

Cost-Saving Operation and Optimization on Metallurgical Reactions in BOF Practice

The aim of the primary steelmaking operation is the oxidation of carbon and phosphorus to ultralow levels with repeatable oxygen contents at the end of blowing. Bath agitation is also implemented at the start of

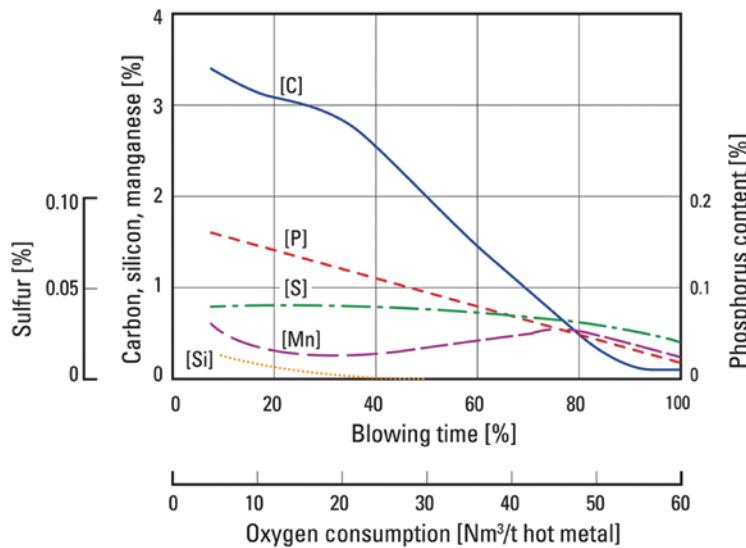
Process control systems are frequently applied at the BOF to help achieve a consistent and low state of oxidation at tap. Methods and aspects of optimizing the various metallurgical reactions in the BOF steelmaking process are discussed.

blowing and after the main decarburization cycle, via bottom blowing of argon and/or nitrogen. The formation of slag and of CO bubbles, and close-to-equilibrium-state conditions, are supported by bottom gas injection. Systems for definition of the endpoint of blowing in terms of phosphorus content and temperature, using heat balance calculations and sublance practice, are likely to realize these aims. The low number of re-blows, and the high direct-tapping rate, reduce tap-to-tap time and cooling scrap consumption. Correct tapping with little slag carryover helps to cut aluminum consumption during deoxidation and improves the oxide cleanliness of clean steel.

Today the basic oxygen process is essentially restricted to decarburization and deposphorization. All other metallurgical process steps take place during secondary metallurgy. These include the removal of sulfur, deoxidation and alloying. In the case of large units, with tapping weights of around 400 tons, the process must be cost-efficient, energy-saving and environmentally friendly. The target here is to utilize heat optimally, in order to melt down the highest possible proportion of cold charge material, such as scrap, pellets and sinter, and to reduce the slag ratio to the minimum necessary. The process runs extremely rapidly and does not permit intervention during the blowing time of around 20 minutes. It is therefore necessary to use computer models for determination of the endpoint of blowing. They consist of heat balances to achieve the targeted tapping temperature, and slag computations to assure optimum deposphorization.

The converter process has only a marginal influence on the oxide cleanliness of the final product (clean steel). The addition of

Figure 1

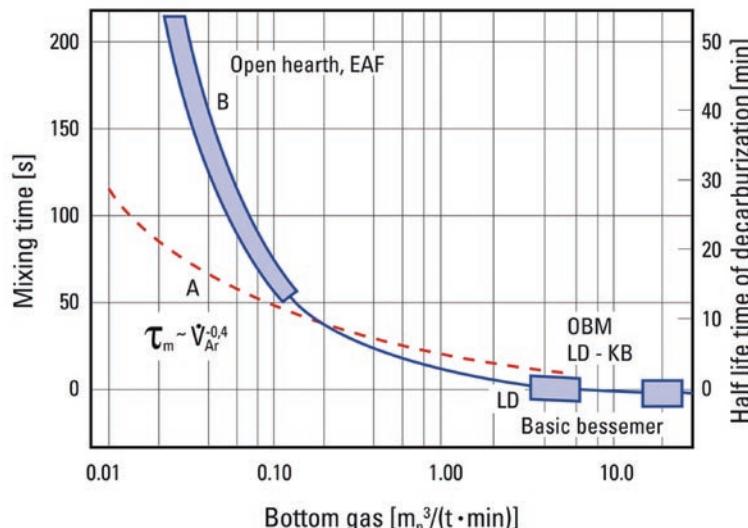


Variation in bath composition during blowing.

