

# Use of Hot Metal With High Phosphorous Content in Combined Blowing BOF Converters

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Modern iron- and steelmaking is based on economic effectiveness, environmental friendliness and

**Many steelmakers are faced with very high [%P] contents in the hot metal coming from blast furnaces. Combined blowing technology is based on top-blown oxygen and inert gas injection through the converter bottom using a jet-stream with supersonic velocity. This paper presents a summary of two decades' experience with combined blowing technology.**

resource-sparing production technologies. The aim for sustainability of the industry in the past 40 years led to success in:

- The reduction of energy consumption.
- The reduction of emissions (dust and CO<sub>2</sub>).
- The reduction of waste and residuals.
- The increase of the total metallic yield.

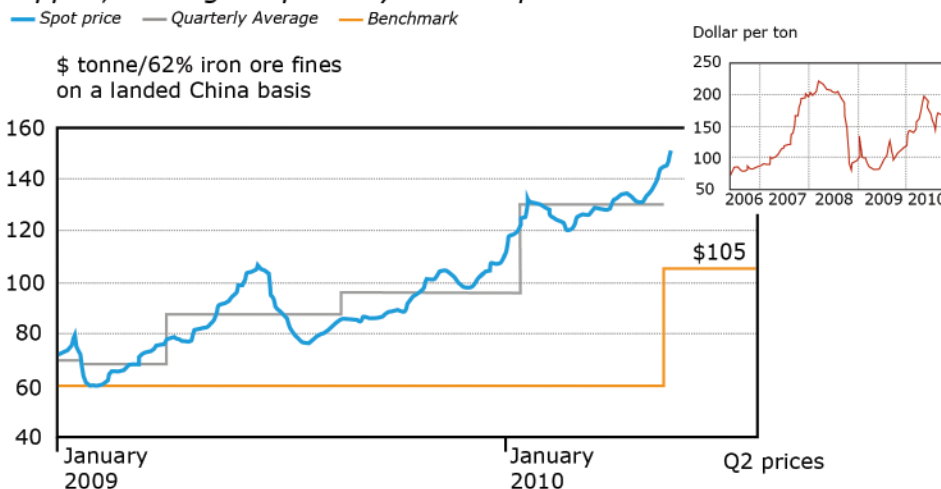
One of the major factors of this success was the change in the raw material base from natural consistency to physical and thermal prepared burden materials like sinter, pellets and metallurgical coke. This change was done in combination with the replacement of low-purity iron sources by premium qualities > 62% iron content and low tramp element (phosphorous, sulfur, manganese, residuals) load. This development caused a change in the iron ore supply and logistics of most countries where raw material sourcing changed from domestic to

seaborne supplies. Today, the major market volumes for iron ores are mined in Australia (41%), Brazil (36%) and India (6%). The coking coal market is dominated by Australia (67%), United States (16%) and Canada (10%).<sup>2</sup>

The recent trend in steel markets, with an exceptional production growth in China even after the downturn in 2008–2009, stresses that raw material prices for coking coal and iron ore are almost back to the hype levels. Since the mining costs have not increased significantly in the past years (although fuels and tuyeres became more expensive), the market prices are dominated by the “fantasy” caused by the spot market price development between China and India. The contract market prices are not directly following the spot market trend, but a marginal increase in the spot market will cause a significant increase on the contract prices as well, as happened in 2Q10 with an increase from US\$60/ton to US\$105/ton. The same effect happens in the case of metallurgical coal, with trends pushed by the flooding in East Australia from US\$129/ton in 2009 back to

Figure 1

*Nippon, Vale agree quarterly iron ore price deal*

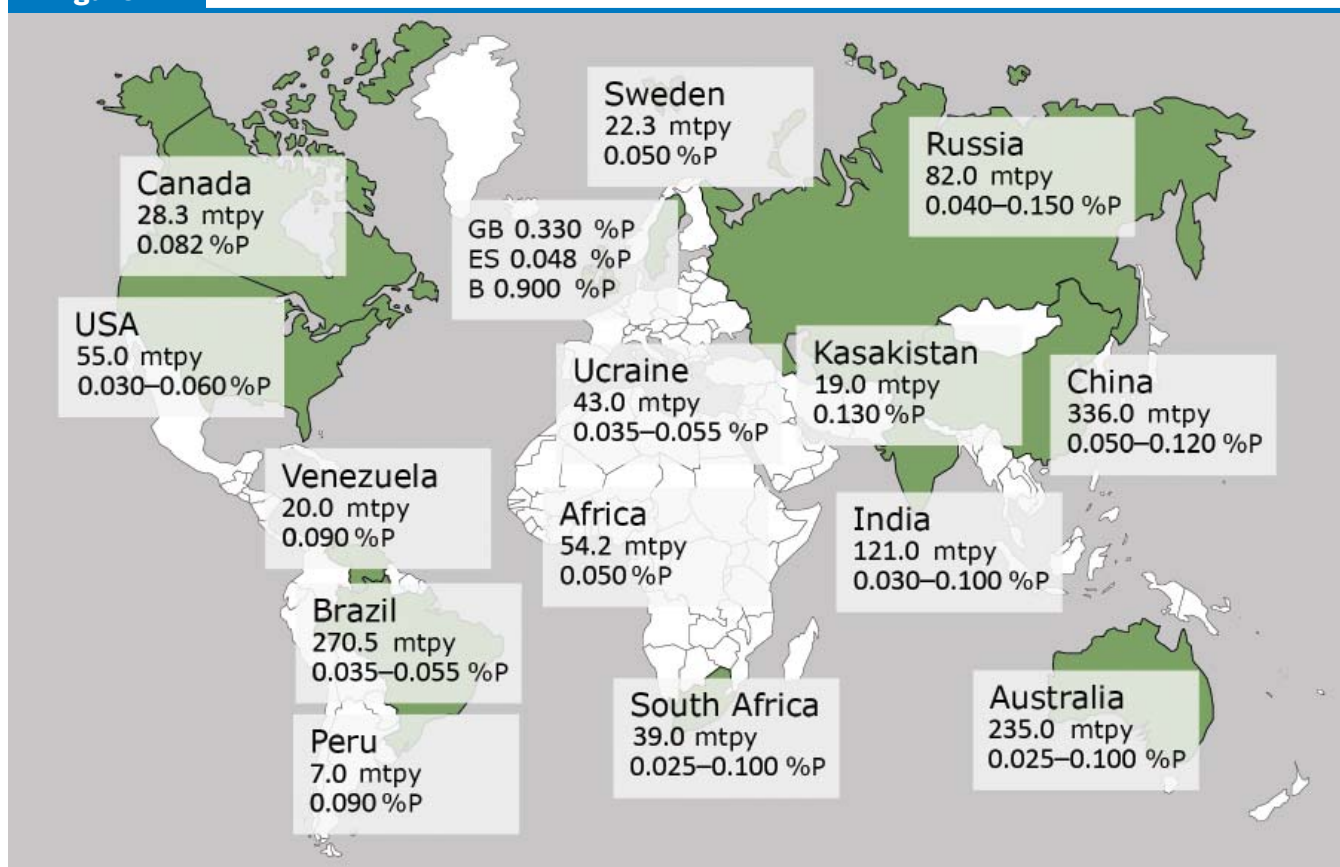


Development in iron ore spot market prices.<sup>3</sup>



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**Figure 2**Iron ore production in the world.<sup>6</sup>

the hype level of US\$300/ton expected for the second half of the actual year. Metallurgical coke from Chinese sources is already back to the levels of US\$400/ton.<sup>4</sup> These trends create for steel producers and their customers a strong demand for new strategies in raw material sourcing that allows for better cost control. Many steel producers are moving back to the old strategy of backward integration, which was common in the age of industrialization. Led by ArcelorMittal, which aims for a backward integration of 70% and higher,<sup>5</sup> steel companies are engaging in coal and iron ore mining projects. But in the long run, this strategy will not stop the price increase spiral significantly, because as long as the world market prices are increasing, captive mining will also inflate the price of the steel products with high raw material price levels.

Alternative concepts are needed to process resources that were not valuable enough in the past to compete with the premium-quality materials on the market.

