Slags’ Effects on Cast Iron Production

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INTRODUCTION

Slags are generated throughout the casting process. Except for the cupola which requires a slag to dissolve coke ash, slags are undesirable materials that are responsible for a large share of problems that occur in the foundry. At best slags represent a heat loss and a disposal problem. At worst they produce casting defects, require relining of furnaces and ladles, cause the loss of alloying elements through oxidation, and have a negative impact on desulfurization. The cost to foundries for these slag related problems is very high.

Foundry slags are liquid oxides derived mostly from refractory and oxidized iron. In melting furnaces, rust, sand, coke ash, dirt and cement also contribute to slag formation. As shown in Table 1, silica and iron oxide are the major contributors to slag. They combine to form low melting liquids.

Table 1. Major Slag Ingredients

- All furnaces and ladles
  - Cast iron oxidation (FeO, MnO, SiO₂)
  - Refractory (SiO₂, Al₂O₃)
- Melting furnaces
  - Rust (Fe₂O₃)
  - Sand (SiO₂)
  - Coke ash (SiO₂, Al₂O₃)
  - Dirt (SiO₂, Fe₂O₃)
  - Limestone (CaO, MgO)
  - Cement (CaO, SiO₂)

Foundry slags of any kind have harmful characteristics but, by far, the most serious problems are created by slags that contain high levels of iron oxide. The discussion of the effect of slags on cast iron production is largely a discussion of the harmful effects created by iron oxide in slag. This paper is divided into two sections. The first section describes, in general terms, the problems created by slags on alloy loss, desulfurization, refractory erosion and casting defects. The second section covers problems and solutions specific to cupolas, induction furnaces and ladles.

SECTION 1. GENERAL NATURE AND SOLUTIONS TO SLAGGING PROBLEMS

ALLOY LOSS

When FeO rich slags come into contact with liquid cast iron the elements, carbon, silicon and manganese, are oxidized to their respective oxides. In effect, iron oxide converts expensive alloy materials into worthless oxides. The consequences are the necessary replacement of expensive alloy and poor iron composition.

\[ FeO_{slag} + C_{iron} = CO + Fe \]  
\[ FeO_{slag} + Si_{iron} = 1/2 SiO_{2slag} + Fe \]  
\[ FeO_{slag} + Mn_{iron} = MnO_{slag} + Fe \]

Although manganese oxide (MnO) is a product of FeO oxidation (reaction 3), it in turn can oxidize silicon and carbon and can create many of the kind of problems ascribed to iron oxide.
DESULFURIZATION

Desulfurization of liquid iron can be carried out in the cupola or in a ladle. The following reaction involving MnO controls the level of sulfur \(^{1,2}\) in the cupola. It is well recognized that the level of CaO in the slag, usually expressed as basicity, is an important controlling factor. Less recognized is that MnO levels in the slag play an equally important role. The higher the MnO level the poorer the desulfurization. MnO is present in the slags as a result of the alloy loss reaction (reaction 3), so FeO indirectly controls desulfurization.

\[ S_{\text{iron}} + CaO_{\text{slag}} + Mn_{\text{iron}} = CaS_{\text{slag}} + MnO_{\text{slag}} \]  

Unlike the cupola, ladle desulfurization using lime/fluorspar (limespar) mixtures (reaction 5) or calcium carbide (reaction 6) is controlled by reactions that do not produce liquid slags \(^{3,4}\). However a product of CaO/CaF\(_2\) desulfurization is solid tricalcium silicate which forms accretions in the ladle.

\[ S_{\text{iron}} + 5/2CaO_{\text{desulfurizer}} + 1/2Si_{\text{iron}} = CaS_{\text{slag}} + 1/2(CaO)_{3}SiO_{2} \]  
\[ S_{\text{iron}} + CaC_{2}_{\text{desulfurizer}} = CaS_{\text{slag}} + 2C_{\text{iron}} \]

The presence of liquid slags, entering with the iron stream or produced by oxidation in the ladle, can seriously reduce the ability to desulfurize. Liquid slags cause agglomeration of the desulfurizer powders which reduces the contact area between desulfurizer and liquid iron (Figure 1).

REFRACTORY PROBLEMS

Almost every vessel that holds or produces liquid iron is lined with refractory materials and is susceptible to refractory erosion by slag. In other circumstances, slags can combine with refractory materials to form accretions that hamper production. The consequences of refractory problems, loss of production and the cost to replace the refractory can be serious. Thus, extending the life of a refractory lining is an important consideration.