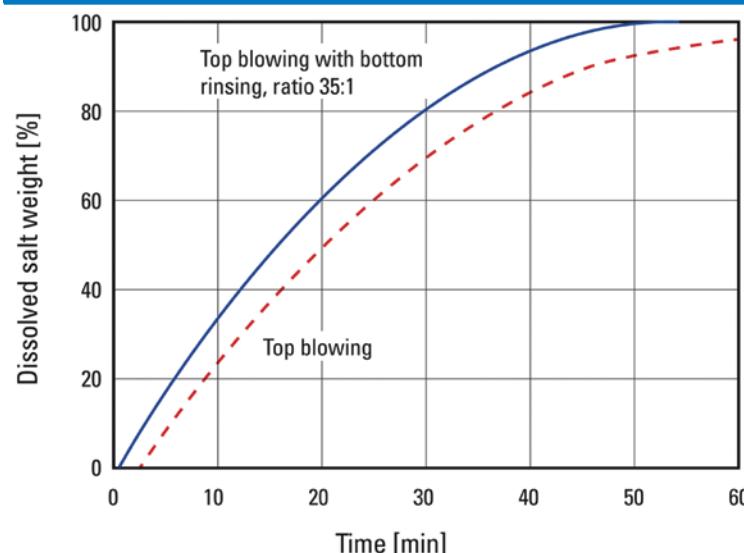


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Figure 2

Mixing time as a function of bottom gas flow (W. Löscher and W. Fix, *Proceedings Internat. Symp. Phys. Chem. Iron Steelmaking*, Toronto, 1982, VI, pp. 20–25).

Figure 3

Dissolution of a salt tablet in water as a function of time.

tion of a salt tablet with bottom rinsing compared to top blowing alone.⁶

Lime Rate

Lime input should be as high as necessary and as low as possible. It is referred to the silicon content of the hot metal and that of the scrap, in order to achieve the necessary slag basicity.⁷ Low slag rates result at extremely low silicon contents in the hot metal and the scrap. Conditions close to equilibrium state are then needed for dephosphorization.

Figure 4 shows a computation model.⁸ A basicity of 3.6, which can be considered optimum for dephosphorization, should be

aluminum reduces the widely spread oxygen content at end of blow almost entirely. The alumina that has formed coagulates in the turbulent flow of the tapping stream, and the bottom gas of the ladle into coarse particles, which dissolve completely into the slag. Nevertheless, the properties of the liquid steel at the end of the BOF process — such as tapping temperature, contents of oxygen in the steel and iron oxide in the slag, as well as slag retention during tapping — should be stable and reproducible for a good starting point of the following secondary metallurgy.

