Metallurgy and lining life in basic oxygen converters

Good control of slag development, oxygen flow and lance practice, and use of bottom stirring and re-blow practice are key aspects of the metallurgical control of steelmaking. Knowledge of interactions between process chemistry, blowing dynamics and converter lining wear can achieve both efficient steelmaking and long converter lining life.

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SLAG COMPOSITION

A lime-saturated slag is important both for steelmaking metallurgy and to prevent excessive wear of the converter lining. Lime added before and during the blow should ensure a saturated slag at the end of the blowing process. Converter slags can be described within the basic ternary system FeO-CaO-SiO_2 (see *Figure 1, upper part*). In this system the so-called C_2S (dicalcium silicate) nose and C_2S saturation line extend far into the inner area of this ternary system. C_3S (tricalcium silicate) saturated slags below the C_2S area occur only within a small band of between 10 and 30% SiO_2 and only slags on the right-hand side of the C_3S area, between 0 and 10% SiO_2, are in equilibrium with pure solid lime. This line is called the CaO saturation line.

In converter slags, the components CaO, FeO and SiO_2 make up typically 80–85% of the total slag constituents. Additions of MnO, MgO, P_2O_5 and Al_2O_3 push the C_2S and C_3S saturation lines towards the binary CaO-SiO_2 boundary system and CaO corner. The lime saturation line of commercial slags shown in the lower part of *Figure 1* extends beyond 20% SiO_2 and is not comparable to the pure ternary system.

To convert the analysis results of commercial slags for use in the pure ternary system, the data for CaO, FeO and SiO_2 (say, 85% total), each individual content figure must be multiplied by the factor 100/85 and in the diagram these figures are marked CaO′, FeO′ SiO_2′. The figure for the FeO content is calculated from the figure for Fe total (Fe x 1.28).

The slag development path for different hot metal Si contents is shown in *Figure 2*. According to this diagram, the general slag development path is as follows: starting from the high FeO′ corner, the SiO_2′ and CaO′ contents rise, as a result of increasing silicon oxidation and lime ▷

