

Chapter 8

Oxygen Steelmaking Furnace Mechanical Description and Maintenance Considerations

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8.1 Introduction

The intent of this chapter is to provide a mechanical description of the basic oxygen furnace (BOF), as well as the maintenance of certain BOF components. The components covered in this report include basically all components of the BOF vessel and the trunnion ring up to the trunnion pins. Excluded areas are probes, couplings, bearings, foundations and the various drive units. The BOF components covered are: top ring and lip ring; cone, barrel, bottom shells and transition knuckle sections or flanges; brick retainer rings, slag shields and taphole assembly; working and safety refractory linings; vessel support system; trunnion ring, trunnion blocks and trunnion pins; cooling system for the vessel or trunnion ring; and oxygen lances.

This chapter is an abridged version of *AISE Technical Report No. 32, Design and Maintenance of Basic Oxygen Furnaces*,¹ with the addition of Section 8.5 which addresses oxygen lance design, and Section 8.6 which addresses sub-lance design.

8.2 Furnace Description

8.2.1 Introduction

This chapter is established to provide a description and preliminary design considerations for the manufacture and supply of BOFs. Basic oxygen furnaces are so called by virtue of the refractory and the additives used in their steelmaking processes. The processes referred to in this chapter are those which involve the treatment of a mixture of steel scrap and molten iron, generally transported from the blast furnace to the BOF. The steel scrap and hot iron are charged into the BOF vessel and oxygen is injected in one of many different methods into the furnace for purposes of producing a steel melt of specific chemical and physical properties.

The processes involved share one common operating factor; the injection of oxygen into the furnace is the agent for decarburizing the molten hot iron and generating the reaction heat required to melt the scrap.

For purposes of this chapter, the terms used will be consistent with the following descriptive definitions. A BOF installation consists of the basic oxygen furnace, furnace support foundation, furnace tilt drive and controls, furnace water cooling system, fume exhaust and cleaning system, oxygen injection system, auxiliary furnace bottom stirring system, process additives system, scrap and hot metal charging system, molten steel delivery and slag disposal system, furnace deskulling system, and other auxiliary steelmaking requirements such as sampling, refractory inspection and relining systems, process computers, etc.

An operating BOF, Fig. 8.1, consists of the vessel and its refractory lining, vessel protective slag shields, the trunnion ring, a vessel suspension system supporting the vessel within the trunnion ring, trunnion pins and support bearings, and the oxygen lance.

The BOF vessel consists of the vessel shell, made of a bottom, a cylindrical center shell (barrel), and a top cone; reinforcing components to the cone, such as a lip ring and top ring; auxiliary center shell and top cone flanges for bolted-on top cones; auxiliary removable bottoms for bottom reline access, or for individual bottom reline of bottom-blown vessels; and a taphole. This list is not intended to be either restrictive or comprehensive, e.g., top cone flanges are not universal.

BOF vessels can be one of the general classifications presented in Fig. 8.2. These are top-blown vessels, in which the oxygen is injected above the hot metal bath by means of a retractable lance; top-blown vessels, in combination with bottom stirring, the latter usually by introducing metered amounts of inert gas at specific locations under the hot metal bath—the introduction of the inert gas is either through porous plugs or tuyeres; bottom-blown vessels, in which the oxygen is injected under the molten metal bath through tuyeres arranged in the bottom of the vessel, and usually carrying pulverized additives; bottom-blown vessels utilizing a calculated source of heat energy provided by hydrocarbon fuel, in a very similar arrangement as the bottom blown vessel; and combination-blown vessels, in which the oxygen is introduced under the bath through tuyeres

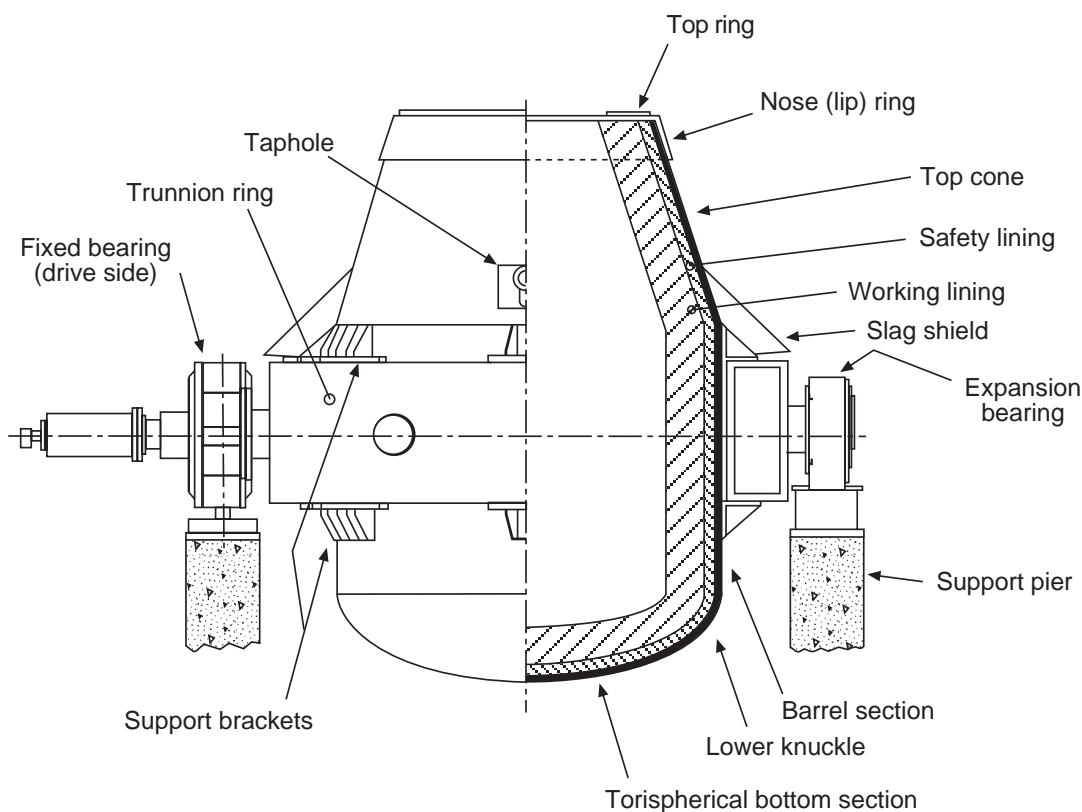


Fig. 8.1 BOF configuration.

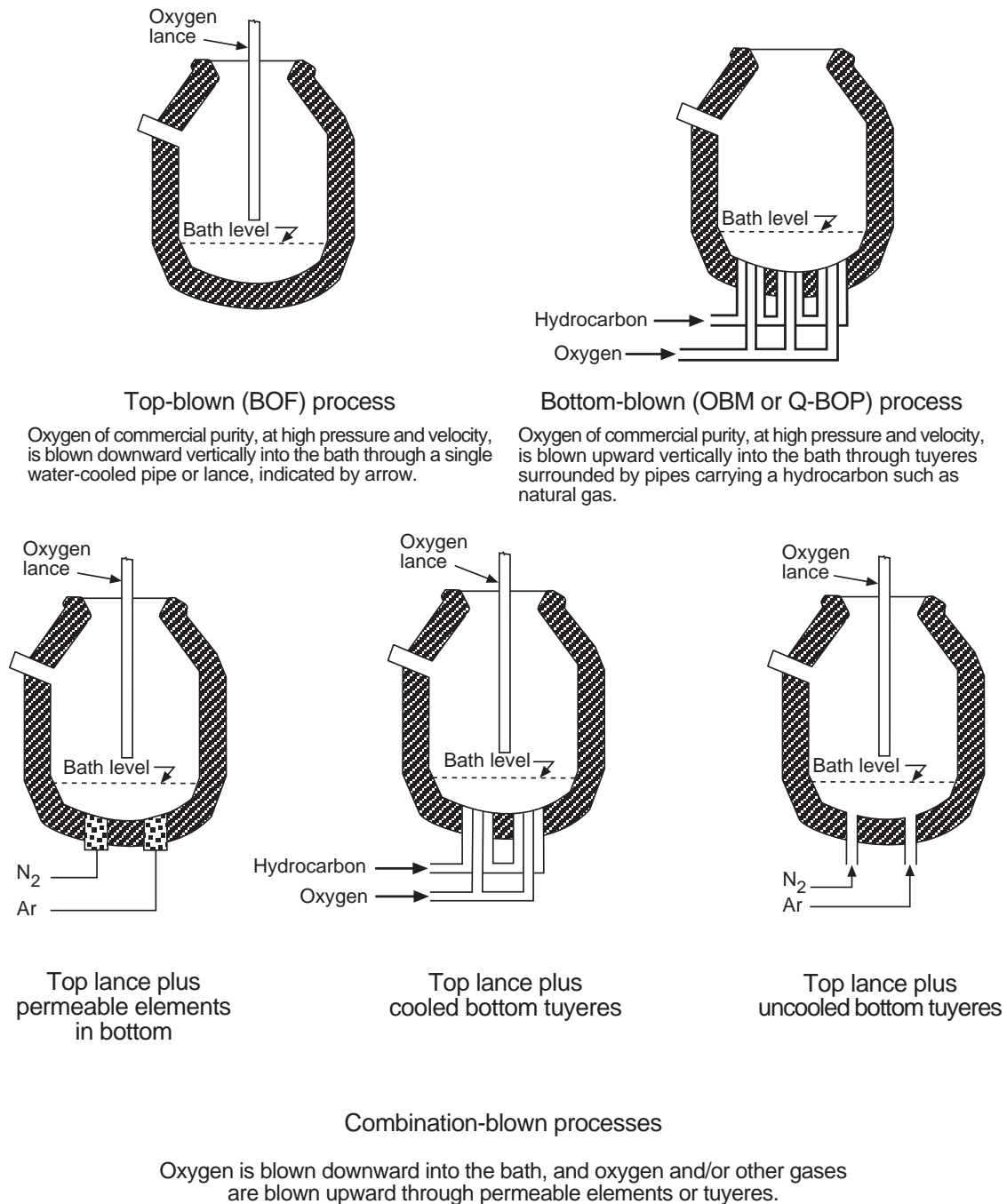


Fig. 8.2 General BOF vessel classifications.

in the bottom of the vessel, as well as above the bath through a lance—the oxygen blown through the bottom usually carries pulverized additives. Fig. 8.3 presents commercially available bottom stirring processes.

8.2.2 Vessel Shape

The shape of the vessel has an influence on the efficiency of the steelmaking process inside. This is particularly the case when the oxygen to the steel bath is supplied only from the top (top blowing). Fig. 8.4 shows a variety of shapes and sizes which were used in North America during the

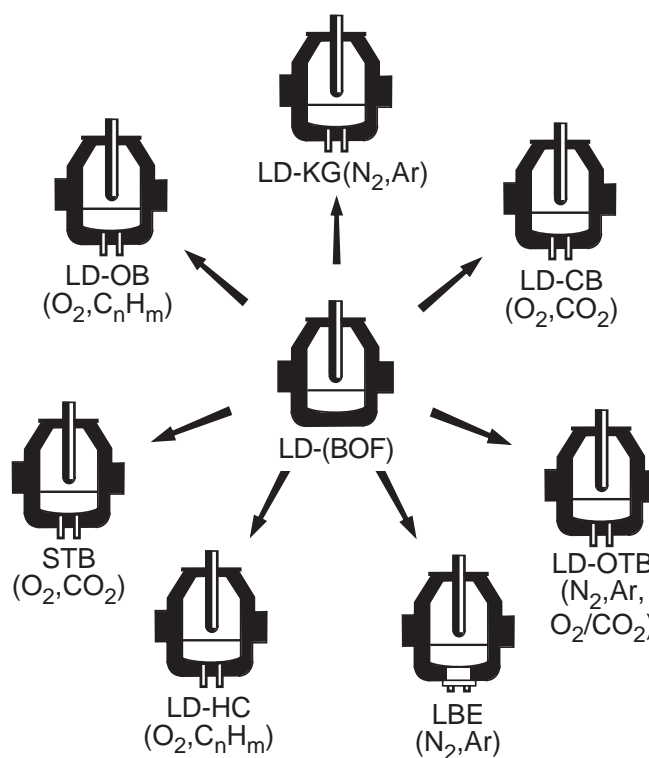


Fig. 8.3 Commercial variations of bottom stirring practices.

period of 1954–1973. Although many factors would influence the shape of the vessel, an approximate rule of thumb which has yielded favorable designs relates to the specific volume of the vessel. In conjunction with the rate of oxygen blowing, Fig. 8.5, and with hot metal composition as controlling factors, operating experience has shown that in general when the specific volume is in excess of 26 cubic feet per net ton of processed steel, Fig 8.6, the yield loss due to slopping is highly reduced.

Except for the case of a greenfield site installation, the optimum vessel shape for the particular application is usually determined by factors other than the oxygen blowing efficiency. The height clearance and the distance between trunnion pin bearing centers are two common factors which limit vessel volume increase in a vessel replacement project.

8.2.3 Top Cone-to-Barrel Attachment

There are generally two methods for the attachment of the top cone of a vessel to its cylindrical section, namely welding or bolting. Welded top cones can be either corner welded or welded with a rounded knuckle. In each case, the inside surface of the shell must be free from offsets because of stress concentrations. Corner welded transitions are more susceptible to cracking than rounded knuckle transitions.

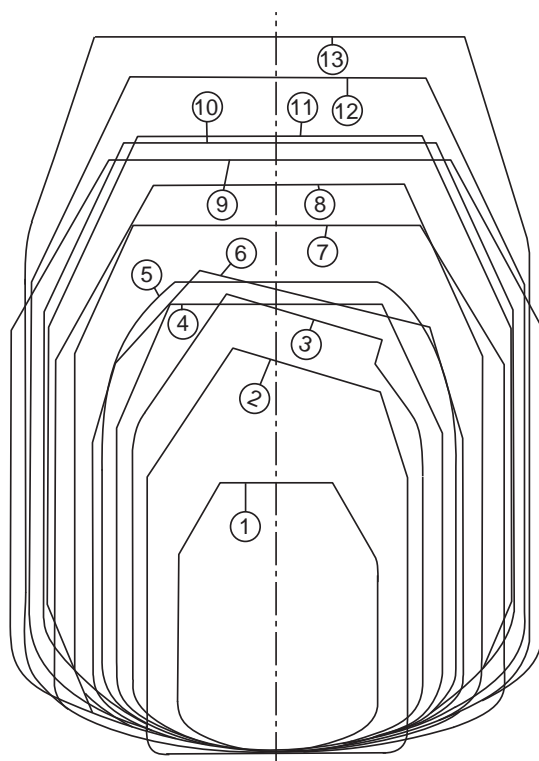
Bolted top cones, on the other hand, necessitate outfitting both the cone and the top of the cylindrical center section with adequately heavy flanges and elevated temperature-resistant bolts and nuts.

The taphole on BOFs built in the U.S. has been placed mostly in the cone section. The centerline of the taphole usually falls on the intersection of the refractory linings of the top cone and the cylinder. In vessels with a top cone knuckle, most of the tapholes fall partly within the knuckle area. In other countries, there are numerous vessels where the tap nozzle is actually located in the top cylinder of the center shell. This is done to utilize the properties of the molten steel flow which are associated with the angle of the tapped molten steel jet, the ferrostatic head, and the control of the

vessel movement during the tapping sequence. This results in improved ladle yield through reduced entrainment of slag in the steel tapped into the ladle.

8.2.4 Methods of Top Cone Cooling

Two components in the top cone of a basic oxygen furnace vessel can benefit from water cooling as a means to maintain their low operating temperature. These are the conical shell itself and the lip ring at the top corner of the cone. At full combustion, these components are exposed to radiant heat reflected back from the BOF exhaust fume hood while the furnace is in the oxygen blow mode. Additionally, they are subjected to convective heat from the vessel interior and radiant heat during tapping and slagging off into the steel ladle and the slag pot, respectively. Experience in a majority of steel mills in the U.S. indicates that the water cooling of these two components has a significantly advantageous effect in prolonging their life.



There are different designs for achieving the water cooling of the conical shell, all of which utilize closure channels for forced circulation of given amounts of cooling water. The design differences are in the pattern of flow based on the arrangement of the channels, and their cross-section. The wetted area, as a percentage of the total conical shell area, plays a significant role in the amount of heat removed. It is possible to create a cooler than desirable cone refractory, which could contribute to the generation of large skull buildups and kidneys inside the cone.

One design type consists of horizontally oriented channels, Fig. 8.7, mostly half-pipes, feeding from and returning into adjacent vertical inlet and outlet headers, respectively. Another design type consists of vertically oriented channels, Fig. 8.8, fed by a series of circumferentially placed inlet and outlet headers in a pattern of upward and downward flows covering the entire surface of the top cone shell. The channels in this type would be either half pipes or equal-legged angles. Water circulation is maintained by forcing the cooling water to the lip ring, either through series or a parallel connections. Most often series connections are used. More flexibility in shutting off individual systems is provided where both the cone and the trunnion ring have their own individual cooling water circuit, controlled from outside the vessel.

In rare occasions, a combination between the two systems has been used, whereby the orientation of the cooling channels was helical. In each case, the

	Company	Estimated Capacity, ton	Operation Date
1	Allegheny	18	1964
2	McLouth	60	1954
3	Acme	75	1957
4	Interlake	75	1972
5	Kaiser	110	1956
6	Dofasco	105	1966
7	Armco	150	1963
8	Wisconsin	120	1964
9	Great Lakes	300	1962
10	Inland	210	1973
11	United States	220	1970
12	Algoma	250	1973
13	Bethlehem	300	1973

Fig. 8.4 Evolution of the size and shape of the BOF vessel.

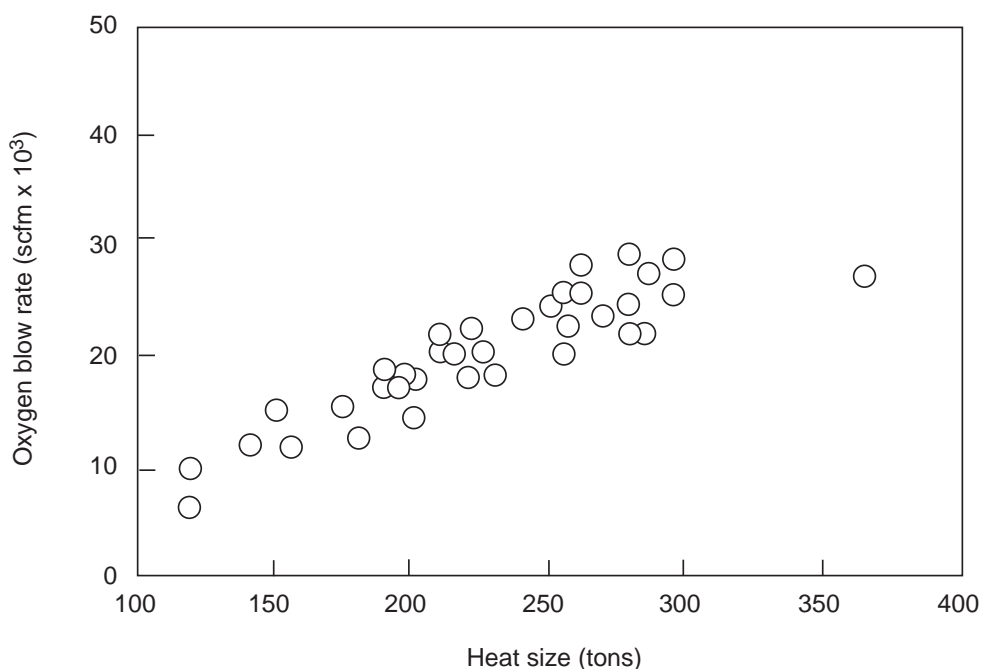


Fig. 8.5 BOF oxygen blowing rate in a sampling of North American shops.

flow has to be carefully calculated to result in a sufficient water velocity, such that the temperature of the water in the individual channels does not exceed the boiling point. Drains must be provided to enable emptying the system of the contained water, and to relieve the water pressure in case of emergency. Additionally, provisions should be made to allow for venting of the system.

A development which has been recently marketed in the industry is the air-mist cooling process which incorporates the use of a system of sprays, Fig. 8.9. Atomized water droplets are applied to

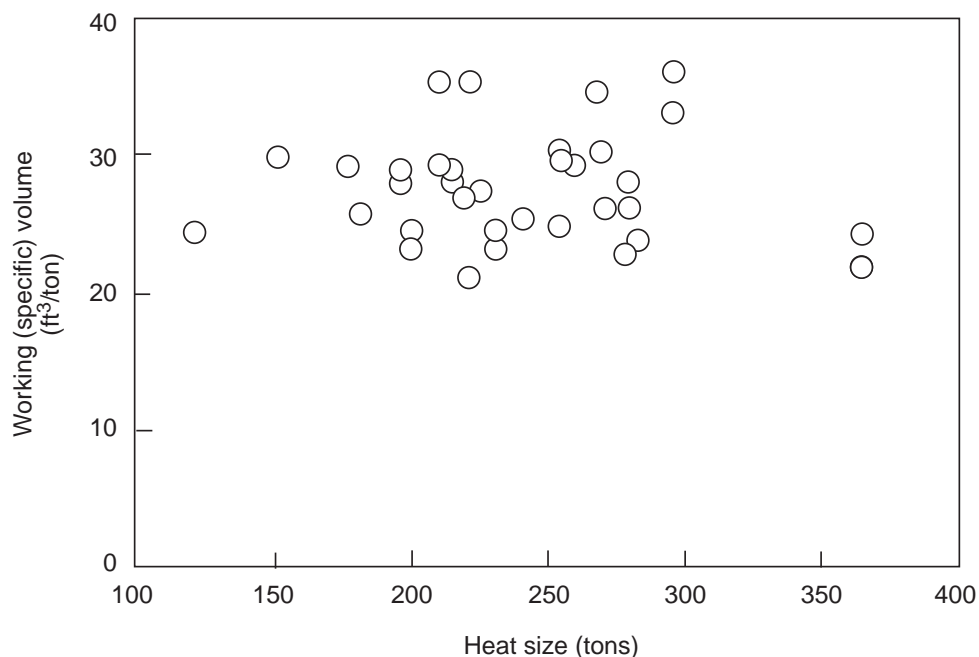


Fig. 8.6 BOF working volume in a sampling of North American shops.

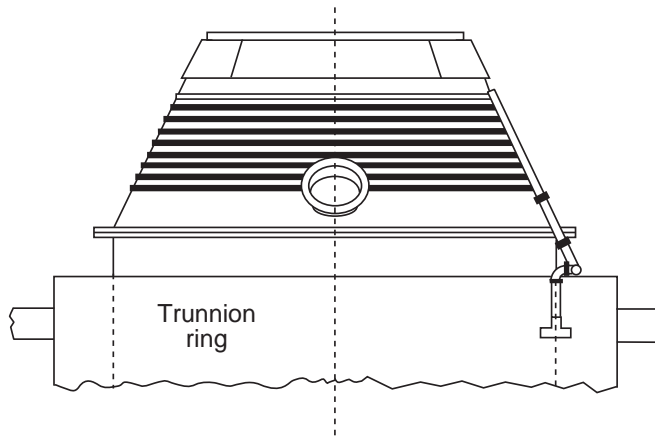


Fig. 8.7 Method of water cooling the nose cone using horizontal channels.



Channel configurations

the surface of the top cone to provide necessary cooling to reduce its temperature. The rate of flow in the sprays is controlled by thermocouples which are applied to the top cone shell.

Lastly, with the application of high conductivity magnesia–carbon bricks, the necessity of cooling the barrel section also becomes evident. To meet this need some plants operate air cooling systems. In these systems compressed air is routed through the trunnion pin to panels located between the

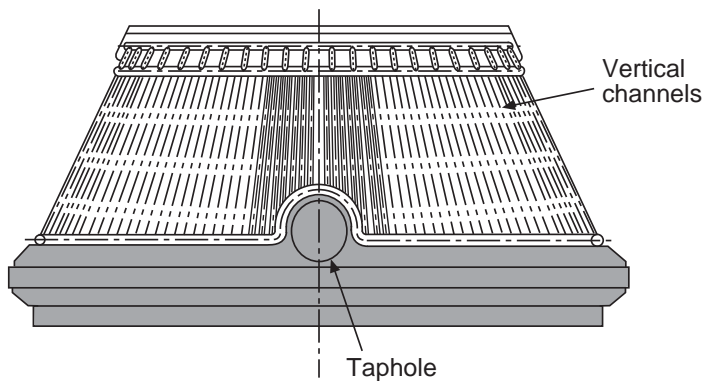


Fig. 8.8 Method of water cooling the nose cone using vertical channels.



Channel configurations

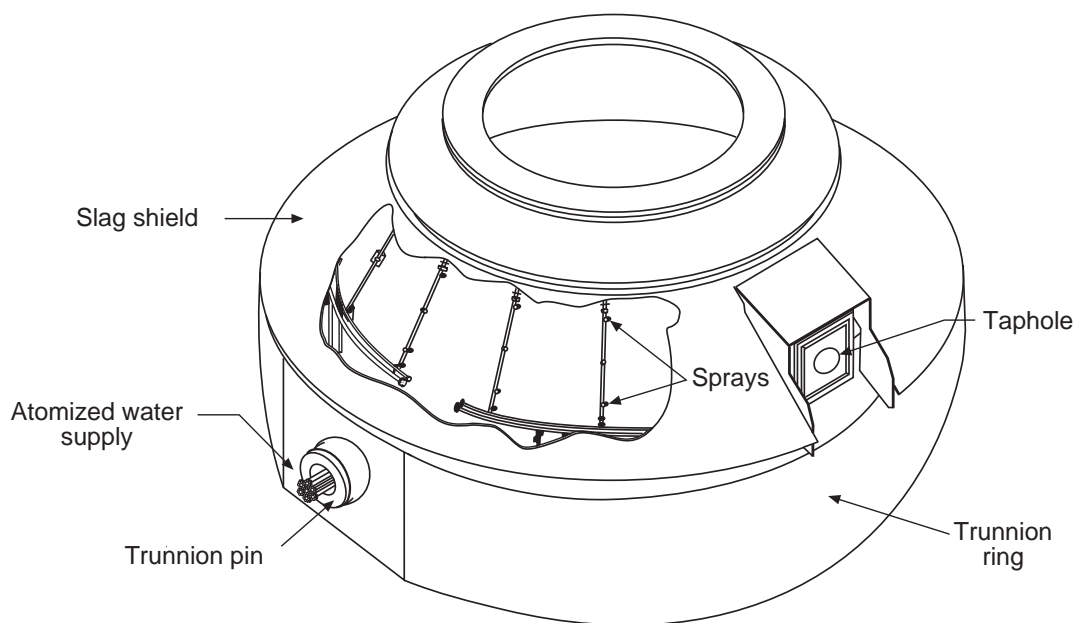


Fig. 8.9 Atomized water supply.

vessel shell and the trunnion ring. Air nozzles on the panels distribute the air uniformly over the barrel surface.

8.2.5 Vessel Bottom

The vessel bottom design is influenced by the process and the weight balance required to optimize the tilt drive system. The common shape is torispherical. For processes requiring the introduction of gases from the bottom of the vessel (through tuyeres), the shape of the bottom tends to be flatter than those which have only top blowing. Also, because some bottom stirring/blowing processes pose more of a burden on the bottom refractory, the bottom is designed to be interchangeable to enhance relining. For example, in the OBM (Q-BOP) process, the refractory lining in the bottom of the vessel wears more than twice as fast as that in the rest of the vessel. Therefore, the bottom is replaced at mid-campaign. This also allows for the maintenance of the tuyeres.

Interchangeable bottoms also allow for relining of the whole vessel from underneath through the bottom hole.

8.2.6 Types of Trunnion Ring Designs

For the basic intended function, the design shape of a trunnion ring normally is circular, Fig. 8.10. In such a design, the vessel and trunnion ring are assembled once for the duration of the useful life of either or both. In certain melt shops, the logistics of operation and maintenance have demanded the assembly and disassembly of the vessel to and from the trunnion ring for refractory relining purposes. The design of the trunnion ring to satisfy this type of service is usually in the form of a horseshoe, that is open-ended, to allow the ease of vessel removal and reassembly. However, circular rings have also been designed for exchange of vessels.

Structurally, the trunnion ring is designed to accommodate the types of load to which it is subjected by the specific method of vessel suspension. In any given design, certain sections of the trunnion ring are subject to shearing forces, bending moments, internal pressure, and/or torsion and to thermal stresses due to non-uniform temperature distribution between the ring inside and outside diameter and the top and bottom flange. Thermal loads must be considered for trunnion ring design,

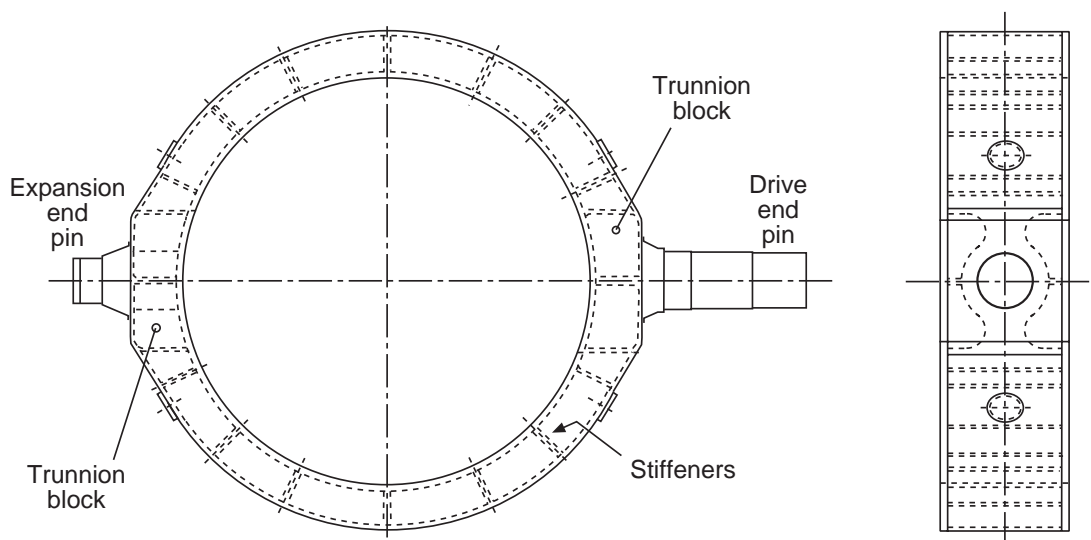


Fig. 8.10 Trunnion ring design.

even in the case of water-cooled rings. The design, therefore, should provide the necessary sizing of the components and manner of assembly (welding, etc.) which can accomplish the required integrity.