Iron oxide is present in large amounts in many of the slags found in foundry vessels and furnaces. Unfortunately, iron oxide is among the best solvents for refractories, and in particular it is a very good solvent for silica refractories.

The vulnerability of refractories to FeO attack can be roughly judged by the amount of refractory that will dissolve in pure FeO. As seen in Table 2, at 1500°C MgO is the least soluble and silica is the most soluble. Thus, silica refractories are the most susceptible to attack by FeO. For this reason, silica is being used less and less in foundry applications despite its very low cost.

**Table 2. Solubility of Oxides in FeO @1500°C**

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Solubility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al(_2)O(_3)</td>
<td>11%</td>
</tr>
<tr>
<td>MgO</td>
<td>5%</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>40%</td>
</tr>
</tbody>
</table>

MgO has the lowest solubility in FeO. As a basic oxide it dissolves readily in acid slags, which unfortunately are the most common type of slags generated in the foundry. As a result MgO refractories are not often used.

Alumina refractories have risen in popularity because they are less sensitive to FeO erosion than silica and are reasonably resistant to acid slags. A refractory that is gaining popularity is alumina containing silicon carbide \(^{5}\). Although silicon carbide should react readily with FeO and dissolve in iron, the success of the refractory is attributed to its high thermal conductivity. This enables the temperature of the refractory at the iron interface to drop below the freezing point of the slag. The refractory becomes coated with solid slag which is much less corrosive than the liquid slag.

As seen in Table 3, MnO is a poorer solvent than FeO, thus, it generally is not the cause of the most serious refractory problems.

**Table 3. Solubility Of Oxides in MnO @1500°C**

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Solubility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al(_2)O(_3)</td>
<td>0%</td>
</tr>
<tr>
<td>MgO</td>
<td>0%</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>25%</td>
</tr>
</tbody>
</table>
Oxides whose melting points exceed the temperature in the furnace can also present serious problems as they adhere to the furnace walls creating bottlenecks and buildups that reduce the working volume of a furnace or ladle, or reduce the efficiency of an electric furnace. The oxides most responsible for accretions are CaO, MgO and Al\(_2\)O\(_3\).

CASTING DEFECTS
Slags entering the mold can produce inclusion defects. Inclusions of FeO-rich slags also create porosity by reaction with carbon to form CO (reaction 1). FeO rich slags can also inhibit proper nucleation of graphite by oxidizing the inoculants (reaction 7).

\[
FeO_{slag} + Ba_{nucleant} = BaO_{slag} + Fe
\]

MINIMIZING SLAG PROBLEMS
Approaches to minimize slag problems are (1) minimize the conditions that produce slag and, in particular, the production of iron oxide or (2) the use of materials and conditions that resist slag attack. Some general solutions are shown in Table 4:

<table>
<thead>
<tr>
<th>Table 4. General means to minimize slag formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use rust-free charge materials</td>
</tr>
<tr>
<td>Don’t use scrap that is too large or too small</td>
</tr>
<tr>
<td>Don’t charge dirt.</td>
</tr>
<tr>
<td>Avoid excessive scrap preheating</td>
</tr>
<tr>
<td>Minimize contact of liquid iron and air</td>
</tr>
<tr>
<td>- Minimize metal transfers</td>
</tr>
<tr>
<td>- Minimize turbulent stirring</td>
</tr>
<tr>
<td>- Create coherent pouring streams</td>
</tr>
<tr>
<td>- Use inert atmospheres</td>
</tr>
<tr>
<td>- Shroud iron streams</td>
</tr>
<tr>
<td>- Cover vessels and troughs</td>
</tr>
<tr>
<td>Use slag resistant refractories</td>
</tr>
</tbody>
</table>

Which methods are practical will depend on the foundry. Some foundries have found that more expensive materials can save money. Removing galvanized steel saves environmental costs. Inert gas added to pressure pour ladles prevents serious magnesium loss. More expensive alumina/silicon carbide refractories are being used in the cupola melt zone. Silicon carbide additions to coreless induction furnaces prolong refractory life. Iron-troughs are being covered. Cupolas are adding refractory linings. In many cases iron entering the mold is filtered. Air streams are being dehumidified and iron streams are being protected from air. Alloys are being added after the cupola with much higher recoveries.