### Iron Ore and Hot Metal Phosphorus Levels in Different Regions of the World

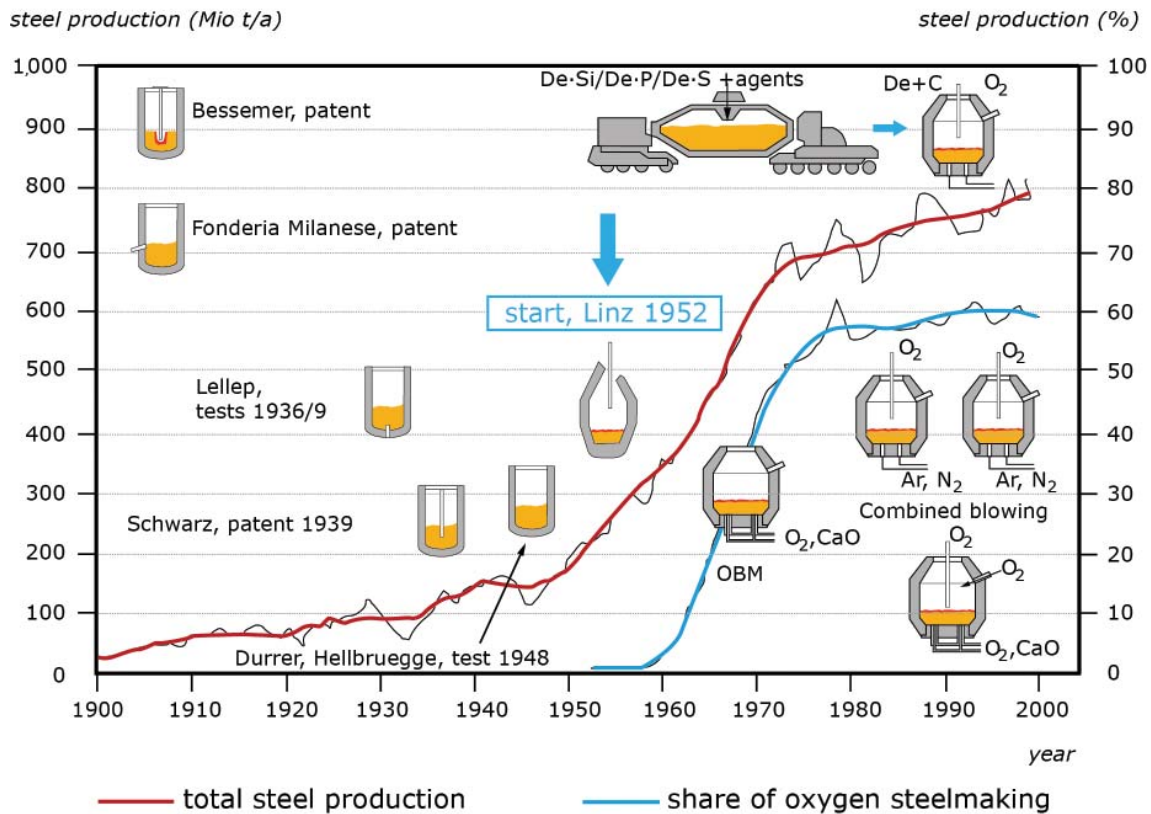
One limitation in iron ore grade quality is the phosphorous [%P] content. [%P] harms the steel product properties and therefore is, similar with sulfur, not desired in steel. In the reduction step, the [%P] input into the blast furnace is naturally converted into the hot metal by 90–100%. The only possibility to limit the [%P] of the hot metal is to use a low-[%P]-containing iron burden. Therefore, low [%P] content, besides the Fe, the Mn, the silica, the alumina, the alkali and the residuals

content, is one of the criteria to define premium iron ore quality.

[%P] input by iron ore is reduced by almost 90–100% into the hot metal. It is clear that higher [%P] content in hot metal requires greater efforts in steelmaking operations. The efforts of higher expenditures for [%P] removal are thereby moving from the iron ore beneficiation to the steelmaking operations. But since the raw material price spiral continues to climb, the benefits from using premium ore quality are more and more overcompensated.

When looking at the iron ore world map in Figure 2,<sup>6</sup> it becomes obvious that today, low and high [%P] sources are available around the globe. Especially in the Commonwealth of Independent States (CIS) region, Pakistan, India, the Middle East, Europe, and also in South America, ores with higher [%P] content are offered to the markets. In the U.S., it is well known that so-called “selective mining” is practiced, which guarantees very low [%P] input to the steel mills. But it also decreases domestic availability and raises the demand for foreign imports. It can be stated that the processing of higher [%P] iron ore resources will improve the iron ore availability and decrease the worldwide stress on the iron ore market.

Similar relations are valid for the sourcing of metallurgical coke and coal. In general, the [%P] contents in coking coal or injection coal are much lower than in the iron ore, but also [%P] in the coke ash will be reduced almost totally into the hot metal. Also in the case of coal, an opening of the sourcing specification will open new

**Figure 3**

The ladle degassing success story.<sup>9</sup>

possibilities for supplies and lower prices. In the end, the total [%P] load in hot metal is determined by the iron burden, the fuels used for melting, and the type and composition of recycling materials used during processing.

### Ancient Process to Remove [%P] in Steel

In the beginning of modern steelmaking, it was common to process high-[%P] (> 1.6%) hot metal in air-operated, bottom-blowing, basic-lined vessels (Basic Bessemer or Thomas Process) and refine it to crude steel. The reason was the availability of high-[%P] domestic iron ore sources, especially in Europe. Although the productivity and the yield of the process are much higher compared to the indirect, regenerative fired open hearth (OH) process, the steel quality produced was not competitive.<sup>7</sup> For example, a Thomas heat of 30 tons could be blown to 1,625°C, low-[P] content < 0.050%, low [C] content at only 13% of (Fe) required in the slag. A 300-ton OH furnace could produce 45 tons/hour to achieve the same low-[P] and [C] with much higher (Fe) or much lower ( $P_2O_5$ ) contents. Also, the processing of low-[P] steel hot metal is required. So, productivity and yield of the Thomas process was significantly higher. On the other hand, the [N] pickup from the blowing air, the ( $P_2O_5$ ) reversion to [P] while tapping the vessel over the mouth and the poor De-S capabilities were clear quality disadvantages, especially in the production of low-carbon flat rolled and cold formed steel.<sup>8</sup>

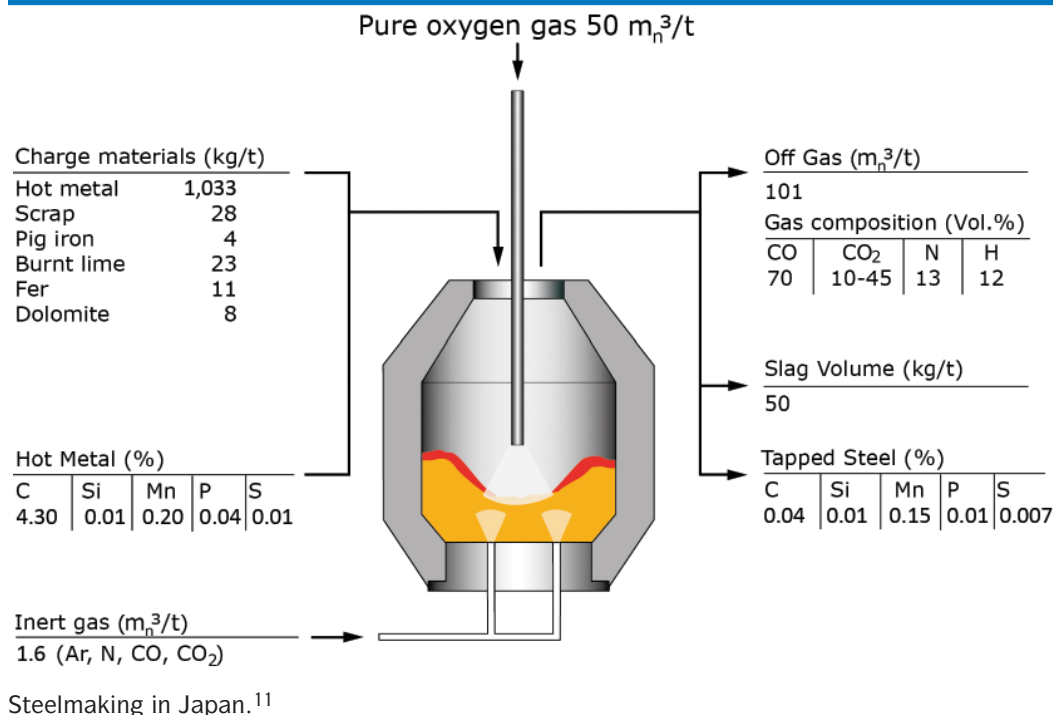
Starting before World War II, steel producers aimed to improve the enrichment of the blowing air by using pure oxygen. The development of this technology was