The cross-section of the trunnion ring is usually rectangular in shape, made up of top and bottom flanges, inner and outer wrapper plates, and inner baffles and diaphragm plates suitable to the design. In water-cooled and non-water-cooled trunnion ring designs, accesses are normally provided, and are located on the outside wrapper plate.

The bearing shaft or pins are normally connected to the trunnion ring via cast or fabricated blocks which are integral parts of the ring. These pins are secured to the ring either by shrinking fitting, welding, or bolting. Other design specifics in the trunnion blocks stem from process needs such as bottom blowing or stirring, slag detecting and stopping, cooling, etc.

8.2.7 Methods of Vessel Suspension

Virtually all commercially available BOF designs utilize the basic concept of supporting the vessel by the trunnion ring. The function of the trunnion ring is to support the vessel at all phases of operation, while allowing it to undergo the thermal expansion necessitated by the process within. As will be discussed in more detail, there is a multiplicity of technically workable vessel suspension system designs, and several are commercially available and industrially tested.

With the exception of a greenfield site installation, not all designs can benefit the application. Usually, the limitations arise in the confined space within which the vessel system has to be installed. If the replacement vessel system requirement also carries with it the need for an increase in the heat size, the problem is further magnified. Fortunately, with the advent of better design methods (e.g., finite element analysis) and materials, these particular design needs can be met.

There are basically two methods to support the vessel by the trunnion ring. In some designs, the vessel rests on the trunnion ring, and in others, it hangs from it. Until the late 1970s, the most popular vessel suspension design in North America was that involving support brackets. The number of brackets used to support the vessel load was a function of the design concept used. Because of the operating and maintenance limitations which the industry has come to realize with bracket support systems, there is now some inclination toward the concept of hanging the vessel from the trunnion ring. To better identify the features of the commercially available and industrially proven

systems, the following is a description of such, without any intent to commercially or technically discredit any design. It should further be emphasized here that these suspension systems are covered by various patents and should not be regarded as public domain.

8.2.7.1 Bracket Suspension Systems

During the 1960s and 1970s, most designs in the U.S. employed the multi-bracket system which incorporated a certain degree of redundancy in load support. When the design involves more than three support brackets, the load distribution among the brackets cannot be accurately predicted. Examples of multi-bracket support systems are shown in Fig. 8.11 and Fig. 8.12. In all bracket design systems, the vessel rests on the trunnion ring. Tilting of the vessel is affected by some form of connection between the vessel and the trunnion ring, some using the same securing mechanism between the bracket-to-trunnion ring while others would have a separate tilt bracket.

In general, bracket suspension systems include cast or fabricated brackets attached by bolting or welding to the vessel shell and supported at the top and bottom surfaces of the trunnion ring. Additionally, the brackets are permitted to move radially, but restricted from lateral (tangential) movement with respect to the supporting trunnion ring. The restriction of the tangential movement is sometimes provided by means of stop blocks, engaged to the brackets by various systems of keys, grooves, tapered wedges and spherical seats.

There are many designs to compensate for the inevitable longitudinal thermal expansion of the vessel. Inclined planes may be located at the bottom and sometimes the top surfaces of the trunnion rings, in the location of the brackets, such that the radial and longitudinal displacement components of the vessel shell's thermal expansion describe the combined inclination of the top and bottom planes. Another method is to restrict the vessel top brackets from axial movement within the trunnion ring, while allowing the bottom brackets to thermally move in the longitudinal direction in equal magnitude to the longitudinal thermal displacement of the vessel shell between the two brackets. In this design it becomes necessary to tie down the top brackets to the top of the trunnion ring by such means as a gib, Fig. 8.12, which enables radial bracket displacement, while preventing the latter's movement away from the trunnion ring.

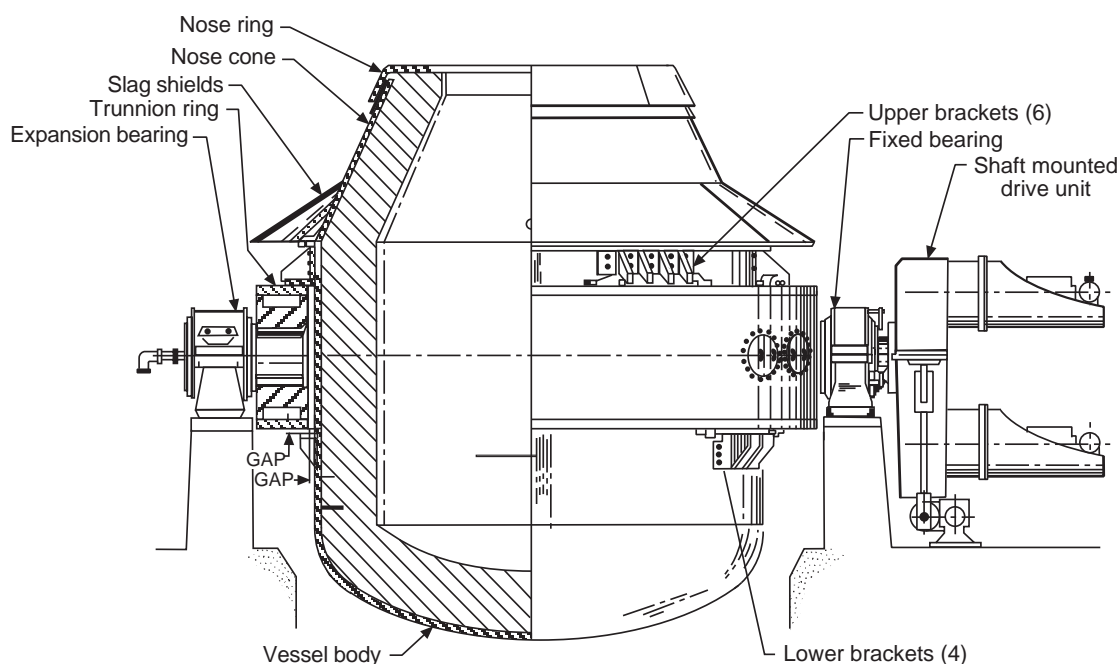


Fig. 8.11 Bracket support system.

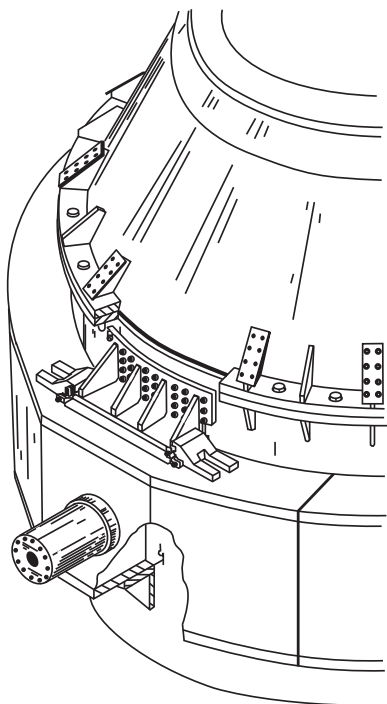


Fig. 8.12 Bracket support system showing detail of gibs.

Vessel suspension brackets, in general, induce a large magnitude of a combination of localized circumferential, longitudinal and twisting moments on the shell, together with membrane and radial forces. If the vessel shell material, geometry, plate thickness and operating temperature are such that the applied bracket stresses could cause plastic deformation and/or creep, the bracket system would then suffer from misalignment symptoms and unequal stress distribution and would become vulnerable to high maintenance requirements.

Geometrically stable vessel shells are the best guarantee for the success of the bracket suspension system. Creep resisting materials for the shell have been used successfully with brackets. Brackets, in general, are located in areas vulnerable to vessel breakouts in cases of burn-throughs. Distorted shells or repaired brackets adversely affect the performance of the bracket suspension system.

Bolted brackets disturb the clean surface inside the vessel and render the bricking of the furnace difficult and time consuming, compared to a smooth internal vessel shell surface. There are, however, solutions to internal surface bolt head protrusion into the shell, which were successfully applied, i.e., bolt heads let into a thickened strake so they are flush on the inside.

To alleviate the load redundancy issue associated with statically undetermined multi-bracketed support systems, some designers chose to reduce the number of supporting members to only two main brackets, one at each trunnion pin location, to support the weight of the vessel and its contents, and a third, smaller bracket for purposes of only tilting the vessel. Thus a statically determined three-point suspension system is provided.

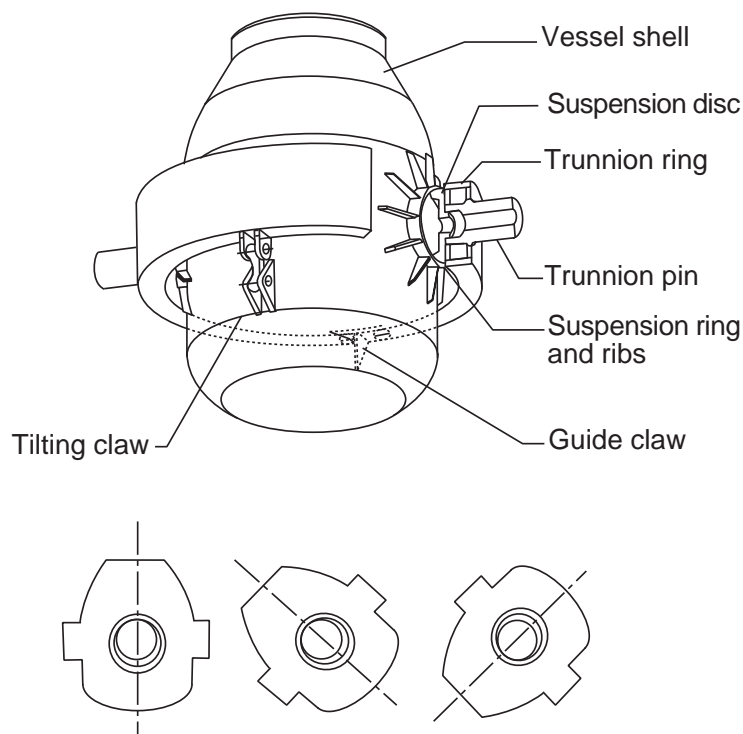
8.2.7.2 Support Disc Suspension System

This system relies on two main circular discs protruding from the trunnion ring center of rotation engaging into two large circular rings attached by welds and radially braced by heavy gussets to the shell, Fig. 8.13. These guarantee the support of the vertical gravitational loads of the vessel and its auxiliary equipment while enabling the vessel to radially and longitudinally expand without restriction. To enable tilting the vessel without relative motion between the shell and the trunnion ring, a third bracket called a tilting claw or toggle is attached to the vessel at a point at the cross-axis of the vessel, supported on the trunnion ring, while a fourth member, called a guide claw, prevents lateral shifting of the vessel in the trunnion ring. This member does not take any gravitational or tilting load. The disc and ring are the supporting members, and are in permanent engagement in all vessel tilting positions, thus avoiding shocks during tilting.

This system creates a smooth surface inside the vessel shell enhancing good and easy bricking of the BOF. It is statically determinate, and enables calculating the precise loads and stresses applied to both the trunnion ring and the shell. Due to the proximity of the disc to the shell, it is expected that the bending and twisting moments can be managed from the design point of view, considering that the load is carried at only two points, compared to at least four in the case of other suspension systems.

The system does not require any adjustment of components and is therefore virtually free of maintenance.

Fig. 8.13 Support disc suspension system.



However, this suspension method requires a larger space between the vessel and the trunnion ring than usually required when utilizing other suspension systems. So, it would be difficult or even impossible to use this system in the case of a replacement BOF vessel, where the available space is already dictated.

The cooling effect on the vessel shell by natural convection is significantly improved as compared to other designs. Furthermore, this large space enables a future installation of an air cooling system for the barrel section.

The disc suspension system is more vulnerable in the case of a breakout due to a burn-through, by virtue of the large shell area required by the ring and its bracing gusset. Repairs to a damaged shell and/or suspension system components in this area become more difficult, as the majority of that area is inaccessible behind the trunnion ring.

8.2.7.3 Tendon Suspension System

This system relies on tying the vessel to the bottom of the trunnion ring from four single brackets distributed circumferentially along the lower shell underneath the trunnion ring. With quick change converters these brackets can be combined into two bracket segments. Pre-stressed (pre-tensioned) tendons penetrate the trunnion ring and are tightened to its top to retain the vessel lower brackets tightly in contact with the bottom surface of the trunnion ring at the point of suspension, while allowing radial displacement of the vessel with respect to the trunnion ring, Fig. 8.14. For absorption of the vessel loads during tilting of the converter, transversal tendons are arranged underneath (with larger vessels above and beneath) the trunnion ring in the region of the trunnion pins as shown in Fig. 8.15. Horizontal stabilizer brackets, similar to the one shown in Fig. 8.16, are sometimes used instead of transversal tendons.

Radial expansion of the vessel shell has to overcome the friction at the supporting surfaces because of the pre-stressed tendons.

This system also provides a clean smooth inside shell surface for easy dependable bricking of the BOF. The largest load carrying member of the lower shell bracket is provided in generally one of

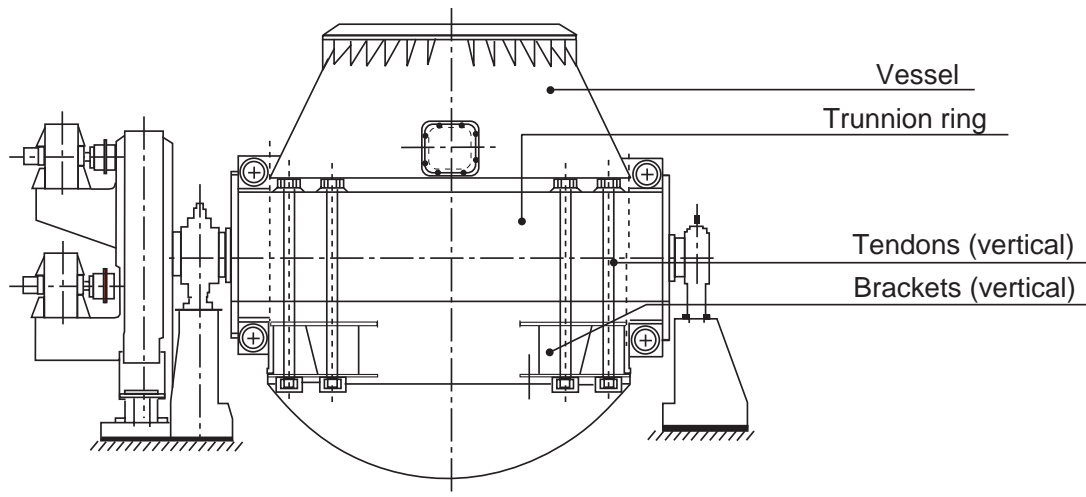


Fig. 8.14 Tendon suspension system, front view.

the lowest temperature shell regions. The stability of the shell, therefore, is expected to be favorable. The tensioning of the tendons is easy to perform with the aid of a tensioning device with direct indication of the tensioning forces. A breakout due to a burn-through could cause difficulties in repairing or replacing the lower brackets.

Experience to date shows that the system appears to require very little maintenance. Also, this system does not occupy any additional room between the vessel and the trunnion ring than that required by a bracket suspension system.

8.2.7.4 Lamella Suspension System

This system relies on suspending the BOF vessel from the lower surface of the trunnion ring by means of a series of two flexible plates oriented in an inclined tangential plane to the shell,

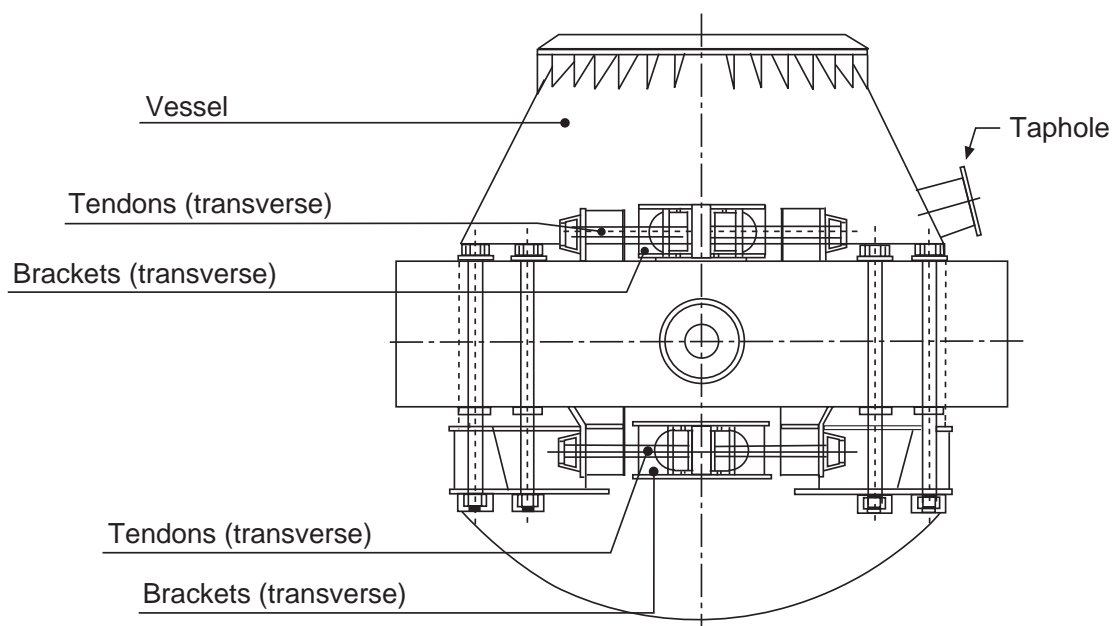


Fig. 8.15 Tendon suspension system, side view.

Fig. 8.16 BOF vessel suspended by lamella plates.

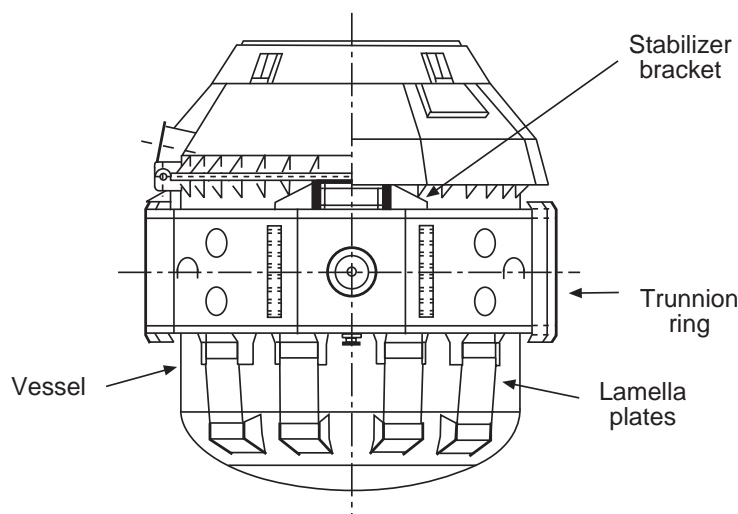


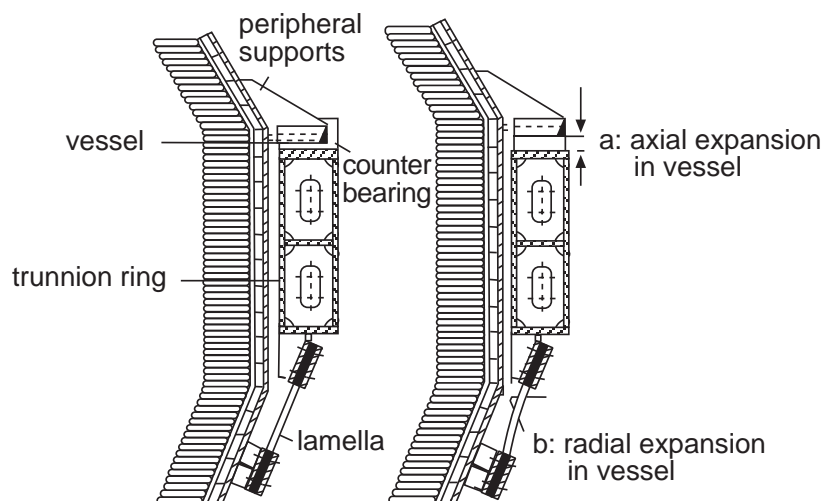
Fig. 8.16 and Fig. 8.17. These plates, called lamellae, are separated from each other by means of a spacer, and enable radial movement of the lower vessel shell against flexural deflection of the two plates about their weak axes. In the direction of their own plane, they possess large strength and stiffness. Therefore, with the aid of a stabilizer bracket between the top shell at the trunnion ring, the system can sustain loads resulting from a tilted or inverted furnace, in addition to an upright vessel.

This system also provides a clean smooth inside shell surface for easy dependable bricking of the BOF. One of the positive features of this design is that the lamella load carrying bracket attached to the lower shell is provided in the shell region of lowest temperature.

The stability of the shell, therefore, is expected to be favorable. A breakout due to a burn-through will not cause difficulties in repairing or replacing the lower brackets of the lamellae.

Experience to date shows that the system requires very little maintenance. Also, this system does not occupy any additional room between the vessel and the trunnion ring than that required by a bracket suspension system.

Fig. 8.17 Principle of operation of lamella plate suspension system.



8.2.8 Vessel Imbalance

The operation of a BOF vessel includes tilting it to either side for purposes of charging, sampling and tapping. The drive train required for this function has to overcome the imbalance, which is created initially by design, of the vessel about the center of rotation. Additionally, the drive mechanism with associated components has to either be able to absorb or attenuate the dynamic or transient type loads which primarily arise during tilting operations.

Two schools of thought exist in the industry regarding the nature of the imbalance in the vessel. One concept is to design the vessel system such that at any time during its operation the imbalance forces are self-righting. In other words, should the drive system fail to hold the vessel, it would return to an upright position. The other concept, which is influenced by purely economic considerations, is one where the vessel system at some stage in its operation becomes overturning if the drive control is lost. The drive system in the latter concept is smaller and therefore lower in cost. However, most of the BOF vessels have adopted the self-righting concept.

The unbalanced torque at the drive side trunnion pin results from the eccentricity of the center of gravity of the rotating masses from the center of rotation of the furnace. The center of gravity of the solid rotating masses, namely the steelwork, refractory and contained water, remains constant with respect to the center of rotation, and the static torque resulting from a 360° rotation of the furnace is a true sine wave. The molten masses on the other hand assume the inside configuration of the refractory lining and under a given angle of tilt will result in a hot metal torque corresponding to the weight of the molten masses and the location of their center of gravity. This latter property is a function of the geometry of the molten mass. By adding the two torques, the static torques of the solid and the molten masses, the total static torque is obtained. This is important in determining the degree of equilibrium of the vessel, and its tendency to movement from a given parked condition. For that reason, the effect of both new and worn lining configurations must be considered.

Coupled with the static unbalanced torque are magnitudes of transient or dynamic torque which can be higher than the static values, depending on the acceleration and deceleration settings in the drive control circuitry, Fig. 8.18. While the operator would prefer a quick responding vessel for

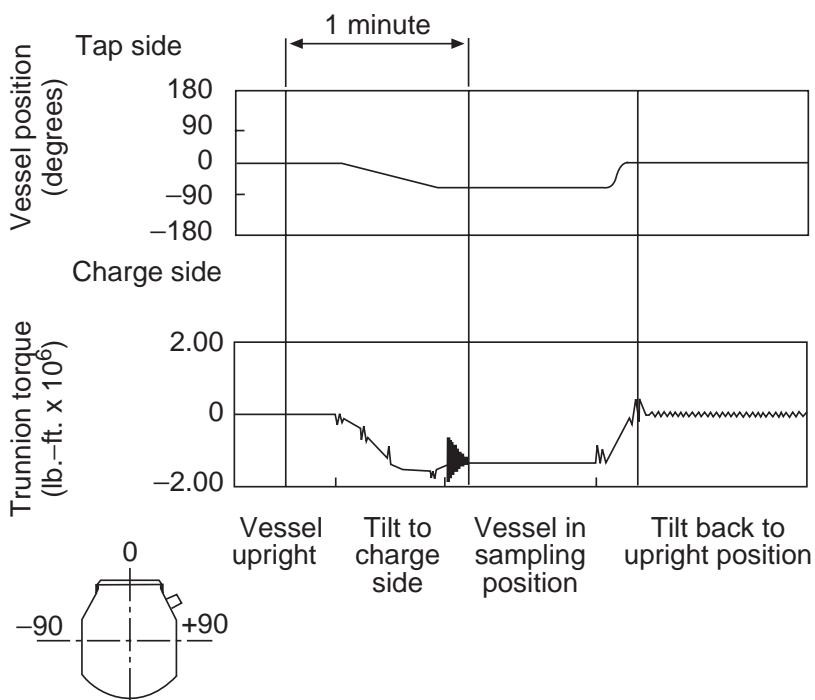


Fig. 8.18 Vessel position and tilt drive torque for a 200 ton BOF.

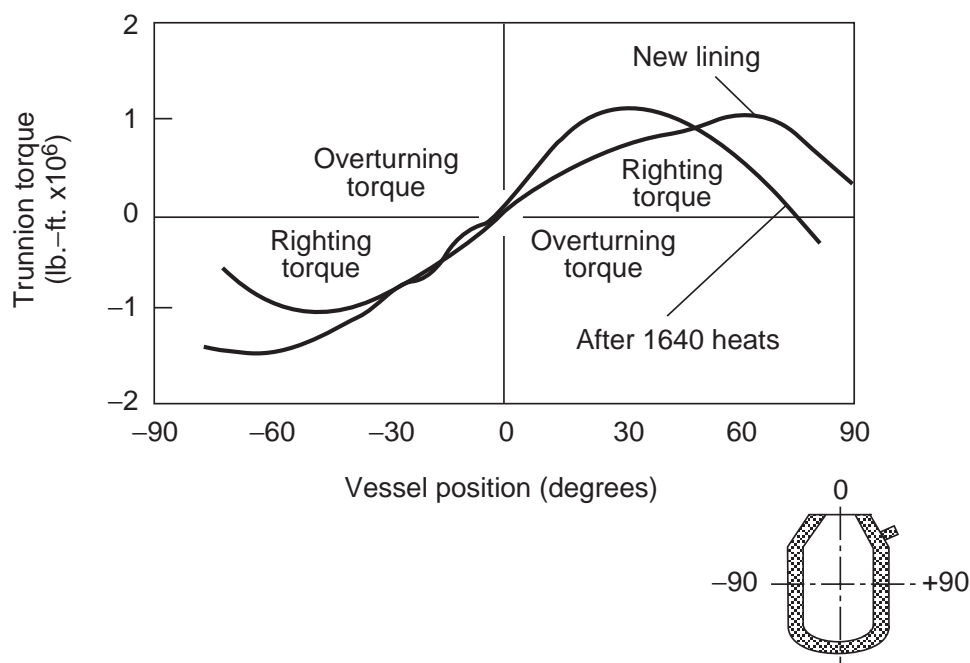


Fig. 8.19 Effect of vessel lining wear on tilt drive torque.

control during the tapping process, such responsiveness usually is detrimental to the integrity of the drive components. An acceleration/deceleration ramp time of four seconds has proven to be an acceptable threshold for imposing the least damage on the drive components.

Uneven and/or non-symmetric refractory lining wear, coupled with skull buildups, play a significant role in changing the vessel unbalance torque. As shown in Fig. 8.19, in one specific installation a 50% increase in static torque was experienced after the refractory lining had produced 1640 heats.

8.2.9 Refractory Lining Design

Fig. 8.20 shows the areas of the refractory lining. The BOF refractory systems are discussed in greater detail in Chapters 3 and 4. A brief description of the requirements of each areas is presented here.

8.2.9.1 Safety Lining

The safety lining is to be made up of burned and/or burned pitch impregnated magnesite refractories. Typical thickness of the safety lining is nine inches. Some companies prefer to use 18 inches on the bottom of the vessel. Refractory retaining bars and rings are installed on the inside of the shell to segment the safety lining so that, during repair, only the worn sections of refractory will be removed and good refractory will be retained. The size and location of the refractory retainers shall be mutually determined jointly by the user, the designer and the refractory supplier.

8.2.9.2 Working Lining

The working lining can vary in thickness depending upon the type of operation and upon the wear rate generally experienced. Higher wear areas should have greater thickness or higher quality materials. The refractories for each area should be selected to have properties that reflect the wear mechanisms of the area where placed. The highest wear areas of the lining should contain brick with properties that reflect the mechanism of wear in that area. Less severe wear areas may contain refractories that are less resistant to the wear mechanisms of the BOF process.

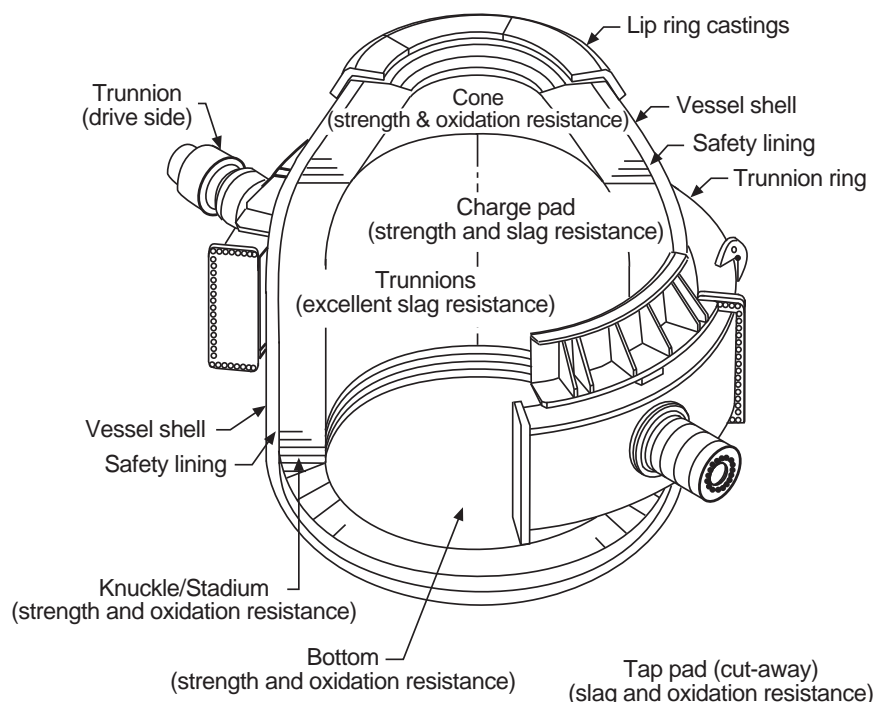


Fig. 8.20 Areas of the refractory lining.