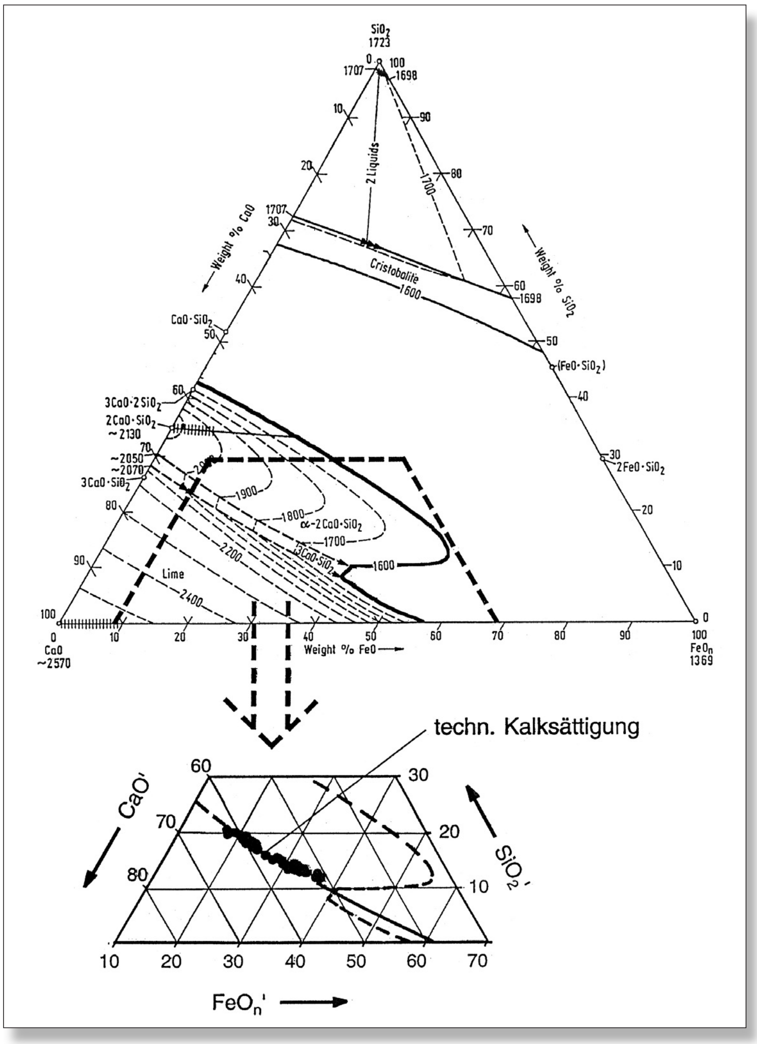


Fig.1 CaO-FeO-SiO_2 ternary system

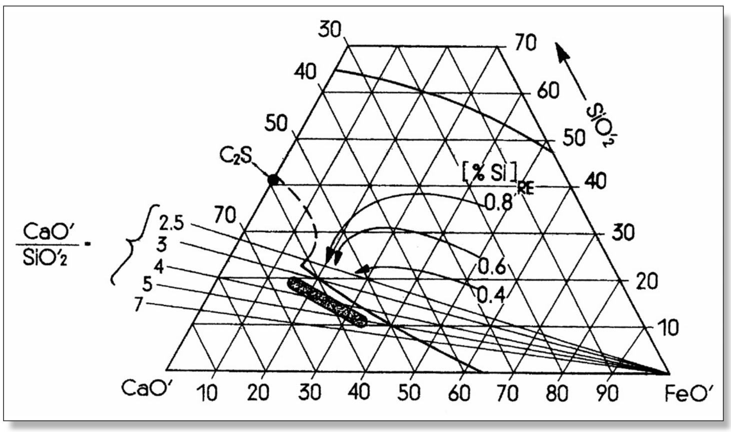


Fig.2 Slag development paths

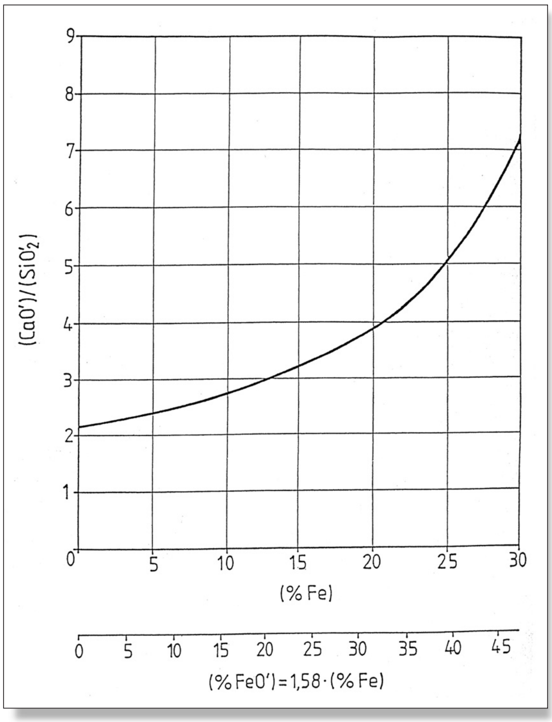


Fig.3 **Relationship between slag basicity and Fe content along the lime saturation line**

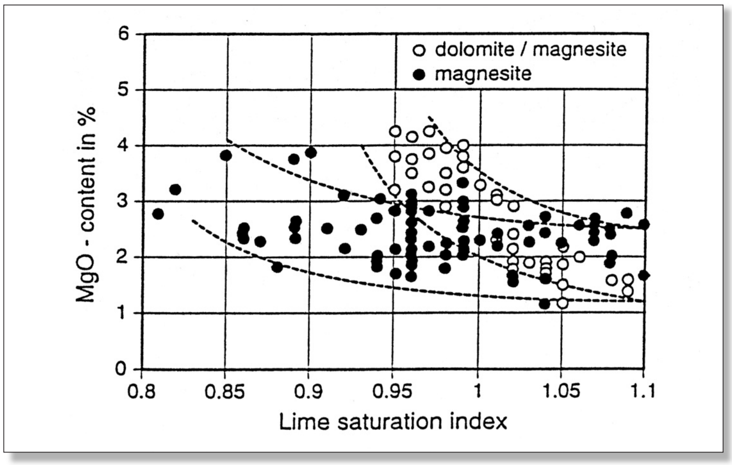


Fig.4 **Relationship between lime saturation index and MgO content**

dissolution. The higher the initial hot metal Si content, the higher the SiO_2 content early on in the blowing process.

At the end of the blow slags should be slightly lime supersaturated in order to avoid excessive refractory wear, ie, they should be within the lower diagram of *Figure 1*. In order to achieve this goal a lime addition rate is necessary which is adapted to the Si content in the hot metal and to the target slag Fe content.

In *Figure 2* lines from the CaO'-SiO_2' boundary system, which are linked to the FeO' corner are shown. Each of these lines represents a certain basicity ratio: CaO/SiO_2. Lines of equal basicity are cut by the lime saturation line. Higher basicity equates to higher Fe (FeO) content in the equilibrium condition. Slags with a composition located on the saturation line are lime saturated. Slags below this line contain excess free lime as it cannot be fully dissolved and the FeO content in the heat may be too low. Slags above this line are lime under-saturated and do not contain enough lime, and the FeO content maybe too high.