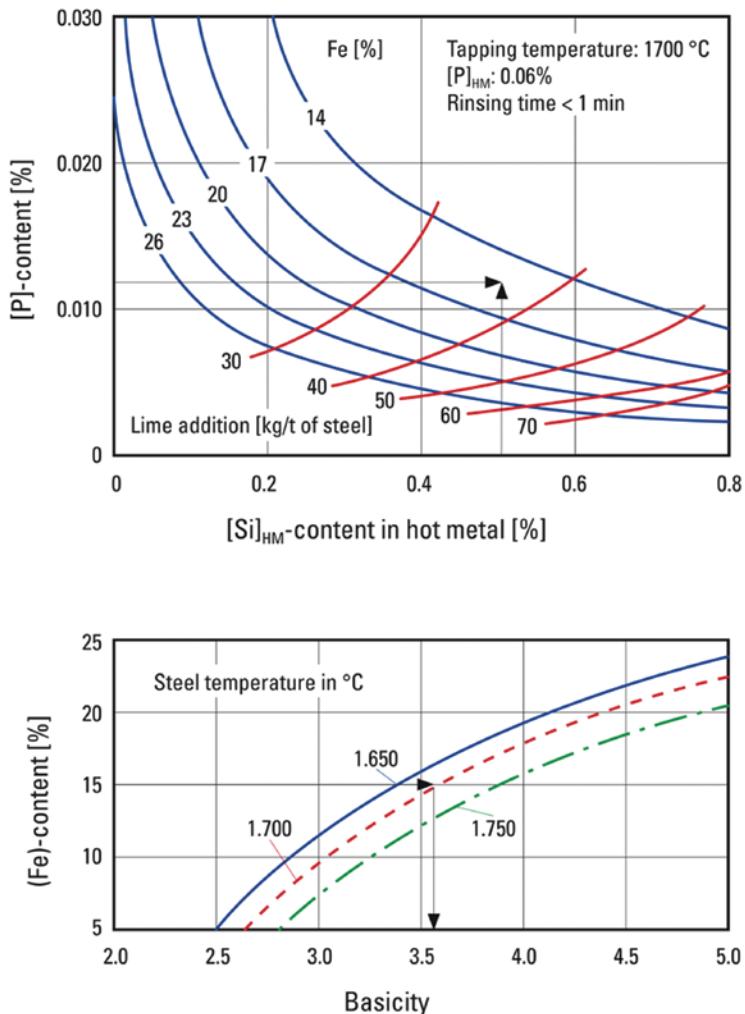
Scrap Charging

Hot metal and scrap rates are calculated using a charge model. The heat-generating reactions, such as decarburization and desiliconization, and the heat-consuming processes, such as meltdown of scrap and the dissolution of the slag-forming agents, are balanced in such a way that tapping temperature is reached within narrow tolerances at the end of blowing. The scrap may be of extremely varied type and quality, and should therefore be analyzed and sorted. It is necessary to promote meltdown at an early stage, in order that large pieces can also be completely dissolved during the time available.¹ Poor flow in the heat must be expected at the start of the process, before decarburization has started. In this phase of the process, it is mainly silicon, manganese and phosphorus that are transferred under oxidizing conditions to the slag. Figure 1 shows that decarburization really starts only after around 20% of blowing time.²

Flow within the heat is desirable for diffusion melting at temperatures below liquidus, and can be assisted by using bottom gas.¹ Argon and/or nitrogen are suitable for this purpose, and can be fed into the heat via bottom nozzles. Eight to 12 rinsing blocks are generally integrated into the bottom of the converter, arranged uniformly in rows across the converter floor. The diameters of the pipes in these blocks are around 2 mm, while the volumetric flow of gas is approximately 0.05 m³/ton steel. In some cases, such as the OBM process, for example, oxygen and slag-forming agents can also be injected via cooled, double-shell sheath tubes.

Mixing time is plotted in Figure 2 as a function of gas blown and of total gas flow,^{3–5} including the reaction gases. The bottom gases play a particularly important role at the start and end of the process, i.e., outside the main decarburization period. Mixing time after the addition of a salt solution to water has been measured in model tests.⁶ Average mixing time depends on vessel geometry and increases with vessel size. A second series of tests (Figure 3) shows the more rapid dissolu-

Figure 4



Calculation fundamentals for the slag composition to achieve a target phosphorus content in the steel at end of blow.

adjusted for a targeted tapping temperature of 1,700°C and an iron content of 15% in the slag. Such slags are close to lime saturation in the quasi-ternary $(\text{CaO})' - (\text{FeO})' - (\text{SiO}_2 + \text{MnO})'$ system. Since selective mining of low-phosphorus ores is relatively unlikely in the future, in view of already high raw-materials prices, it is important to provide good conditions for depophosphorization. At the same time, extremely low phosphorus contents are increasingly being demanded for more and more steel plant products. If one assumes a phosphorus content in the hot metal of 0.060%, and a target phosphorus content of 0.012% at tapping, one can calculate from the upper diagram a lime input rate of 38 kg/ton steel for a silicon content of 0.50% in the hot metal. It is clearly apparent that the slag ratio decreases as silicon content in the hot metal falls. Low silicon contents can be adjusted in the blast furnace process or by means of pretreatment for desilicization and depophosphorization.