8.2.9.2.1 Cone The cone should contain refractories having good oxidation resistance and good strength. Generally, slag resistance is not a serious consideration.

8.2.9.2.2 Charge Pad The charge pad represents the most important mechanical impact zone. This area is subject to impact during the charging of scrap, and it is subject to erosion during the charging of liquid hot metal. The charge pad should contain refractories with high hot strength to withstand the charging of scrap and hot metal. Slag resistance and oxidation resistance are also desirable properties for charge pad brick.

8.2.9.2.3 Tap Pad The tap pad should contain refractories that are resistant to molten steel and to BOF slag. The oxidation resistance of these materials should also be good.

8.2.9.2.4 Taphole Taphole refractories must have good resistance to molten hot metal erosion and to slags. Tapholes are replaced frequently and a magnesite-based material is gunned around the taphole brick to fill any holes left by the removal of the old taphole refractory. This gunning material must also be resistant to slag attack and molten metal erosion.

8.2.9.2.5 Trunnions Trunnion brick should possess exceptional resistance to BOF slags. Good high temperature strength and oxidation resistance are also desirable.

8.2.9.2.6 Knuckle/Stadium Knuckle/stadium brick should have good resistance to molten metal erosion and thermal shock.

8.2.9.2.7 Bottom Bottom brick should have good resistance to molten metal erosion, oxidation and thermal shock, especially for bottom blown converters.

8.2.9.3 Refractory Shapes

Refractory shapes for BOF linings are generally key shapes. Certain areas of the vessel may contain special shapes. The cone may contain a parallelogram shape that permits easy deskulling of the cone early in the campaign. Also, the bottom may contain BOF key-wedge-arch shapes to accommodate the concentric ring bottom design.

8.2.9.4 Burn-in Practice

Before a newly lined vessel system can be rotated for operation, a burn-in procedure is necessary to heat the brick for expansion to secure it in place. The burn-in procedure consists of loading coke and other combustible materials into the vessel, igniting them, and starting the heating procedure by lowering the oxygen lance into the vessel. The proper burn-in procedure requires the following.

8.2.9.4.1 Time A controlled burn-in requires 3.5 to 4 hours at a heatup rate of 500°F per hour to 2000°F to allow for a more gradual temperature adjustment of the refractory. The vessel can be immediately charged once burn-in is complete.

Some shops still use tar-bonded magnesite refractories in the cones. These materials are normally manufactured to withstand a slow heatup and can be burned in as described above. However, some materials may still be available that have not been so manufactured, and in this case, they may exhibit slumping as they are heated slowly through the temperature range of 400–600°F. The refractory supplier should be consulted on this matter. For this latter material, a rapid heatup avoids the slumping, and burn-in should consist of heatup to 2000°F over a time period of 1.5 hours.

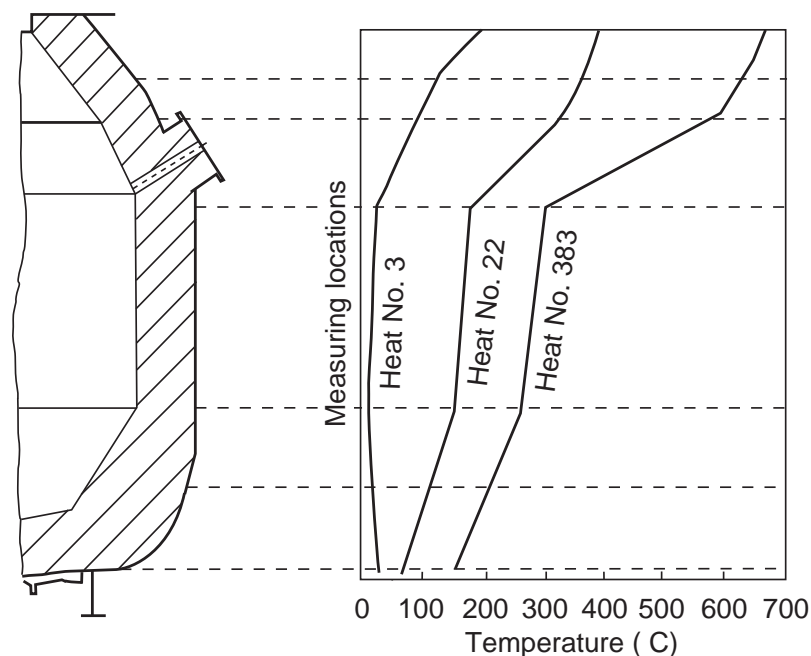
8.2.9.4.2 Temperature Monitoring Temperature during burn in should be monitored and controlled by thermocouple. The thermocouple wire can be inserted through the taphole and should be of sufficient length to reach well into the vessel. Although it will be difficult to achieve a steady state, the rate of temperature increase should follow the desired rate as closely as possible. The initial flare-up upon ignition will exceed the desired rate, but will fall within 30 minutes to the expected curve. It is at this time that the blowing of the oxygen should commence and be increased to allow the temperature to rise at the desired rate.

8.2.10 Design Temperatures

8.2.10.1 Vessel Shell Temperature

A general idea of the temperature levels which prevail in the shell are shown in Fig. 8.21. These levels vary around the periphery of the vessel, and are influenced by the variation in refractory lining thickness.

Fig. 8.21 Shell temperature measurements on a 220 ton BOF.



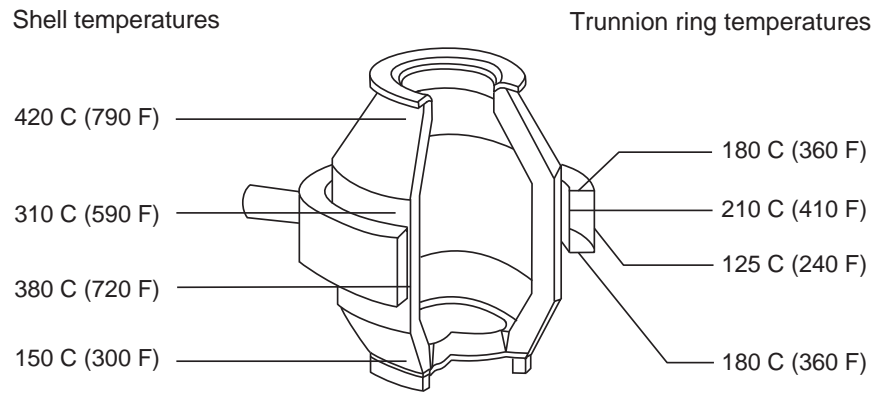


Fig. 8.22 Temperature measurements on a converter shell and trunnion ring.

At certain locations in the shell, the temperature level can become high enough to affect the useful life of the vessel by lowering the material resistance to deformation under load. In the barrel section, temperature levels at mid-height are usually highest, Fig. 8.22. The cooling effect from a water-cooled trunnion ring plays a role in lowering the temperature levels in this portion of the vessel. An example of such is shown in Fig. 8.23.

Designs have been worked out to provide external cooling for the shell around the trunnions. An example of one is shown in Fig. 8.24.

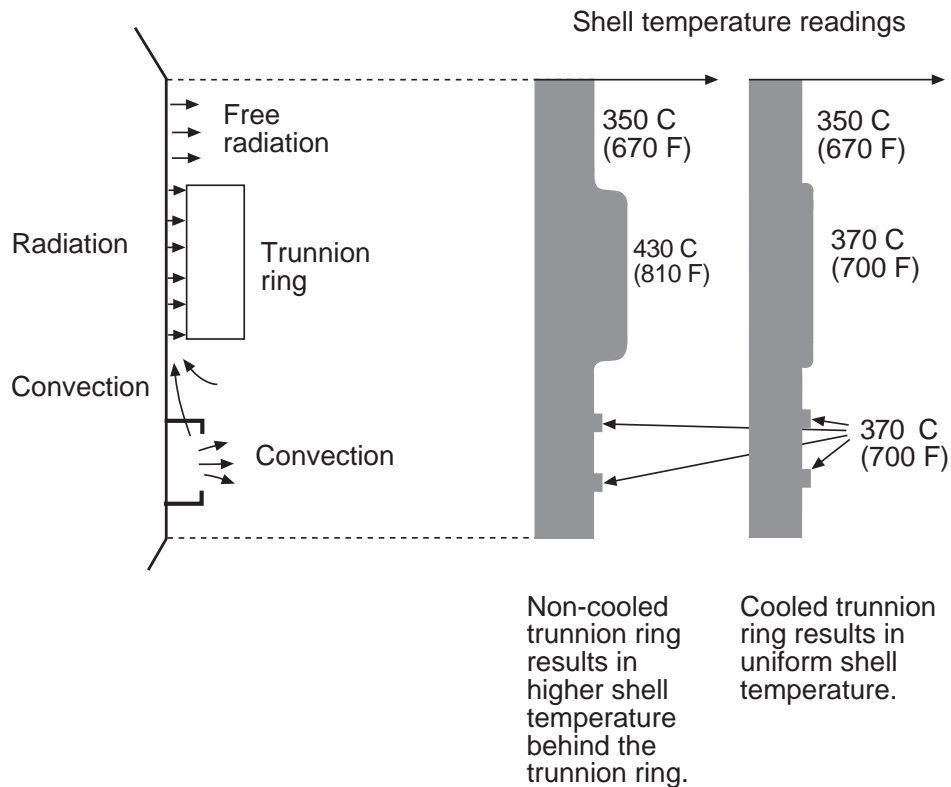


Fig. 8.23 Influence of trunnion ring cooling on BOF shell temperature.

The most significant benefit of external cooling on the vessel has been on the nose cone. In addition to maintaining or prolonging the structural integrity of the cone, there are basically two methods of closed system of water cooling utilized. One method is to apply the cooling tubes in the horizontal direction (circumferential flow) and the other is to apply them along the cone generator. The life of a non-water-cooled nose cone is usually curtailed by the severe distortion which then precludes the ability to maintain the refractory lining. While the use of material which has higher resistance to deformation at the elevated temperatures in the cone can help prolong its life, the concept of water cooling has far more advantages. Without water cooling, the cone shell can reach temperature levels in excess of 1000°F.

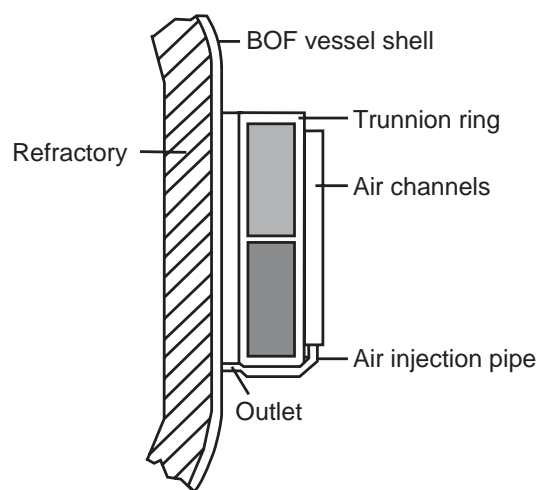


Fig. 8.24 Method of cooling vessel shell with air jets, U.S. Patent No. 5,039,067.

8.2.10.2 Effect of Shell Temperature on Vessel Suspension System

The temperature distribution along and around the vessel is not uniform. This non-uniformity in temperature, especially around the shell periphery, affects certain suspension designs more than others. In multi-bracket suspension designs, where axi-symmetric radial expansion growth is essential to the proper functioning of the bracket securing system, overstress problems occur in both the suspension components and the vessel shell. Even in bracket designs where axi-symmetric radial expansion is not essential, the existence of a temperature distribution other than that assumed by design can affect the proper functioning of the support system. Yet there are suspension systems, the performance of which is much less dependent on the temperature variation along and around the vessel.

8.2.10.3 Trunnion Ring Temperature

In the early to mid 1960s, virtually all BOF systems installed in the U.S. had dry or non-water-cooled trunnion rings. After an average of five years most of these systems were replaced because of severe distortion in both the vessel shell and the trunnion ring. In the early 1970s almost every system was replaced with a water-cooled trunnion ring, allowing the useful life to be extended threefold. While water cooling maintains the structural integrity of the trunnion ring, it also serves to lower the temperature level of the portion of the vessel which is in close proximity to it. As is shown in Fig. 8.23, a temperature reduction of 100°F or higher can be achieved.

The dimensional stability in the trunnion ring, which is affected by water cooling, has many merits, among which are: alignment of the trunnion pins is preserved; structural integrity of the suspension system, especially in the case of a multi-bracket support system, is better preserved; and a cooled trunnion ring can be used as a reference in monitoring the permanent growth (due to creep) of the vessel shell.

While many BOF installations utilize water-cooled trunnion rings, there are several which are still operated dry (without water cooling). The concern and therefore the refrain from using water cooling stems from the potential hazard associated with the large volume of water present in the event of a vessel breakout.

8.2.10.4 Refractory Design Temperatures

The temperature-related destructive mechanism of refractories is slag attack—the higher the temperature, the greater the slag attack. The refractory lining must be designed to withstand slag attack at the maximum operating temperature of the furnace.

8.2.11 Design Pressures and Loading

8.2.11.1 Shell

During the operation of a BOF, the vessel shell is subjected to a complex system of loads and stresses, some uniform and some localized, depending on the design of the trunnion ring, the suspension system, and the geometrical configuration of the vessel.

In general, the loads acting on a BOF vessel shell can be categorized as: gravitational loads, including the weight of the steelwork, refractory lining, charge materials and residual skull buildup; impact loads due to charging of scrap into the furnace; impact loads due to deskulling the furnace mouth or cones, by either a floor deskuller, or mechanical means such as a pneumatic chisel or a swung-loaded chisel; and dynamic loads resulting from vessel rotation for turndown and tapping.

The above loads are usually transmitted to the trunnion ring and the support or suspension system will interact, to a larger or a smaller degree, depending on the system design, with the vessel shell at the attachment areas. Such loads are ultimately transmitted as localized bending, twisting or membrane stresses, to the shell plate.

The following loads, on the other hand, generate vessel shell stresses usually unsensed by the outside support system or the trunnion ring, if the design and function of the suspension system are not flawed. Internal pressures result from the thermal expansion of the hot refractory brick, acting in the radial direction and the axial vessel direction—these pressures are reflected as membrane stresses on all shell components, except at corners of cones and bottoms, where bending stresses will result. Ferrostatic pressures are generated from the molten masses in the furnace—the effect of the ferrostatic head is similar to that in a tilted charging ladle. Non-uniform temperature distributions in the shell produce non-uniform stress loading of the shell.

A type of load which affects both the shell and the support system arises from large variations in temperature in the shell. These large differences in temperature result from both process variations within the vessel and non-uniform refractory lining wear. Yet another condition of significant temperature variations develops in both the vessel shell and trunnion ring during sustained vessel tapping.

The performance of the vessel shell under the applied loads and stresses is a function of many variables, namely: the magnitude of the stresses and the location, area and configuration of the shell at the attachment of the suspension system; the design, and the effect of load transmittal from the shell to the trunnion ring; and the material of the shell, its thickness and its behavior at elevated operating temperatures.

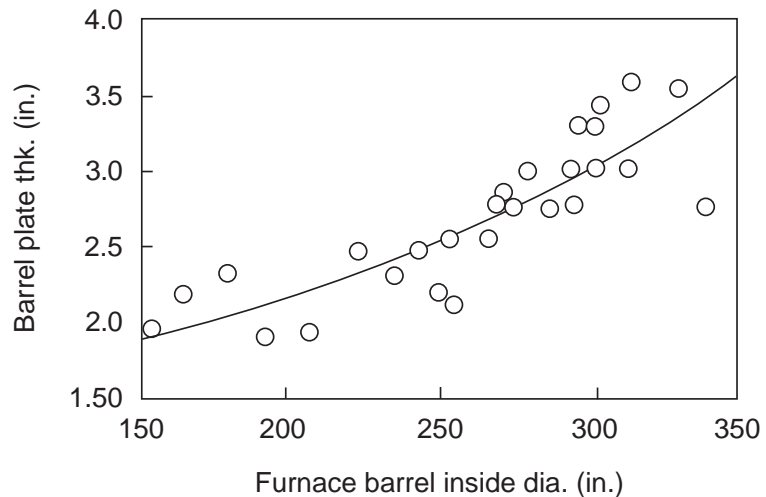
In North America, the experience has been that shell temperatures reach levels which affect the long term stability under the computed acceptable levels of stresses at room temperatures. For the same wall thickness, and correspondingly the same operating shell stresses, utilizing alternate materials of the creep resistant variety has proved successful.

8.2.11.2 Minimum Thickness Requirement

Selection of the suitable shell thickness in a BOF vessel shell is influenced by many factors, among which are: tonnage rating of the vessel; actual geometrical size of the vessel; particulars of design of certain areas of the vessel shell, such as water cooling of the conical shell; physical and creep properties of the material of the shell; nature and magnitude of loads applied from the suspension system to the shell; thickness and type of refractory used; operating conditions and degree of wear of refractory during the campaign; temperature of operation within the furnace; and methods of deskulling and applied mechanical loads.

Due to the number of uncontrolled factors in operating a BOF, it will be a difficult, if not an impossible, task to derive formulae to compute the above effects on the magnitude of the loads applied

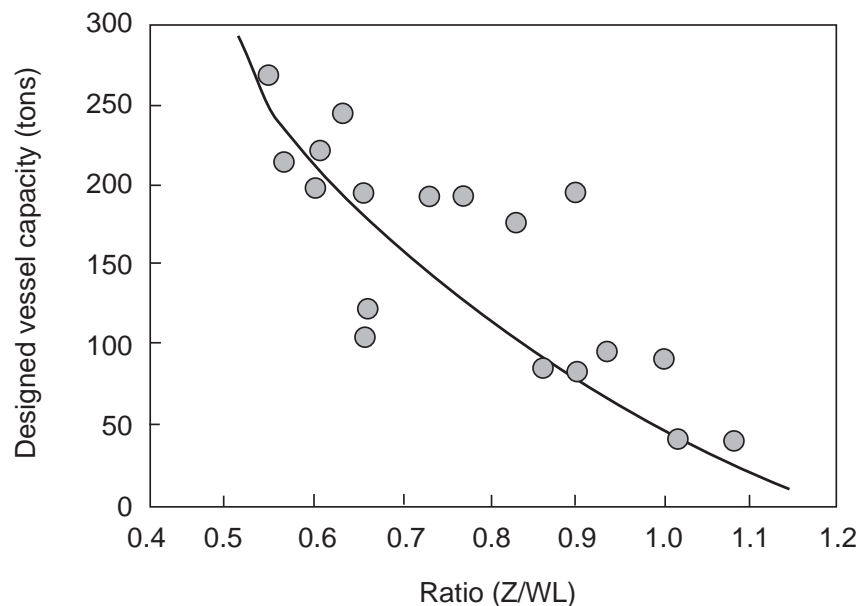
Fig. 8.25 Historical design data for BOF barrel plate thickness.



to the shell, whether from the interaction with the suspension system, or from within the vessel interior. It is anticipated that the recent investigative work, which was done and is being continued on the analysis of the structural behavior of the BOF vessel, that the load mechanisms involved can be better defined.²

It is for this reason that quantification of the shell thickness relies mostly on experience of the designers and the BOF manufacturers with their particular designs and suspension systems. A survey of BOF installations shown in Fig. 8.25 provides some idea of the complexity involved in selecting the suitable shell thickness. A similar collection of historically established dimensional information on the design of trunnion rings is shown in Fig. 8.26.

Fig. 8.26 Historical design data for BOF trunnion rings.



Z = Section modulus of trunnion ring (in.³)
 W = Total load on trunnion ring (tons)
 including vessel, lining and heat weight
 L = Distance between bearings (ft.)

8.2.11.3 Bottom Stirring and Bottom Blowing

The term bottom stirring means the injection of essentially inert gases into the bottom of the BOF vessel, penetrating the bottom shell and the bottom refractory lining, under the molten bath, to agitate the molten masses for such purposes as homogeneity of the melt after introducing additions in the furnace and improving the interaction between the steel bath and the slag. There is usually no direct chemical reaction associated with bottom stirring. The gas injection is either by means of refractory material porous plugs embedded in the bottom lining, or by means of tuyeres, penetrating the bottom lining.

On the other hand, the term bottom blowing means injection of oxygen, singularly, with additives (such as pulverized lime) or in addition to hydrocarbon fuels (such as natural gas, pulverized coke or fuel oil), all routed in the same manner to initiate reactions in the bath. The injection of the oxygen under the molten bath is usually done by means of tuyeres, mostly of annular design, in which the fuel shrouds the oxygen nozzle. The preservation of the tuyere and the bottom refractory are major objectives of the annular design.

In each case the gas lines and the fuel and additive lines (if any) are piped through one or both hollowed trunnion pins of the BOF and down to the bottom shell of the vessel.

As recommended in pressure vessel design, cutting a hole in a shell requires structural reinforcement. Additionally, special care shall be taken in separating the oxygen and the fuel lines. They are usually introduced through opposite trunnion pins. The piping must take into consideration the relative displacement of the vessel with respect to the trunnion ring. Therefore, a series of expansion joints must be designed into the piping. External protection of the piping from heat and falling debris is required. Oxygen piping must be properly cleaned for oxygen service and must be of stainless steel construction. If additives are injected with the oxygen, spark and abrasion resistant materials will be required in key areas of the pipe line.

In association with bottom stirring and, to a more pronounced degree, bottom blowing, it is important to expect generation of additional low frequency vibration in the vessel. These vibrations result partially from the thermodynamic changes and chemical reactions encountered during the passage of either gas in the molten bath, and the propagation of hot metal waves generated in the surface of the bath due to the induced agitation. These oscillations will encumber (and increase the stresses in) the shell, suspension system, trunnion ring, bearings and support pedestals and foundations. Therefore, it is important to carefully plan for possible future process requirements when considering new BOF installations.

In top blown vessel systems, the bearing support is normally not subject to forces along the trunnion axis. However, in systems where gases are introduced in the vessel from the bottom or sides, forces along the trunnion axis are developed, and if the supporting bearing pedestals and piers are not sized properly, undesirable vibration problems result. The expansion side trunnion pin support is normally not subject to this axial load, because the ladder bearing there allows axial movement, without significantly resisting it. The drive side bearing support, however, has to resist these forces, not only in terms of strength, but also dynamic compliance. Both bearing supports, however, have to resist horizontal vibration loads acting perpendicularly to the axis of rotation.

The excitation forces in a bottom-blown or bottom-stirred system are primarily a result of the mass motion of the molten steel inside the vessel. An example of such lateral vibration is shown in Fig. 8.27, where actual field measurements were acquired on the support system of an OBM (Q-BOP) installation. Combined with the forces developed due to chemical reactions within, the overall frequency spectrum contains many components. Coincidence of the excitation frequency of force with the natural frequency of the vessel support system will create resonant vibration problems not only in the support structure, but also in the vessel components.

In past installations, where vibration measurements were acquired, the frequency of axial vibration from melt activity was in the range of 0.3–0.4 Hz. The expansion side bearing support does not participate in resisting this horizontal force developed as a result of the melt activity in the vessel.

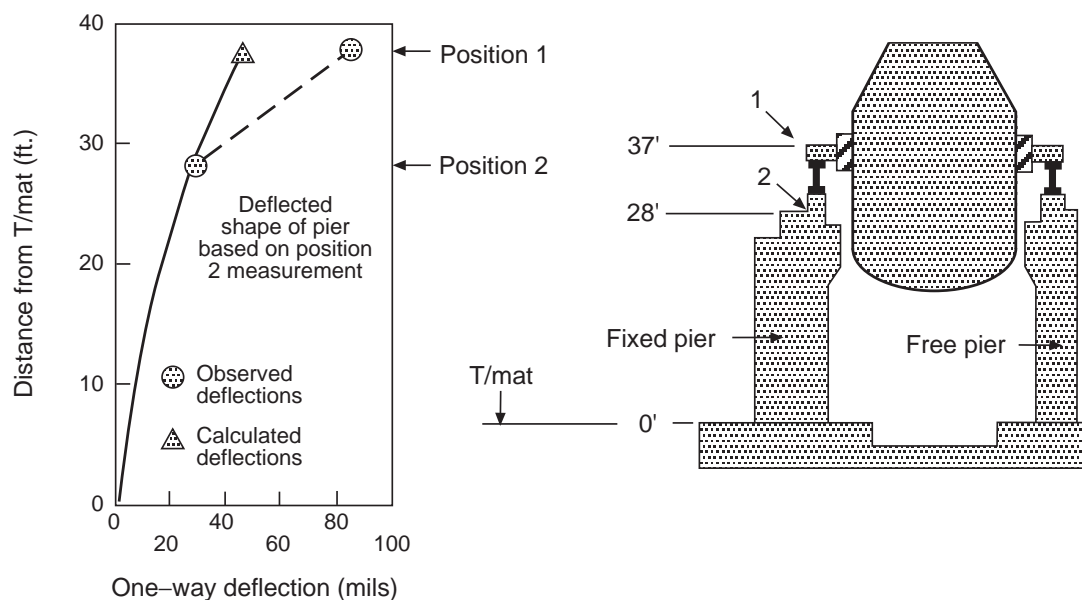


Fig. 8.27 OBM (Q-BOP) support vibration.

As a result, the magnitude of the horizontal force resulting to the drive side pier from melt activity (in the OBM or Q-BOP process) in the vessel is roughly 15% of the total weight supported by both piers.

8.2.11.4 Creep

The useful life of a BOF vessel is normally determined by the change in the space or air gap between the vessel and the supporting trunnion ring. Examples are shown in Fig. 8.28, Fig. 8.29 and Fig. 8.30. The permanent deformation in the vessel due to the mechanism of material creep causes an outward growth, which reduces the air gap.

When this gap is or nearly exhausted, the vessel system is taken out of service. The stresses in the shell which are largely responsible for this growth are due to the thermal expansion of the refractory within.

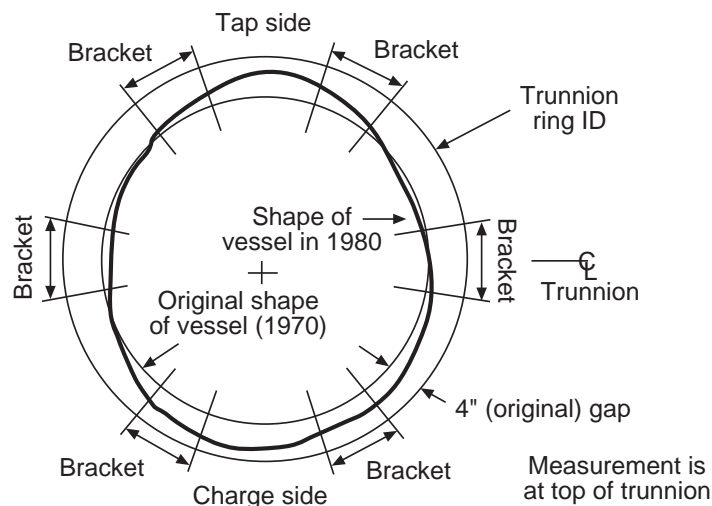


Fig. 8.28 BOF vessel distortion.

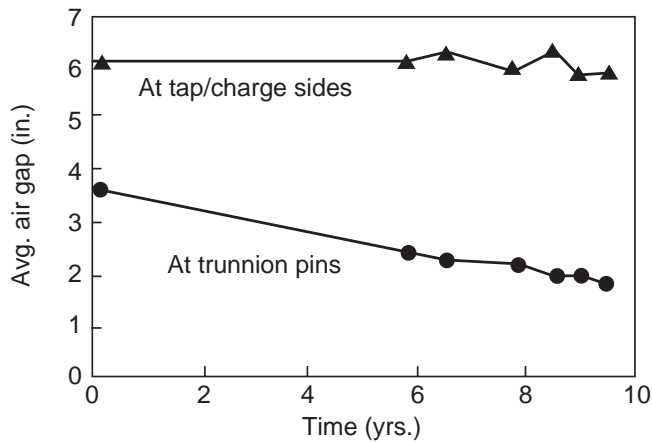


Fig. 8.29 Change in vessel-to-trunnion ring air gap in a water-cooled trunnion ring system.

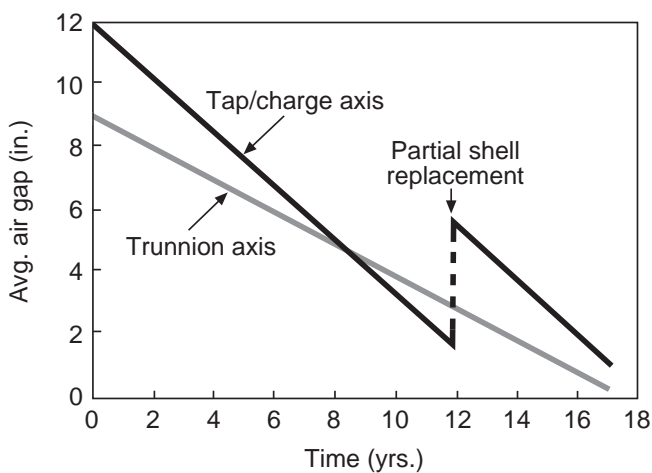


Fig. 8.30 Monitoring of vessel-to-trunnion ring air gap in a non-water-cooled trunnion ring system.

Material creep is a time related phenomenon. In steel, the mechanism is most pronounced at temperature levels above 800°F. As shown in Fig. 8.31, the complete creep life cycle is composed of three stages.