Figure 3 is derived from *Figure 2* by using the intersection points between the lines of equal basicity and the saturation line, and defines the lime saturation line of a commercial slag. Slags below the line are lime under-saturated and the slags above the line contain excess lime.

The requirement of a lime-saturated slag at the end of the blow in order to avoid excessive refractory wear is valid both for pure dolomite and magnesite linings. *Figure 4* documents results from the Didier research department and illustrates increased slag MgO solubility as the degree of CaO under-saturation increases.

The practice of working with lime under-saturated slags is a result of an incorrect assumption that CaO will be replaced by an equivalent quantity of MgO (contained in the dolomite). A reduction in the amount of lime added

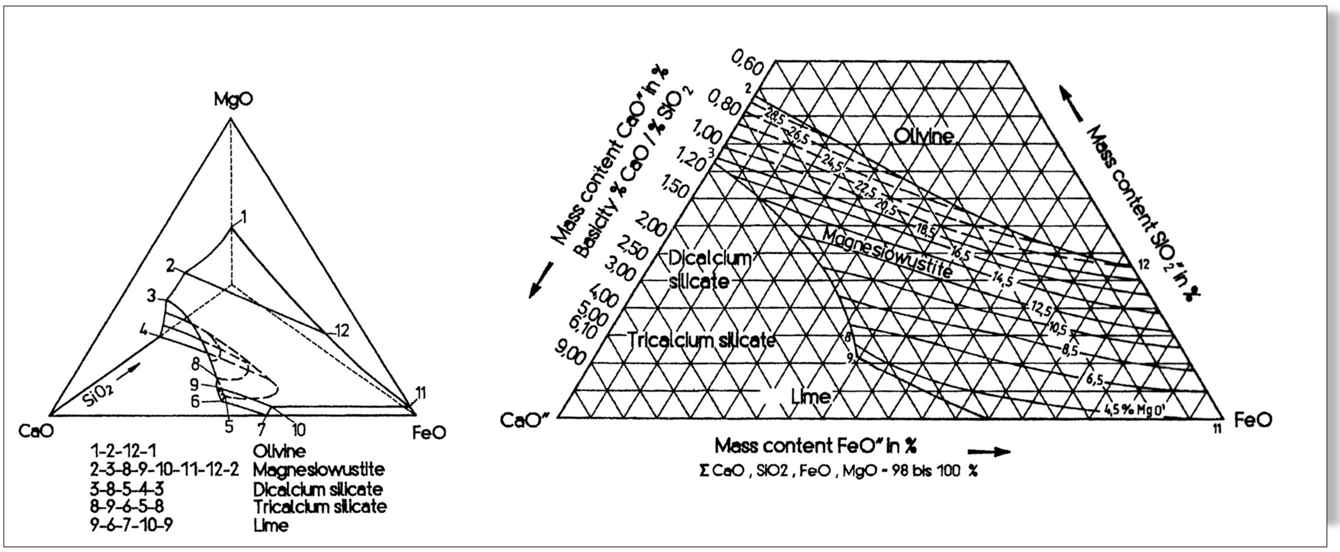


Fig.5 **MgO saturation in CaO-FeO-SiO_2-MgO system**

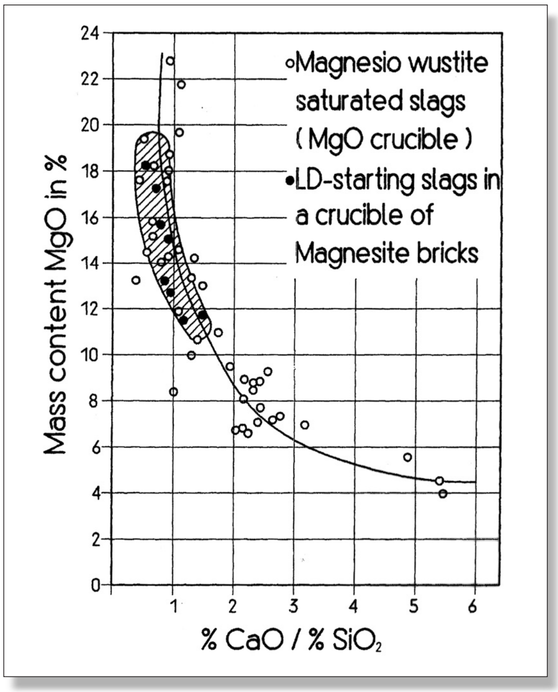


Fig.6 **Relationship between slag basicity and MgO saturation**

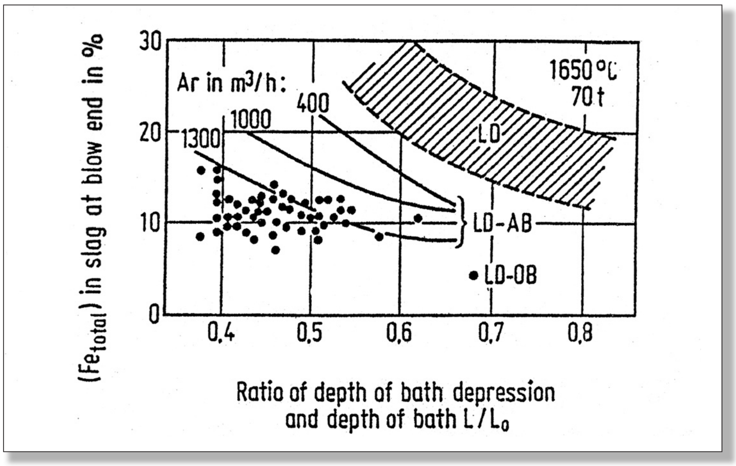


Fig.7 **Effect of bath penetration on slag Fe content**

automatically leads to low basicity figures. There are steel plants working with basicities below 2–2.5, however, in order to stay on the lime saturation line the slag Fe contents must be kept below 10%. This is metallurgically undesirable if dephosphorisation is required. An Fe content of 17–18% is more practical.

When using a magnesite lining, in order to minimise lining wear the slag should be both CaO and MgO saturated. The maximum soluble MgO contents in the FeO-CaO-SiO_2-MgO system are illustrated in *Figure 5*. According to this figure the MgO solubility increases with increasing SiO_2 content. *Figure 6* shows the maximum soluble MgO content along the lime saturation line in this quaternary system. Slags with low basicity, equivalent to low FeO content in the slag according to *Figure 3*, have the highest MgO solubility, therefore a magnesite lining is most heavily attacked early in the blow when the slag basicity is still low. MgO solubility decreases with increasing basicity and FeO. *Figure 6* also indicates that even for a low slag basicity of 2.0, 8% MgO can be dissolved in the final slag, whereas it is 6% for a normal basicity of 3.5.