possible after the introduction of the Linde-Fränkl process for industrial-scale production of pure oxygen in the late 1920s. With oxygen enrichment, it was possible to equalize the steel quality to the levels of the OH process and to increase the productivity further. But the use of oxygen through the converter bottom caused new challenges in operations, such as severe bottom wear, and was limited to a maximum of 25%. Another advantage of the oxygen use was the reduction of the nitrogen ballast that increased the sensible heat generated by the decarburization and created the demand for additional cooling agents.<sup>9</sup>

The opportunity to melt the internal scrap produced in an integrated mill without using other furnace installations forced voestalpine's decision to invest in the development of the ladle degassing (LD) process with 100% pure oxygen blowing through a water-cooled lance in Austria in the 1950s. Another reason for the decision to use a blowing process for the planned capacity increase in Linz was the lack of heavy oil, coal and purchase scrap resources available in Austria, which are necessary to operate an OH plant.<sup>10</sup> The results of the process regarding crude steel purity (C, P, Mn, O, N, S) at low (Fe) and low slag volume and high [Fe] yield was so successful that the process spread quickly. After only 20 years in operation, the LD process and its process alternatives are used in almost 80% of the world steel production.

Today, crude steel production worldwide has almost doubled the levels of the year 2000, but the share of process remained the same. Only a few OH plants have survived the change in the CIS. Only one Thomas steel



**Figure 4**

mill is still operating in the highlands of Columbia, which is called Aceria Paz del Rio (APDR).

The conversion of European steelmaking to the oxygen blowing processes at the end of the 1960s opened the door for blast furnace operations to switch from high-[%P] domestic iron ore supplies to much cheaper high-[Fe] and low-[P] foreign sources developed in Brazil and Australia. The use of these ores allowed for the reduction of the gangue volumes related to iron production and a huge improvement in energy consumption savings and byproduct utilization development, which made the aim for sustainability (yield increase, energy consumption reduction, dust and CO<sub>2</sub> emission reduction, and full recycling and zero waste concepts) possible.

The technology used to achieve these goals is different across continents. Europe moved from being a domestic producer to an import (raw materials)-based producer. In the U.S., traditionally, steel production was based on high-quality hot metal. Here, selective mining is used to control iron ore accompaniments. In Japan, an alternative technology to deal with higher impurities was developed. As shown in Figure 5, the pretreatment of hot metal is common practice in this major steelmaking country. Figure 4 demonstrates the effect of very low [Si] and [P] content in hot metal on the achievable process results.<sup>11</sup>

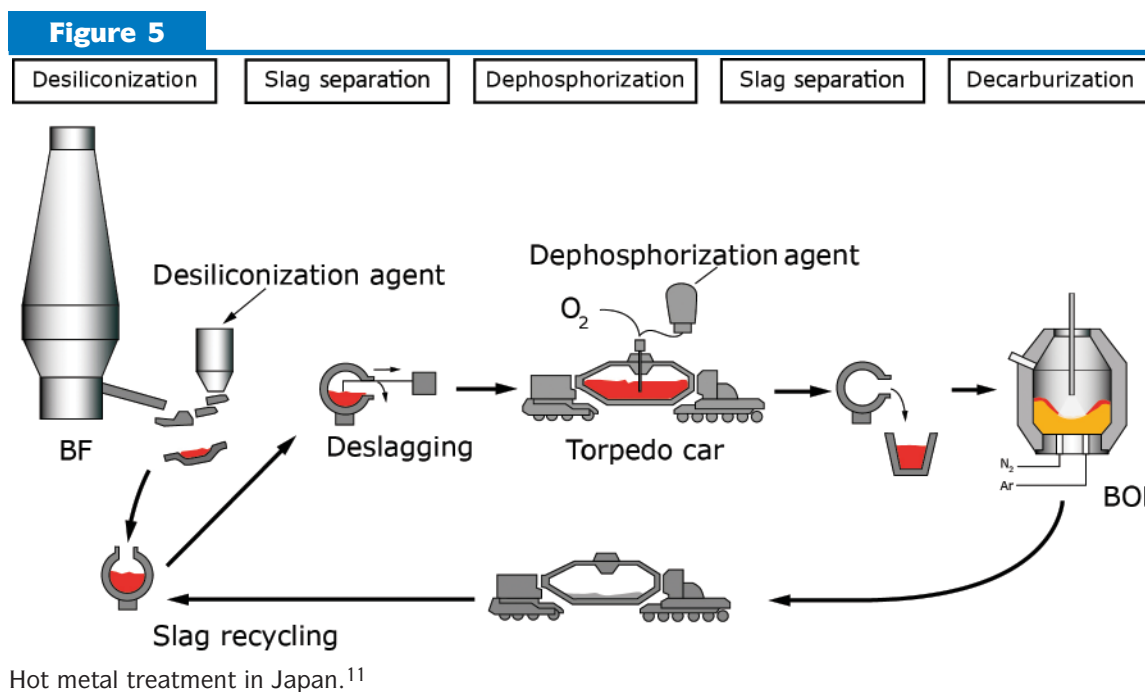
Very low slag volume, high yield, and very low [C], [Mn], [S], [N], residuals and [P] content in crude steel are achievable with this technology. In the meantime, the Japanese have developed their technology to be implemented even in brand-new steel plants. The new Sumitomo meltshop in Wakayama, commissioned in 2002, has a two-aisle BOF shop where one hot metal de-Si and de-[%P] vessel serves two de-[C] vessels at a time. This unique shop configuration illustrates the recent status of the Japanese primary steelmaking technology.<sup>12</sup>

Another process used in the beginning of LD steelmaking is the LD-AC process, developed to utilize the high-[%P]-containing Belgian and French domestic iron ores for steelmaking applications.<sup>13</sup> The process is quite similar to the Japanese technology, but the process is operated in a single LD vessel. In the first blowing period, pulverized lime is injected together with oxygen via a center hole in the blowing lance on top of the melt to enforce slag forming. After de-Si and de-[%P], the process is interrupted, the silica- and [%P] oxide-rich slag is removed from the melt, and in the second blowing period, the de-C work is carried out. The process is a compromise between the clear disadvantages of using torpedo ladles as metallurgical reactors and the double BOF vessel strategy used in Japan today, but applicable in case of higher input [%P] in the BF iron ore and fuels. The economics depend strongly on the installation configuration of the site. If there is an overcapacity of the meltshop compared to the refining and casting facilities, this process is economical in case of high-[%P] hot metal. If the meltshop is the bottleneck in an integrated steelmaking facility, other solutions must be implemented.

The latest attempts to utilize high [%P] iron ores and hot metal with high silicon and manganese content are reported from ArcelorMittal Temirtau, Kazakhstan. In this plant, the challenge is to survive with hot metal containing 0.25–0.45% of P, 0.90% of [Si] and 0.80% of [Mn]. The operation conditions for the installed top-blowing-only 330 mt/heat vessels are not favorable. High slag volumes and heavy slopping during blowing are accompanied with this practice. A single-slag versus a double-slag practice is being discussed within the company due to vessel campaign life and productivity aspects.