In the primary stage, large deformation or strain occurs in a relatively short time. Depending on the material, temperature and level of stress, this period could be a matter of a few days or even hours. In the secondary stage, the rate of strain is significantly lower, and this stage essentially represents

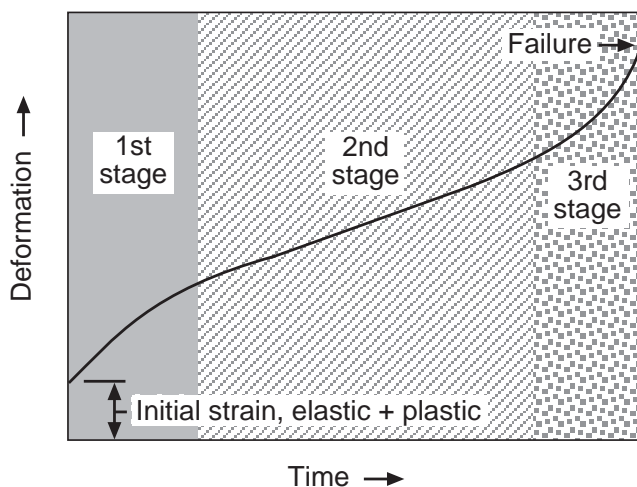


Fig. 8.31 Classical creep life cycle.

the useful life span of the structure. In well designed structures, this period normally represents many years of service. The tertiary stage represents an unstable region, in which the point of rupture is not very predictable. As can be seen, the strain rate is very high here.

The factors which, therefore, influence the rate of the BOF shell growth are stress level, shell temperature level (i.e., refractory practice), and the shell material resistance to deformation at elevated temperature.

Proper refractory lining design and operating practice influence both the stress and temperature levels developed in the shell. Material selection for the application can serve a very significant role here. The use of chrome-molybdenum steel grades has brought about a significant improvement in BOF vessels in North America. Fig. 8.32 shows the change in strength in various BOF vessel steels at elevated temperature levels.

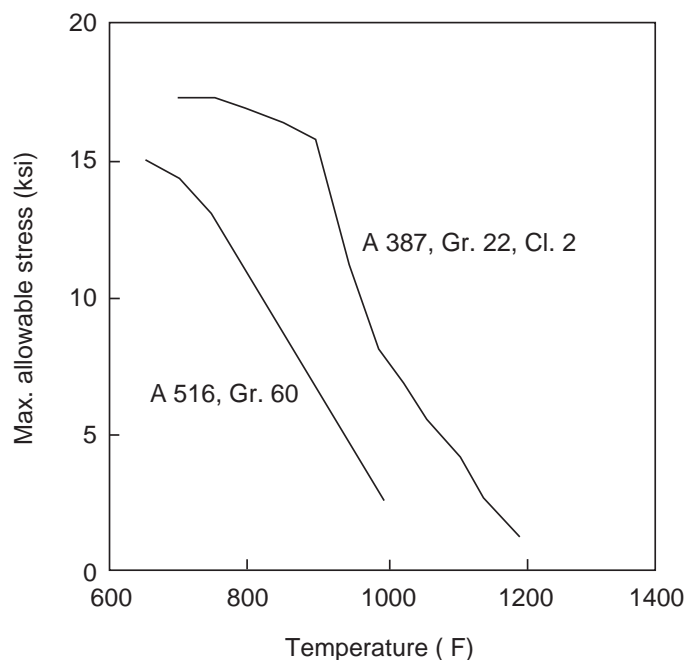


Fig. 8.32 Effect of service temperature on strength of BOF vessel steels.

8.2.11.5 Suspension System

The nature of loading on the vessel shell and the trunnion ring is a function of the specific type of suspension mechanism incorporated.

8.2.11.6 Trunnion Ring and Pin

Again, the nature of vessel suspension influences the type of loading on the trunnion ring and in some cases the trunnion pin.

8.2.11.7 Refractory Lining Design

BOF working and safety linings are made from standard refractory shapes. The lining has to be strong enough to resist severe operating conditions associated with relining, burn-in and with high temperature operation of the vessel.

8.2.11.7.1 Loading on Refractories Loading on refractories will develop as a result of the weight of brick courses, the weight of the cold scrap and hot metal during charging of the vessel, the weight of liquid metal and slag during operation, and the contained pressure from the vessel shell during refractory lining expansions.

8.2.11.7.2 Stresses in the Lining Stresses in the lining will develop during operation and therefore refractories must resist thermomechanical stresses caused by thermal and permanent expansion of the lining in the horizontal directions and by the restriction imposed on the brick by the steel shell. Linings also must withstand mechanical abuse caused by deskulling of the lip ring and the cone and stresses caused by sudden temperature increases during burn-in of the lining and as a result of thermal cycling between heats.

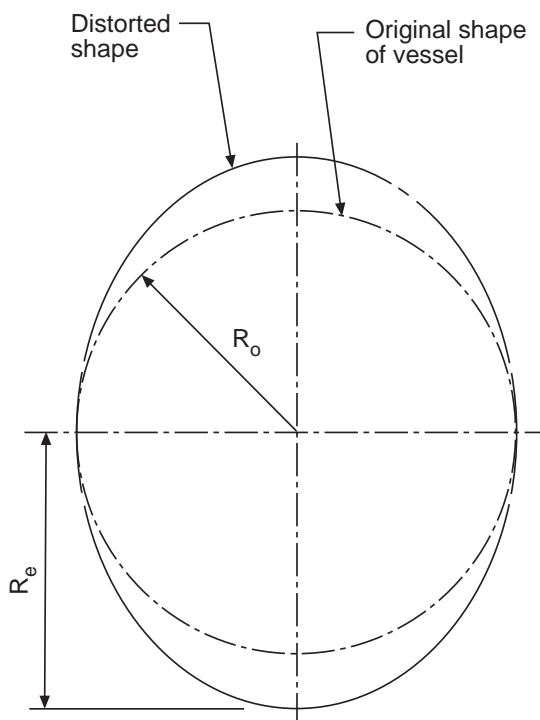


Fig. 8.33 Simulated distortion in a BOF vessel due to creep.

8.2.12 Method of Predicting Vessel Life

The absolute useful life of the vessel material is limited by the time it takes to rupture under a given stress and temperature. In the practical sense, the useful life is limited only by the primary and secondary stages of creep, as shown in Fig. 8.31. In the case of a BOF vessel, the practical and useful life is determined or measured by the depletion of the air gap between the vessel and the trunnion ring. One method, which has been commonly used in the industry, is to periodically monitor this air gap change and predict the end of the vessel life using a straight line projection.

Rarely do BOF vessels deform symmetrically with respect to the central or vertical axis. In some systems, the deformation or distortion occurs along the charge to tap axis and in others along the trunnion axis.

Schematically, therefore, the common distortion in the BOF vessel is in the form shown in Fig. 8.33. Using the anticipated or measured changes in the vessel, the total creep strain which the material at the tap and charge side would or has undergone can be evaluated in one of many approximate methods.

Documented creep data is normally provided in the form of strain rate at the test temperature and stress levels. As indicated earlier, for steel, the information is usually developed at temperature levels above 800°F. Test data also include the total strain at which rupture occurs, again for the specific temperature and stress levels.

For an estimated circumferential (hoop) stress level, coupled sometimes with the mechanical stresses resulting from suspension loads, and the average operating temperature level of the shell in the trunnion ring area, a strain rate can be determined from the data established for the shell material. An example of such data is shown in Fig. 8.34 and Fig. 8.35. If the projection of the

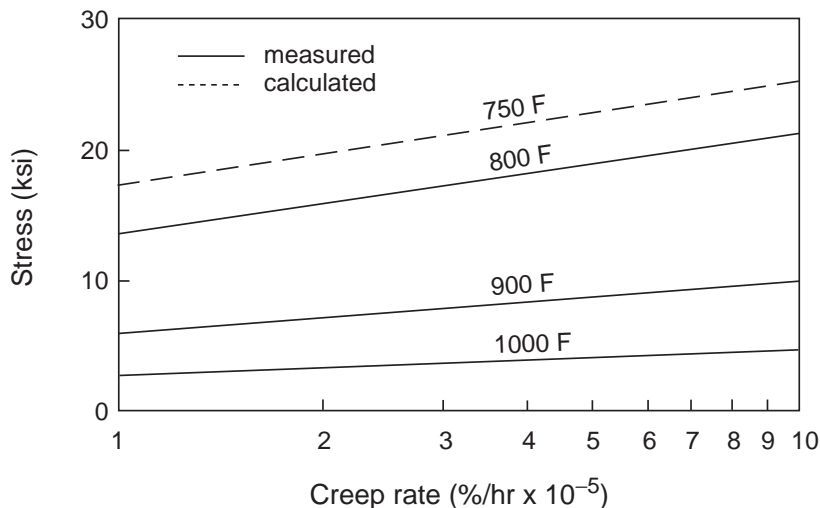
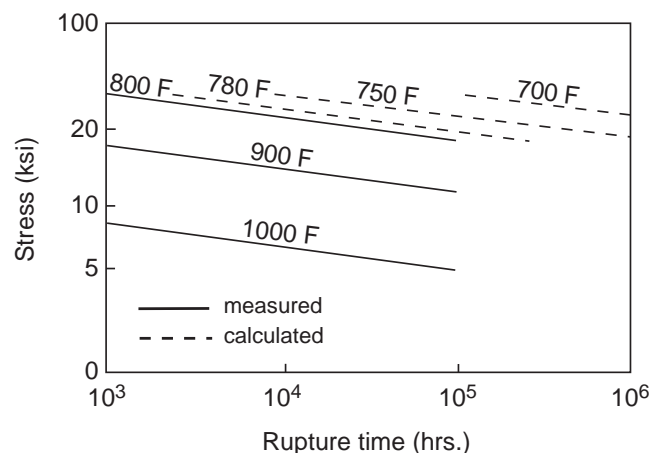


Fig. 8.34 Creep rate curves for medium carbon steel.

Fig. 8.35 Stress rupture curves for medium carbon steel.



remaining useful life is being made for a vessel system which has already been put in service, a better method of establishing the strain rate would be to use the recorded permanent shell growth.

8.2.13 Special Design and Operating Considerations

8.2.13.1 Protective or Slag Shields

Certain components of the vessel-trunnion ring system require protection from the relatively hostile environment resulting from the oxygen blowing process. In general, the suspension system components require protection. The air gap provided between the vessel and the trunnion ring is protected with slag shields. These are segments of steel, usually bolted to supports on the cone, and serve the function of covering the top of the trunnion ring including the mentioned air gap. There are other forms of protective shields designed to suit the particular concept of suspension.

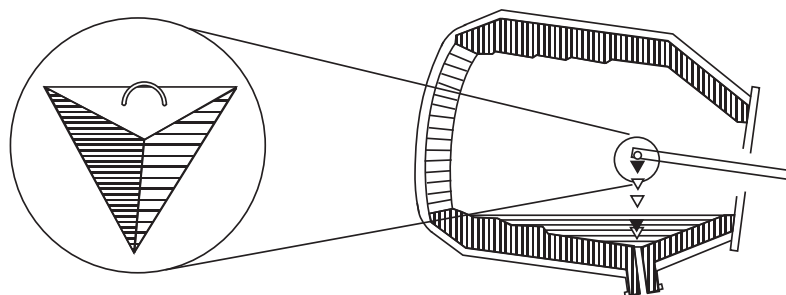
8.2.13.2 Skull Buildup and System Stability

The effects of the refractory lining wear and skull buildup in altering the unbalance torque in the tilt drive are discussed in Section 8.2.8. What is to be emphasized here are the necessary measures which should also be taken to provide for the unusual loading on the vessel suspension, which may not have been anticipated, such as if the user decides to use a skull cleaning system which puts undue loads on the vessel system parts. Deskulling systems which incorporate stationary blades mounted on the charge floor can induce unusually high loads on the vessel system if not used with discretion.

8.2.13.3 Taphole Slag Detection and Retention

Many attempts have been made over the past decade or so to retain the slag in the BOF vessel during tapping. The concept of a floating ceramic ball or a pyramid, Fig. 8.36, has worked well in some

Fig. 8.36 Refractory plug used for slag retention in the BOF vessel.



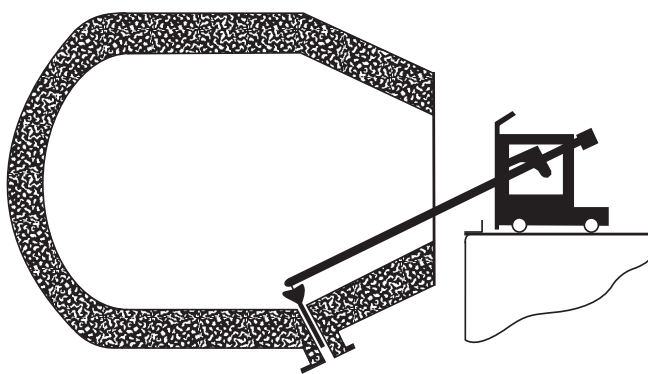


Fig. 8.37 Method of positioning the dart-type slag stopper in the taphole.

shops but not others. The basic principle involved is to drop a floating stopper in the bath prior to tapping and let the stopper plug the taphole from inside the vessel after all the steel is tapped out, while retaining all the slag. The specific density of the stopper material is made such that it floats on the molten steel but not the slag. A modified version of such floating stoppers shaped in the form of a dart has found better performance in shops where a special machine was designed to position the stopper at the taphole from inside the vessel, Fig. 8.37. Usually, BOF shops with adequate floor space on the tap side appear to have the most success with such systems, as this design then allows the installation of the proper machinery and, thus, the precise placement of the floating stopper.

Another concept of slag retention which has come into use over the last fifteen years is a pneumatic device which is installed at the taphole on the outside of the vessel. An electromagnetic slag detector actuates a stopper which closes the taphole after all the steel is tapped. An example is shown in Fig. 8.38. With this system the stream emerging from the taphole is cut by the dynamic impact of the gas blown into the taphole. Sealing performance does not depend on taphole wear.

8.2.13.4 Bottom Blowing

Bottom blowing injection devices, practices and gases differ from one shop to another. The refractories in the area where bottom stirring devices are located should be very high quality magnesia-graphite brick with graphite contents of 10 to 20%. These refractories may contain fused grain. In some cases, burned, impregnated brick designed to have excellent thermal shock resistance is used.

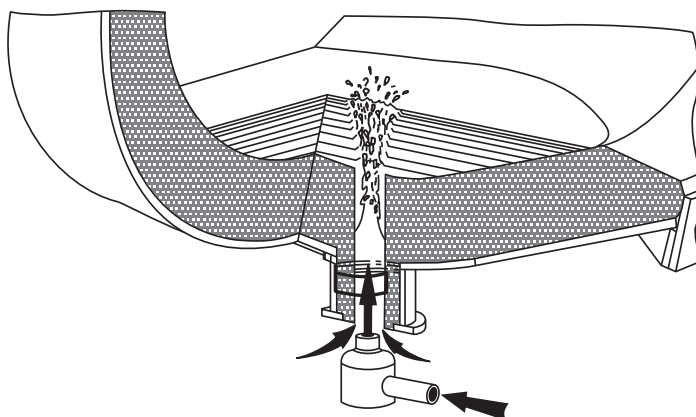


Fig. 8.38 Pneumatic slag stopping device.

8.3 Materials

Materials of construction and welding consumables must be selected with due regard for the stresses, the service temperatures, the interaction with lining materials, and the thermal and mechanical cycling of the BOF process.

A detailed description of the specific type of steel materials, welding materials, materials testing and refractory selections commonly used are discussed in detail in Reference 1.

8.4 Service Inspection, Repair, Alteration and Maintenance

8.4.1 BOF Inspection

Proper inspection and maintenance of a BOF is necessary to produce long life of the equipment and a minimum of maintenance cost throughout its life.

The recommended areas for inspection do not rule out the need for inspecting other components which may be unique to the user's BOF design, and as stated in the Manufacturer's Maintenance Manual.

8.4.1.1 Frequency of Inspection

At a minimum, visual inspection of an active BOF is recommended during any operational cycle. Physical inspection of certain areas and components is recommended during scheduled and non-scheduled downturns. Physical inspection of all areas is recommended after each campaign or sooner if duration of campaign exceeds regular intervals of inspection for certain areas.

The recommended frequencies are stated in the following critical areas.

8.4.1.2 Critical Areas for Inspection

The following components are recommended for inspection. The components may not be representative of all BOFs but are intended to provide guidance in identifying the more critical areas for inspection.

8.4.1.2.1 Lip Ring and Top Ring The buildup of skull on the top of the vessel is to be completely removed and the lip ring and top ring are to be checked for excessive warpage, cracks and/or loose bolts. Any sections that are warped or cracked and can hinder the retention of the refractory in the vessel are to be repaired and/or replaced. Any loose bolts and/or broken bolts are to be tightened or replaced.

Skull removal and inspection or repair of these components are to be accomplished during the campaign on scheduled and non-scheduled downturns as required to maintain their integrity. Complete inspection and repair and/or replacement are to be made after each campaign.

8.4.1.2.2 Slag Shields The slag shields are to be inspected for warpage due to heat. If this warpage is excessive and the shields no longer protect the suspension system, nose cone cooling member, or trunnion ring, these sections should be replaced.

Inspection, repair and/or replacement are to be accomplished during the campaign on scheduled and non-scheduled downturns as required to maintain their integrity. Complete removal of slag shields is to be accomplished after each campaign to facilitate inspection of the slag shield attachment brackets and other components under the slag shields.

8.4.1.2.3 Tapping Nozzle Welded shell nozzles are to be inspected after each campaign for cracked welds and for burn-throughs. These should be repaired before placing the furnace back into operation.

Removable nozzles are to be inspected during and after a campaign to check for cracked welds, burn-throughs and damage to the retaining lugs. All of these conditions should be repaired before placing the furnace back in operation.

8.4.1.2.4 Bolting Flanges The bolting flanges of a removable nose cone are to be inspected after each campaign for cracked welds, loose or broken bolts and any warpage causing excessive gaps.

All cracked welds should be repaired. Loose bolts should be tightened and broken bolts replaced. Excessively warped areas of the flange should be cut out and replaced.

8.4.1.2.5 Water-Cooled Nose Cone and/or Lip Ring Any leakage that would occur during operation of the furnace should be eliminated by either repairing or isolating the leak by means of diverting the water through valving or through a complete shutoff.

After each campaign all water cooling components should be inspected and repaired as required.

8.4.1.2.6 Removable Bottoms The removable bottoms on bottom-blown vessels are to be inspected throughout the campaign for leaks in the tuyere supply piping. Any leaks are to be isolated immediately and repaired.

During bottom changes the removable bottom proper and the attachment bolts or clamp-link assemblies are to be inspected for any damage. Repairs should be made as required.

8.4.1.2.7 Refractory Retainers Horizontal and vertical refractory retainers are to be inspected during each safety lining replacement. Cracked welds should be repaired and any distorted or missing sections should be replaced.

8.4.1.2.8 Vessel Suspensions System Components Every BOF is designed and furnished with a suspension system to support the vessel in the trunnion ring. Many are furnished with vessel connections that are either welded or bolted to the vessel shell and are restrained to the trunnion ring with welded blocks and tapered wedges.

During the campaign any noticed movement of the vessel in the trunnion ring or abnormal noises observed during rotation should be investigated immediately.

After each campaign the following vessel suspension system components are to be inspected.

8.4.1.2.8.1 Vessel Shell Connections All welds are to be inspected for cracking.

8.4.1.2.8.2 Vessel Bracket Connections Connection bolts are to be inspected and any loose bolts are to be tightened. Any broken bolts are to be replaced. The fit of back plates to the shell and of bottom plates to the trunnion rings is to be inspected for distortion.

8.4.1.2.8.3 Retention Hardware Retention blocks are to be inspected for attachment and for distortion of machined surfaces. Adjustable retaining wedges are to be inspected for looseness and distortion. All necessary repairs and adjustments should be made in order to maintain the integrity of the system and to prevent any damage to the shell and the trunnion ring.

8.4.1.2.8.4 Trunnion Ring After each campaign the trunnion ring is to be checked for deformation. The pin alignment in the main trunnion bearings is to be checked and recorded, as well as the axial displacement of the trunnion pin in relation to the center of free bearing. Also, the position of the trunnion pin in each trunnion casting is to be checked. Once per year, the access covers to the outer wrappers are to be removed (after removal of water lines if the trunnion rings are water cooled) and all internal compartments and diaphragms inspected for any cracked welds or members; repairs are to be made as required. Before access covers are replaced, water cooling passages should be cleaned and freed of all debris so as not to cause clogging.

8.4.1.3 Refractory Service Inspection

Service inspections of the refractory lining are necessary to insure that there are no uncontrolled problems with the lining. The areas to be inspected include the cone, charge pad, tap pad, trunnions,

knuckle/stadium and bottom. These inspections are normally carried out visually; however, many companies also rely on a laser lining thickness measuring instrument.

Visual inspection of the lining shall be made by the operator after each heat.

Laser readings should be obtained on a new vessel every other day. As the vessel wears, the frequency of laser readings should be increased to daily. If heats known to be detrimental to linings are made, laser readings should be made after these heats.

In addition to being useful for judging when the reline of the furnace shall take place, these measurements can also provide an indication of the effectiveness of zoning practices (i.e., the practice of installing different quality refractories in various areas of the furnace in an attempt to achieve uniform wear rates). Among the other uses for these readings, two significant uses are to identify operating practices that accelerate wear rates, and to help in scheduling routine maintenance of the working lining of the vessel.

8.4.2 BOF Repair and Alteration Procedures

8.4.2.1 General

During the life of the BOF, repair and alteration by the user may be required to maintain the structural integrity of the BOF. It is important to distinguish between a BOF repair and a BOF alteration.

A repair constitutes a rework of the BOF in order to maintain the structural integrity of the various BOF components. A repair is defined as a rework of one or more components of the BOF without deviation from the original BOF design.

An alteration can be either a form of rework in which a structural component of the BOF is changed from the original specified geometry, or a change in the BOF operating conditions, such as deviation from specified deskulling practices, increasing heat size, adding bottom gas blowing, addition or deletion of cooling systems and/or slag shields or any other such process changes.

8.4.2.2 Procedure for BOF Repair

A BOF repair may be made in the field by the BOF user or his agent. To make a satisfactory repair the following procedure is recommended:

1. The BOF user shall prepare a list of problem areas and operating restrictions.
2. The BOF manufacturer or qualified agent shall submit a rework plan to the BOF user for review and comment.
3. If the BOF manufacturer or qualified agent agrees the user has adopted an appropriate repair procedure, then the user can proceed with the proposed repair.
4. Repair welding of the integral vessel and trunnion ring components shall meet the requirements of ANSI/NB-23 Chapter III for welding, preheat and postweld heat treatment.
5. An inspection of the complete repair shall be made by the user or a qualified agent selected by the user. If the repair was made by a party selected by the user, the complete repair inspection results shall be made available to the repair party.
6. All work on the BOF shall be done in accordance with OSHA safety requirements.

8.4.2.3 Procedure for BOF Alteration

A BOF alteration may be made in the field by the BOF user or his agent. To make a BOF alteration the following procedure is recommended:

1. The BOF user shall prepare an outline of the proposed alteration.
2. The BOF manufacturer or qualified agent shall perform a structural analysis of the alteration consistent with the requirements of these specifications. Complete structural details and requirements shall be determined by the analysis and made available to the user.
3. Following the analysis, the BOF manufacturer or qualified agent shall prepare a proposal which includes details of the alteration and follow the procedures recommended for BOF repair.
4. In the case where the alteration is a change in the operating condition such as a significant increase in tap temperatures or a major change in refractory types, and not a structural alteration, the BOF user shall review the change in operating conditions with a BOF manufacturer or qualified agent to determine the impact of the operating conditions on the structural integrity of the BOF. If necessary the recommended alteration procedure shall be followed.

8.4.3 Repair Requirements of Structural Components

8.4.3.1 General

The BOF shall be maintained such that the structural components can function as intended in the original design. The refractory linings shall be maintained such that the design temperatures for the BOF shell and structural components are not exceeded during typical BOF operations.

8.4.3.2 Crack Repair

Temporary crack repair shall be made by drilling holes at the ends of crack tips. The end of cracks shall be detected by appropriate NDE methods.

The hole drilling technique is a temporary repair used only to curtail the crack growth. When the holes are drilled, immediate plans should be made to make a permanent repair of the crack. Permanent crack repair shall be made by either removing the cracked section and replacing with patch plates, or by complete gouging and grinding of the cracked section and replacement of the removed material with weld deposits.

8.4.3.3 Vessel Shell or Trunnion Ring Wrapper Patch

The shell patch shall be made to replace severely distorted or buckled sections of the shell, as well as any portion of the shell in which the thickness is less than 70% of the original design thickness due to a washout (partial burn-through).

In the case of a molten metal breakout, the opening should be enlarged to a distance of three times the plate thickness beyond the edge of the breakout. The patch and matching cut out portion of the shell plate or wrapper plate must have rounded corners with a radius equal to or greater than three times the plate thickness. The recommended maximum misalignment tolerance should be 25% of plate thickness. The patch plate must be welded with butt joints attained by double bevel welding or other means which will result in the same quality of deposited weld on the inside and outside weld surface. To minimize weld shrinkage, the root opening between the patch plate and the cutout in the shell plate should be minimized in accordance with sound welding practice.

The patch plate material must have a material specification number and grade equal to the original plate material. Alternate grades can be used with guidance from the designer/builder.

Temporary or permanent patching by the use of overlapping patch plates attached with fillet welds is not recommended.

8.4.3.4 Repair of Welds

The repair of welds is necessary when the weld strength has deteriorated due to wear, corrosion or other causes, resulting in loss of weld dimension or due to weld cracks and other signs of weld strength loss.

The existing weld should be removed, preferably by grinding, and replaced with a weld defined by the BOF design.

Preheat temperatures and postweld heat treatment must be imposed based on the criticality of the weld, the thickness of material being welded and other factors of the repair.

8.4.3.5 Refractory Maintenance

The practice of gunning, spraying, slagging, and slag splashing the refractories in a BOF is very important to maintaining the structural integrity of the BOF components. Such maintenance helps to protect a lining from excessive wear caused by either mechanical damage and/or corrosive mechanisms. Maintenance also helps to effectively utilize downtime to extend campaign life.

The refractory at the mouth of the vessel needs to be maintained by spraying in order to maintain the proper mouth opening and to protect the top ring and lip ring from being subjected to molten metal contact during tapping and slagging operations. The taphole area must be repaired and/or sprayed regularly in order to maintain proper thickness in this area so as not to experience burn-throughs during tapping. Trunnions are a weak area in the vessel and spraying may be required in these areas. In the case of a bottom blown or bottom stirred vessel, the tuyere areas must be maintained to prevent damage to the removable bottom and tuyeres. Any location in the refractory lining that has deteriorated either by normal wear or premature damage should be sprayed and built up in order to alleviate vessel shell temperatures higher than designed for and possible burn-throughs. Spraying should be in thin coats of approximately two inches, or as specified by those qualified (such as the material manufacturer or other responsible expert). Heavy coats are likely to fall off and not adhere to the refractory lining.

Slagging maintenance is possible on the charge pad and the tap pad. This is carried out by allowing a small portion of the slag to remain in the bottom of the vessel after a heat. The vessel is then rotated from one pad to another to place thin coatings of this slag on the pads. A shallow pool of slag may also be allowed to remain on one or the other of the pads while the furnace lays on its side between heats. Slag that is used for maintenance may also be treated by adding dolomite to make it more refractory. For maximum effectiveness, slagging should be done frequently. Techniques to slag the trunnion areas, such as nitrogen blow slag splashing, are recommended when available.

8.4.4 Deskulling

8.4.4.1 General

External and internal deskulling is a very important operation of maintaining the BOF. Failure to remove skull buildup can adversely affect the center of gravity of the vessel, causing unsafe operating conditions.

8.4.4.2 Gradall-Mounted Pneumatic Deskullers

This is the most effective method used as it is possible to remove the external and internal skull buildup and, with proper operation, it does not impose extreme impact loads on the BOF components.

8.4.4.3 Floor-Mounted Deskullers

Various types of deskulling devices mounted into the floor structure on the charging side of the vessel are used to continuously scrape the skull buildup from the nose of the vessel. These are

effective, but must be maintained so as not to cause damage to the BOF, should the scraping members come into direct contact with the vessel during rotation. This method can cause damage to the tilt drive gearing, trunnion bearings and suspension system from the impact loads transmitted during deskulling.

8.4.4.4 Crane-Suspended Deskullers

Various items such as the scrap charging box, purposely designed battering rams, etc. can be used to impact the nose of the vessel as they are suspended from the charging crane hook(s). Such methods are not recommended due to the significant damage that can occur to the tilt drive gearing, trunnion bearings and suspension system from the impact loading.

8.4.4.5 Post-combustion

This technique can be used to control skull buildup in the vessel, particularly in the upper cone area. Consideration must be given to the potential for excessive refractory wear and damage to the vessel lip structure and brick retaining top plates.

8.5 Oxygen Lance Technology

8.5.1 Introduction

In modern steelmaking production, a water-cooled lance is used as the refining tool by injecting a high velocity stream of oxygen onto a molten bath. The velocity or momentum of the oxygen jet results in the penetration of the slag and metal to promote oxidation reactions over a relatively small area. The jet velocity and penetration characteristics are functions of the nozzle design. This section will discuss the design and operation of water-cooled oxygen lances as they apply to modern steelmaking practices in the BOF.

8.5.2 Oxidation Reactions

The primary reason for blowing oxygen into steel is to remove carbon to endpoint specifications. The principle reaction which results from the oxygen lancing is the removal of carbon from the bath as CO. This is an exothermic reaction which adds heat to the system. A small amount of CO₂ is also produced, but 90% or more is usually CO. As will be discussed later, the burning of this CO inside the furnace by reacting with oxygen is called post-combustion.

Other elements such as Si, Mn, and P are also oxidized and are absorbed in the slag layer. These reactions are also exothermic, further contributing to the required heat to melt scrap and raise the steel bath to the necessary temperature. The oxidation of the silicon is particularly important because it occurs early in the oxygen blow and the resultant silica combines with the added lime to form the molten slag. Table 8.1 presents the oxidation reactions during the steelmaking process.

Table 8.1 Oxidation Reactions in Steelmaking

Reaction	Change in Free Energy at 1600°C (kcal/mole)
$C + \frac{1}{2}O_2 = CO$	-66
$2CO + O_2 = 2CO_2$	-57.4
$Si + O_2 = SiO_2$	-137.5
$Mn + \frac{1}{2}O_2 = MnO_2$	-58.5
$2P + \frac{5}{2}O_2 = P_2O_5$	-148.5

The oxidation reactions occur in the jet impact zone, called a dimple, which is created by the impingement of the oxygen. The depression in the liquid bath is a function of the oxygen jet momentum or the thrust, which is calculated by the following equation:

$$F = W \frac{V_e}{g} \quad (8.5.1)$$

where,

- F = force
- W = mass flow rate
- V_e = exit velocity
- g = the acceleration of gravity

The jet thrust and impact angle are optimized to achieve the desired chemical reactions and bath agitation through the design of the nozzle, Fig. 8.39.