The lower diagram in Figure 4 also shows that depophosphorization is heavily dependent on temperature. Phosphorus contents shift toward lower values as steel temperature drops. In this particular respect, the ladle furnace can be of importance. Here, heats can be tapped as much as 100°C colder. The low P-contents are retained with slag-free tapping, and the specified casting temperature is then achieved by means of electrical heating. The lime must be dissolved quickly and completely. The phosphorus oxidized at the start of the process should, on the one hand, be transferred to the slag, meaning that a reactive slag is necessary. On the other hand, lining wear should be kept as low as possible. At a low lance position and with a hard jet, the stream of blowing oxygen drives the slag-forming agents out of the hot spot and on to the boundary of the vessel, where lime dissolution is hindered, due to poor mixing and low temperatures. A surplus of lime must be avoided, in order to prevent the occurrence of free lime in the slag and assure environmentally acceptable use of steel plant slags in highway construction.

Figure 5 shows the quasi-ternary $(\text{CaO})' - (\text{FeO})' - (\text{SiO}_2 + \text{MnO})'$ system, including the slag routes and phosphorus distribution. The MgO saturation curves are not shown in this ternary system. The cut applies to a constant MgO content of 5%. It should, however, be pointed out that as a result of the dilution effect, the MgO concentration falls from 13% in the early slags down to only 7% in the final slags.^{2,9-10} The bottom gas promotes dissolution of lime, while at the same time, the flow in the heat prevents suppressed boiling and the ejection of slag. The quieter blowing process makes it possible to increase lance height and favors the dissolution of lime.

Coolant Rates

In cases of restricted blast furnace capacity and shortage of hot metal, production can be increased by means of higher scrap rates, pellets or sinter. One way to improve energy efficiency is a higher level of post-combustion in the converter. Thanks to bottom stirring, a quiet blowing process with no ejection or flooding of the vessel can be assured, despite higher lance positions. A higher lance position promotes post-combustion of CO to CO_2 , which achieves a significantly higher level of heat generation and improves energy efficiency. Figure 6 shows the results achieved using a 50-ton converter with and without bottom gas. The degree of post-combustion measured in the offgas is higher during the entire process by around 4%. It thus becomes possible to raise the scrap rate from 185 to 225 kg per ton of steel.¹¹⁻¹²