## Metallurgy of Hot Metal De-[P]

The fundamentals of hot metal de-[%P] are described in various publications from Japanese and Korean



steelmakers.<sup>14</sup> Low silicon level ( $< 0.2\%$ ) of the hot metal is known to be a precondition for the high-efficiency oxygen use for de-[%P]. Therefore, the hot metal is treated by iron-oxide-based flux injection into the torpedo car. The silica-rich slag must be drained before entering the next processing steps. After de-[%Si], the hot metal is transferred to the de-[%P] station, where oxygen and iron oxide- and lime-containing fluxes are continuously injected into the melt. If availability is a problem, dry gas cleaning system, BOF dust (high FeO) and lime powder can be used economically. A few problems are reported from the de-[%P] treatment:

- Slag foaming is observed when the O/CaO ratio is too high in the beginning.
- Temperature losses become significant when too much flux must be used to achieve the de-[%P] targets.
- Time consumed for pretreatment is too long to match with the sequence of the BOF.

Slag foaming can be avoided by controlling initial silicon content of the hot metal and by controlling the iron oxide/lime ratio, which should be increased slowly during the 30- to 35-minute treatment time. Temperature losses are basically generated by the flux volume injected ( $\cong 0.025^\circ\text{C/kg}$ ). De-[%P] efficiency is favored by lower hot metal temperatures, but the hot metal temperature should not be too low to guarantee proper handling and sufficient scrap rate in the BOF.

A mixture of nitrogen and oxygen gas is used as the injected shrouding gas to compensate heat losses. With the moderate treatment speed, the time consumed for the de-[%P] accelerates to 30–35 minutes per batch.

Taking into account that the de-[%S] process requires reducing atmosphere, the slag must be skimmed again after the oxidizing de-[%P] treatment. Because this precondition cannot be guaranteed properly enough for highly efficient de-S, highly reactive sodium carbonate (2–3 kg/ton) is used. Since the sodium is also reacting with C, [Si] and [P], low contents of [Si] and [P] in the melt are favorable. Disadvantages of the use of sodium are:

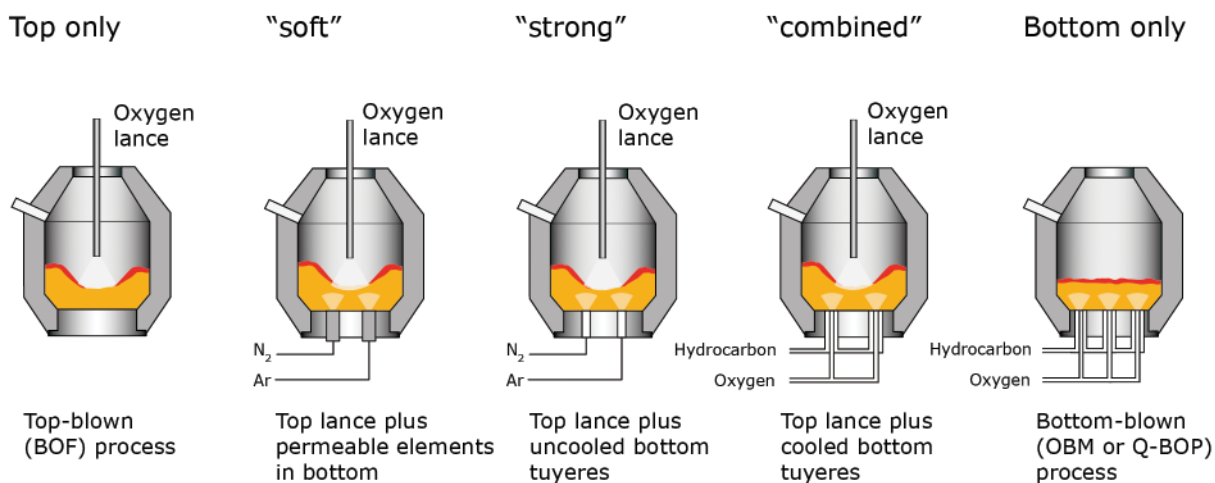
- Sodium is a hazardous alkali metal. Fumes generated during treatment must be completely collected.
- Alkali attack increases chemical erosion on torpedo car refractory.
- The recycling of the de-S slag skimmed at the end of the injection treatment becomes more difficult.

As an advantage, sodium reduces the iron losses in the slag because it decreases the slag viscosity so that iron droplets kept in the slag can settle back into the melt. Deep de-S treatment of the hot metal will be done in the charging ladle by injection of lime and magnesium, if required. A summary of the results and consumption figures of the hot metal treatment is given in Table 1.

**Table 1**

**Hot Metal Treatment in Korea<sup>14</sup>**

	Hot metal (t/TLC)	EP dust (kg/t)	Lime (kg/t)	Na <sub>2</sub> O <sub>3</sub> (kg/t)	[Si] (%)	[P] (%)	[S] (%)	Temp. (°C)	Treatment time (min./tLC)
Before treatment	259.7	27.1	14.6	2.1	0.12	0.085	0.023	1,274	50
After treatment					0.04	0.041	0.004	1,273	

**Figure 6**

The oxygen steelmaking process "family."<sup>15</sup>

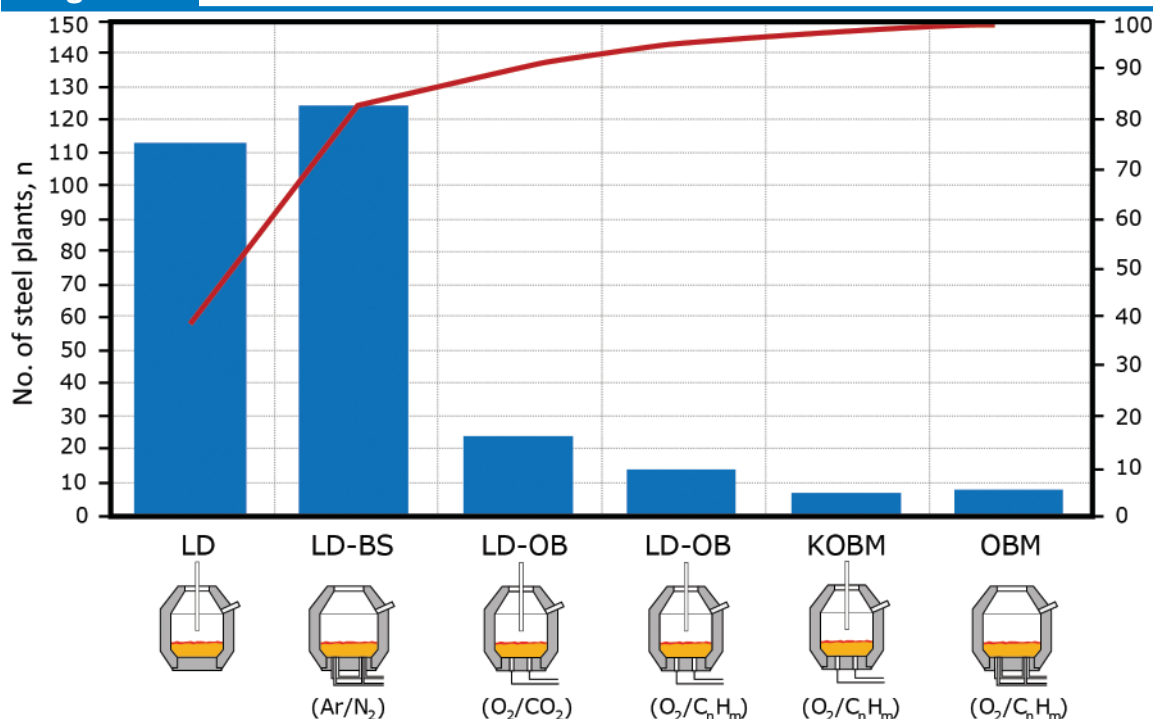
### The Modern BOF Blowing Technology

Because of the poor de-S capacity of the oxidizing refining process, the state-of-the-art technology in oxygen steelmaking in the world today is de-S hot metal pretreatment combined with oxygen refining in the BOF vessel. Silicon and manganese are generally limited by low fuel operation and use of low-manganese iron ore in the blast furnace to levels of 0.25–0.55% [Si] and 0.20–0.40% [Mn]. The [%P] content in the hot metal is controlled by the use of low-[%P] iron ores to levels of 0.060–0.090%, which can be handled economically in the operation. The process installations used vary from "top-blowing-only" to