8.5.3 Supersonic Jet Theory

Nozzles are designed for a certain oxygen flow rate, usually measured in scfm (Nm^3/min), resulting in a certain exit velocity (Mach number), with the required jet profile and force to penetrate the slag layer and react with the steel bath in the dimple area.

Supersonic jets are produced with convergent/divergent nozzles, Fig. 8.40. A reservoir of stagnant oxygen is maintained at pressure, P_o . The oxygen accelerates in the converging section up to sonic velocity, Mach = 1, in the cylindrical throat zone. The oxygen then expands in the diverging section. The expansion decreases the temperature, density, and pressure of the oxygen and the velocity increases to supersonic levels, Mach > 1.

As the oxygen jet exits into the furnace, at a pressure P_e , it spreads and decays. A supersonic core remains for a certain distance from the nozzle. Supersonic jets spread at an angle of approximately 12° .

Proper nozzle design and operation are necessary both to efficiently produce the desired steel-making reactions and to maximize lance life. If a nozzle is overblown, which means that the oxygen jet is not fully expanded at the time it exits the nozzle, shock waves will develop as the jet

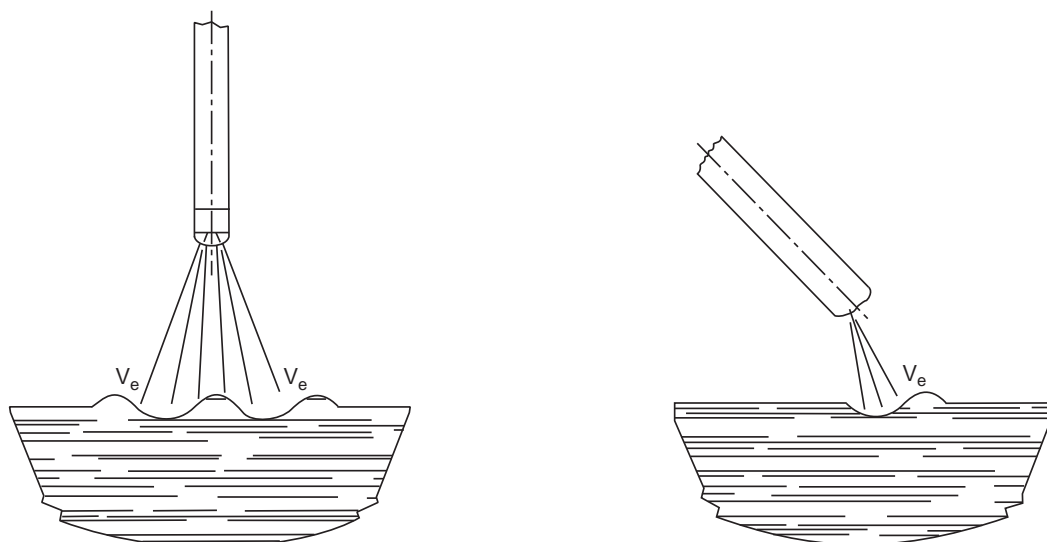


Fig. 8.39 Effect of nozzle design on impact angle and jet thrust.

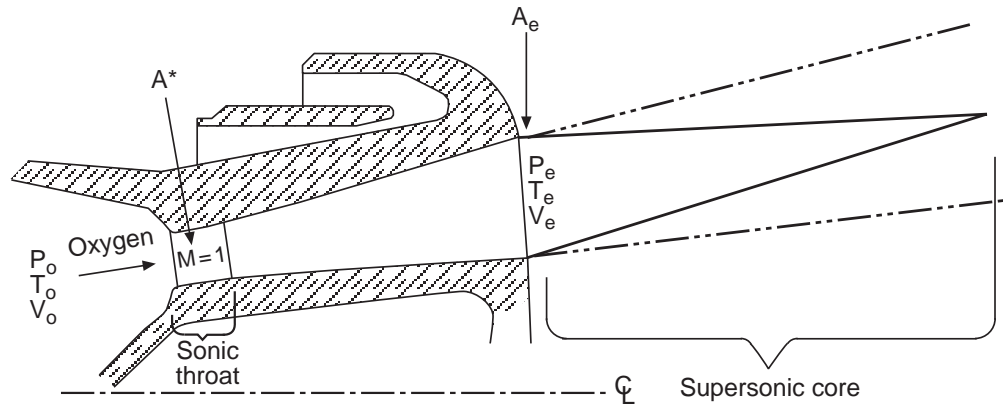


Fig. 8.40 Mechanics of supersonic jet formation.

expands outside of the nozzle. Useful energy is lost in these shock waves, and an overblown jet will impact the steel bath with less force than an ideally expanded jet.

Nozzles are underblown when the jet expands to a pressure equal to the surrounding pressure and then stops expanding before it exists the nozzle. In this case, the oxygen flow separates from the internal nozzle surface. Hot gases from the steel vessel then burn back or erode the nozzle exit area. This erosion not only decreases the lance life, but also results in a loss of jet force, leading to a soft blowing condition. Overblowing and underblowing conditions are demonstrated in Fig. 8.41.

Fig. 8.42 displays the major components of the BOF oxygen lance. These include oxygen inlet fittings, the oxygen outlet (lance tip), which is made of a high thermal conductivity cast copper design with precisely machined nozzles to achieve the desired flow rate and jet parameters. Cooling water is essential in these lances to keep them from burning up in the vessel. The lance

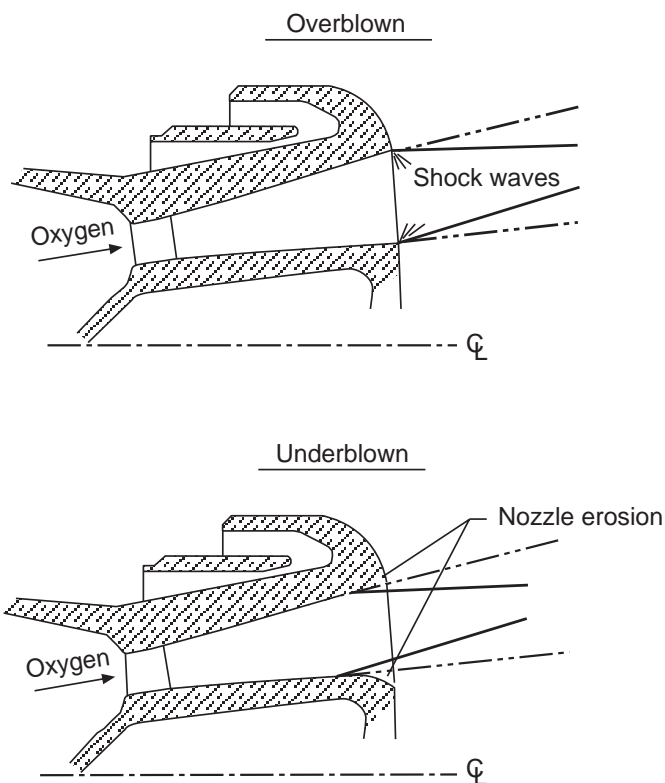


Fig. 8.41 Overblown and underblown conditions at the nozzle tip.

barrel is a series of concentric pipes, an outer pipe, an intermediate pipe and the central pipe for the oxygen. Lances must be designed to compensate for thermal expansion and contraction. The outer barrel/pipe of the lance is exposed to the high temperatures in the furnace. As its temperature increase it expands and the overall lance construction internally is constructed with O-ring seals and various joints, but can accommodate the thermal expansion and contraction while in service. The lance also has a stress-free design and it must be built with mill duty construction quality to be able to withstand the normal steel mill operating conditions. Fig. 8.43 presents various types of BOF lance tips.

Fig. 8.44 is a schematic cutaway of a lance tip displaying the oxygen nozzle and the water channels. This figure shows a typical 5-hole BOF lance tip. Its important components are the water cooling channels where the cooling water flows through the center of the tip and exits through the outer pipe of the lance. It is designed to get maximum velocity of cooling water in the tip area, which is exposed to the highest temperatures.

8.5.4 Factors Affecting BOF Lance Performance

There are a number of factors affecting the performance and the efficiency of the lance. The performance of the lance depends on the conditions in the furnace. The hot metal silicon content is very important—this effects the amount of slag that forms, the amount of slag that has to be penetrated by the jet, and also controls the amount of steel slopping in the furnace. The lance operating height is also very important and must be included in the nozzle design calculations. If the lance is too

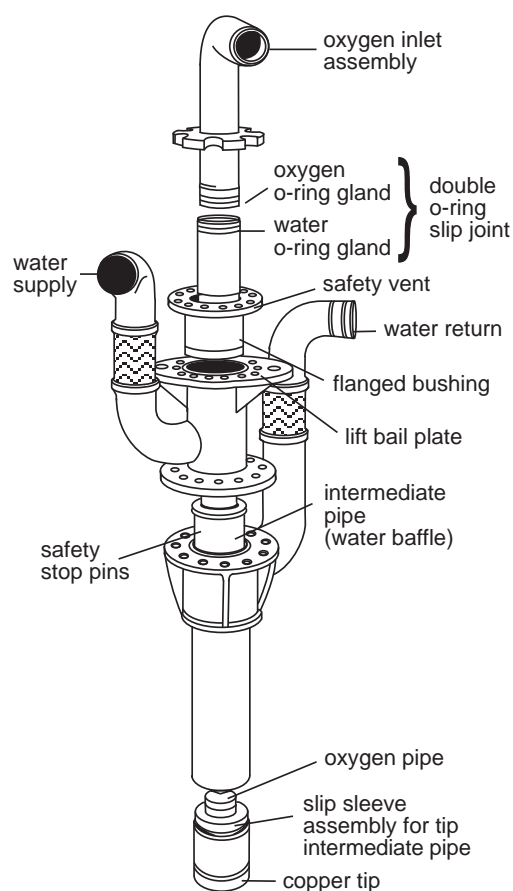


Fig. 8.42 Top adapter assembly of the BOF oxygen lance.

Fig. 8.43 Various types of BOF lance tips.



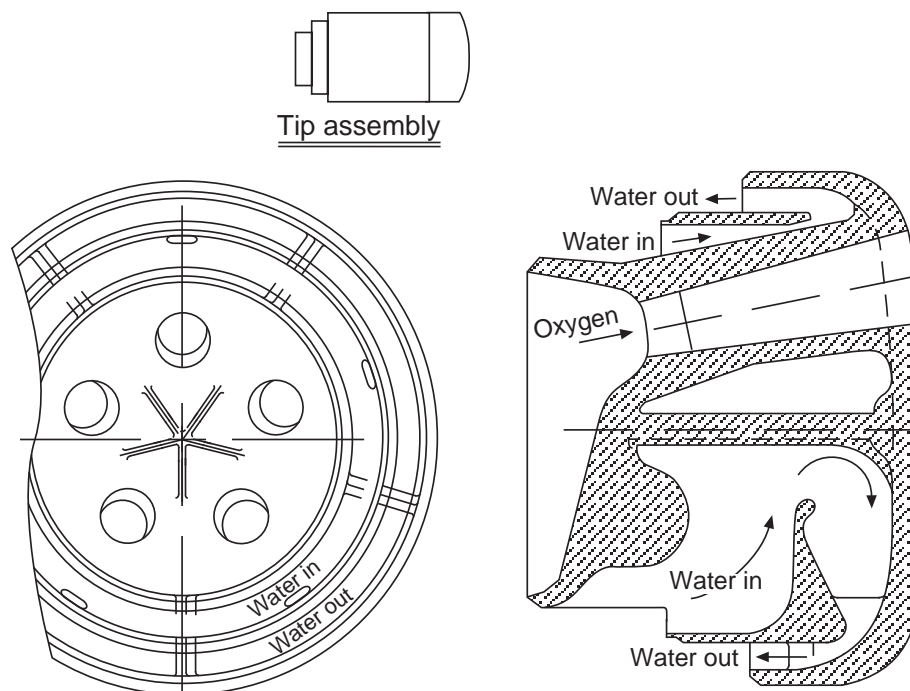


Fig. 8.44 Schematic of a typical 5-hole BOF lance tip.

low in the furnace it is exposed to extremely high temperatures and the heat transfer from the cooling water may not be sufficient to keep the face of the lance from melting or being burned away prematurely. If the lance is too high, the thrust of the jet becomes less efficient and the refining time will take longer, and more oxygen will be required to achieve the necessary decarburization and steel temperature. The oxygen flow rate is a design parameter that is sometimes limited by the oxygen supply system, and/or emissions concerns. The exit velocity of the Mach number is also a factor that is used in the design of the lances. Generally the higher the Mach number the more forceful the jet is.

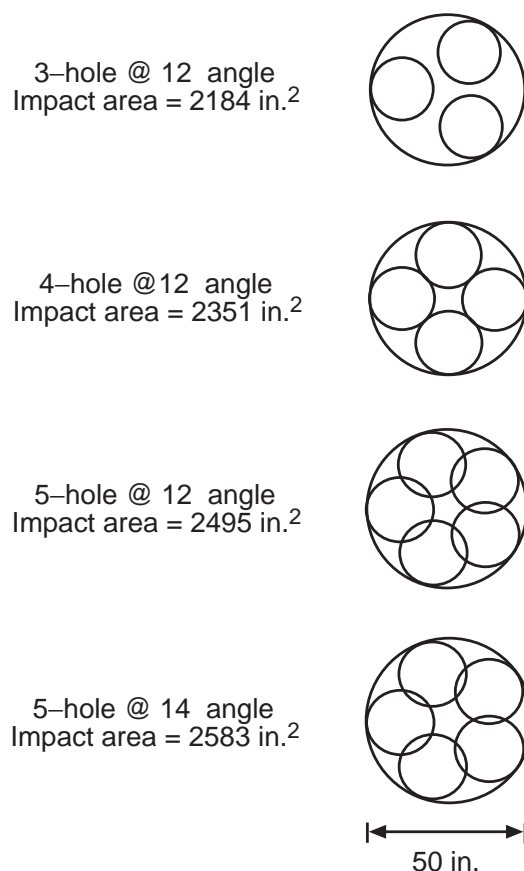
Also, important considerations are the number of nozzles and the nozzle hole angle. When BOFs were originally developed, the first ones were operated with a single nozzle blowing directly down unto the bath. This caused a lot of slopping and molten material was ejected straight up the mouth of the vessel. Three hole nozzles slightly angled were developed to minimize slopping, resulting in a high process yield. Currently many BOFs are operating with 4, 5, or 6-nozzle configurations. Fig. 8.45 shows the effect of increasing the number of nozzles and nozzle exit angle on the impact area in the bath. As the nozzle angle is increased more of the lateral force component, rather than a vertical force component develops, contributing to more stirring and agitation in the bath. However, if the lateral component of the jet becomes excessive, higher refractory wear will occur.

8.5.5 Factors Affecting BOF Lance Life

Lance life varies from shop to shop, depending on the various operating practices. A typical lance life may be 200 heats, although there are some shops which can achieve up to 400 heats per lance and others may not be able to achieve 150 heats. Cooling water is critical to maintain high lance life. The flow rate must be maintained at the design rate. The cooling water outlet temperature should not exceed 140° to 150°F. Water quality is also important. If the water is contaminated with oxides or dirt, deposits will form inside the lance pipes and tip, resulting in a negative effect on heat transfer and ultimately reducing lance life. Operating height is critical for achieving the proper jet penetration of the bath. However if the lance is too low, the tip face may erode or melt.

Oxygen flow rate = 20,000 scfm
Mach No. = 2.0
Lance height = 72 in.

Fig. 8.45 Impact area as a function of number of nozzle holes and nozzle angle.



Underblowing causes nozzle exit erosion and lance tip failure. Excessive skull buildup on the lance tip must be mechanically removed or burned off—both of these practices could cause damage to the lance.

8.5.6 New Developments in BOF Lances

The first recent development was the post-combustion lance. Because 90% of the gas evolving from the oxidation reactions of the bath is carbon monoxide, it is desirable to further combust this carbon monoxide to form carbon dioxide. This reaction is highly exothermic, resulting in additional heat for the steelmaking process. This is a practice that is being done in several BOF shops in North America. This practice requires a dual-flow oxygen lance, which has two oxygen outlets. The main supply of oxygen is distributed through the lance tip similarly to a conventional lance, Fig. 8.46. The auxiliary oxygen is controlled separately and is blown at a higher elevation in the vessel. The function of the auxiliary oxygen is to react with the carbon monoxide coming off the bath, thus creating additional thermal energy which could be used to melt additional scrap, and help to control skull buildup in the mouth of the vessel.

The second recent development for oxygen lances is its use to splash a protective coating of slag containing high levels of MgO onto the walls of the BOF, Fig. 8.47. This is done after the steel has been tapped out of the furnace with some residual slag remaining. The oxygen supply is switched

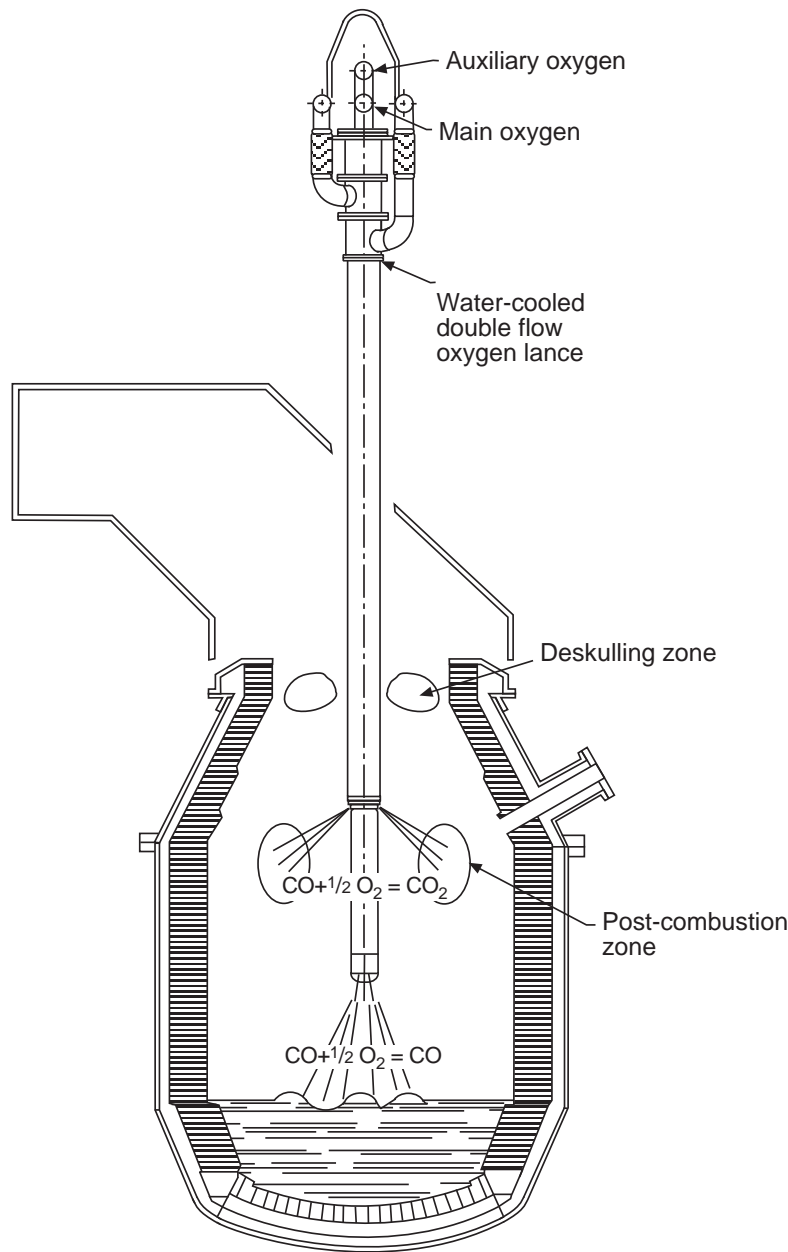


Fig. 8.46 Schematic of a post-combustion oxygen lance.

off and the nitrogen supply is switched on. The lance is lowered to 2–4 feet above the vessel bottom. The nitrogen is then turned on, splashing the molten slag onto the walls of the vessel and creating a protective slag coating over the refractories. This slag coating has successfully increased the typical refractory life from 3000 heats to over 20,000 heats per campaign. Furthermore the gunning requirements have also been decreased to less than one pound per ton of steel produced.

8.6 Sub-Lance Equipment

The purpose of a sub-lance is to measure carbon content, bath temperature, soluble oxygen, and bath level, and to secure a steel sample in an oxygen steelmaking vessel while in the upright position. Such sub-lance systems employ mechanical and electrical devices to perform measuring and

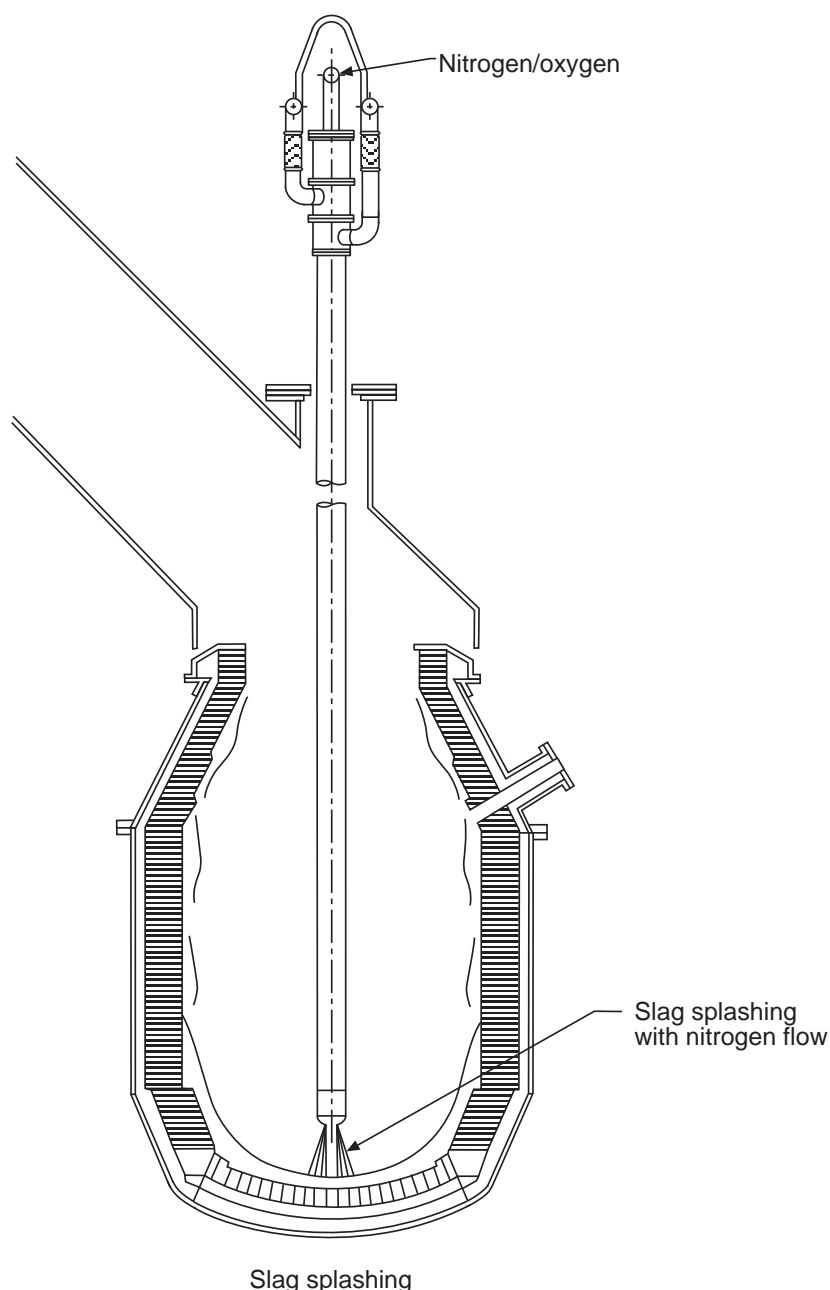


Fig. 8.47 Schematic of a slag splashing oxygen lance.

monitoring functions, and to provide a steel sample for spectrographic analysis. Fig. 8.48 provides a schematic of the process control outputs generated from sub-lance measurements.

During the heat cycle, after a predetermined amount of oxygen has been blown, the oxygen blow rate is reduced and an in-blow test is made by lowering the sub-lance at a controlled speed through the hood opening. The sub-lance is stopped at the test elevation 20 in. below the bath surface. This test elevation is fixed and is regulated from heat to heat by the process computer to compensate for lining wear throughout the campaign. All pertinent data gathered is transmitted to process computers for adjustments to the oxygen blow cycle and coolant additions to finish the heat at the tap carbon and temperature aims. After the blow cycle is completed, the sub-lance is lowered to the test elevation to measure the finished tap carbon and temperature and to retrieve a metal sample for

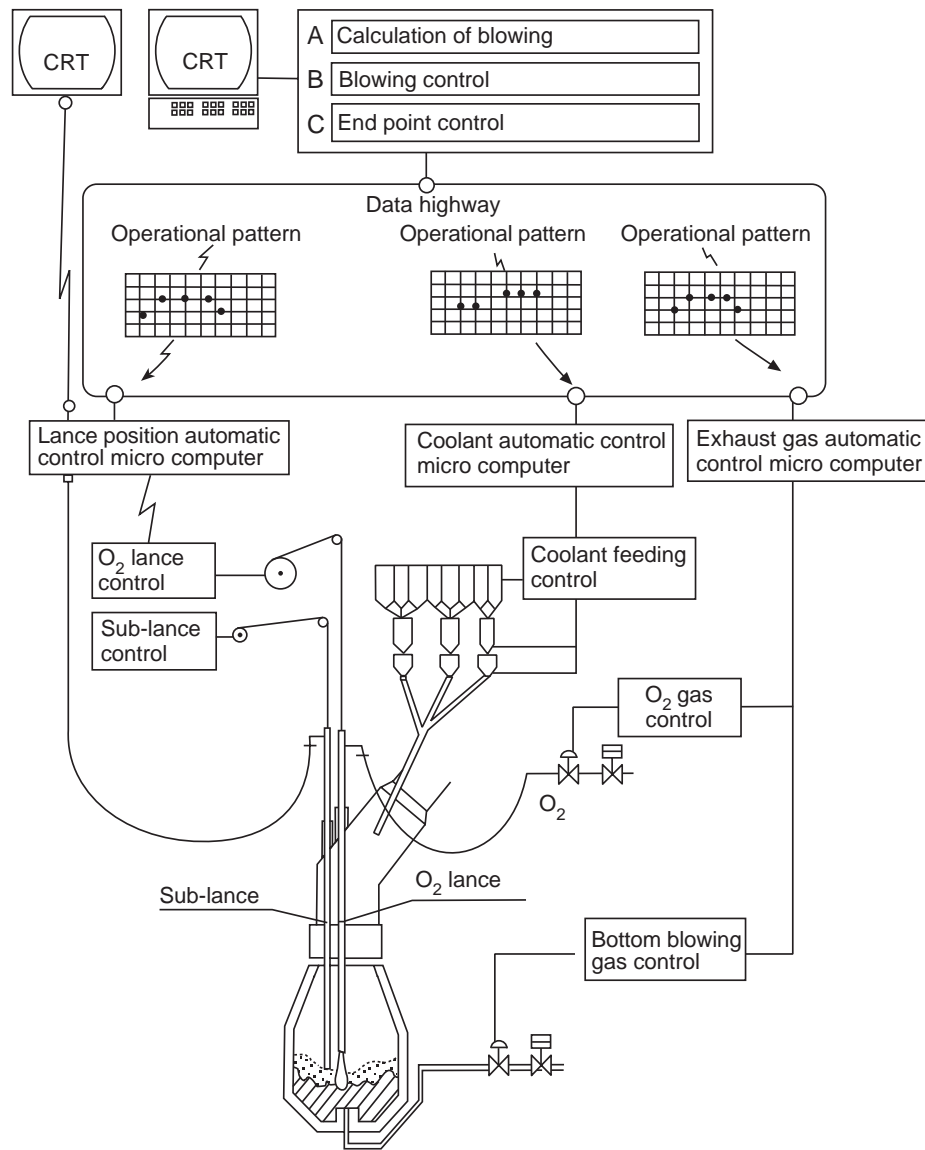


Fig. 8.48 Schematic of process control outputs generated from sub-lance measurements.

spectrographic analysis. Fig. 8.49 illustrates the heat cycle and process control models with in-blow and end-blow sub-lance measurements.

The sub-lance is raised and lowered within a guide frame by means of a hoist drive incorporating a drum, wire rope and a series of sheaves. An encoder mounted on the hoist drive indicates position of the sub-lance and provides data for a programmable limit switch to control sub-lance travel and positioning. A cylinder-actuated slidegate is located on the BOF hood to provide a porthole for sub-lance access to the vessel. The slidegate is continuously cooled by a nitrogen purge arrangement. Cooling water for the sub-lance is continuously supplied from the return system on the oxygen lance. Should the system pressure be insufficient, booster pumps may be utilized.