SECTION 2. CONSIDERATION OF EQUIPMENT SPECIFIC PROBLEMS

CUPOLA

FeO Production
More slag is produced in cupolas than any other vessel in the cast iron foundry. As indicated many slag forming materials are introduced to the cupola with the charge materials. Oxidation of iron also takes place inside the cupola, both in the heat transfer zone (equation 8) and melt zone (reaction 9). The predominant oxides are lime, silica and iron oxide.

\[
Fe_{solid} + CO_2 = Fe_2O_3_{solid} + CO
\]

\[
Fe_{liquid} + 1/2O_2 = FeO_{slag}
\]

Cupola conditions that affect the formation of FeO are listed in Table 5

<table>
<thead>
<tr>
<th>Table 5a. Cupola Conditions That Generate FeO</th>
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<tbody>
<tr>
<td>Thin scrap</td>
</tr>
<tr>
<td>High steel/cast</td>
</tr>
<tr>
<td>High oxygen levels in the blast</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5b. Cupola Conditions That Reduce FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot blast</td>
</tr>
</tbody>
</table>
Table 5 provides a range of options to minimize the production of FeO. The ideal tool to help make decisions about the most cost effective ways to achieve this goal is the AFS Cupola Model 6,7. The Model will be available for sale in early 2004.

Alloy Loss

It is well recognized that cupolas can experience large alloy losses, as much as 40%. Most of the alloy loss takes place in the slag layer in the cupola well. Figure 2 illustrates the mechanism.

Iron oxides introduced to the cupula with the charge materials and those produced internally (shown as white drops) liquefy and run into the slag where they dissolve. Liquid iron drops (black) pass through the slag and the alloy elements in the iron react with the dissolved FeO (reactions 1-3). Because of the high surface area of the iron drops, the oxidation of alloy proceeds rapidly until the amount of FeO in the slag is greatly depleted. The deeper the slag layer the more time available for reaction and hence the more alloy oxidized and the greater the depletion of iron oxide.

Clear evidence for the reaction between FeO and dissolved silicon (reaction 2) in the slag layer is given in Table 6. Table 6 gives the composition of slags taken at the tap hole and just above slag layer, 5 minutes apart 8. As seen, both slags have similar compositions, except for SiO2 and FeO. As described in Figure 2, the content of FeO above the slag layer is high and silicon is low. At the taphole the concentrations are reversed.

Table 6. Slag Composition In and Above Slag - Basic Cupola Operation

<table>
<thead>
<tr>
<th>Sample location</th>
<th>CaO</th>
<th>CaF2</th>
<th>CaS</th>
<th>MgO</th>
<th>Al2O3</th>
<th>MnO</th>
<th>SiO2</th>
<th>FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above slag layer</td>
<td>38.4</td>
<td>9.5</td>
<td>1.0</td>
<td>9.0</td>
<td>4.1</td>
<td>1.9</td>
<td>9.9</td>
<td>26.1</td>
</tr>
<tr>
<td>Taphole</td>
<td>38.4</td>
<td>11.7</td>
<td>2.0</td>
<td>14.0</td>
<td>5.0</td>
<td>1.5</td>
<td>26.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

An example of the of the alloy problems created by iron oxide is seen in the performance of briquetted cast iron borings. Foundries that charge significant amounts of briquetted cast iron borings frequently experience wide fluctuations in silicon and manganese recovery. The variations result from different levels of rust in the briquettes which, upon melting, oxidize carbon, silicon and manganese (reactions 1-3).

Figure 3 shows the affect of FeO on the residual silicon and manganese levels in commercial briquetted cast iron borings after melting 9. Although not shown, the affect on carbon was the same. Briquettes of cast iron borings that contain 25% rust contribute no alloy to the charge. Figure 4 shows how this affects overall silicon recovery in a cupula melting 25% briquetted cast iron borings 9. As seen, silicon recovery varied from 70% to 85% depending on the levels of residual alloy after reaction with FeO.

This example is not meant to discourage the melting of briquetted cast iron borings. A simple screening test was devised to rapidly measure the iron oxide content of a briquette. Briquettes delivered to the foundry had to be certified as to its alloy content after melting.

There is a slag conditioning treatment that can eliminate all alloy loss. It is accomplished by adding metallic aluminum to the charge. Generally 1-2% aluminum will react with all the iron oxide in the cupula (reaction 8) providing 100% recovery of C, Si, and Mn 1.

$$3FeO_{slag} + 2Al_{iron} \rightarrow Al_{2}O_{3}slag + 3Fe + \text{heat}$$  \hspace{1cm} (10)

Figures 5-7 demonstrate the beneficial affect of aluminum addition on cupula performance 10. Figure 5 shows the degree of recovery of silicon with the addition of 1.5% aluminum to the charge. As seen, there was an almost immediate increase in silicon when charges containing aluminum enter the melt zone (0 hour). This represented a change in the silicon yield from 75% to 100%. Not shown was a similar recovery of manganese and carbon.