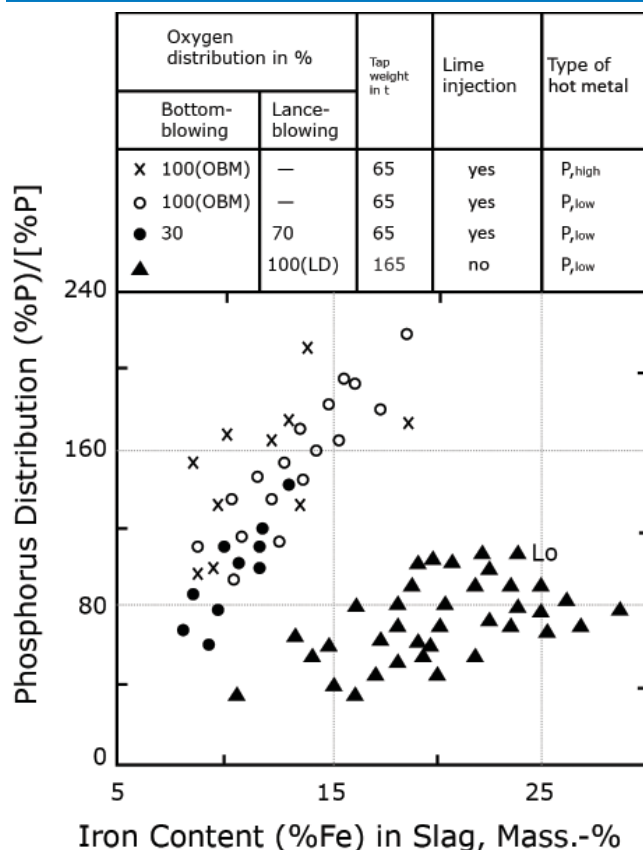
"bottom-blowing-only," with a number of combined blowing process types used in operation (Figure 6).

Looking at the applied installation, it becomes obvious that the world is separated in two major philosophies — the bottom-stirring and the top-blowing operations, with a majority utilizing the metallurgical advantages of the bottom-stirring technology. The combined, or bottom-blowing, process applications today represent only 5% of the total number of plants operated.<sup>16</sup> Of course, it must be mentioned that in Japan, the use of oxygen via bottom tuyeres is the standard technology.

The question of why almost 40% of the operating BOF plants today do not apply the metallurgical advantages related to the quicker and closer approach to

**Figure 7**

The application of oxygen steelmaking process variety.

**Figure 8**


Achievable [%P] partition in different process variants.<sup>13</sup>

equilibrium by operating bottom stirring process types is rather difficult to understand. On one hand, the availability of cheap, low-[%P]-containing iron ores in recent decades made it easy to fulfill the increasing demand of ultralow-[%P] steel products without the necessity of enhanced processing activities. On the other hand, the demand for ultralow [%P] content in steel is not a general approach from the product side. The demand

of superior quality steel on the market is estimated to be only 10% of the total volume.

This relationship is also valid in the portfolio of a single steel plant. The main volume of steel products simply does not require highly sophisticated production technologies like bottom stirring or bottom blowing. In that case, other operation parameters — like vessel campaign life, for example — are more in the operations' focus.

But when the process comes to the limits and ultralow-carbon grades must be produced, low-[%P] steel grades are required or high-[%P]-containing metal must be processed, the advantage of the combined blowing processes becomes obvious. Figure 8 shows results from a comparison of a top-blowing-only and a bottom-blowing-only process regarding de-[%P]. It is obvious that the bottom-blowing variant achieves much higher de-[%P] levels.

In Figure 9, similar results are shown for the “end of blow” and the “post-stir” results in a top-blowing process with inert gas bottom stirring.

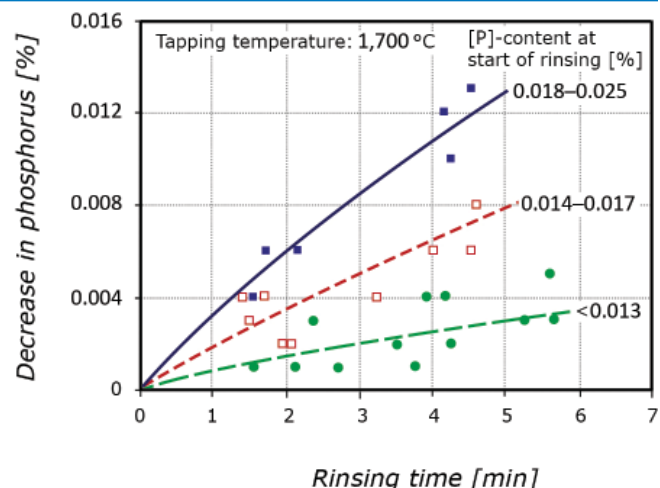
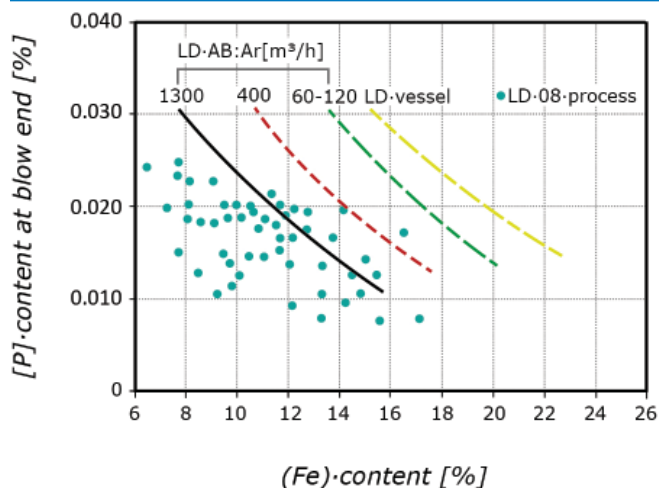
Several types of bottom-stirring elements are available on the market today. They are, namely:

- Multihole or porous plugs.
- Fork stirrers.
- Single-hole stirrers.
- Annular gap inert gas tuyeres.
- Oxygen tuyeres with annular gap cooling gas shrouding.

Of course, every product on the market has its own individual pros and cons. But the most important questions are:

- Can the bottom-stirring elements survive in the operations environment?
- Is the equipment doing the job for which it was installed or not?

These questions cannot be answered generally, but are strongly dependent on the individual production

**Figure 9**


Achievable [%P] content in steel in top-blowing LD with inert gas bottom stirring.<sup>17</sup>



environment of the given meltshop. Generally speaking, the following may be valid theses:

- If the quality program of an individual meltshop requires low and ultralow carbon [%C] content in the steel, it is favorable to relieve the vacuum degassing capacity and blow down all heats to carbon levels below 350 ppm. This can be achieved at moderate steel oxygen [O] and slag iron oxide (%FeO) by bottom stirring to control iron losses and deoxidation agent consumption related to nonmetallic inclusion forming during processing.
- If the quality program of an individual meltshop requires low [%P] content in the steel, de-[%P] in oxygen steelmaking, which is a transition reaction between metal and slag, can be enhanced by vigorous stirring. This effect helps in the case of very low [%P] required in crude steel, as well as in case high-[%P]-containing hot metal must be processed.
- If economics of steelmaking are part of the focus, it can be stated clearly that efficient mixing of steel and slag during processing will improve the yield and consumption figures of the process in many different performance indicators, as follows:
  - Homogeneous melt.
  - Faster scrap melting.
  - Lower [%C] at blow end.
  - Lower [%O] at blow end.
  - Higher [%Mn] yield.
  - Controlled [%N] yield.
  - Controlled tap temperature adjustment by post-stirring.
  - Lower slag [%FeO].
  - Higher de-P and de-S capacity of the slag.
  - Lower slag volume.
  - Less slopping.
  - Lower oxygen consumption ( $\sim 2 \text{ m}^3/\text{tLS}$ ).
  - Fewer reblows for [%P] and [%C].
  - Higher flexibility with respect to hot metal composition.
  - Lower slag flux consumption.
  - Higher scrap rate possible.
  - Higher Fe yield (up to 1% improvement).