Consumables for measurement of carbon content, bath temperature, and soluble oxygen, and for securing a steel sample are pre-loaded into a cassette and are conveyed mechanically to the probe tip. Prior to connection of the probe to the sub-lance, and also during the measurement cycle, nitrogen purging is performed to provide good electrical contact between the probe and the probe holder. Following capture of the metal sample from the bath, a probe retrieval system is used to

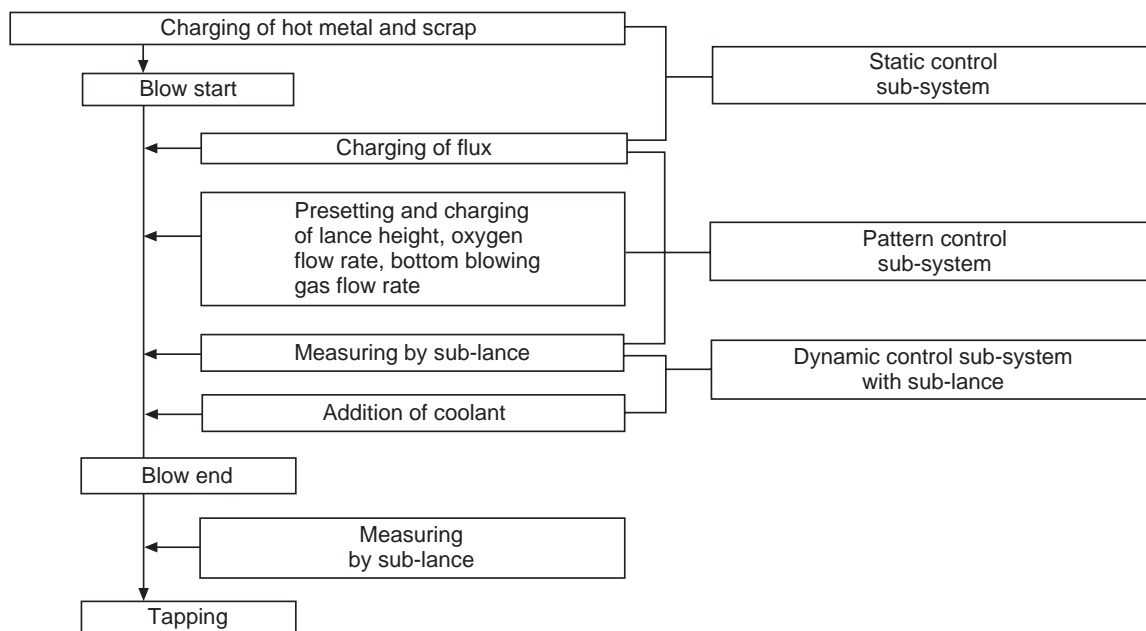


Fig. 8.49 Heat cycle with in-blow and end-blow sub-lance measurements.

detach the sample from the sub-lance and deposit it in a vertical transport tube for delivery to the charging floor. The metal sample may then be sent via pneumatic tube transport to the laboratory for spectrographic analysis.

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Chapter 9

Oxygen Steelmaking Processes

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9.1 Introduction

9.1.1 Process Description and Events

The oxygen steelmaking process rapidly refines a charge of molten pig iron and ambient scrap into steel of a desired carbon and temperature using high purity oxygen. Steel is made in discrete batches called heats. The furnace or converter is a barrel shaped, open topped, refractory lined vessel that can rotate on a horizontal trunnion axis. The basic operational steps of the process (BOF) are shown schematically in Fig. 9.1.

The overall purpose of this process is to reduce the carbon from about 4% to less than 1% (usually less than 0.1%), to reduce or control the sulfur and phosphorus, and finally, to raise the temperature of the liquid steel made from scrap and liquid hot metal to approximately 1635°C (2975°F). A typical configuration is to produce a 250 ton (220 metric ton) heat about every 45 minutes, the range is approximately 30 to 65 minutes. The major event times for the process are summarized below in Table 9.1.

These event times, temperatures, and chemistries vary considerably by both chance and intent. The required quantities of hot metal, scrap, oxygen, and fluxes vary according to their chemical compositions and temperatures, and to the desired chemistry and temperature of the steel to be tapped. Fluxes are minerals added early in the oxygen blow, to

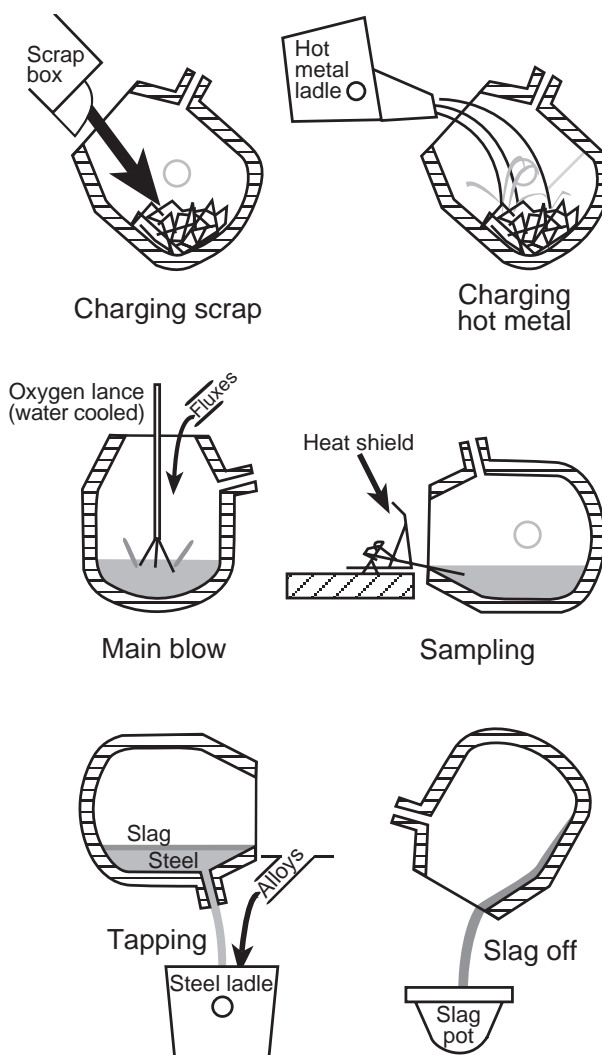


Fig. 9.1 Schematic of operational steps in oxygen steelmaking process (BOF).

control sulfur and phosphorous and to control erosion of the furnace refractory lining. Input process variations such as analytical (hot metal, scrap, flux and alloy) and measurement (weighing and temperature) errors contribute to the chemical, thermal and time variations of the process.

Table 9.1 Basic Oxygen Steelmaking Event Times

Event	Min.	Comments
<i>Charging</i> scrap and hot metal	5–10	Scrap at ambient temperature, hot metal at 1340°C (2450°F)
<i>Refining–blowing</i> oxygen	14–23	Oxygen reacts with elements, Si, C, Fe, Mn, P in scrap and hot metal and flux additions to form a slag
<i>Sampling</i> –chemical testing	4–15	Steel at 1650°C (3000°F), chemistry and temperature
<i>Tapping</i>	4–8	Steel is poured from furnace into a ladle, typical size = 250 tons
<i>Pouring slag off</i> at furnace	3–9	Most slag is removed from furnace, in some shops slag is used to coat furnace walls

The energy required to raise the fluxes, scrap and hot metal to steelmaking temperatures is provided by oxidation of various elements in the charge materials. The principal elements are iron, silicon, carbon, manganese and phosphorous. The liquid pig iron or hot metal provides almost all of the silicon, carbon, manganese and phosphorous, with lesser amounts coming from the scrap. Both the high temperatures of the liquid pig iron and the intense stirring provided when the oxygen jet is introduced, contribute to the fast oxidation (burning or combustion) of these elements and a resultant rapid, large energy release. Silicon, manganese, iron and phosphorous form oxides which in combination with the fluxes, create a liquid slag. The vigorous stirring fosters a speedy reaction and enables the transfer of energy to the slag and steel bath. Carbon, when oxidized, leaves the process in gaseous form, principally as carbon monoxide. During the blow, the slag, reaction gases and steel (as tiny droplets) make up a foamy emulsion. The large surface area of the steel droplets, in contact with the slag, at high temperatures and vigorous stirring, allow quick reactions and rapid mass transfer of elements from metal and gas phases to the slag. When the blow is finished the slag floats on top of the steel bath.

Controlling sulfur is an important goal of the steelmaking process. This is accomplished by first removing most of it from the liquid hot metal before charging and later, inside the furnace, by controlling the chemical composition of the slag with flux additions.

9.1.2 Types of Oxygen Steelmaking Processes

There are basically three variations of introducing oxygen gas into the liquid bath. These are shown schematically in Fig. 9.2. Each of these configurations has certain pros and cons. The most common configuration is the **top-blown** converter (BOF), where all of the oxygen is introduced via a water-cooled lance. The blowing end of this lance features three to five special nozzles that deliver the gas jets at supersonic velocities. In top blowing, the stirring created by these focused, supersonic jets cause the necessary slag emulsion to form and keeps vigorous bath flows to sustain the rapid reactions. The lance is suspended above the furnace and lowered into it. Oxygen is turned on as the lance moves into the furnace. Slag forming fluxes are added from above the furnace via a chute in the waste gas hood. A process description is in Section 9.4 of this chapter.

In the **bottom-blown** converters (OBM or Q-BOP), oxygen is introduced via several tuyeres installed in the bottom of the vessel, Fig. 9.2. Each tuyere consists of two concentric pipes with the oxygen passing through the center pipe and a coolant hydrocarbon passing through the annulus between the pipes. The coolant is usually methane (natural gas) or propane although some shops

have used fuel oil. The coolant chemically decomposes when introduced at high temperatures and absorbs heat in the vicinity, thus protecting the tuyere from overheating. In bottom blowing, all of the oxygen is introduced through the bottom, and passes through the bath and slag thus creating vigorous bath stirring and formation of a slag emulsion. Powdered fluxes are introduced into the bath through the tuyeres located in the bottom of the furnace. The first part of Section 9.5 is a process description of the OBM (Q-BOP).

The **combination blowing** or **top and bottom blowing**, or **mixed blowing** process (Fig. 9.2 shows these variants) is characterized by both a top blowing lance and a method of achieving stirring from the bottom. The configurational differences in mixed blowing lie principally in the bottom tuyeres or elements. These range from fully cooled tuyeres, to uncooled tuyeres, to permeable elements. Section 9.5 summarizes further details about combination blowing processes.

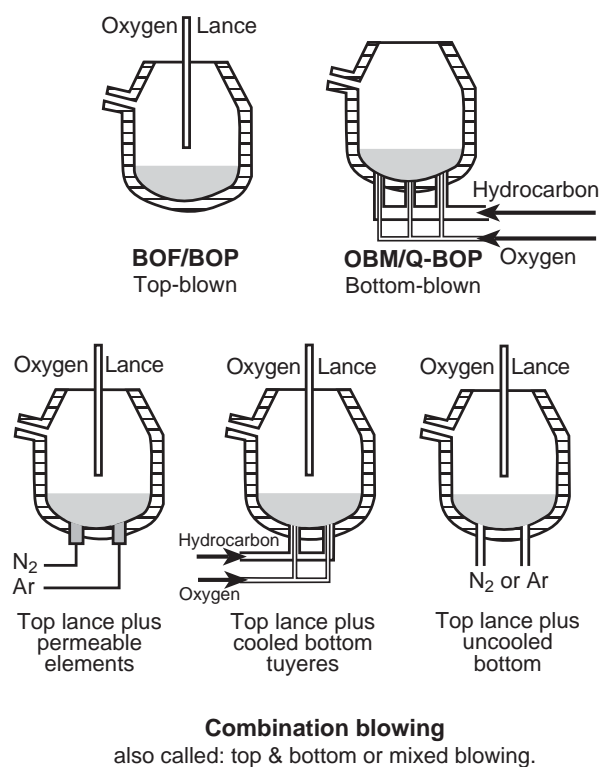


Fig. 9.2 Methods of introducing oxygen and other gases into the steelmaking converter.

9.1.3 Environmental Issues

The oxygen steelmaking process is characterized by several pollution sources and most require emission control equipment. These sources are: hot metal transfer, hot metal desulfurization and skimming of slag, charging of hot metal, melting and refining (blowing), BOF tapping, handling of dumped BOF slag, handling of fluxes and alloys, and maintenance (burning of skulls, ladle dumping, etc). Thus, compliance to emission standards is an important design and operating cost factor for the operation.

9.1.4 How to Use This Chapter

The process falls into several basic component parts which determine important control and economic parameters. Accordingly, this chapter is organized into the process component headings of Sequence of Operations, Raw Materials, Process Reactions and Energy Balance, Variations of the Process, Process Control Strategies, and Environmental Issues.

The use of this chapter depends on your level of knowledge and interest in the details. It is geared to bring together several more detailed chapters, such as furnace design, refractory practices, oxygen lance design and physiochemical principles, and to describe how these underlying factors contribute to the oxygen steelmaking process. If you are a steelmaking novice, reading this chapter first is a good way to get a brief, yet coherent description of the process. Once you have the big picture, then it is easier to focus on the chapters on detailed design and first principles. If you are more experienced and want to review or deal with a specific issue, you may turn directly to one of the component sections or to one of the underlying principle chapters.

A note on References: The material for this chapter is an assimilation of many different sources. For continuity, rather than specifically cite every source, the references are listed at the end of the chapter both as a source acknowledgment and as a supplemental reading list. This list is organized in the same chapter section format. The references are numbered for citing figures and tables.

9.2 Sequence of Operations—Top Blown

9.2.1 Plant Layout

To understand the sequence of the oxygen steelmaking process, one must examine the design, layout and materials flow of the facilities. Figs. 9.3, 9.4 and 9.5 show a 275-ton BOF that illustrates the process. Shops vary considerably in basic layout. Reasons for these layout differences are: type of product (ingots, cast product or both), the parent company's operating and engineering culture, the relationship of the infrastructure and material flows to the rest of the plant, and age of the facility. (Is the plant an updated older facility or a new greenfield site?) Flow of materials plays a key role in the design of the shop. Handling of raw materials (scrap, hot metal, fluxes, alloys, refractories), oxygen lances in-and-out, slag handling, gas cleaning, and transport of steel product must be accomplished smoothly with minimum delays and interference.

Fig. 9.3 is a plan view of a two-furnace shop and Fig. 9.4 is an elevation of the same plant but looking to the west. Figure 9.5 is an elevation looking to the north. BOFs, OBMs (Q-BOPs) and other variants can have similar layouts except for oxygen conveying and flux handling details. All shops feature transportation systems for hot metal and scrap.

9.2.2 Sequence of Operations

9.2.2.1 Scrap Handling

Scrap for a heat is ordered and prepared well in advance of actually charging the furnace. It is selected according to size and quality and then is brought into the plant via railroad cars, usually gondolas. It is loaded and mixed into an open ended scrap box which sits on a transfer car. Loading the box is usually done by magnet or grapple crane in a remote area from the shop. The box/car is frequently weighed during loading. Some shops use a crane scale to weigh and accumulate each magnet load. Weights are entered into the shop computer when the loading is completed. The transfer of scrap from rail cars to charging box is done in an attached bay to the BOF shop which is large enough to handle eight to 24 hours of scrap supply. The scrap box is then conveyed by rail to the charging aisle. A few shops use rubber tired platform carriers rather than rail cars to move the scrap box into the shop.

9.2.2.2 Hot Metal Pouring

The hot metal system consists of a track(s) and one to three pouring stations. The liquid pig iron arrives from the blast furnace in a train of torpedo shaped, refractory lined railroad cars called submarines (subs) or torpedoes. Each car is positioned over a track scale and weighed prior to pouring. There is a trunnion at each end of the car which allows the operator to rotate the open top toward a transfer ladle located in an adjacent pit. Generally, it takes one or two subs to fill the hot metal transfer ladle. The control room or operator's pulpit is equipped with controls for rotating the sub, operating the ladle transfer car, reading scales, taking temperatures, desulfurization equipment, and sending samples to a chemistry lab. The pouring operation, which generates considerable dust emissions, is accomplished under an enclosed hood equipped with an evacuation system and a baghouse. The dust generated at pouring, called kish, is mainly fine flaked graphite which precipitates from the carbon saturated metal as its temperature drops during pouring. The poured weights and measured temperatures are entered into the shop process control computer.

9.2.2.3 Hot Metal Treatment

The hot metal transfer ladle sits on a transfer car at the outside wall of the charging aisle, usually out of the crane's reach. Here many shops treat the hot metal by injecting a mixture of lime and magnesium to remove sulfur. This process is called hot metal desulfurization. During hot metal treatment, sulfur is removed from approximately 0.025 wt% to as low as 0.002 wt% and the time of injection will range from five to twenty minutes. A gas collecting and filtration system collects the fumes from

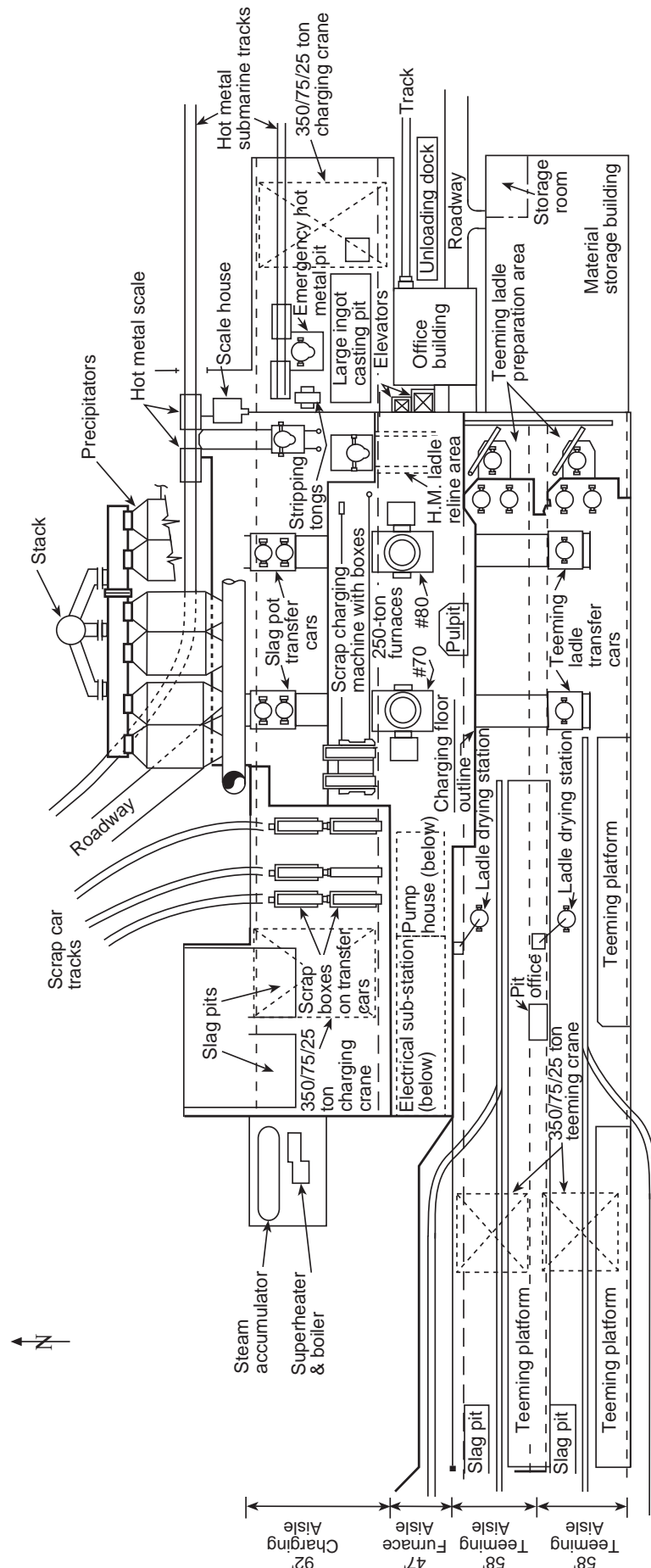


Fig. 9.3 Plan view of 275 ton BOF shop.

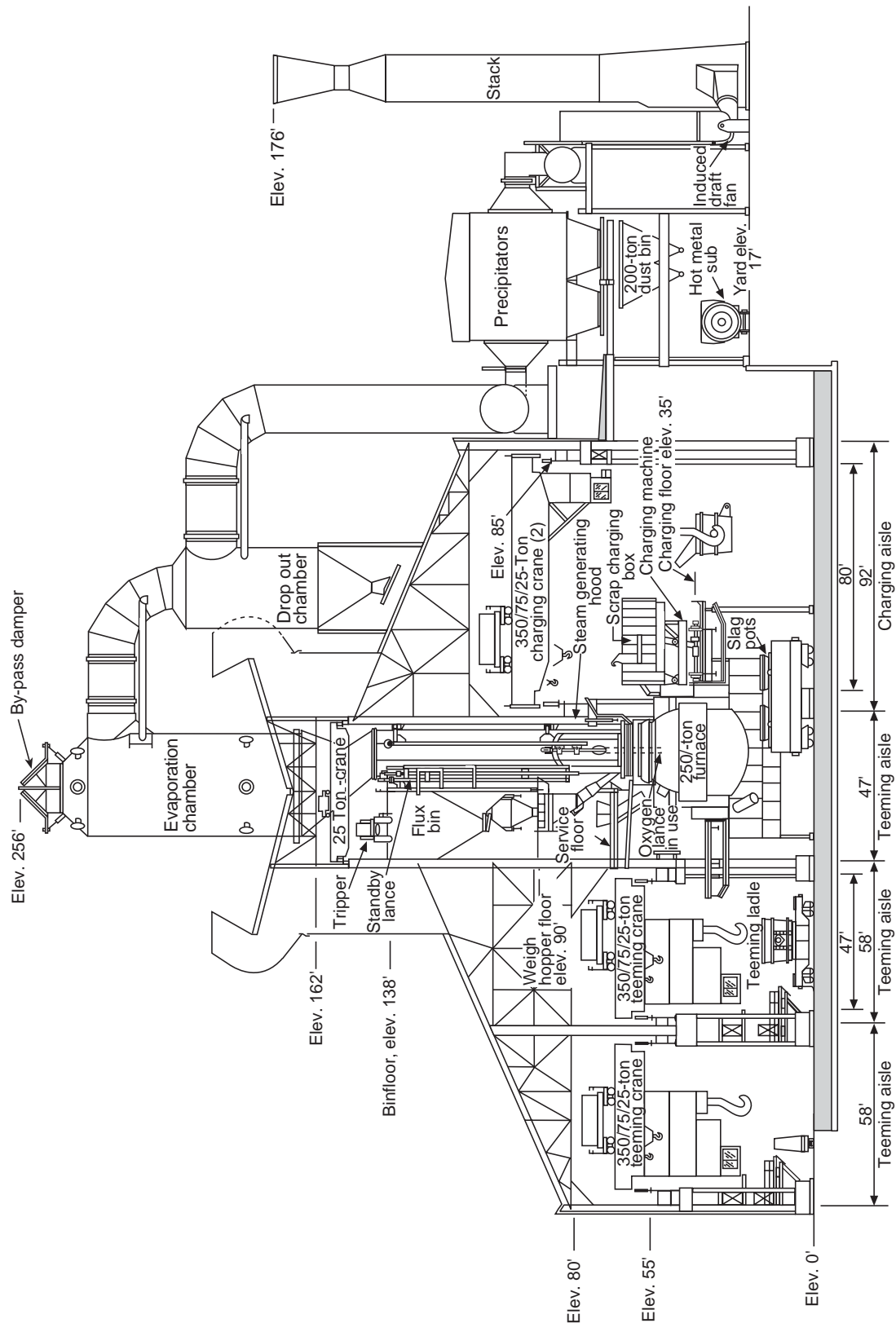


Fig. 9.4 Elevation of 275 ton BOF shop—looking west.

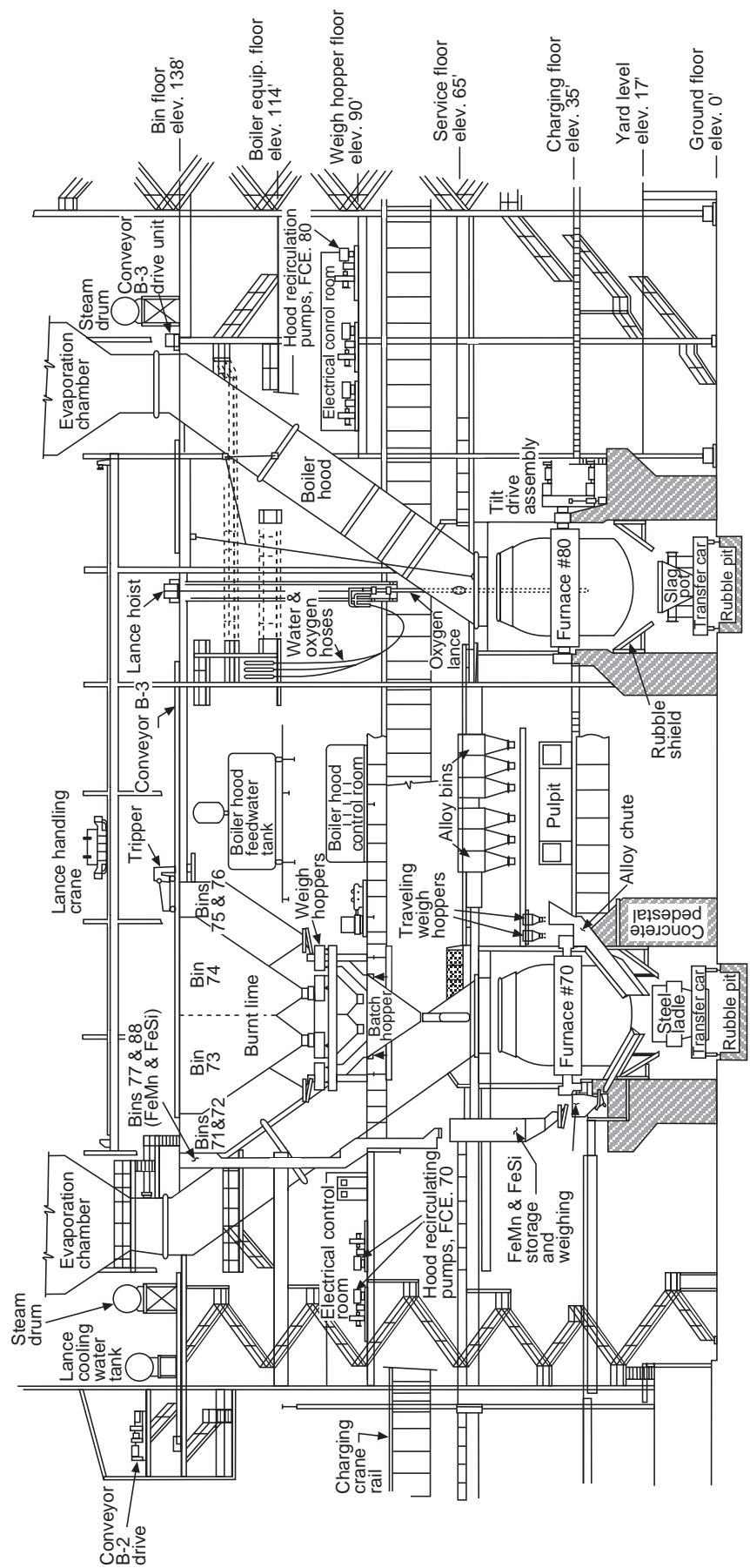


Fig. 9.5 Elevation of 275 ton BOF shop—looking north.

the desulfurization process as well as collecting the pouring fumes. After desulfurization, the ladle is tilted by the crane or in a special cradle just to the point of pouring. In this position, the sulfur containing slag floating on the iron is scraped off into a collection pot using a hydraulic manipulating arm. This slag removal process is called skimming. Often, much metal is scraped out of the ladle along with the sulfur containing slag. Thus there is an iron yield loss due to deslagging that ranges from 0.5 to 1.5% depending on equipment design and operator skill. Hot metal temperature is measured using disposable thermocouples mounted on a mechanical arm called a pantograph. When the hot metal pouring and treatment are finished, the ladle car moves into the charging aisle and the ladle becomes available for pickup and charging by the charging crane. Details of hot metal treatment are found in Chapter 7.

9.2.2.4 Charging the Furnace

The BOF furnaces are open-topped, refractory-lined vessels located in the adjacent aisle called the furnace aisle. The furnaces rotate on trunnions so they can be tilted both toward the charging and tapping aisles. The furnace refines the steel in an upright position although it is capable of rotating 360°. The furnace aisle contains the furnaces, flux conveying system, furnace alloy chute and oxygen lances in a top-blown shop. Here, the furnace aisle is very high to accommodate loading and operation of 60–70 foot long oxygen lances. There is a space and capital cost advantage of an OBM (Q-BOP) that does not require the high elevation for lances.

In nearly all North American shops, scrap is charged first. Many shops lift and tilt the box emptying the scrap into the furnace with the charging crane. Charging scrap before hot metal is considered a safer practice that avoids splashing. The crane method usually has faster scrap charging times. However, many shops load the scrap boxes onto special charging machines that can move on rails in front of the furnace. This scrap charging machine has a hydraulic tilting mechanism that raises the scrap box to 45° and charges them one at a time. It usually holds two scrap boxes. While the scrap charging machine is often slower than the crane, it frees up the charging crane for other duties and more quickly handles two box charges per heat when required.

After scrap is charged, liquid hot metal is charged into the furnace using the charging crane in the charging aisle. The ladle is tilted and the liquid hot metal is poured into the furnace. This process takes one to five minutes depending on the design of the furnace hood and shop fugitive emission systems. Some shops can charge quickly because the fume from pouring into the furnace is effectively collected by the hood and a closed roof monitor collection system. Other shops with less advanced fume collection systems, must pour rather slowly to minimize the heat and fume cloud, thus taking a lengthy three to five minutes to charge hot metal.

9.2.2.5 Computer Calculations

Prior to pouring hot metal and charging scrap, a computer calculation is initiated by the pulpit operator to determine the charge recipe. The grade and temperature and chemistry aims are loaded into the shop computer beforehand when a heat is put on the schedule line-up. The temperature and chemical content of the hot metal can vary significantly. The hot metal is sampled and analyzed at the chemistry lab—a process that takes from three to ten minutes—and the results and ID are transmitted to the computer. The temperature of the hot metal is measured in the ladle after it is poured and that result is transmitted to the computer. The chemistry of the scrap is calculated from the known mixture of the scrap; its temperature is assumed to be ambient. Thus, all of the characteristics of the charged materials and the heat aims are available for the charge recipe calculation. The principal aim parameters for the furnace heat are carbon and temperature. Other specific aims are sulfur, phosphorous and slag composition (%FeO level). Missing any of these aims can be very costly later and can require time consuming corrective actions or create significant quality problems. Often, there are several update calculations as items are weighed and charged to correct for minor weighing irregularities and mistakes. The results of these calculations are principally the amounts of coolants, fluxes and oxygen. Most shops' calculations have features that allow early calculation of hot metal and scrap weights as well. All shops use the charge recipe calculation.

Some shops have sensors (sub-lance, light meter, bomb-drop thermocouples, etc.) that measure carbon and/or temperature near the end of the blow. The sensor's measurements are used to make late oxygen and coolant corrections to bring the carbon and temperature to aims. This saves time and money by reducing the frequency of corrective actions.