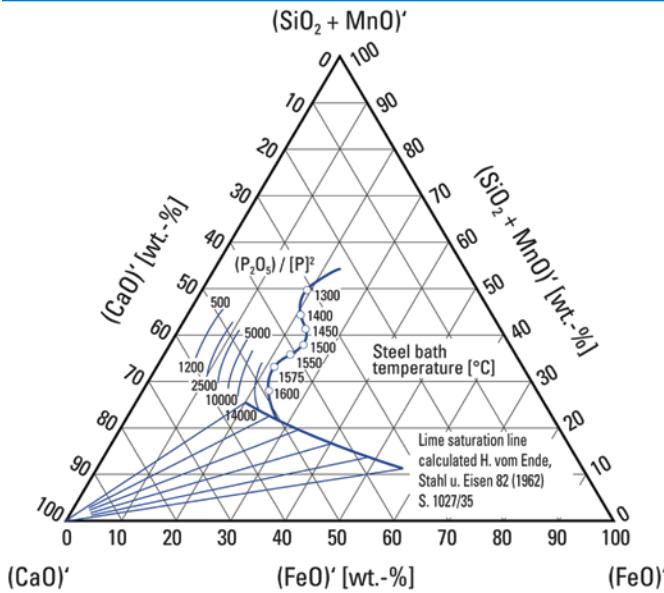
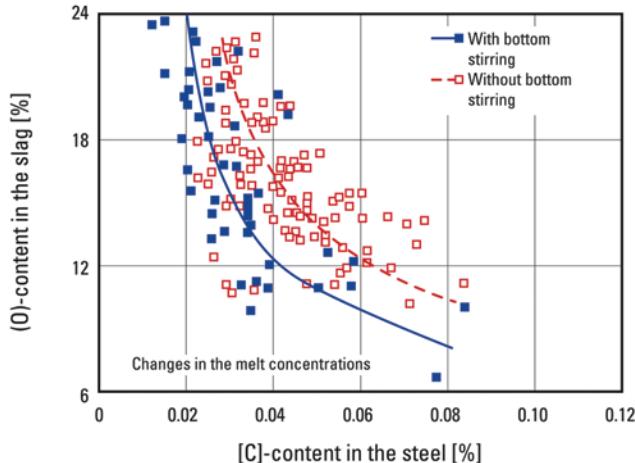
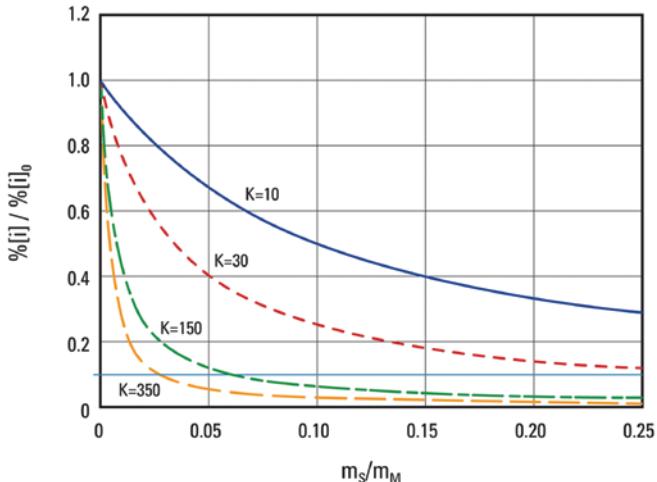
Figure 5

Figure 9

[C] and (O) content using bottom gas after end of blow (G. Denier, J-C. Grosjean, M. LeMaire, F. Schleimer, R. Henrion and F. Goedert, *Iron & Steelmaker*, 7 (1980), No. 8, pp. 5–11).

Figure 10

Refining with liquid slag under equilibrium conditions (W. Pluschkell, Institute of Metallurgy, TU Clausthal, 2004).

Bottom Stirring

Good mixing of the bath is an advantage in many ways. During the main decarburization phase, the CO generated is the “bath motor.” Assistance via bottom blowing is necessary at the start and end of the process, however. Both nitrogen and argon can be used for this, whereby nitrogen causes the frequently undesirable nitrogen pickup in the heat. CO₂ has also been used as a bottom gas in some cases, but this results in a certain cooling of the heat. The use of oxygen as a bottom gas will not be examined here. In practical operation, nitrogen is generally used for bubbling until the main decarburization phase is almost completed.¹³ Up to this point, the CO acts as a sink for the nitrogen, conveying it out of the heat. Argon is then substituted for nitrogen around the mid-blowing-time point. The bottom nozzles must be kept open at all times so that the flow of gas is not interrupted. Slag splashing with residual slag to increase the service life of the lining is permissible only on the precondition that it is possible to monitor and control the growth of the converter bottom. Uncontrolled growth here results in a reduction of inner converter volume and produces disadvantages in terms of foaming and slag flooding. Undesirable ejection also occurs simultaneously. In addition, slag splashing costs time, and therefore reduces converter availability and productivity.

Impurities

The trend is clearly toward a demand for steels with ever lower impurity contents. The term used in Japan is “100 ppm steel,” which should not contain more than this quantity of impurities in total. Phosphorus and nitrogen contents, in particular, can be controlled in

the converter process. The mixing of steel and slag is necessary for approaching the metallurgical equilibria at the end of blowing. This has beneficial effects both on decarburization and on dephosphorization. It is even possible to rinse the steel after the end of blowing, while waiting for the analysis results, which permits yet another improvement. In addition, the potentials for direct tapping, without needing to wait for the analysis results, are improved. The vacuum treatment time can also be shortened by lower carbon contents for the same iron content in the slag.