- Better condition for substance use.
- Better precondition for oxygen measurement and aluminum adjustment.
- Lower (%FeO) content in the ladle slag.
- Lower aluminum consumption (up to 0.3 kg/t).
- Narrow Al range in molten steel achievable.
- Savings of manganese alloys.
- Increased refractory campaign life.

- If vessel lining life is (for whatever reason) in the focus of operations, bottom stirring with the available systems is reaching its limits. On the one hand, vigorous stirring through the bottom requires open surface diameter of the stirring elements. On the other hand, vigorous stirring is in conjunction with higher bottom wear that limits the campaign life. The question arises if there is a technical solution imaginable that combines both targets: long lining campaign life and efficient stirring results.

The answer and decision of which way to go must be approved for every steelmaking facility individually, as mentioned earlier. But if [%P] content in crude steel or in hot metal becomes the topic, the following discussion must be taken into account.

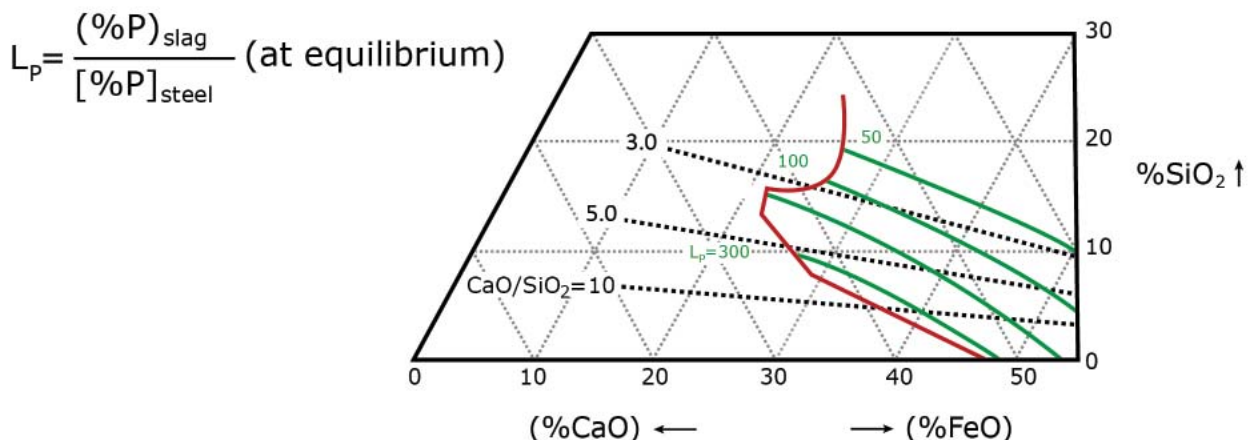
### De-[%P] Modeling and Consequences for BOF Operation Modifications

The mechanism of de-[%P] was studied in many research publications in the last 50 years and can be stated as common knowledge. The commonly known reaction equations indicate that oxidizing atmosphere is required for sufficient [%P] removal.

But in industrial steelmaking operations, the [%P] is not reacting directly with the oxygen to  $\text{P}_2\text{O}_5$ , but FeO to liquefy solid lime into the slag, and the stable combination of the [%P]-pent-oxide with the liquid lime is the key reaction for successful de-[%P]. The de-[%P] capacity of the slag generally will be described by the solubility product  $L_P$ , which is shown as the quotient of [%P] in slag and [%P] in steel in Figure 10.<sup>19</sup>

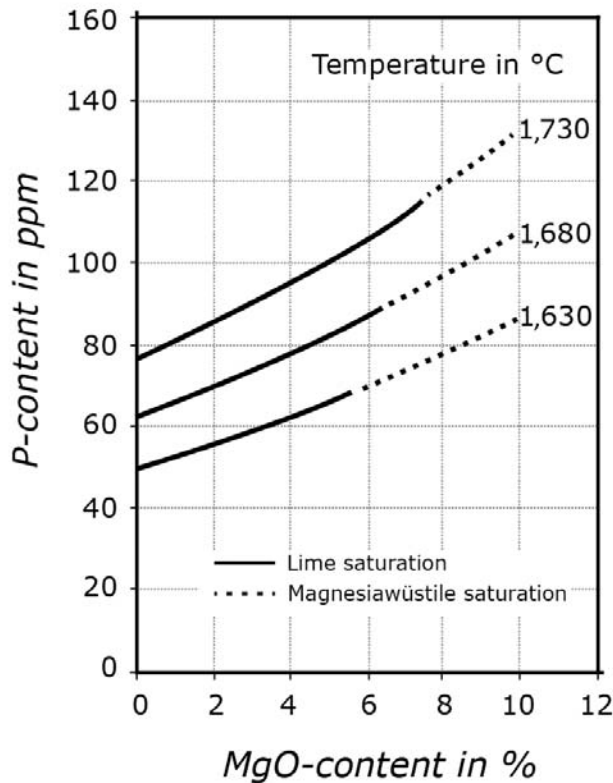
In the diagram in Figure 10, the lines of equal basicity ( $\% \text{CaO} / \% \text{SiO}_2$ ) and  $L_P$  demonstrate that  $L_P$  is very

**Figure 10**



Phosphorus distribution  $L_P$  and slag composition.<sup>19</sup>



**Figure 11**


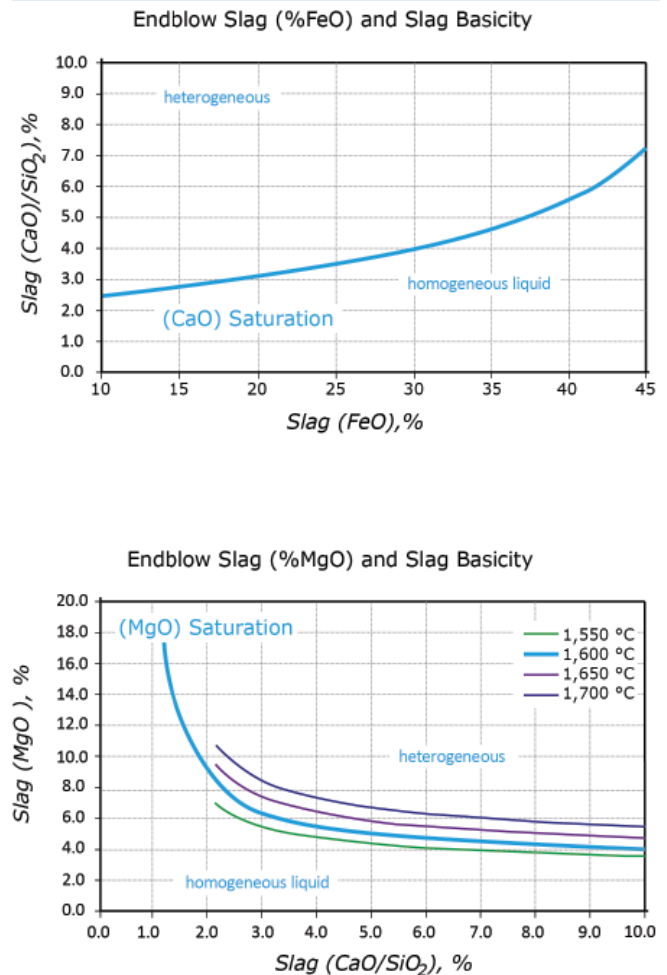
Achievable steel [%P] and (%MgO) and steel temperature.<sup>20</sup>

sensitive on the slag (%FeO) content and on the slag basicity. High basicity and high FeO content of the slag favors de-[%P]. At the normal operation ranges of the BOF with a basicity of 3.0 and a (%FeO) content of 20%, [%P] distribution levels of 150 can be obtained in equilibrium.

Other parameters to enhance de-[%P] are the steel temperature level and the slag (%MgO) content. Low steel temperature favors the reaction and low (%MgO) content as well (Figure 11). On the other hand, it is known that high slag (%MgO) supports refractory maintenance.