Above the saturation line all the MgO cannot be molten, thus for instance, with an MgO-saturated slag, a further increase in slag basicity will cause MgO to be precipitated and increase the viscosity of the slag, with the result that heavy build-ups on the converter bottom and walls can occur (bottom build-ups of 2.5m are possible). These build-ups prolong lining life (a new record in the USA: 70,000 heats!), but the metallurgy is also influenced by changes in the bath level and the inner converter diameter in the bath level area. This can be seen in *Figure 7*, illustrating the change in jet penetration depth, L, on slag FeO. If the bath depth, L_0, reduces for a constant penetration depth of the oxygen jets, the FeO content in the slag will increase. This means that deeper baths require deeper oxygen jet penetration, ie, harder blowing lances.

Lining life is influenced by the slag analysis throughout the blow. In the boundary system FeO-SiO_2, shown in *Figure 1*, there is a compound fayalith ($2FeO.SiO_2$) with a very low melting point of 1,205°C. The higher the hot metal Si content the longer the time period that is required to pass through the area of fayalith-containing slags. This area, together with the high MgO solubility at the low basicities that exist at this part of the blow, have a very unfavourable influence on lining life. Therefore, it is very important that the added lime dissolves quickly in order to raise the slag basicity as early as possible.

The use of soft burnt lime and a sufficiently large lance distance to the metal bath at the beginning of the blow (which enhances Fe oxidation and therefore lime dissolution), are favourable to achieving this aim. Also to facilitate early lime solution the lime addition should be complete within three to four minutes of blow start.

In some plants fluorspar (CaF_2) is added to flux the lime, especially when high basicities (up to 6) are required, or with low FeO slags, otherwise the amounts of undissolved lime (from C_2S precipitation) would be too high. Fluorspar lowers the melting point of CaO and C_2S and the viscosity of the converter slag. Additions, however, should be minimised because the volatile and aggressive compound SiF_4 is formed, which heavily attacks the steel pipes of the waste gas system above the converter. The fluorspar addition also reduces the melting point of the refractory of the converter lining. Typical plant consumptions are 1–3kg/t liquid steel. Alumina (Al_2O_3) has a similar melting point lowering effect but reacts more slowly.