9.2.2.6 Oxygen Blow

After scrap and hot metal are charged, the furnace is set upright and the oxygen is supplied through a water-cooled lance. There are two lance lift carriages above each furnace but only one lance is used at a time; the other is a spare. The oxygen blow times typically range from 13 to 25 minutes from one shop to another with an average of about 20 minutes. The oxygen is added in several batches. Each batch is characterized by a different lance height above the static steel bath and sometimes by an oxygen rate change. These blowing rates and lance heights vary considerably from shop to shop and depend on the pressure and quality of the oxygen supply. The oxygen blow rate ranges from 560 to 1000 Nm³ per minute (20,000 to 35,000 scfm). A practical limit on the rate is often the volume of the furnace and the capacity of the gas collection and cleaning system to handle the gaseous reaction product and fume. A typical example of the oxygen batches is summarized in Table 9.2.

Table 9.2 Example of Oxygen Batches in a BOF

Batch No.	Lance Ht, in.	Oxygen Volume at Lance Change, Nm ³
1	150	850
2	120	1700
3 (main)	90	balance (to approx 14,200)

The first batch lance height is very high to avoid the possibility of lance tip contact with the scrap and to safely establish the oxidizing, heat generating reactions. If the lance would contact the pile of scrap in the furnace, a serious water leak could result causing a dangerous steam explosion.

The second batch lance height is usually approximately 20 to 30 inches lower than the first batch and approximately 20 to 30 inches higher than the main batch. The purpose here is to increase the reaction rate and control the early slag formation. This second or middle batch generates some early iron oxide to increase proper slag formation.

The main batch is where most of the action occurs—it is by far the longest batch. The lance height is an empirical compromise between achieving faster carbon removal rates and proper slag making. Some shops have more than three batches. Some change oxygen conditions (blow rate and lance height) nearly continuously. Other shops will raise the lance and change the blow rate near the end of the main batch to control the viscosity and chemical reactivity of the slag by raising its FeO content.

The position of the lance is very important for proper functioning of the process. If the lance is too high, the slag will be over stirred and over-oxidized with higher FeO percentages. This will cause higher than normal yield losses and lower tap alloy efficiencies due to oxidation losses. Further, the rate of carbon removal is reduced and becomes erratic. Slag volume increases and there is an increased chance of slopping, which is an uncontrolled slag drooling or spilling over the top of the furnace. When the lance is too low, carbon removal increases somewhat, slag formation, slag reactivity, and FeO are reduced and sulfur and phosphorus removal problems often occur. If the lance is very low, then spitting of metal droplets or sparking occurs which cause severe and dangerous metallic deposits, called skulls, on the lance and the lower waste gas hood.

Obviously, there is a correct lance height. It varies from shop to shop and depends on furnace configuration, lance configuration and oxygen supply pressure or flow rate. Each shop must find its

own best lance height and comply with it. The problem is how to measure it. It can change quickly and significantly as a result of changes in furnace refractory shapes. Traditional measurement methods have been burn-off tests, where a pipe is wedged in an oxygen port. The lance is then lowered and the pipe is allowed to melt off at the slag-metal interface. This is done while waiting for a chemistry just before tap. This test has been erratic due to the temperature and fluidity of the slag, time of immersion, and initial protection of the pipe. This test has fallen out of favor because it is dangerous for the operator to attach the pipe to the lance.

More modern techniques include mathematically integrating the furnace volume from a refractory lining laser scan or determining the distance to the bath/slag using a radar unit mounted above the furnace. Generally, the radar method measures the height of the slag surface after it has collapsed at the end of a low carbon blow. There is uncertainty about the location of the slag steel interface but the measurement is considered better than none.

9.2.2.7 Flux Additions

Soon after the oxygen is turned on, flux additions are started and are usually completed at the end of the second batch of oxygen. The fluxes control the chemistry and sulfur and phosphorus capacity of the slag. The principle active ingredients from the fluxes are CaO (from burnt lime) and MgO (from dolomitic lime). The CaO component is used principally to control sulfur and phosphorous.

The dolomitic lime is used to saturate the slag with MgO. The principle ingredient of the furnace refractories is MgO. Steelmaking slags without it are very corrosive to the lining. The corrosion rate is reduced dramatically when MgO is added to saturate the slag. It is much cheaper to satisfy the slag's appetite for MgO from dolomitic lime than by dissolving it from the lining.

Another flux addition sometimes used in high carbon heats is fluorspar (CaF_2 , or spar). This mineral is charged to dissolve the lime and to reduce the viscosity of the slag. It is used for making high carbon heats, ($>0.30\% \text{C}$ at the end of blow) because the iron oxide concentrations are low on these heats. Iron oxides help dissolve lime in lower carbon heats but these oxides are present in low concentrations in high carbon heats. To compensate for less FeO, many shops use spar to dissolve the lime. However, spar is used very sparingly because it is very corrosive on refractory linings. Unfortunately there is no corrosion inhibiting practice or ingredient to stop the corrosive effects of spar. In addition, spar forms hydrofluoric acids in the gas cleaning system that seriously corrode any metal surfaces in the hood and cleaning systems. Finally, significant fluoride emissions are serious pollution and health hazards.

Coolants are other additions often made at about the same time as fluxes. There are several types of coolants. Iron ore, either lump or pellets, are the most common type. Varieties of limestone (calcium and/or magnesium carbonates) are often used but the cooling effects are less dependable than ores. Some shops use pre-reduced pellets which contain about 93% iron and thus behave similar to scrap. The coolant amounts are calculated by the computer. Ore (iron oxide) should be added as soon as possible to achieve early lime dissolution and to reduce the possibility of vigorous reactions and slopping at mid blow.

9.2.2.8 Final Oxygen Adjustments and Dynamic Sensors

The third or main batch is usually blown at 80 in. to 95 in. lance height above the bath depending on furnace design, practice and available oxygen pressure.

In many shops, the oxygen lance height is changed near the end of the blow to control the iron oxide (FeO) in the slag. Some shops activate their dynamic control systems to measure carbon and temperatures at this point. Oxygen is turned off based on either the static charge calculation or based on a modified result calculated from the dynamic sensor(s).

9.2.2.9 Turndown and Testing

After the blow is finished, the furnace is then rotated towards the charging side. Often the slag is very foamy and fills up the upper volume of the furnace. This foam will often take several minutes to collapse and settle down on its own. Thus, the operators will often toss pieces of wood or cardboard or scrapped rubber tires onto the bath to increase the collapse of the foam.

There is a heat shield on the charging floor on a track that is positioned in front of the furnace during the blow. The mouth of the furnace is rotated toward the charging side nearly 90° so the operator can look inside the furnace and sample the heat for chemical analysis and temperature measurement. Here, he also assesses the furnace condition to determine when and if any special maintenance is required.

9.2.2.10 Corrective Actions

Based on the chemical laboratory results, the melter decides if the heat is ready for tap or requires corrective action—a reblow and/or coolant. If a corrective action is required, the furnace is set upright. A reblow of additional oxygen may be required, with or without coolants or fluxes, to arrive at the desired (aim) chemistry and temperature. Usually, after a corrective action, another furnace turndown is required, adding five to eight minutes to the heat time. When the heat is ready, the furnace is rotated upward and over toward the tap side.

9.2.2.11 Quick Tap Procedures

Japan and some European shops reduce sampling and testing times to one to three minutes by using a quick tap procedure. Most of these shops use sub-lances to measure temperature and carbon by the liquidus thermal arrest technique. This testing is done without moving the furnace from the upright position. Success of quick-tap depends on consistently meeting the sulfur and phosphorus specification. This procedure can save three to six minutes of lab analysis time. These shops simply proceed immediately to tapping the furnace. Consequently, such shops often turn out 60 heats per day from two active furnaces.

Some North American shops have adopted a simplified variation of the quick-tap practice. A few have sub-lances. Others use the bomb drop-in thermocouples with or without oxygen sensors. Here a heavy cast iron bomb assembly with a specially wound and protected lead wire is dropped into the furnace. The wire lasts long enough to get a reading. The readings are more accurate if the oxygen is stopped but some shops get a usable reading during the blow. Again, tramp elements, S, P and other residuals are assumed to be acceptable and tapping proceeds immediately. Some two furnace shops use this technique to minimize production losses when one of the furnaces is being relined or repaired.

9.2.2.12 Tapping

For tapping, the furnace is rotated to the tap side and the steel flows through a taphole into a ladle sitting on a car below. The slag floats on top of the steel bath inside the furnace. Near the end of tapping (four to ten minutes) a vortex may develop near the draining taphole and entrain some of the slag into the ladle. There are various devices used to minimize or detect the onset of slag. Heavy uncontrolled slag entrainment into the ladle has a significant adverse effect on production costs and steel quality.

During tapping, alloys are added to adjust the composition to the final levels or to concentrations suitable for further ladle treatment processes. Typically, 2000 to 6000 lbs of alloys are added at tap. After tap, the ladle may be transported for further processing to a ladle arc furnace and/or a degasser. Some shops and some grades permit transport to ingot teeming or to the caster without any further treatments.

An increasing number of grades require limiting the amount of slag carryover to the ladle and close control of slag viscosity and chemical composition. Various devices have been developed to minimize slag draining from the furnace. There are two main techniques. One method consists of slowing down the pouring stream at the end of tap with a refractory plug. Usually a ball-shaped device, called a ball, or a cone shaped device, called a dart, is dropped into the taphole using a carefully positioned boom near the end of tap. These devices have a controlled density, between steel and slag, causing them to float at the slag-steel interface. Thus, it plugs the tap at about the time steel is drained out. These units can be very erratic depending on the geometry of the furnace, device shape and slag characteristics. But many shops have successfully minimized slag carryover into the ladle. Another approach is to detect slag carryover with a sensor coil installed around the taphole refractory. With suitable instrumentation, this system gives the operator an accurate and early warning of slag draining through the taphole at which time tapping is stopped by raising the furnace. The net result of these slag control/detection practices is to reduce furnace slag in the steel ladle, thereby improving chemical consistency and reducing the extent of post-tapping treatments and additions.

The condition and maintenance of the taphole and the furnace wall around it can influence alloy recovery consistency and metallic yield. Poor taphole maintenance and practice can lead to a burn-through in either the furnace shell or the taphole support frame. A very small taphole can significantly increase the tap time, reducing productivity, steel temperature, and nitrogen pickup in the ladle. A very large taphole will not allow enough time to add and mix the alloy additions in the ladle. Further, aged tapholes have ragged streams with higher surface areas that will entrain air, which in turn dissolves more oxygen and makes control of oxygen levels in the steel difficult.

A newly installed taphole yields a tap time of seven or eight minutes. Tapholes are generally replaced when the tap time falls below four minutes. A very important aspect of the melter/operator's job is to carefully monitor the condition and performance of the tap hole.

Steel is often lost to the slag pot, a yield loss, when a pocket or depression develops near or around the tap opening. Such a depression can prevent several tons of steel from being drained into the ladle. Again, the operator must carefully monitor yields and furnace condition and make repairs to prevent this problem.

9.2.2.13 Slagging Off and Furnace Maintenance

After tapping, the furnace is rotated back upright to prepare for furnace maintenance. The remaining slag is either immediately dumped into a slag pot toward the charging side or it is splashed on the walls of the furnace to coat the lining and thereby extend its life. This slag splashing (coating) maintenance is done by blowing nitrogen through the oxygen lance for two to three minutes, see Section 4.2. Often, the furnace is simply rocked back-and-forth to coat or build up the bottom, charge and tap pad areas. Dolomitic stone or dolomitic lime additions are made to stiffen the slag for splashing or to freeze the slag to the bottom. Frequently, repairs by spraying a cement-like refractory slurry are made as required prior to the next charge.

The furnace is then ready for the next heat.

9.2.3 Shop Manning

9.2.3.1 Introduction

Another way of looking at the steelmaking process is to look at how the operators and workers run the process. The shop crew is very much a coordinated team. Virtually all oxygen steelmaking shops operate around the clock—21 shifts per week. Some are able to schedule a down or repair turn once per week or every other week in conjunction with a similar scheduled blast furnace outage. Similarly, the down stream caster facility will also schedule a repair outage.

When manning is summarized, the manning levels are expressed on a per turn basis. To get the totals for 21 turns per week (three turns per day times seven days per week) multiply the turn manning by four and add the management, staff and maintenance forces (who work only five day turns).

The example here will cover a two furnace shop producing about 40 to 45 heats per day. Three furnace shop issues and exceptions will be noted in the discussion. The actual figures in a given shop may vary from the example presented here as different shops have different numbers of furnaces (two or three) and different demands (steel grades and production levels).

9.2.3.2 Hot Metal

Transporting the hot metal subs to the BOF requires one man if the engine has radio control. The pouring station has an operator who weighs and pours and an assistant who plugs in electric power to tilt the subs and moves the train locally and changes the subs at the pouring station. If there is desulfurizing, there will be one or two other operators to desulfurize, skim and maintain the equipment. A three furnace shop will double this crew to operate two or three pouring and treatment stations.

9.2.3.3 Charging Crane

A charging crane operator is required, often with a relief operator. Busy shops may operate two charging cranes with a relief operator serving the charge and scrap cranes. Often one relief crane operator serves both the charging and teeming or the casting crane.

9.2.3.4 Scrap

Scrap is often premixed by a contractor or a plant crew at a separate facility nearby. Gondolas bearing scrap are transported into the BOF by the plant railroad. There will be one or two scrap crane operators (depending on how many heats the shop makes) loading and weighing the boxes. The charging crane then picks up the scrap boxes and charges them into the furnace or puts them on a charging machine.

9.2.3.5 Furnace and Charging Floor

The overall responsibility for production of the shop during the turn belongs to the turn supervisor. There is a furnace crew consisting of a melter (who is the crew leader and is responsible for making the heat), pulpit operator who operates the computer, lance and flux systems, and two or three furnace operators. In small, lean shops, the melter is also the turn supervisor. The furnace operators actually position the furnace for charging, (operate a scrap charging machine if there is one) and test the heat by sampling the heats for chemistry and temperature. They also weigh up alloys, tap the heat and maintain the furnace refractory—all under the melter's supervision. In larger, high productivity shops, there may be one of these crews and a melter for each active furnace. In this case, the turn supervisor coordinates all shop activities.

9.2.3.6 Flux Handling

There is a track-hopper operator who controls equipment that unloads the fluxes and alloys from rail cars and trucks. Often there is an assistant at the unloading station at ground level, with the operator on the top floor where the conveyer dumper is located. Generally, this operation occurs on day turn in smaller shops or day and afternoon turns in larger shops.

9.2.3.7 Maintenance

There is an on-turn maintenance crew which responds to delay and breakdown calls and performs certain preventative maintenance procedures that are safe during furnace operation. Usually, the day time crew is larger to handle calls and do preventative maintenance. The maintenance crew also

load and unload oxygen lances and maintain the oxygen system. Turn maintenance people consist of mechanical millwrights and electricians (three to ten millwrights and electricians). The day turn crew also includes instrument calibration, instrument repair and electronic skillspersons.

9.2.3.8 General Labor

Often, there is a small day turn labor crew (one to three persons) which operates a forklift trucks to transport various alloy additions for tapping and assists getting spray materials ready for furnace maintenance. The operators also run a mechanical sweeper and hand sweep around the shop to maintain good housekeeping.

9.2.3.9 Chemistry Lab

In older shops there is a vacuum conveyer systems where samples are transported to the chemistry lab. Laboratory manning will vary widely depending on how centralized the lab is to the whole plant. An increasing number of shops are installing robot labs for faster and more convenient service of chemical analysis. However, the robot lab requires an operator whose responsibility is supervising calibration, changing grinding media, and lubrication and maintenance of mechanical and optical equipment. The advantages of a well maintained robot lab are speed and consistency in sample preparation and analysis rather than labor savings.

9.2.3.10 Refractory Maintenance

Often furnace maintenance is done by the floor furnace crew. However, larger and busier shops will have an outside contractor or a separate crew to spray repair the furnaces. This crew may operate only during day turns and consists of two or three persons.

9.2.3.11 Relines and Major Repairs

Maintenance may schedule a crew to make hood and furnace shell repairs while relining is going on. Often, special code welding skills (usually hood or thick shell repairs) are required and are often done by an outside contractor. With the growth of slag splashing, which causes infrequent relines, hood repair work must be scheduled several times between relines.

9.2.3.12 Ladle Liners

Hot metal and steel ladles are a very important component of steelmaking. Hot metal ladle life is typically 1500 pours and a typical small shop will carry a fleet of four or five ladles of which two or three are active. Steel ladles last from 60 to 150 heats. Steel ladle fleets may vary from eight to 25 depending on the size of the shop. Relining of ladles is usually supervised by the Teeming Supervisor. Ladle lining crew sizes vary widely.

9.2.3.13 Management and Clerical

Finally, management and clerical staffs vary widely from shop to shop. The General Supervisor (sometimes called Area Manager) supervises the day-to-day operation and plans the course of the facility. Often there are separate area supervisors (five day turns per week only) covering hot metal pouring and treatment, furnace floor operations, scrap and flux loading, and maintenance. Usually there is a small clerical staff (one to five), a practice engineer, and a small, assigned crew of metallurgical or quality assurance (QA) people.

In summary, even in a small shop, the steelmaking team brings together many different skills working in concert. In addition to the production crew, there are numerous support groups, principally maintenance, that keep the shop running smoothly. Table 9.3 summarizes the manning of a small BOF shop.

Table 9.3 Example of Manning a Small Two Furnace BOF Shop

Position	Area	Turns	Number
General Supervisor	Supv	Day	1
Hot Metal Supervisor	Supv	Day	1
Furnace Supervisor	Supv	Day	1
Scrap & Flux Supervisor	Supv	Day	1
Maintenance Supervisor	Supv	Day	1
Melter	Supv	All	4
Maintenance Supervisor	Turn	All	4
Hot Metal Pourer	Turn	All	4
Hot Metal Assistant	Turn	All	4
Desulf and Skim	Turn	All	4
Charging Crane	Turn	All	8
Charging Crane Relief	Turn	All	4
Pulpit Operator	Turn	All	4
Furnace Operator	Turn	All	12
Scrap Crane	Turn	All	4
Track Hopper	Turn	Day	2
Track Hopper Assistant	Turn	Day	2
Labor	Turn	All	4
Maintenance	Turn	All	Varies
Ladle liners		Day	Varies
Metallurgist	Staff	Day	2
Clerical	Staff	Day	2

9.3 Raw Materials

9.3.1 Introduction

The basic raw materials required to make steel in the oxygen steelmaking process include: hot metal from the blast furnace, steel scrap and/or any other metallic iron source (such as DRI), ore (Fe_2O_3), and fluxes such as burnt lime (CaO), dolomitic lime (CaO-MgO), dolomitic stone ($\text{MgCO}_3\text{-CaCO}_3$) and fluorspar (CaF_2).

Scrap, charged from a scrap box, is the first material to be charged into the furnace. The hot metal is then poured into the vessel from a ladle, after which the oxygen blow is started. The fluxes, usually in lump form, are charged into the furnace through a bin system after the start of the oxygen blow. The fluxes can also be injected into the furnace in powder form through bottom tuyeres.

The composition and amounts of raw materials used in the steelmaking process vary from one shop to another, depending on their availability and the economics of the process. The basic raw materials used in the oxygen steelmaking process are described below.

9.3.2 Hot Metal

The hot metal, or liquid pig iron, is the primary source of iron units and energy in the oxygen steelmaking process. Hot metal is usually produced in blast furnaces, where it is cast into submarine shaped torpedo cars and transported either to a desulfurization station or directly to the steelmaking shop.

9.3.2.1 Composition

The chemical composition of hot metal can vary substantially, but typically it contains about 4.0–4.5% carbon, 0.3–1.5% silicon, 0.25–2.2% manganese, 0.04–0.20% phosphorus and

0.03–0.08% sulfur (before hot metal desulfurization).¹ The sulfur level in desulfurized hot metal can be as low as 0.001%. The composition of the hot metal depends on the practice and charge in the blast furnace. Generally, there is a decrease in the silicon content and an increase in the sulfur of the hot metal with colder blast furnace practices. The phosphorus contents of the hot metal increases if the BOF slag is recycled at the sinter plant.

Carbon and silicon are the chief contributors of energy. The hot metal silicon affects the amount of scrap charged in the heat. For example, if the hot metal silicon is high, there will be greater amounts of heat generated due to its oxidation, hence more scrap can be charged in the heat. Hot metal silicon also affects the slag volume, and therefore the lime consumption and resultant iron yield.

9.3.2.2 Determination of Carbon and Temperature

The hot metal is saturated with carbon, and its carbon concentration depends on the temperature and the concentration of other solute elements such as silicon and manganese. The carbon content of the hot metal increases with increasing temperature and manganese content, and decreases with increasing silicon content.

It is important to know the temperature and the carbon content of hot metal at the time it is poured into the BOF for steelmaking process control. The hot metal temperature is normally measured at the hot metal desulfurizer or at the time it is poured into the transfer ladle from the torpedo cars. If the hot metal temperature has not been measured close to the time of its charge into the BOF, then it can be estimated using the last hot metal temperature measurement, in conjunction with a knowledge of the rate of the hot metal ladle temperature loss with time, and the time elapsed between the last temperature measurement and the BOF charge. Typically, the temperature of the hot metal is in the range of 1315–1370°C (2400–2500°F). Once the temperature is measured or calculated, the carbon content of the hot metal at the time of charge can be estimated using a regression equation, which is mainly in terms of the temperature, hot metal silicon and manganese. Calculating the carbon in this manner has turned out to be as accurate as analyzing it chemically while saving considerable lab effort.

9.3.2.3 Hot Metal Treatment

Desulfurization is favored at high temperatures and low oxygen potentials. Also, the presence of other solute elements in the metal such as carbon and silicon increases the activity of sulfur, which in turn enhances desulfurization. Thus low oxygen potential and high carbon and silicon contents make conditions more favorable to remove sulfur from hot metal rather than from steel in the BOF.

Not all hot metal is desulfurized. Hot metal used for making steel grades with stringent sulfur specifications is desulfurized in the hot metal desulfurizer. The hot metal is poured into a transfer ladle from a torpedo car. It is then transported to the desulfurization station where the desulfurizer can reduce hot metal sulfur to as low as 0.001%, but more typically to 0.004 or 0.005%.

Typical desulfurizing reagents include lime-magnesium, and calcium carbide. Powdered reagents are generally injected using nitrogen gas. Apart from reducing sulfur to low levels, a hot metal desulfurizer can also allow the blast furnace operator to increase productivity by reducing the limestone burden and thereby producing higher sulfur hot metal.

It is important that the slag produced after hot metal desulfurization is removed effectively through slag skimming. This slag contains high amounts of sulfur, and any slag carried over into the BOF, where conditions are not good for desulfurization, will cause sulfur pickup in the steel.

9.3.2.4 Weighing

The weighing of the hot metal is done on a scale while it is being poured into the transfer ladle. It is very important that the weight of the hot metal is accurately known, as any error can cause problems in turndown chemistry, temperature and heat size in the BOF. This weight is an important input to the static charge model.

9.3.3 Scrap

Scrap is the second largest source of iron units in the steelmaking operation after hot metal. Scrap is basically recycled iron or steel, that is either generated within the mill (e.g. slab crops, pit scrap, cold iron or home scrap), or purchased from an outside source.

The scrap is weighed when loaded in the scrap box. The crane operator loads the box based on the weight and mix requirements of the upcoming heat. Then the box is transported to the BOF. It is important that the crane operator loads correct amounts and types of scrap (the scrap mix) as indicated by the computer or a fixed schedule. Otherwise the turndown performance of the heat will be adversely affected. Some typical types of scrap used in a BOF heat, and few of their properties are listed in Table 9.4.

Normally, the lighter scrap is loaded in the front, and the heavier scrap in the rear end of the box. This causes the lighter scrap to land first in the furnace as the scrap box is tilted. It is preferable that the lighter scrap fall on the refractory lining first, before the heavier scrap, to minimize refractory damage. Also, since heavy scrap is more difficult to melt than light scrap, it is preferable that it sits on top so that it is closest to the area of oxygen jet impingement and hence melt faster.

Scrap pieces that are too large to be charged into the furnace are cut into smaller pieces by means of shears or flame cutting. Thin, small pieces of scrap such as sheet shearings and punchings are compressed into block like bundles called bales using special hydraulic presses. Normally, larger, heavier pieces of scrap are more difficult to melt than lighter, smaller ones.

Unmelted scrap can cause significant problems in process control. It may result in high temperatures or missed chemistries at turndown. Bottom or mixed blowing, which can significantly enhance the mixing characteristics in the furnace, improves scrap melting of larger pieces.

Stable elements present in scrap, such as copper, molybdenum, tin and nickel cannot be oxidized and hence cannot be removed from metal. These elements can only be diluted. Detinned bundles, where tin is removed by shredding and treating with NaOH and then rebaled, are available but at considerably higher cost. Elements such as aluminum, silicon and zirconium can be fully oxidized from scrap and become incorporated in the slag. Elements which fall in the middle category in terms of their tendency to react, such as phosphorus, manganese and chromium distribute themselves between the metal and slag. Zinc and lead are mostly removed from scrap the bath as vapor.

Most steelmaking shops typically use about 20 to 35% of their total metallic charge as scrap, with the exact amount depending on the capacity of the steelmaking process. Much of this capacity depends on factors like the silicon, carbon and temperature of the hot metal, use of a post combustion lance, and external fuels charged, such as anthracite coal. The scrap ratio is also influenced by the relative cost of scrap and hot metal.

9.3.4 High Metallic Alternative Feeds

Direct reduced iron (DRI) is used in some steelmaking shops as a coolant as well as a source of iron units. DRI typically contains about 88–94% total iron (about 85–95% metallization), 0.5–3%C, 1–5% SiO₂, 3–8% FeO and small amounts of CaO, MgO and Al₂O₃.² DRI may contain phosphorus in the range of 0.005 to 0.09%, sulfur in the range 0.001 to 0.03% and low concentrations of nitrogen (usually less than 20 ppm).

DRI is normally fed into the BOF in briquetted form size at approximately 1 in. The DRI briquettes are passivated (by coating or binder) to eliminate any tendency to pyrophoricity (spontaneous burning) so that they can be handled conveniently in the steelmaking shop. DRI is usually fed into the steelmaking furnace through the bin system.

Certain elements such as nickel, copper and molybdenum can be added to the heat with the scrap charge. These elements do not oxidize to any significant level and they dissolve evenly in the metal during the oxygen blow. These additions can also be made after the oxygen blow, or in the ladle during tapping.

Table 9.4 Types of Scrap used in the BOF and Their Characteristics and Chemistry *From Ref. 1, updated from Ref. 9.*

Type of Scrap	Melting	Relative Cost	Bulk Density	Yield	Fe	C	Si	Mn	P	S	Cr	Cu	Ni	Mo	Sn
Plate and structural	easy	moderate	45	94.6	95.5	0.25	0.10	0.10	0.025	0.025	0.09	0.13	0.09	0.02	0.025
Punching and plate	easy	moderate	50	94.0	96.0	0.20	0.10	0.30	0.015	0.025	0.06	0.09	0.06	0.01	0.008
No.1 Heavy melting	easy	average	50	93.3	94.5	0.25	0.10	0.30	0.020	0.040	0.10	0.25	0.09	0.03	0.025
No. 2 Bundles	easy	inexpensive	50	88.0	90.0	0.25	0.10	0.30	0.030	0.090	0.18	0.50	0.10	0.03	0.100
No. 1 Busheling	easy	very expensive	60	95.7	98.0	0.15	0.01	0.30	0.010	0.020	0.04	0.07	0.03	0.01	.008
Ironmaking slag scrap	difficult	expensive	125	90.0	91.5	4.50	1.50	1.20	0.130	0.040	0.05	0.05	0.02	0.01	0.005
Briquetted iron borings	reactive at turnaround	cheap	180	88.9	90.0	3.00	1.80	0.65	0.100	0.090	0.40	0.20	0.40	0.02	0.015
Home pit	fair	cheap	75	83.2	83.0	0.05	0.10	0.50	0.020	0.025	0.06	0.04	0.08	0.01	0.005
Home crops and skulls	fair to difficult	cheap	125	92.5	94.0	0.10	0.10	0.45	0.020	0.014	0.06	0.04	0.08	0.01	0.005
Hot metal	—	moderate	—	90.7	93.8	4.50	0.50	0.50	0.065	0.040	0.02	0.02	0.02	0.01	0.005

White areas indicate areas of potential trouble.

9.3.5 Oxide Additions

9.3.5.1 Iron Oxide Materials

Iron ore is usually charged into the BOF as a coolant and it is often used as a scrap substitute. Iron ores are available in the form of lumps or pellets, and their chemical compositions vary from different deposits as shown in Table 9.5.³ Iron ores are useful scrap substitutes as they contain lower amounts of residual elements such as copper, zinc, nickel, and molybdenum. The cooling effect of iron ore is about three times higher than scrap. The reduction of the iron oxide in the ore is endothermic and higher amounts of hot metal and lower amounts of scrap are required when ore is used for cooling. Iron ores must be charged early in the blow when the carbon content in the bath is high to effectively reduce the iron oxide. The reduction of the iron oxides in the ore produces significant amounts of gas, and consequently increases slag foaming and the tendency to slop. Late ore additions have a detrimental affect on iron yield and end point slag chemistry. If only ore is used as a coolant just before tap, the slag becomes highly oxidized and fluid, enhancing slag carryover into the ladle. The delay in the cooling reaction from the unreduced ore causes a sudden decrease in temperature or a violent ladle reaction resulting in over-oxidation of the steel.

Table 9.5 Iron Ore Chemical Compositions *From Ref. 3.*

Ore	Country	Fe	SiO ₂	Al ₂ O ₃	CaO	MgO	P	S	Mn
Minnesota	USA	54.3	6.8	0.4	0.25	0.10	0.23	—	1.0
Carol Lake	Canada	64.7	3.9	0.35	—	—	.005	—	0.2
Cerro Bolivar	Venezuela	63.7	0.75	1.0	0.3	0.25	0.09	0.03	0.02
Goa	India	57.8	2.5	6.5	0.7	0.3	0.04	0.02	—
Itabira	Brazil	68.9	0.35	0.6	—	—	0.03	0.01	0.05
Tula	USSR	52.2	10.1	1.25	0.3	0.1	0.06	0.1	0.35

9.3.5.2 Waste Oxides

Economic and environmental issues have driven steel producers to recycle the waste iron oxides generated in the process. The increasing price of scrap, in addition to the increasing costs involved in the environmentally safe disposal of waste oxides, have encouraged steelmakers to recycle these materials back into the steelmaking process. Throughout the plant, various waste oxides and mill scales are collected and used in the sinter plant to produce some of the feed for the blast furnace. However, this does not consume all available oxides. In recent times, methods have been developed to substitute waste oxides in the BOF in place of ore. Mill scale has been used as a coolant in the BOF in amounts ranging from 5,000 to 25,000 lb.⁴ Mill scale was found to be very effective in increasing the hot metal to scrap ratio; however, it causes heavy slopping during the process. Mill scale and other iron oxide additions are reduced during the main blow releasing iron and oxygen. This additional oxygen becomes available for carbon removal thus speeding up the overall reaction. Slopping is likely caused by the increased slag volume associated with using more hot metal (more pounds of Si and C generate more SiO₂ and CO, respectively) and by the increased reaction rate.