As the consequence, an optimum slag consistency at both (%CaO) and (%MgO) saturation and vigorous stirring of slag and steel to guarantee an optimum exchange rate between steel and slag are required. As previously mentioned, low temperature should be operated in the process, since high slag (%FeO) causes costly yield losses and should be reduced down to the economic limits.

Slag saturation with lime and (%MgO) was investigated in the past by many different authors. Lime saturation is dependent on the slag (%FeO) content (Figure 12). The higher the (%FeO), the higher the demand for basicity in the slag. If basicity is too high, the offered lime cannot be utilized quickly enough. If the slag is too liquid, high corrosion attack on the refractory lining will occur. A sufficient point in BOF operations is a (%FeO) of 20% at a basicity of 3.0. To reach (%MgO) saturation at affordable slag volume levels, a minimum basicity of 3.0 is also required. At this level, the saturation content of (%MgO) will be almost 6.0%, depending on the melt

**Figure 12**


(%CaO)/(%SiO<sub>2</sub>) lime (top) and (%MgO) saturation in steel-making slags (bottom).<sup>21</sup>

temperature. Higher (%MgO) causes a heterogeneous, viscous slag that has less reactivity for de-[%P].

Stirring can be enhanced by additional bottom stirring. The energy created through bottom-stirring elements can be described by Equation 1.  $\varepsilon_B$  is the kinetic energy dispatched from bottom stirring, which is directly proportional to the gas blowing rate and the melt temperature. But the stirring energy is oppositely proportional to the melt weight and the number of stirring elements. Therefore, single-hole plugs must be more effective than multihole plugs.<sup>22</sup>

$$\varepsilon_B = \left( 28.5 \cdot Q_B \cdot T \cdot N_t^{-0.833} / W \right) \cdot \lg \left( 1 + \frac{H}{148} \right) \quad (\text{Eq. 1})$$

where

$\varepsilon_B$  = kinetic energy dissipated from bottom stirring [J/minute],

$Q_T$  = gas blowing rate [ $\text{m}_n^3$ /minute],

$T$  = absolute temperature of hot metal [K],

$N_t$  = number of stirring elements [n],

$W$  = hot metal weight [t/heat] and

$H$  = metal bath depth [cm].

Practically, in BOF operations, in the beginning of the process, silicon, manganese and phosphorus are being oxidized. The slag is formed by (%FeO) generation liquefying the solid flux additions. Since the conversion of silicon to silica is the fastest reaction, enough and reactive lime must be charged in the early stage of the process to avoid the formation of a corrosive operation slag. When the silicon is burned out of the melt, decarburization continues at full speed, but the other elements stay constant. At the end, when decarburization becomes slower, (%FeO) increases again and enhances de-[%P] as well (Figure 13).

As mentioned before, the lime must be of good reactivity to guarantee quick solution in the acidic, highly corrosive primary slag of the process. In case of huge amounts of lime necessary to buffer elevated hot metal silicon, another technology to charge the lime (powder injection) must be considered.

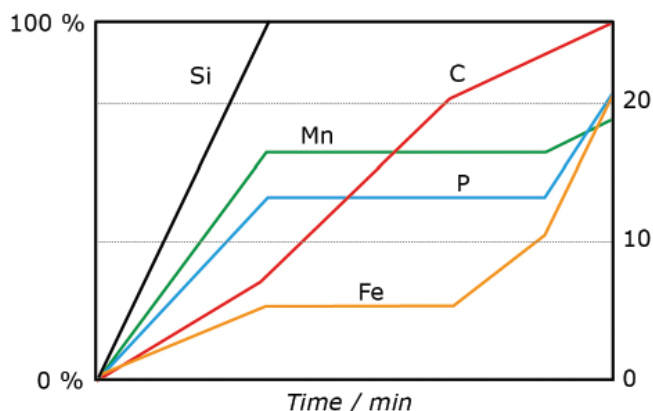
Slag splashing technology is a proven technique to increase furnace campaign life to very high limits. Operating a BOF without any demand for reline for five years is an example of a result achieved in the past. But on the other hand, slag splashing works out best when the slag is creamy and sticky. The disadvantage of these sticky slag types is that normally the bottom of the vessel is built up with slag coating. Therefore, it is necessary to control the bottom thickness on a regular basis to maintain the function of the bottom stirring. In case the slag layer on the vessel bottom is too high, bottom melting must be considered.

## Possibilities to Deal With Higher [%P] Levels in Common BOFs

As already shown in Figures 8–10, several measures can be implemented to enhance De-[%P]. A possibility to describe the interaction between the different parameters is to use a multivariate analysis to evaluate a statistical de-[%P] model. A resulting formula for a bottom-stirring converter was published by Genma and others in 1987 in Japan.<sup>23</sup> This formula was used to compare the actual log  $L_P$  results of a top-blowing-only vessel. To compare the results, another multivariate analysis was carried out for the actual data.

Figure 14 shows the results of the comparison. It becomes obvious that by using the bottom stirring, all results are moved to higher log  $L_P$  levels, which again proves the positive effect of the bottom stirring on de-[%P]. The whole blue  $L_P$  cluster, which is an effect of the metallurgical spread in the data, is moved to another area with a 20% higher de-[%P] capacity. This competitive advantage can be used either to achieve lower final [%P] content in steel or to allow higher initial [%P] content in the hot metal in case this pays off from the use of cheaper burden materials and fuels in the blast furnace. The consequent use

**Figure 13**



Oxidation reactions during blow of a BOF vessel.<sup>19</sup>

of a sufficient post-stirring of about three minutes after end of blow further decreases the final [%P] by 30%.

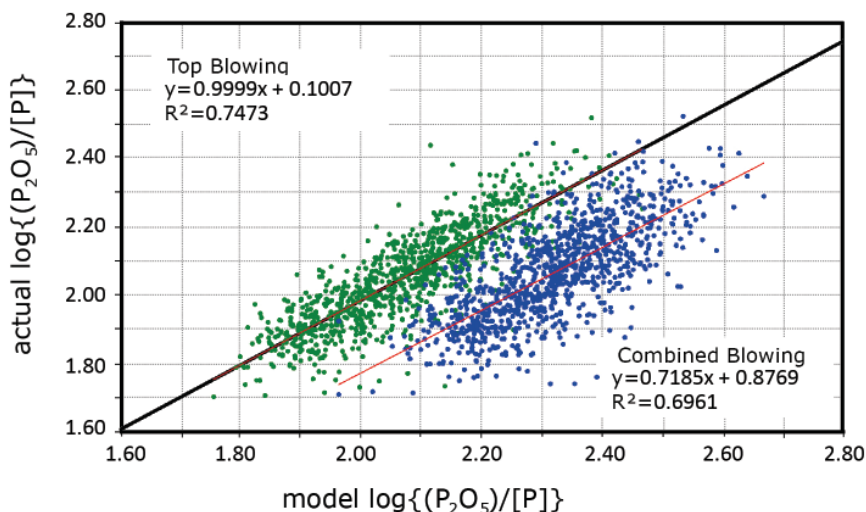
Figure 15 demonstrates the leverage effect of the de-[%P] capacity log  $L_P$ . If the target [%P] in the final BOF sample is set to 100 ppm due to the expected pickup during the following refining treatment and/or the product quality requirements, at low log  $L_P$  levels of 1.70 the initial [%P] must be limited below 0.035%. At medium  $L_P$  levels of 2.20, the initial [%P] already can be extended to 0.090%. When coming to a high log  $L_P$  level of 2.40, the initial [%P] content in the hot metal can be elevated to 0.140%.