PHOSPHORUS REMOVAL

The achievable steel phosphorus level is affected by hot metal P%, slag basicity and FeO. *Figure 8* shows the ▷

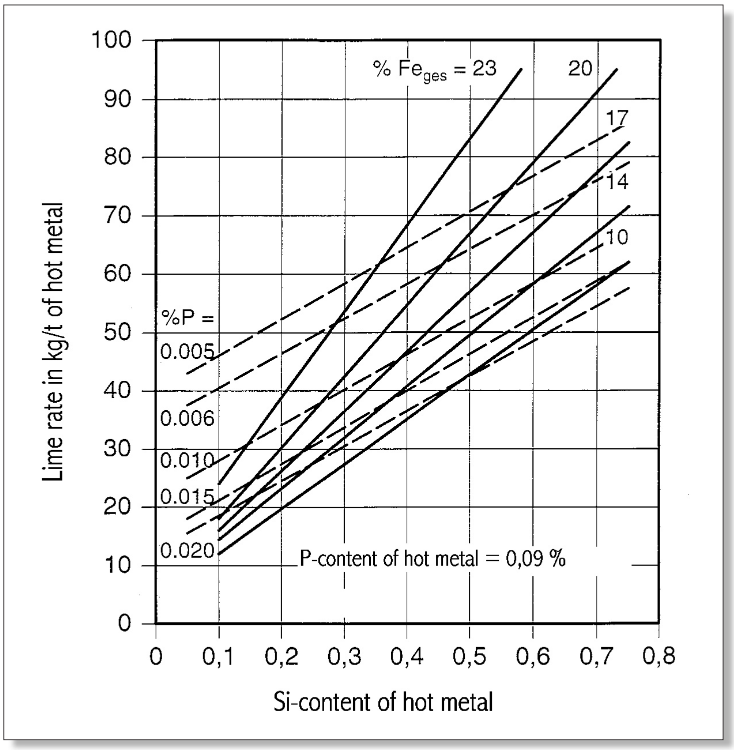


Fig.8 Some factors influencing steel P level

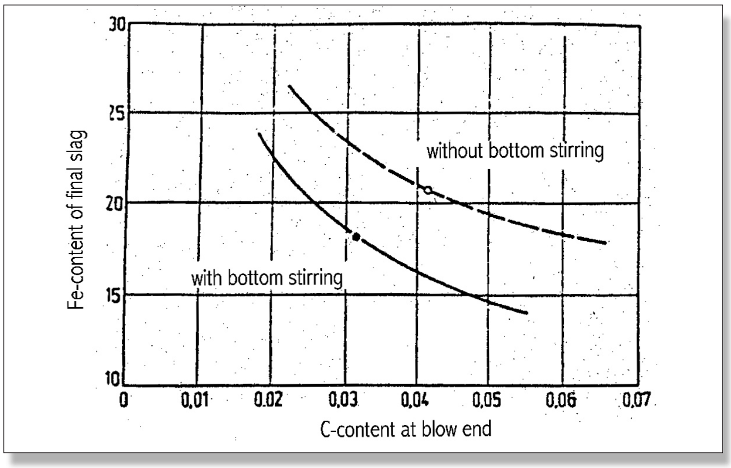


Fig.9 Influence of bottom stirring on slag Fe content

calculated required lime addition rates and influence of slag Fe content for a hot metal with 0.09% phosphorous. Phosphorus removal is also inversely related to steel temperature.

LIME QUALITY

Lime is not pure CaO. It contains impurities such as SiO_2 and Al_2O_3 which must be compensated for in the additions calculations. Also, its metallurgical efficiency is affected by the particle size and reactivity (or degree of burning). The ideal particle size is 10–50mm, as particles below 6mm are extracted from the converter, together with the waste gas; up to 30% in some cases. If this happens the slag produced can be under-saturated, causing additional converter lining wear.

Lime with a wide particle size range also separates when charging into storage bunkers such that coarse material travels to the outer side of the cone shaped charging pile with the fine grained material remaining in the inner area. Thus, when charging the lime from the bunker, lime quality will be variable, with negative consequences for steel chemistry, temperature control and converter lining life.

BATH MOVEMENT AND BOTTOM STIRRING

Another important precondition to achieve consistency and controllability of blowing behaviour, and a low rate of variation of the results after the end of the blow, is a sufficient bath movement during blowing. During the main decarburisation phase there is good bath movement as a result of CO formation. With decreasing bath movement at C contents below ~0.30% resulting from reduced CO gas formation, bath movement decreases considerably, therefore, during this phase of the blow, this task has to be fulfilled by lowering the blowing lance. Although the stirring effect, induced by the lance, is much less than with CO formation, it ensures that bath stirring is maintained to the end of the blow. This is one reason why bottom stirring with inert gases was introduced into many steel plants. Although the gas quantity blown through the converter bottom via plugs (typically in the range 0.01–0.05Nm^3/t/min) is small compared to the top blown oxygen, its stirring effect has multiple benefits in ensuring the slag and bath are in greater equilibrium and in producing lower and more controllable Fe levels in turndown slags (see *Figure 9*) which are beneficial for converter lining life.