An additional benefit was a significant increase in iron temperature due to the exothermic reaction between aluminum and FeO [reaction 10]. Figure 6 illustrates the increase in iron temperature. In this case the temperature rose about 85°C. The temperature rise was not instantaneous as in the case of silicon. It required about four hours to reach the maximum temperature which is the amount of time it took to change completely form a silica-rich to an alumina-rich slag (Figure 7). As indicated by the lines accompanying the data in Figures 6 and 7, the time required to change the temperature and slag composition is accurately accounted on the assumption of instantaneous mixing of slag entering the slag layer.

The complete recovery of alloy removes one of the most serious drawbacks to cupula melting, that is, variable iron composition.
Some permanent mold foundries add aluminum to advantage. They usually charge old motor blocks that contain the aluminum pistons. Many foundries will not add aluminum for fear of pinhole problems from the residual aluminum in the iron. Aluminum-pinholing is a very poorly understood phenomenon and is not universal. The probable cause is reaction of water vapor in green sand with aluminum nitride in the iron. The problem is counteracted by adding sea coal to the sand. It is also possible to remove the residual aluminum by oxidation with a ladle treatment using SiO2/CaF2 as the oxidant. The benefits of aluminum additions are so great to make it worth while to determine if plant conditions are or are not sensitive to the problem.

Desulfurization
Limestone additions are primarily made to the cupola to liquefy coke ash, sand, and dirt. The slag is also used to desulfurize the iron by the following reaction, involving sulfur, calcium oxide and manganese.

\[ S_{\text{iron}} + CaO_{\text{slag}} + Mn_{\text{iron}} = CaS_{\text{slag}} + MnO_{\text{slag}} \] (4)

This reaction generally achieves chemical equilibrium in the cupola. This being the case, the sulfur level in the tapped iron is a function of slag basicity and the MnO content of the slag. Sulfur levels in the iron decrease with increasing basicity and decreasing MnO.

Figure 8 shows the relationship as it relates to basicity. At any given basicity, the range of attainable sulfur levels depends on carbon equivalent. The higher the carbon equivalent, the lower the sulfur level in the iron. As apparent from the figure, there is little benefit to increase basicity beyond B=1.2.

Although the relationship between sulfur level and slag basicity is well recognized, the important role of MnO is less understood. Figure 9 illustrates the effect of MnO.

Since MnO is a product of the alloy loss reaction involving FeO (reaction 1), it is necessary to minimize FeO production in order to achieve the lowest sulfur levels. To produce the sulfur levels below 0.01%, MnO levels of no more than a few tenths of a percent can be tolerated. To achieve effective desulfurization with neutral slags requires that MnO levels in the slag are no greater than 2 or 3%. Acid slags contain very little sulfur hence the level of MnO is unimportant.

Refractory Erosion
As indicated earlier, there are two distinct types of slags in the cupola. In the slag layer in the cupola well the slags contain mostly CaO and SiO2. Above the slag layer the predominant oxides are CaO and FeO. These slags are much more corrosive in nature and their corrosiveness is exacerbated by the high temperatures that exist in the regions above the tuyeres.

The CaO-FeO slag above the slag layer is basic hence silica based refractory perform very poorly in this region. MgO refractory might be best suited for use in this region. However, alumina refractory is most often used, perhaps due to cost considerations.

Even alumina refractory is rapidly eroded by slag attack in the region above the tuyeres. This leads to the considerable loss of heat. Recently, alumina/silicon carbide refractories have been used in this region with good results. The improvement stems from the high thermal conductivity of the refractory. This sufficiently lowers the temperature on the hot side of the refractory to allow a frozen layer of slag to form which serves to protect the refractory. This slows the erosion process and leads to heat savings with ensuing benefits of lower fuel requirements, higher iron temperatures, improved alloy recovery and lower refractory maintenance, which offsets the extra cost for refractory.

The slag above the taphole is much less corrosive than the slag above the tuyeres. Alumina refractory or silicon carbide/alumina refractory is most commonly used today. For basic slag operation, the refractory can be MgO or carbon.

