in slags that are not only more refractory compatible, but also less susceptible to changes in FeO levels. The following were observed after the changes were implemented:

(a) The consumption of monolithic patching material decreased from 7.0 to 5.5 lb. per ton of steel produced.
(b) The gunning material consumption decreased from 2.4 to 0.7 lb. per ton.
(c) Furnace brick life doubled
(d) The energy consumption per heat decreased from 339 to 323 kWh/ton.
(e) Tons per hour increased from 113 to 119.5
(f) Lime (blended lime) consumption increased from 98 to 109 lb. per ton.

The following comment is from Nucor Darlington regarding the new slag practice: "It is difficult to say exactly how much of this improvement is attributable to improved slag chemistry and foamingness because other changes were made at the same time. Bank materials were upgraded and major equipment maintenance was done during this period. However, we do attribute a significant portion of the improvement in kWh/ton and refractory performance to the practice changes that were suggested."

The validity and applicability of the model was also tested at a number of other steel plants by observing their practice, taking slag samples, and comparing the target and actual slag compositions to the compositions recommended by the slag model. Excellent agreement was found between the predicted and the observed foaming behavior in the furnace.

6.3 The effect of Temperature on Slag Foaming

It was mentioned earlier that a typical phenomenon in EAF steelmaking is that the foaminess in furnace tends to diminish towards the end of the heat. The Isothermal Stability Diagrams clearly show that an increase in the FeO content of the slag increases the amount of liquid present, adversely impacting the effective viscosity and hence foaming properties. This fluxing effect of FeO can be somewhat curtailed by targeting a MgO content slightly above the MgO saturation
curve. However, the slope of the liquid composition path is such that the slag will eventually move through the MgO saturation field into the all liquid field (see line X – X’ in Figure 6).

A very important factor that has not been addressed yet is the effect of temperature on the phase relations and hence the effective viscosity of the slag. In all of the examples presented, a temperature of 1600°C (2912°F) was used. This temperature is typical for steelmaking and most experimental data is available at this temperature. Under steelmaking conditions, the temperature in the furnace gradually increases towards the end of the heat so that tap temperatures are typically around 1700°C (3050°F). This increase in temperature could dramatically affect the foaming properties of the slag. A slag that had good foaming properties at 1600°C might foam very poorly at 1700°C since the slag could be completely liquid.

The effect of temperature on phase relations and the corresponding shift of the liquidus curves is demonstrated in Figure 12. The increase in fluidity with increasing temperature results in a decrease in the amount of second phase particles in the slag. The increased fluidity might also diminish the reduction reaction of the injected carbon, resulting in an increase in the FeO content of the slag. This "one-two" punch is normally too much for the slag to absorb, and foaming in the furnace dramatically drops off.

In shops where an auxiliary feeding system (roof or pneumatic injection) is available, adjustments to the slag composition (by the addition of refractory oxides) throughout the heat is possible. It is especially useful to add lime or dolomite to the furnace to restore foaming conditions when the foaming in the furnace starts to deteriorate due to increased temperature and/or FeO levels. The addition of the refractory oxides at this point will increase the basicity of the slag and "shrink" the all-liquid area, thus offsetting the temperature effect.

![Figure 12. Isothermal Stability Diagrams at 1600 and 1700°C for a B₃ = 2.0](image-url)
6.4 The merits of injecting of Magnesia or raw dolomitic stone into the furnace

Most conventional steelmaking operations do not have the luxury of auxiliary feeding systems and have to rely on the injection of refractory oxides through the slag door. These injections are typically "band-aid" additions in order to prolong the foaming in the furnace. Figure 13 shows the potential benefit of injecting MgO fines in the slag toward the end of the heat to maintain foamy conditions. Consider slag K in this diagram. As the composition of slag K moves from K toward K₂ the fluidity of the slag increases as the FeO content of the slag increases. Initially the foaming properties of the slag increases from point K to K₁ but then decreases from K₁ to K₂ as the slag becomes too liquid to foam adequately. The injection of MgO fines into the slag at point K₁ will change the slope of the liquid path and the composition of the slag will now follow the path K₁ to K₃, thereby maintaining the presence of second phase particles and sustaining the foamy conditions.

Figure 13. Isothermal Stability Diagrams showing the effect of MgO injection on the path of the liquid composition

The effectiveness of the MgO injection is dependent on the initial MgO levels in the slag. For example, consider slag T in Figure 13 where the initial MgO content is too low. The injection of MgO fines into slag T will probably only show a small improvement on foaming due to localized chilling of the slag, but the chemical effect as shown for slag K, will be absent.

The injection of dolomitic stone into the furnace towards the end of the heat has the capability of prolonging the foaming conditions in a similar fashion as MgO. Consider the possible benefits of using dolomitic stone:
a) Dolomitic stone is significantly cheaper than magnesia fines
b) Dolomitic stone is more readily available than magnesia fines
c) The calcination reaction of the stone is endothermic and will "chill" the slag locally, thereby increasing the effective viscosity of the slag

\[(Ca,Mg)(CO_3)_2 + \text{heat} \rightarrow [CaO+MgO] + 2 CO_2(g)\]
d) The calcination reaction releases CO\(_2\) gas bubbles into the slag. As 50\% of the weight of the stone is attributable to CO\(_2\), significant amounts of gas bubbles can be generated.
e) The CaO and MgO released into the slag locally increases the basicity, increasing the amount of second phase particles and hence foaming properties. However, for the chemical effect of dolomitic stone to be equivalent to MgO, double the amount has to be added due to the weight loss of CO\(_2\).

7. CONCLUSIONS

Over the past several years, new processes have evolved in the steelmaking industry, often in an effort to improve steel quality and lower total costs. One area where steelmakers have invested significant resources is in slag foaming in the EF. Although their efforts have been consistent, some steelmakers have met with less than consistent results in achieving and maintaining a good foamy slag practice.

This paper has attempted to provide a comprehensive, yet practical explanation of the mechanics of slag foaming in the EAF. And throughout the paper, both the requirements and methods of achieving and maintaining a good foamy slag practice has been discussed in great detail. In effect, an attempt has been made to prove that a good foamy slag practice is based on science, rather than luck.

One of the best ways to maximize the effectiveness of a process is to provide some general training and knowledge of the process in conjunction with tools for monitoring the process. The tools need to be efficient (in terms of time), effective and of course user friendly. This criterion has been incorporated in the development of the foamy slag model. By employing a mass balance approach, and graphically displaying the results on an ISD, steelmakers can not only monitor their existing slag practice, but can also design foamy slags to better suit their operations.

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REFERENCES