Plug position is important both for metallurgical effectiveness and lining wear (see *Figure 10*). If the plugs are positioned too far away from the centre two different currents in the steel bath are formed which considerably reduce mixing and therefore affect the metallurgical equilibria. Stirring plugs located far away from the centre increase the wear of the converter lining in the transition area between converter bottom and wall (knuckle area).

RE-BLOWING

Re-blowing for final adjustment of temperature or analysis is often required, but at the expense of increased iron oxidation and hence higher refractory wear. For instance, a reblow of less than one minute will raise the temperature 20°C, but will also increase the slag Fe by 5%. *Figures 11a* and *11b* illustrate greater uniformity in slag FeO when using bottom stirring.

Although theoretically lime should be added during re-blowing in order for it to stay on the saturation line (as a

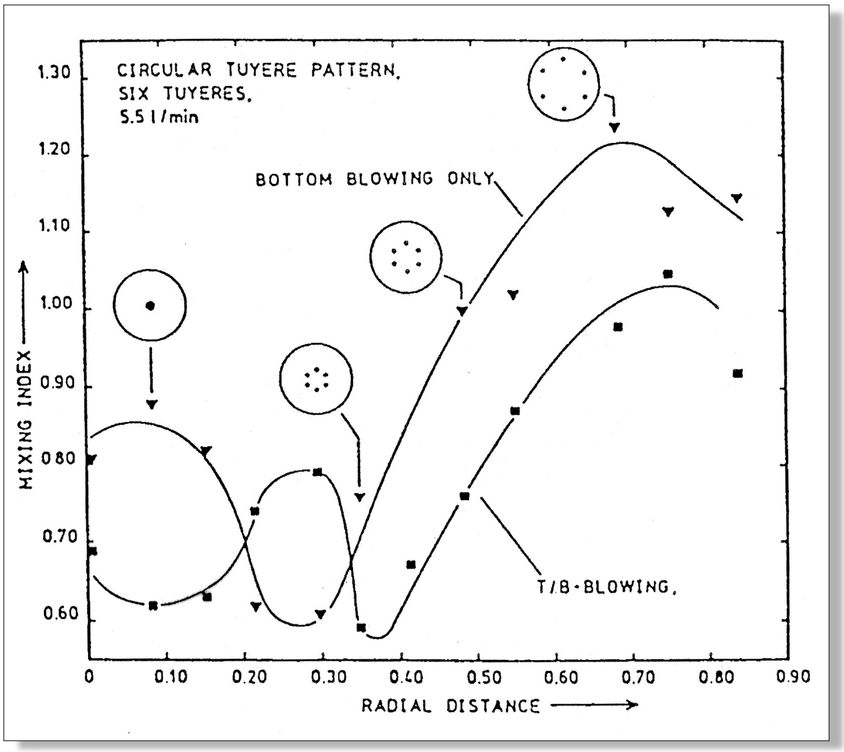
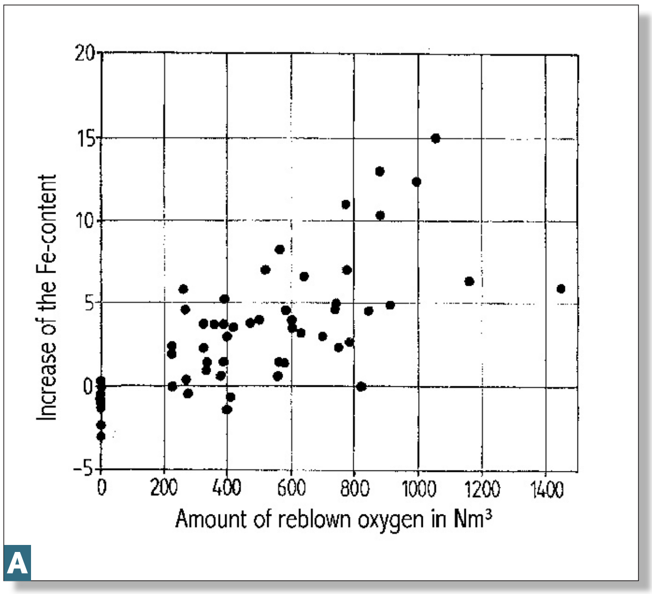
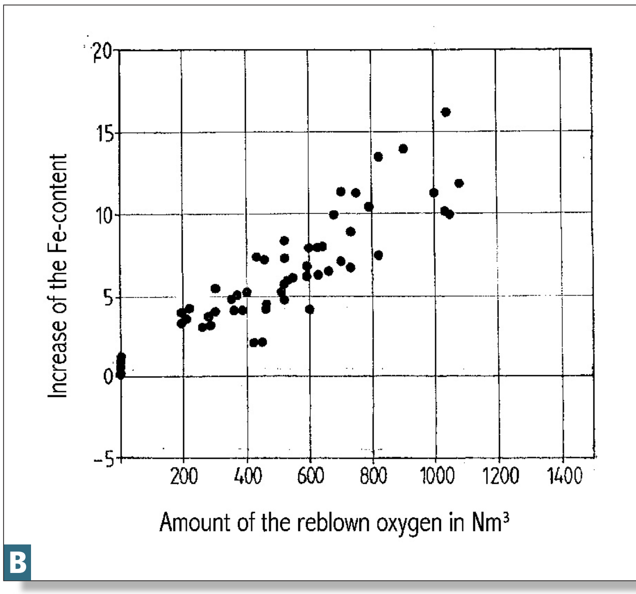