CORELESS INDUCTION FURNACES

Slag Formation
Far less chemical reaction takes place in coreless induction melting furnaces than in the cupola. Induction furnaces produce about one-third the amount of slag than do cupolas. Compared to the cupola no limestone is needed to flux coke ash; cement bonded ferroalloys are not employed, easily oxidized charge materials such as borings and turnings are not used and no desulfurization is attempted. The external sources of slag-forming materials are given in Table 7.
Table 7. External Sources of Slag-Forming Materials

- Sand adhering to cast charge materials (SiO₂)
- Dirt (Fe₂O₃/SiO₂)
- Rusty scrap (Fe₂O₃)
- High scrap preheat temperatures (Fe₂O₃)

**Alloy Loss**

Compared to the cupola less FeO is produced due to lower contact between the atmosphere and the iron. Although the absolute amount of FeO produced is lower, the FeO concentration in the slag is higher because the slag has less opportunity to react with alloy elements due to the limited contact between slag and metal. The amount of alloy loss generally reported is between 5 and 10%. The level of losses should be proportional to the aspect ratio of the furnace and inversely proportional to AC frequency. The lower the frequency the greater is the velocity of iron at the iron/slag interface. Thus, furnaces operating at 60cps should experience greater alloy losses than high frequency furnaces.

**Desulfurization**

The high FeO levels in the slag, its acidic nature and lack of stirring preclude any desulfurization.

**Refractory Erosion**

The major slag problem encountered in coreless induction furnaces is erosion of the nearly universally used silica refractory. Although an alumina based refractory would encounter less erosion due to lower solubility in FeO rich slags, silica refractory is almost universally used, ostensibly due to lower cost. To reduce the corrosive action of the FeO-rich slags, silicon carbide is added to the slag to sacrificially remove FeO by the following reactions:

\[
3FeO_{\text{slag}} + SiC = SiO_{2\text{slag}} + CO + 3Fe \tag{11}
\]

\[
FeO_{\text{slag}} + SiC = Si_{\text{iron}} + CO + Fe \tag{12}
\]

The density of SiC (3.2 g/cc) is almost the same as slag (3.5 g/cc). Thus, it remains suspended in slag, which maximizes the time available for reaction. SiC usage is about 5-10 lbs/ton iron. A technique that might retard slag attack is the addition of a thickening agent that would reduce the rate of diffusion of FeO to the refractory surface.

**HOLDING FURNACES AND LADLES**

The iron held in holding furnaces and ladles is generally quiescent and relatively little slag is created. Thus, compared to melting furnaces, there is relatively little alloy loss generated and the attack on refractory is slower.

Refractory erosion problems in holding furnaces can be accelerated if desulfurization slags are permitted to enter the furnace. Oxidation of reactive elements such as magnesium or excessively high temperatures in the inductor can produce insoluble materials that create build ups. Serious refractory problems have been created by the Zn present in iron produced from galvanized steel scrap. Problems of alloy oxidation can be minimized with covered vessels and, even better, covered vessels using inert atmospheres.

There are two very important processes that are carried out in ladles: desulfurization and alloy addition. Alloy additions to ladles are made to adjust the chemical composition of the iron and to inoculate the iron. The former is generally made to correct a deficiency in the iron composition or in some cases to obtain a higher alloy yield than in the cupola. Inoculation is carried just prior to pouring iron into the mold in order to obtain a desired microstructure. Both desulfurization and inoculation can be seriously affected by slags.

Ladle desulfurization employing CaO/CaF₂ (limespar) or CaC₂ can reduce sulfur levels in iron to as low as 0.002%, an order of magnitude lower than the best cupola performance.

As indicated earlier, the most serious problem limiting the reduction of sulfur is agglomeration of the desulfurizer (Figure 1) due to the presence of slags. The slags are either introduced with the iron stream or produced in-situ through oxidation. The problem is avoided by taking three steps. (1) prevent cupola slags from contaminating the iron stream (2) use a deep layer of desulfurizer in the ladle to prevent air from oxidizing the iron and (3) use desulfurizer with the optimum average particle size of 1mm.
The importance of particle size is illustrated in Figure 10 for CaO/CaF₂ desulfurizer. The particle size refers to CaO. Very small particle sizes are easily agglomerated even with very small amounts of slag. The optimum size is seen to be 1mm. At this point the input and output sizes are the same. It is at this size that particles become insensitive to slag because they can break away from each other due to motion in the desulfurizer layer. This is equally true for larger particles. However, beyond 1mm the particle surface to volume ratio gets smaller so it is less effective for desulfurizing. This work was conducted in a laboratory reactor, however, the size was verified in commercial operations.