Carbon — Low carbon contents at the end of blowing are desirable in many steels. This is true, in particular, in the case of automotive body sheet, but has also recently begun to apply increasingly to engineering steels, due to the improved weldability achieved. With restricted oxygen content, a low carbon content can be adjusted by means of thorough mixing. This simultaneously saves deoxidation agents, such as aluminum. Figure 9 shows oxygen content in the slag as a function of carbon content. For the same oxygen content of 14%, the carbon content in rinsing-gas-treated heats can be reduced after the end of blowing from an average of 0.08% down to 0.03%.^{15–18}

Phosphorus — The phosphorus content of steel plays an increasingly important role in the steelmaking process today. It is generally specified at less than 0.015% and, in many cases, lower than even 0.012%. To achieve these results with low slag ratios and limited Fe-contents in the slag, it is necessary to approach the equilibria closely, with optimum adjustment of slags to a point close to lime saturation. Intensive mixing of the steel and

slag, particularly at the end of blowing, is the key precondition for this. Nernst's distribution concept, in which the ratio of phosphorus content in the slag and in the liquid metal $K_{N,P} = (P)/[P]$ is observed under equilibrium conditions, is suitable for operational use. A simple mass balance produces:

$$\frac{i}{i_0} = \frac{1}{1 + K_N Y}$$

(Eq. 1)

where

i_0 = the initial content in the metal phase,
 i = the initial content at equilibrium and
 Y = relative slag ratio $m_{\text{slag}}/m_{\text{metal}}$.

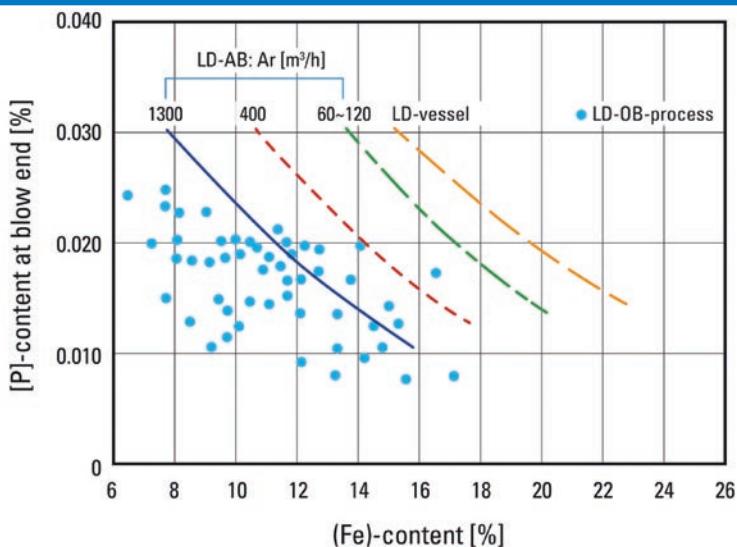
At the relative slag ratio of 0.07 typical for the converter process, the Nernst factor must be above 150 in order to reduce element content by a factor of 10 (Figure 10).

In addition, Figure 11 shows phosphorus contents at the end of blowing for the LD process and for various bottom-gas flowrates.^{19–25} The scatter band for achieved phosphorus contents shifts toward lower iron contents in the slag as argon flow increases. 0.015% phosphorus in the steel is thus achieved in the LD process at around 22% iron in the slag, but around 13% iron in the slag when a flow of bottom gas is used.

In Figure 12,⁸ other results demonstrate that after-rinsing of the heat for a few minutes makes possible a further reduction of phosphorus content, even at the high temperature of 1,700°C, with an increase in phosphorus distribution. Here, however, the temperature decrease during rinsing also becomes apparent. The influences of initial phosphorus content and of rinsing time on the decrease in phosphorus content are both shown in Figure 13.⁸