Fig.10 **Effect of bottom plug position on stirring efficiency**

Fig.11 **Effect of bottom stirring on re-blow slag oxidation, a) without, b) with stirring.**





result of the Fe increase), in most cases this is not done, and especially not in cases when the re-blow is required to raise temperature, as the temperature increase by the Fe oxidation would be compensated for, to a large extent, by the heat consumption for lime dissolution. Although under-saturated slags with quite high Fe contents and temperatures are acceptable for metallurgical reasons, they are extremely detrimental to lining life and the damage is greater the longer the molten steel is kept in the vessel between blow end and tapping.

USE OF IRON ORE

Iron ore pellets, which are added to cool the steel bath, also have an influence on lining life due to the increase in molten FeO. Excessive amounts of added ore should be avoided because the additional amount of oxygen introduced by the ore leads to an uncontrollable blowing behaviour. Ore addition should preferably be completed during the main decarburisation period otherwise there may be insufficient carbon available to reduce the melted ore. However, there are BOF shops that do add ore ▷

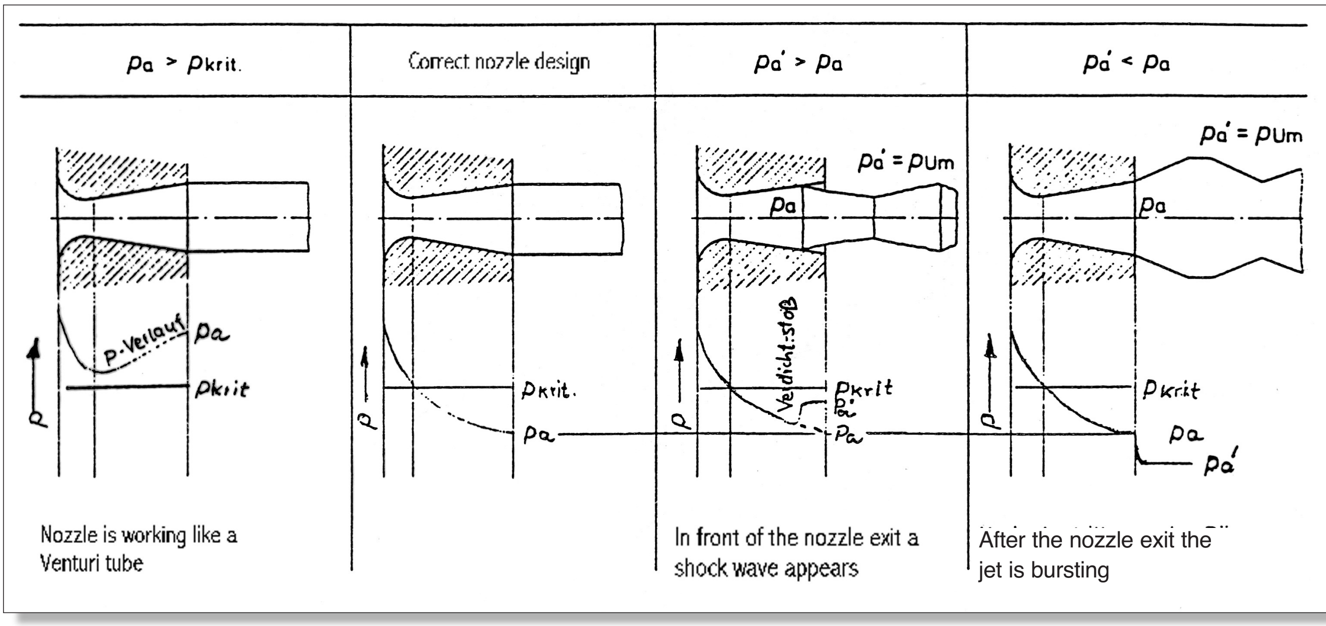


Fig.12 Different operating states for a Laval nozzle

towards the blow end as a way of achieving lower turn down phosphorous contents, as phosphorus removal is enhanced with higher FeO levels.