Ladles used for desulfurization with CaO/CaF₂ become encrusted with tricalcium silicate (reaction 5). The deposit is easily removed by allowing the empty ladle to cool to room temperature. On cooling tricalcium silicate transforms to dicalcium silicate and calcium oxide. Due to volumetric changes accompanying the phase transformation the solid material is reduced to a fine powder.

Special attention needs to be paid to the pouring ladle as slags play such an important role in defect formation: inclusions, blow-holes and poor inoculation. Two of these problems are illustrated in the following example.

A foundry was adding Ba/Ca/Al ferrosilicon inoculant to pouring ladles and then filling the ladles with molten gray iron. Consistently good inoculation could not be achieved. When good inoculation was achieved the castings suffered from blow-hole problems. The analysis of ladle slags from good and poor inoculations, given in Table 8, suggested the cause.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Partial Slag Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Barium</td>
</tr>
<tr>
<td>Good Inoculation</td>
<td>11.1</td>
</tr>
<tr>
<td>Poor Inoculation</td>
<td>39.3</td>
</tr>
</tbody>
</table>

With good inoculation the slag contained large amounts of FeO and relatively small amounts of the barium inoculant. The opposite was true with poor inoculation. It suggested that the ladle slags ordinarily contained high levels of iron oxide. When the slag levels were high, the time that inoculant and slag were in intimate contact was sufficient for the barium to be oxidized (reaction 7). When the slag levels were low, the inoculant escaped oxidation. Thus slags entering the mold were rich in FeO which created porosity defects (reaction 1). In this situation FeO was responsible not only for the cost of lost inoculant but also for the cost of a considerable casting scrap.

A large reduction in casting defects would be achieved if slag is prevented from entering the mold. This is facilitated by frequent slagging of pouring ladles. Automated iron pouring systems create more problems than manual-pouring, because of infrequent slagging. Filters placed in the mold are a partial but not a complete solution. One effective method might be to add thickeners to the slag so that they would not be easily entrained in the iron stream. Finally, efforts to develop improved ladle designs would be worthwhile.

IRON TRANSFERS

Slag is produced when iron is transferred from one unit to the other. For example in large ductile iron foundries, the iron can be transferred as many as six times between melting and pouring. The primary product in iron transfers is FeO, thus, generating conditions for alloy loss and refractory erosion. Oxidation can be minimized by ensuring coherent metal streams and shrouding the iron streams to prevent access by air.

SUMMARY

In summary, with the current financial stress in the foundry industry greater attention needs to be paid to the costs incurred from the pervasive presence of FeO-rich slags. Many of the solutions may require more expensive materials but they do not require large capital outlays. Cost/benefit studies should make clear how to effectively reduce cost and improve quality.
Figure 1. CaO/CaF$_2$ desulfurizer taken from a production reactor showing moderate agglomeration.

Figure 2. Cupola well showing iron oxide (white) and iron (black) drops.
Figure 3. Residual silicon and manganese concentrations in commercial cast iron briquettes after melting.

Figure 4. Dependence of silicon recovery in a cupola versus the residual silicon concentration in cast iron briquettes after melting.
Figure 5. Silicon concentration versus time for a cupola melting without aluminum (-4 to 0 hour) and with aluminum (0 to +4 hours). Zero hour is when aluminum entered the melt zone.

Figure 6. Iron temperature versus time for the operation described in Figure 5. The line is the theoretical line based on the assumption of instantaneous mixing of slag entering the slag pool.
Figure 7. Silica (closed circles) and alumina (open circles) concentrations in slag versus time. The lines are the theoretical lines based on the assumption of instantaneous mixing of slag entering the slag pool.

Figure 8. Sulfur concentration versus slag basicity assuming 10% slag and chemical equilibrium for reactions 2 and 3.
Figure 9. Dependence of the sulfur concentration on the MnO content of the slag.

Figure 10. Average particle diameter of CaO/CaF₂ desulfurizer before ($d_i$) and after ($\bar{d}_i$) desulfurization in a laboratory reactor.
REFERENCES

5. Volk R.J., “Application of an Alumina-Silicon Carbide Gunning Refractory to the Cupola Melt Zone,” Refractories for Foundries, 33rd Annual Symposium on Refractories, American Ceramics Society, St. Louis Section, St Louis, MO, (March 21 1997)
10. Katz, S., Unpublished data
17. T. Mutton, Private Communication