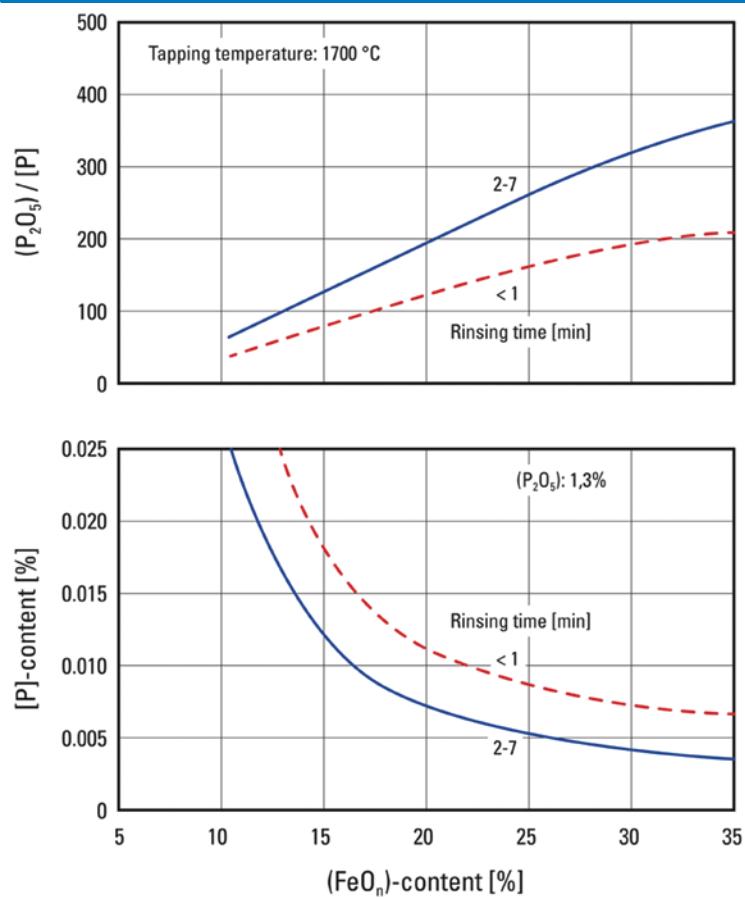
Nitrogen — Today there is also a demand for ultralow nitrogen contents. These are important, particularly in the BOF process, in order to guarantee that the inevitable nitrogen pickup in subsequent secondary metallurgy and continuous casting does not lead to the limits being exceeded. J. Kempken and W. Pluschkell¹³ have performed simulation computations for the profile of nitrogen contents in the LD process. Importation of nitrogen with the hot metal has practically no influence on ultimate nitrogen content, whereas more nitrogen is introduced into the heat from the scrap, the later the scrap is dissolved. Of greater importance is the precise time of switchover of the rinsing gas from nitrogen to argon. Figure 14 shows that nitrogen contamination is lower, the earlier argon is used.¹³ The mid-blowing point (i.e., half the blowing time) is considered

Figure 11

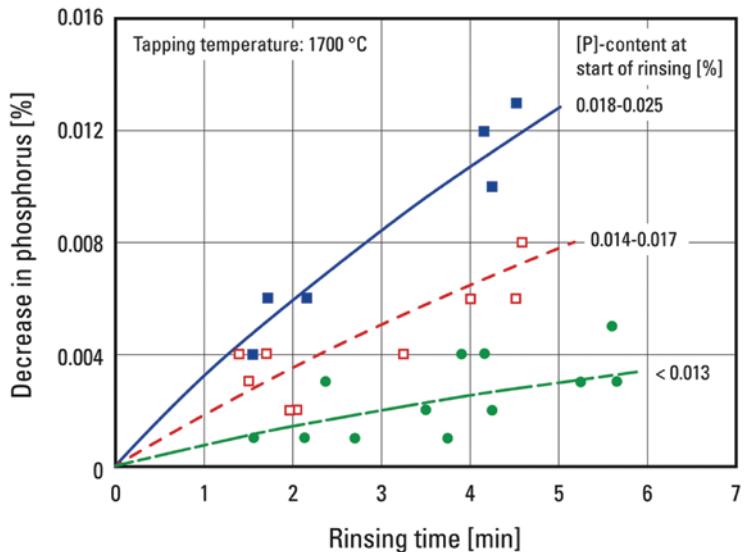


Realized end phosphorus contents and (Fe) contents with bottom stirring (T. Kai, H. Nakagawa, M. Hirai, S. Murakami, M. Nakajima and H. Araki, *Trans. Iron Steel Inst. Japan*, 20 (1980), p. B-506).