If ore is always charged to the same side of the converter through the charging chute, the FeO-rich slag which is formed locally at the trunnion area causes localised lining wear. For this reason some BOF shops vary the ore addition side to the converter.

LANCE PATTERN AND LANCE TIP DESIGN

During a typical 14–22 minute blowing time, the iron is refined and many tonnes of scrap and slag forming agents are melted. During this period the dynamics of slag formation have to be controlled in a way that achieves an optimum blowing process and the desired final turn down temperature and steel composition. One of the tools for control of slag formation is the blowing lance.

The blowing process is strongly influenced by the lance tip design and the lance distance to the metal bath. The basis for the calculation of a lance design and the number of nozzles is the required oxygen flow rate per minute. The necessary blowing hardness is determined by the size of the converter, the bath depth and by the input materials to be processed. More slag, for instance as a result of high hot metal Si content, requires higher blowing pressure. In general the blowing pressures are between 8 and 15 bar as measured right in front of the nozzles inside the lance tip. At the point of smallest nozzle diameter the blowing pressure is about half the pressure in front of the lance tip (the so-called Laval pressure = 0.528 x pressure in front the nozzles inside the tip). Maximum sonic speed is achieved as the nozzle diverges in the flow and as the pressure in front of the nozzles increases. For blowing pressures of 8–15 bar, exit velocities of Mach 1.95–2.36 are achieved. The length of the diffusor has to be specifically designed for the oxygen blowing pressure respective to the oxygen velocity. If the diffuser is too short or too long, shock waves are created. In *Figure 12* different operating states or conditions that can occur in a Laval nozzle are illustrated. When the oxygen exit pressure Pa does not correspond to the pressure for which the Laval nozzle is calculated (the surrounding pressure in the vessel), there will be a disturbed flow within or after the Laval nozzle. The recompression pushes whichoccur within the diffusor or within the free oxygen jet lead to pulsations of the oxygen jet and therefore to a loss of energy. Three typical cases are possible:

- The exit pressure Pa is above the critical pressure Pkrit
- The Laval nozzle behaves like a Venturi nozzle. The flow is accelerated the converging part of the nozzle, then retarded in the diverging part. All velocities are below sonic speed
- The exit pressure Pa' is below the pressure Pkrit, but above the exit pressure Pa on which the calculation is based. In this case the gas has sonic speed at the smallest nozzle diameter with recompression pushes in the diverging nozzle area. The oxygen jets come away from the diffusor walls inside the nozzle.
- The exit pressure Pa' is below both the pressure Pkrit and the exit pressure Pa on which the calculation is based. After the oxygen jet leaves, the diffusor

expansion occurs at a wider angle than the diffuser angle with recompression of the jets further away from the nozzle.

All these non-design conditions reduce the kinetic energy of the oxygen jet and change the blowing characteristic of the lance. Such shock waves are also produced if the calculated set oxygen flow rate is altered during use. For a fixed lance distance, changes in the oxygen flow rate change the impingement pressure of the oxygen jets at the metal bath surface so the blowing characteristic gets softer or harder. Both under-blown and over-blown nozzle tips have a softer blowing characteristic because of the kinetic energy loss as result of the shock waves. In addition, under-blown nozzles damage the diffuser exits and therefore reduce the lance tip life. Blowing behaviour is better controlled if the lance distance to the metal bath is altered while working with a constant oxygen flow rate.

Many steel plants work with a fixed lance pattern during blowing which must lead to variable results if there are variations in the amounts and chemistry of the added input materials. Dynamic lance control which adapts to different conditions is of great benefit.

POST COMBUSTION

Oxygen flow rate should preferably be constant throughout the blow. Unfortunately, in many steel plants the oxygen flow rate is reduced at times during the blow because of slopping or simply because it is laid down in the blowing program. Depending on the duration and the amount of the reduced oxygen flow rate, this can have adverse consequences for converter lining life. An under-blown nozzle produces shock waves, which lead to an intensive re-mixing with the up-streaming CO/CO_2 gas, and therefore to additional post-combustion of CO to CO_2.

In addition, the lance distance itself also has an influence on post-combustion. With increasing lance distance, (softer blowing), the CO_2 increases and although, theoretically, a 1% CO_2 increase can melt an additional 5–5.5kg scrap/t of steel, the practical result is only a marginal increase at the expense of a considerable increase in lining wear, especially in the upper cone of the converter. The reason is that with increasing post combustion the temperature of the waste gas surrounding the oxygen jets increases and acquires a burner characteristic, able to reach temperatures of 3,000°C. **MS**

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