Of course the achievable log  $L_P$  level is not dependent on stirring intensity only, but also on other performance indicators as:

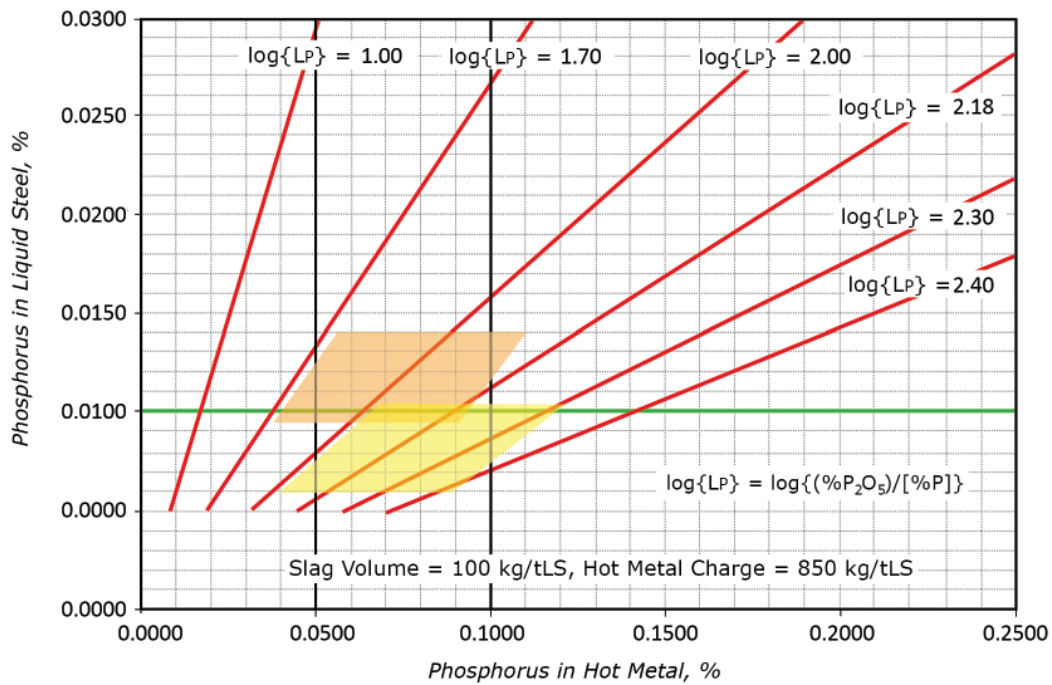
- Tapping temperature of steel.
- Slag (%FeO) content.
- Slag V-ratio (%CaO)/(%SiO<sub>2</sub>).
- Slag (%MgO).

**Figure 14**

Dephosphorization Model Results



Multivariate de-[%P] models with and without bottom stirring.<sup>24</sup>

**Figure 15**

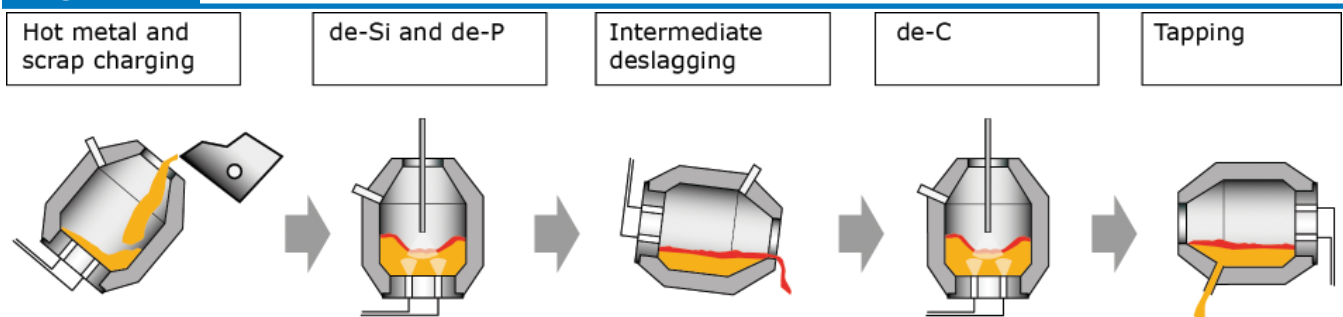
Initial [%P], final [%P] and de-[%P] capacity  $L_P$ .

These indicators directly influence the  $(\%P_2O_5)$  in the slag. Some authors report that [%C] in steel also influences the LP level, but since most of the plants are aiming for a fixed [%C] at the end of the blow, there is not enough variation in the results to evaluate this parameter. Others indicators, such as slag volume, can be varied in operation to increase the de-[%P] phorisation mass at a given log LP. By looking at the economics, it becomes clear that every 10 kg increase of the slag volume increases the [%Fe] yield loss by 15% or by US\$0.45/ton. On the opposite side an increase in the slag ( $\%FeO$ ) by 1% increases the [%Fe] yield loss at a slag volume of 100 kg/ton by only US\$0.24/ton.

These relationships become important in case the availability of high [%P] captive iron ore attracts the processing compared to expensive foreign low-[%P] ore imports. Bottom stirring in oxygen steelmaking (according to the significantly higher de-[%P] capacity  $L_P$  offered to optimize the process) allows opening the “P-window” of the blast furnace burden if beneficial. But of course, also the enhanced process effectiveness

reaches its limits when too-high levels of de-[%P] must be achieved, especially at sites where hot metal silicon cannot be controlled in narrow ranges at low levels. Since de-[%P] requires high slag basicity (3.0–4.0) the silica must be compensated by an aligned addition of lime and dolomite. It is obvious that the flux consumption and the total slag volume are a result of the silica level in the hot metal. Another possibility to increase the de-[%P] capacity significantly is to carry out the process at low process temperature, as is common in Japan today,<sup>24</sup> but also in other countries as well.<sup>25,26</sup> Most of the plants converted their traditional torpedo ladle treatment to a double-slag BOF vessel operation with intermediate deslagging (Figure 16). In this case, hot metal, scrap and lime are charged into the vessel and oxygen blow is started. At the end of de-Si and the dryout of the ( $\%FeO$ ) in the slag (approximately 10–12 blowing minutes), the blow is stopped and intermediate deslagging is carried out.

Due to the low temperature of the melt in the first half of the blow, the slag has excellent de-[%P] capacity

**Figure 16**

The multi-refining converter process (MURC) at Nippon Steel.<sup>24</sup>



**Figure 17**

Heavy slopping caused by high slag volume.

in case it is liquid. Basicity can be kept low ( $< 2.0$ ) to achieve sufficient results, and therefore slag volume is not as high as at the end of blow, and ( $\%FeO$ ) is low as well. By supporting the bottom-stirring elements, the slag can be drained quickly by more than 80% without metal losses. After deslagging, the vessel is moved back into blowing position, fresh fluxes in a rather small amount can be charged and de-C can be finished within a short second blowing period (approximately 8–10 blowing minutes). Since in the second blow the basicity is very high, the slag has good de-[%P] capability and causes only low refractory wear because ( $\%FeO$ ) content is low as well. After tapping the steel, the rest of this slag can be kept liquid in the vessel to replace fresh flux additions for the next heat.

Of course, the double slag operation mode requires additional processing time for the intermediate deslagging, which reduces furnace availability on the first glance. But in case of high slag volumes to be processed, heavy slopping will occur, which requires significant reduction of blowing speed to keep the melt inside the vessel. A reduction of 50% in the blowing speed for 5 minutes will cause a delay of the end of blow similar to the time consumed for the intermediate deslagging.

## Conclusions and Summary

Premium-quality iron ore prices are rising steadily, caused by the huge demand of the economic growth in

China. In other regions of the world, lower-quality iron ore is available with higher phosphorous content. For steel producers, it can be beneficial to utilize these ores in case the sources are captive.

The knowledge to process the hot metal with higher [%P] content was standard practice before and in the beginning of the LD process in steelmaking. Because of the availability of high-purity and cheap, overseas iron ores, the captive mines were closed and production was quickly converted to high productivity and low-energy consumption, i.e., to the technical standards of today. In the next decade, the constraints to reduce raw material cost will take steelmaking technology back to the de-[%P] strategies of the past.

Introduction of bottom stirring will intensify the reactivity of the slag in the process to achieve low [%P] in the steel with higher hot metal [%P] input. In case the silicon content of the hot metal cannot be controlled in a narrow range at a low level, a double-slag process with intermediate deslagging, which is common practice in Japan, is recommended.

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