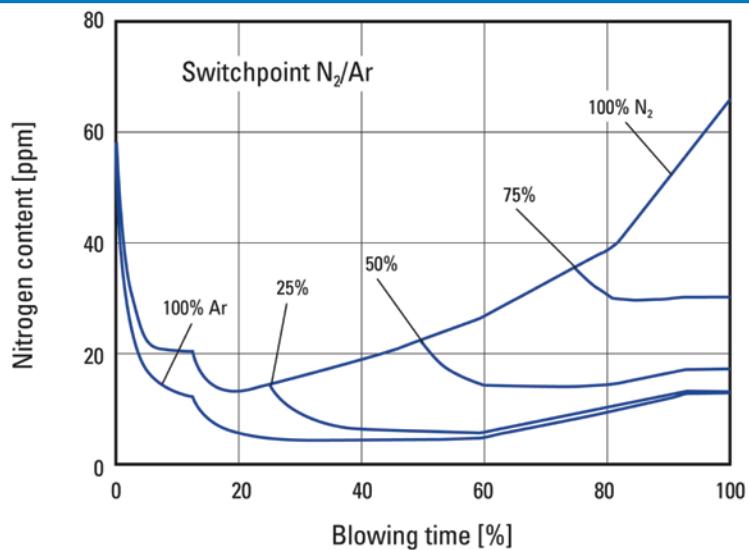
Figure 12



[P] contents in steel as a function of the iron oxide content in the slag.

Figure 13

Decrease in phosphorus content during rinsing after end of blow for various contents.

Figure 14

Profile of nitrogen contents during blowing, showing the influence of N₂/Ar bottom stirring (J. Kempken and W. Pluschkell, *Stahl und Eisen*, 115 (1995), No. 8, pp. 67–73).

the optimum, since earlier changeovers produce only slight improvements.

Residual nitrogen content in the blowing oxygen has also been recognized as a further source of nitrogen contamination. This residual content should be reduced to the lowest possible level. When all provisions are implemented, values of 17–19 ppm at the end of blowing can be achieved as the lower limit.

Conclusion and Summary

The current converter process is restricted to decarburization and dephosphorization.

All other metallurgical treatments take place during secondary metallurgy. This is also true of oxide cleanliness (clean steel). With widely spread oxygen contents in the steel, the alumina generated during deoxidation forms coarse oxides in the turbulent flow during tapping and stirring. These dissolve completely in the slag.

The process runs extremely quickly and does not permit any intervention. For this reason, models are used to compute energy balances for determination of the endpoint, using a subscale measurement. Intensive bath mixing throughout the process is necessary for optimum exploitation of heat transfer during scrap meltdown, slag formation, and for approach to the thermodynamic equilibrium. Bottom rinsing with nitrogen and/or argon promotes such mixing processes, particularly at both the start and end of the converter cycle, when decarburization has not yet started or has terminated. Slag ratios must be kept small, in order to reduce refractory wear. High lime input rates should also be avoided, to prevent the occurrence of free lime contents, which would preclude ecologically safe use in highway engineering.

Slag splashing to increase the service life of the converter lining costs converter availability and is of only limited cost-efficiency, due to the resultant losses in productivity. Uncontrolled growth of the converter bottom decreases converter capacity and may block the bottom bricks. Bottom stirring and approximation to the equilibria make it possible, at simultaneously lower (Fe) contents, to achieve lower carbon and phosphorus contents. This saves deoxidation agents and, due to the carbon contents achieved, it also shortens vacuum treatment times. Low phosphorus contents increase the potential for the practice of direct tapping. In order to limit nitrogen contents at tapping, the scrap should be melted down quickly, the point of switchover from nitrogen to argon should be at around half the blowing time, and the residual nitrogen content in the blowing oxygen should be as low as possible.

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This paper was presented at AISTech 2008 — The Iron & Steel Technology Conference and Exposition, Pittsburgh, Pa., and published in the Conference Proceedings.



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