Waste oxide briquettes (WOB) containing steelmaking sludges, grit, and mill scale have also been charged into the furnace as a scrap substitute.⁵ The waste oxides collected from the BOF fumes during the blow are high in iron content, typically more than 60 wt.%. These fumes, fines (sludge) and coarse (grit) waste oxide particles are blended, dried, mixed with lime and binders, and pressed into pillow-shaped briquettes. The briquettes are then cured for over 48 hours to remove their moisture. A typical composition of WOBs is 35 wt.% sludge, 20 wt.% grit, and 45 wt.% mill scale, see Table 9.6.⁵

Table 9.6 WOB Chemical Compositions *From Ref. 5.*

Composition	Wt. %
Total Fe	55–62
Metallic Fe	3–5
FeO	38–46
Fe ₂ O ₃	29–32

Additions of WOBs are made early in the oxygen blow when the carbon content in the bath is high to ensure the reduction of ferrous, ferric, and manganese oxides to metallic iron and manganese. If the WOBs are added late in the blow, the oxides are likely to stay unreduced, resulting in yield loss, slopping, and a highly oxidized slag at turndown. WOBs are about two times better coolants than scrap, because their oxide reduction is endothermic, and therefore a higher hot metal ratio is required when WOBs are used for cooling—a situation similar to using ore. Various studies show that using WOBs causes no adverse effects on lining wear, molten iron yield, turndown performance and ladle slag FeO in the BOF.

9.3.6 Fluxes

9.3.6.1 Burnt Lime

In basic oxygen steelmaking, burnt lime consumption ranges from 40 to 100 lb. per net ton of steel produced. The amount consumed depends on the hot metal silicon, the proportion of hot metal to scrap, the initial (hot metal) and final (steel aim) sulfur and phosphorus contents. Burnt lime is produced by calcining limestone (CaCO₃) in rotary, shaft, or rotary hearth type kilns.¹ The calcining reaction is given below:



The calcination of high-calcium limestone will produce burnt lime containing about 96 wt.% CaO, 1 wt.% MgO, and 1 wt.% SiO₂. The sulfur content in burnt lime ranges from 0.03 to 0.1 wt.%. Most shops require less than 0.04 wt.% S in the lime to produce low sulfur steels.^{1,6} Since an enormous amount of burnt lime is charged into the BOF within a short period of time, careful selection of the lime quality is important to improve its dissolution in the slag. In general, small lump sizes (1/2–1 in.) with high porosity have higher reactivity and promote rapid slag formation. The most common quality problems with either burnt or dolomitic lime are uncalcined inner cores, excess fines and too low a reactivity (calcined too hot or too long).

9.3.6.2 Dolomitic Lime

Dolomitic lime is charged with the burnt lime to saturate the slag with MgO, and reduce the dissolution of dolomite furnace refractories into the slag. Typically dolomitic lime contains about 36–42 wt.% MgO and 55–59 wt.% CaO.¹ Similarly, the dolomitic stone contains about 40% MgCO₃. The dolomitic lime charge into the BOF ranges from 30 to 80 lb. per net ton of steel produced, which represents about 25 to 50% of the total flux charge into the furnace (burnt plus dolomitic lime). The large variation in these additions strongly depends on experience and adjustments made by the steelmakers. These are based on observations of chemical attack of the slag on furnace refractories. Most of the dolomitic lime produced in the United States is obtained by calcining dolomitic stone in rotary kilns. The calcining reaction of the dolomitic stone is similar to that of limestone:



In some BOF operations dolomitic stone is added directly into the furnace as a coolant, and as a source of MgO to saturate the slag. It can also be added to stiffen the slag prior to slag splashing. It is important for the steelmaker to control the chemistry and size of the dolomitic lime.

9.3.6.3 Limestone

In most BOF shops limestone (CaCO_3) or dolomitic stone, ($\text{CaCO}_3 \cdot \text{MgCO}_3$) is frequently used as a coolant rather than as a flux. Limestone is commonly used to cool the bath if the turndown temperature is higher than the specified aim. When limestone is heated, the endothermic calcining reaction occurs producing CaO and CO_2 , causing a temperature drop in the furnace. The extent of the temperature drop just before tap depends on the furnace size and slag conditions and is known for each shop. For example, in a 300 ton heat, 1000 lb. of limestone will drop the temperature of the bath by about 6°C (10°F).

9.3.6.4 Fluorspar

Calcium fluoride or fluorspar (CaF_2) is a slag fluidizer that reduces the viscosity of the slag. When added to the BOF it promotes rapid lime (CaO) dissolution in the slag by dissolving the dicalcium silicate ($2\text{CaO} \cdot \text{SiO}_2$) layer formed around the lime particles which retards the dissolution of the lime in the slag. In recent times, fluorspar has been used very sparingly because of its very corrosive attack of all types of refractories, including both furnace and ladle. Also, the fluorides form strong acids in the waste gas collection system which corrode structural parts and are undesirable emissions.

9.3.7 Oxygen

In modern oxygen steelmaking processes a water-cooled lance is used to inject oxygen at very high velocities onto a molten bath to produce steel. With the increasing demands to produce higher quality steels with lower impurity levels, oxygen of very high purity must be supplied. Therefore, the oxygen for steelmaking must be at least 99.5% pure, and ideally 99.7 to 99.8% pure. The remaining parts are 0.005 to 0.01% nitrogen and the rest is argon.¹

In top-blown converters, the oxygen is jetted at supersonic velocities ($\text{Mach} > 1$) with convergent-divergent nozzles at the tip of the water-cooled lance. A forceful gas jet penetrates the slag and impinges onto the metal surface to refine the steel. Today, most BOFs operate with lance tips containing four to five nozzles and oxygen flow rates, (in 230 to 300 ton converters), that range from 640 to 900 Nm^3/min (22,500 to 31,500 scfm).⁷ Figure 9.6 shows an schematic of a typical five-nozzle lance tip. The tip is made of a high thermal conductivity cast copper alloy with precisely machined nozzles to achieve the desired jet parameters. The nozzles are angled about 12° to the centerline of the lance pipe and equally spaced around the tip. The tip is welded to a 12 inch seamless steel pipe (lance barrel) about 60 feet long. Cooling water is essential in these lances to keep them from burning up in the furnace. At the top of the lance, armored rubber hoses are connected to a pressure-regulated oxygen source and to a supply of recirculated cooling water. Details of the convergent-divergent nozzles are also shown in Fig. 9.6. As the oxygen passes the converging section it is accelerated and reaches sonic velocity ($\text{Mach} = 1$) in the cylindrical throat section. Then it expands in the diverging sec-

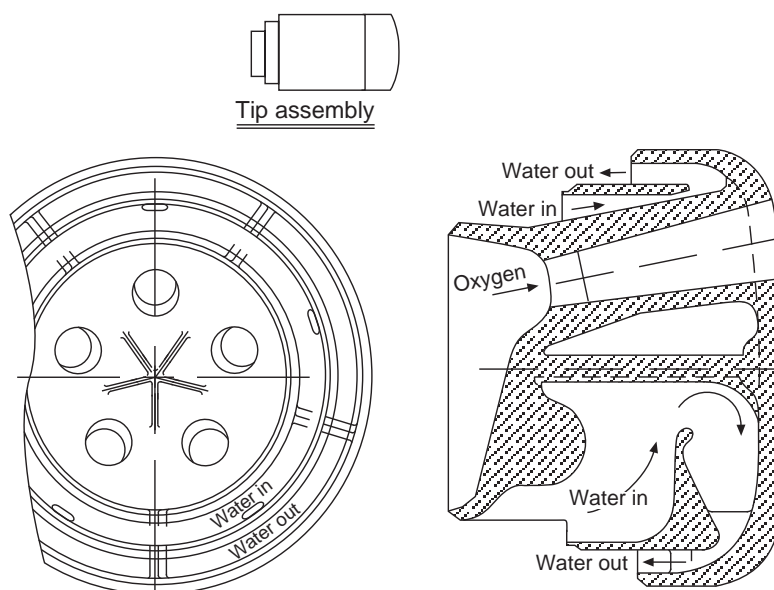


Fig. 9.6 Convergent-divergent nozzles. From Ref. 1.

tion and its temperature and pressure decreases while its velocity increases to supersonic levels ($\text{Mach} > 1$). The supersonic jets are at an angle of about 12° so that they do not interfere with each other.

In bottom-blown converters, the oxygen is injected through the bottom of the vessel using a series of tuyeres. About 14 to 22 tuyeres are used to blow about 4.0 to 4.5 Nm^3 of oxygen per minute per ton of steel.⁸ Powdered lime, mixed with the oxygen, is usually injected through the liquid bath to improve lime dissolution and hence slag formation during the blow. The tuyeres consist of two concentric pipes, where oxygen flows through the center pipe and a hydrocarbon fluid, such as natural gas or propane, used as a coolant, flows through the annular space between both pipes.

9.4 Process Reactions and Energy Balance

9.4.1 Refining Reactions in BOF Steelmaking

In the oxygen steelmaking process, impurities such as carbon (C), silicon (Si), and manganese (Mn) dissolved in the hot metal are removed by oxidation to produce liquid steel. Hot metal and scrap are charged into the furnace and high-purity oxygen gas is injected at high flow rates, through a lance or tuyeres, to react with the metal bath. The oxygen injection process, known as the blow, lasts for about 16 to 25 minutes and the oxidation reactions result in the formation of CO , CO_2 , SiO_2 , MnO , and iron oxides. Most of these oxides are dissolved with the fluxes added to the furnace, primarily lime (CaO), to form a liquid slag that is able to remove sulfur (S) and phosphorus (P) from the metal. The gaseous oxides, composed of about 90% CO and 10% CO_2 , exit the furnace carrying small amounts of iron oxide and lime dust. Typical oxygen flow rates during the blow range between 2 – 3.5 Nm^3 per minute per ton of steel (70 – 123 scfm per ton), and in general the rate of oxygen injection is limited either by the capacity of the hood and gas cleaning system or by the available oxygen pressure

The commercial success of oxygen steelmaking is mainly due to two important characteristics. First, the process is autogenous meaning that no external heat sources are required. The oxidation reactions during the blow provide the energy necessary to melt the fluxes and scrap, and achieve the desired temperature of the steel product. Second, the process is capable of refining steel at high production rates. The fast reaction rates are due to the extremely large surface area available for reactions. When oxygen is injected onto the metal bath a tremendous amount of gas is evolved forming an emulsion with the liquid slag and with metal droplets sheared from the bath surface by the impingement of the oxygen jet.¹⁰ This gas-metal-slag emulsion, shown in Fig. 9.7, generates large surface areas that increase the rates of the refining reactions. The reaction mechanisms and the slag-metal reactions are discussed in detail in Chapter 2. Therefore, only a brief discussion of the sequence of these reactions during the blow are provided in this section.

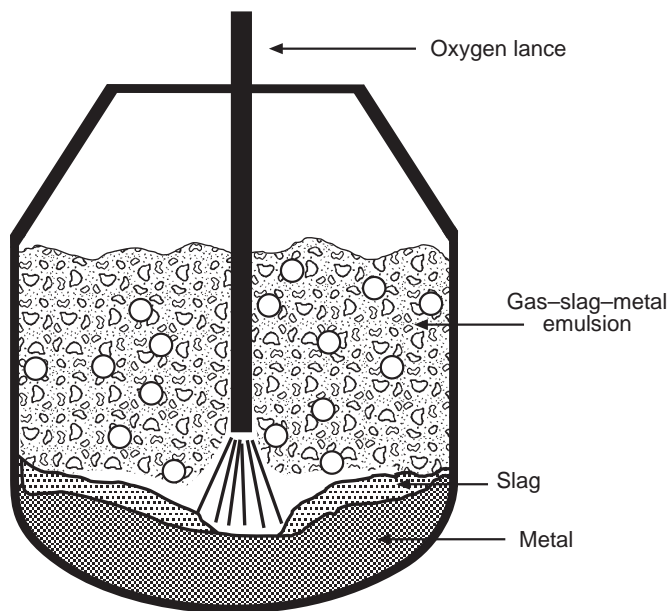


Fig. 9.7 Physical state of the BOF in the middle of the blow.

9.4.1.1 Carbon Oxidation

Decarburization is the most extensive and important reaction during oxygen steelmaking. About 4.5 wt% carbon in the hot metal is oxidized to CO and CO₂ during the oxygen blow, and steel with less than 0.1 wt% carbon is produced. The change in the carbon content during the blow is illustrated in Fig. 9.8,¹¹ which shows three distinct stages. The first stage, occurring during the first few minutes of the blow, shows a slow decarburization rate as nearly all the oxygen supplied reacts with the silicon in the metal. The second stage, occurring at high carbon contents in the metal, shows a constant higher rate of decarburization and is controlled by the rate of supplied oxygen. Finally, the third stage occurs at carbon contents below about 0.3 wt.%, where the decarburization rate drops as carbon becomes less available to react with all the oxygen supplied. At this stage, the rate is controlled by mass transfer of carbon, and the oxygen will mostly react with iron to form iron oxide. Also in this stage, the generation of CO drops and the flame over the mouth of the furnace becomes less luminous, and practically disappears below about 0.1 wt.% carbon.

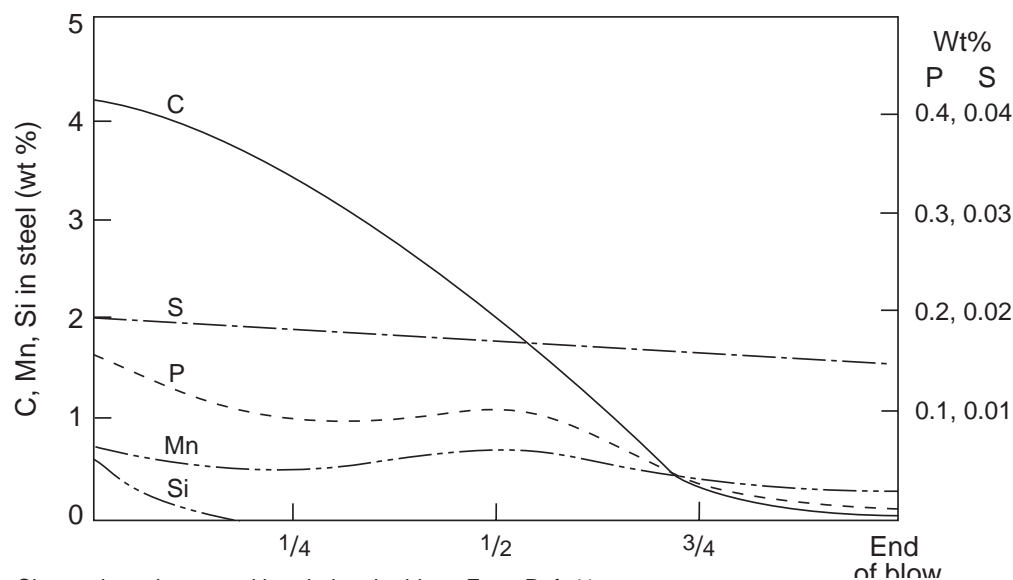


Fig. 9.8 Change in melt composition during the blow. From Ref. 11.

9.4.1.2 Silicon Oxidation

The strong affinity of oxygen for Silicon will result in the removal of almost all the Si early in the blow. The Si dissolved in the hot metal (0.25–1.3 wt.%) is oxidized to very low levels (<0.005 wt.%) in the first three to five minutes of the blow as shown in Fig. 9.8. The oxidation of Si to silica (SiO₂) is exothermic producing significant amounts of heat which raises the temperature of the bath. It also forms a silicate slag that reacts with the added lime (CaO) and dolomitic lime (MgO) to form the basic steelmaking slag. The amount of Si in the hot metal is very important since its oxidation is a major heat source to the process and it strongly affects the amount of scrap that can be melted. It also determines the slag volume and consequently affects the iron yield and dephosphorization of the metal. In general, more slag causes less yield but lower phosphorus.

9.4.1.3 Manganese Oxidation

The reaction involving the oxidation of Manganese in steelmaking is complex. In top-blown processes Mn is oxidized to MnO early in the blow and after most of the silicon has been oxidized, the Mn reverts into the metal.¹² Finally, as shown in Fig. 9.8, towards the end of the blow the Mn in the metal decreases as more oxygen is available for its oxidation. In bottom-blown processes, such as the OBM (Q-BOP), a similar pattern is found, but the residual Mn content of the steel is higher than for top-blown processes due to better stirring.^{13,14}

9.4.1.4 Phosphorus Oxidation

Dephosphorization is favored by the oxidizing conditions in the furnace. The dephosphorization reaction between liquid iron and slag can be expressed by reaction 9.4.1.¹⁵ Phosphorus removal is favored by low temperatures, high slag basicity (high CaO/SiO₂ ratio), high slag FeO, high slag fluidity, and good stirring.^{12,15} The change in the phosphorus content of the metal during blow is shown in Fig. 9.8. The phosphorus in the metal decreases at the beginning of the blow, then it reverts into the metal when the FeO is reduced during the main decarburization period, and finally decreases at the end of the blow.¹² Stirring improves slag-metal mixing, which increases the rate of dephosphorization. Good stirring with additions of fluxing agents, such as fluorspar, also improves dephosphorization by increasing the dissolution of lime, resulting in a highly basic and fluid liquid slag.



9.4.1.5 Sulfur Reaction

The BOF is not very effective for sulfur removal due to its highly oxidizing conditions. Sulfur distribution ratios in the BOF (% S slag /% S metal ~4–8) are much lower than the ratios in the steel ladle (% S slag /% S metal ~300–500) during secondary ladle practices. In the BOF, about 10 to 20% of sulfur in the metal reacts directly with oxygen to form gaseous SO₂.¹⁵ The rest of the sulfur is removed by the following slag-metal reaction



Sulfur removal by the slag is favored by high slag basicities (high CaO/SiO₂ ratio), and low FeO contents. The final sulfur content of steel is also affected by the sulfur contained in the furnace charge materials, such as hot metal and scrap. The sulfur content in the hot metal supplied from the blast furnace generally ranges from 0.020 to 0.040 wt.%, and if the hot metal is desulfurized before steelmaking the sulfur content in the hot metal can be as low as 0.002 wt.%. Heavy pieces of scrap containing high sulfur contents must be avoided if low sulfur alloys with less than 60 ppm (0.006%) of sulfur are being produced. For example a slab crop of 2273 kg (5000 lb.) containing 0.25 wt.% S (12.5 lb. of sulfur) can increase the sulfur content of steel by about 15 ppm (0.0015%) in a 300 ton BOF.

9.4.2 Slag Formation in BOF Steelmaking

Fluxes are charged into the furnace early in the blow and they dissolve with the developing oxides to form a liquid slag. The rate of dissolution of these fluxes strongly affects the slag-metal reactions occurring during the blow. Therefore, it is important to understand the evolution of slag during the blow. Several investigators have studied slag formation in oxygen steelmaking,^{16,17} and a detailed review of these investigations is given by Turkdogan,¹¹ and Deo and Boom.¹⁸

At the beginning of the blow, the tip of the oxygen lance is kept high above the bath surface, at about 3.5 m (12 ft), which results in the formation of an initial slag rich in SiO₂ and FeO. During this period large amounts of burnt lime and dolomitic lime are charged into the furnace. The lance is then lowered and the slag starts to foam at around one third of the blow due to the reduction of the FeO in the slag in conjunction with CO formation. The drop in the FeO content in the slag is shown in Fig. 9.9. Also, as the blow progresses, the CaO dissolves in the slag, and the active slag weight increases. Finally, after three quarters into the blow, the FeO content in the slag increases because of a decrease in the rate of decarburization. The resulting slag at turndown in top-blown converters (BOF or BOP) have typical ranges: 42–55 wt.% CaO, 2–8 wt.% MgO, 10–30 wt.% FeO_T, 3–8 wt.% MnO, 10–25 wt.% SiO₂, 1–5 wt.% P₂O₅, 1–2 wt.% Al₂O₃, 0.1–0.3 wt.% S. In the OBM (Q-BOP) or bottom-blown converter, the total FeO in the turndown slag is lower, ranging between 4–22 wt.%

During the blow, the temperature of the metal gradually increases from about 1350°C (2450°F) to 1650°C (3000°F) at turndown, and the slag temperature is about 50°C (120°F) higher than that of

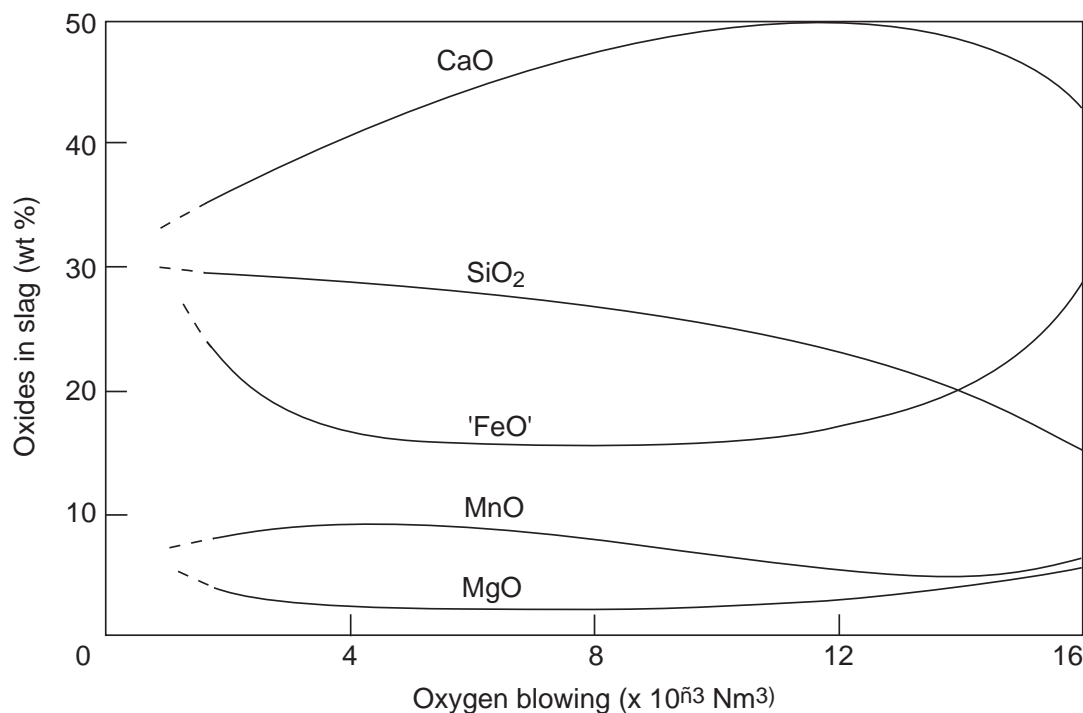


Fig. 9.9 Change in slag composition during the blow. From Ref. 11.

the metal.¹⁹ The slag at turndown may contain regions of undissolved lime mixed with the liquid slag, since the dissolution of lime is limited by the presence of dicalcium silicate ($2\text{CaO}\cdot\text{SiO}_2$) coating, which is solid at steelmaking temperatures and prevents rapid dissolution.¹¹ The presence of MgO in the lime weakens the coating. Thus, charging MgO early speeds up slag forming due to quicker solution of lime.

9.4.3 Mass and Energy Balances

As shown in Fig. 9.10, hot metal, scrap, and iron ore are charged with the fluxes, such as burnt and dolomitic lime, into the furnace. Oxygen is injected at high flow rates and gases, such as CO and CO_2 , and iron oxide fumes (Fe_2O_3) exit from the mouth of the furnace. At turndown, liquid steel and slag are the remaining products of the process. The oxidation reactions occurring during the blow produce more energy than required to simply raise the temperature of the hot metal, from about 1350°C (2450°F) to the desired turndown temperature, and to melt the fluxes. Most of the excess heat is used to increase the amount of steel produced by melting cold scrap and by reducing iron ore to metal. Some heat is also lost by conduction, convection, and radiation to the surroundings.

It is important to exactly determine the amount of each material to charge and the amount of oxygen to blow to produce steel of desired temperature and chemistry. The specific method for determining these amounts varies with each BOF shop; however, in general these computations are based on mass and energy balance calculations. A simple mass and energy balance is presented in this text for illustration purposes. A more detailed treatment can be found in the literature.¹

Consider the production of 1000 kg of steel. Fluxes, such as burnt and dolomitic lime, are added to the furnace with the iron ore early in the blow. Before any calculation can be made it is required to specify the compositions and temperatures of the input materials, such as hot metal, scrap, iron ore, and fluxes, and also the temperature and chemistry specifications of the steel product. Table 9.7 shows typical compositions. The sequence of calculations required to determine the amounts of input materials necessary to produce 1000 kg of steel product is summarized as follows:

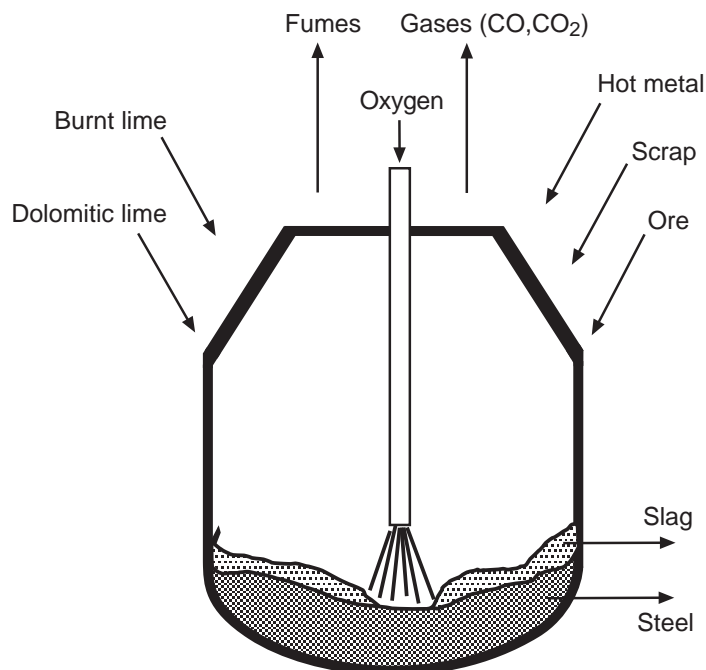


Fig. 9.10 Input and output materials in the BOF.

Table 9.7 Chemistries of Input and Output Materials in the BOF

Element	Hot Metal	Scrap	Steel	
% Fe	93.61	99.493	99.797	
% C	4.65	0.09	0.040	
% Si	0.60	0.020	0.005	
% Mn	0.45	0.360	0.138	
% P	0.06	0.012	0.010	
% S	0.01	0.025	0.010	
Other	0.61			
Compound	Burnt lime	Dolo-lime	Slag	Iron Ore
%CaO	96.0	58.0	47.86	—
%SiO ₂	1.0	0.8	12.00	0.77
%MgO	1.0	40.5	6.30	—
%FeO _T	—	—	26.38	—
%Fe	—	—	—	65.8
%Al ₂ O ₃	0.5	0.4	1.30	—
%MnO	—	—	5.00	0.20
%H ₂ O	1.3	1.4	—	—
%P ₂ O ₅	—	—	1.16	—

94.3.1 Determination of the Flux Additions

The fluxes added to the process strongly depend on the hot metal silicon, the weight of hot metal, the lime to silica ratio (%CaO/%SiO₂), and the amount of MgO needed in the slag to avoid the wear of furnace refractories. The lime to silica ratio should range from two to four to achieve a basic slag during the blow. Also, approximately 6–12 wt.% of MgO is required, depending on slag temperature and chemistry, to saturate the slag and consequently retard dissolution of the furnace refractories.⁷

For a typical lime to silica ratio of four, each kg of SiO_2 in the slag requires 4 kg of CaO. For the example shown in Table 9.8, about 11.26 kg (24.78 lb.) of SiO_2 are produced from the oxidation of the hot metal silicon, and 47.92 kg (105.42 lb.) of CaO per metric ton of steel are required to neutralize the SiO_2 in the slag. The amounts of burnt lime and dolomitic lime needed are computed from the CaO and MgO requirements as shown in Table 9.8. In actual BOF operations, higher dolomitic lime additions are made than those predicted by the present example to ensure MgO saturation.

Table 9.8 Material and Energy Balance for the Production of 1000 kg (2200 lb.) of Steel

Input			Output		
Hot Metal	kg	lb.	Steel	kg	lb.
Fe	821.60	1807.5	Fe	997.97	2195.5
C	40.81	89.78	C	0.40	0.88
Si	5.26	11.58	Si	0.05	0.11
Mn	3.95	8.69	Mn	1.38	3.04
P	0.53	1.16	P	0.10	0.22
S	0.09	0.19	S	0.10	0.22
BF slag	5.40	11.88			
Total	877.64	1930.8	Total	1000.0	2200.0
Scrap	kg	lb.	Slag		
Fe	200.53	441.16	CaO	47.92	105.42
C	0.18	0.40	SiO_2	12.01	26.42
Si	0.04	0.09	MgO	6.35	13.97
Mn	0.72	1.60	FeO_T	26.42	58.12
P	0.02	0.05	MnO	5.00	11.01
S	0.05	0.11	P_2O_5	1.13	2.49
Total	201.55	443.41	Al_2O_3	1.3	2.86
Ore	kg	lb.	Total	100.13	220.29
Fe	11.52	25.35	Fumes	kg	lb.
SiO_2	0.130	0.285	Fe	16.02	35.24
MnO	0.034	0.075	Total	27.52	60.61
Other	5.134	11.294			
Total	16.818	37.0			
Fluxes	kg	lb.	Gases:	kg	lb.
CaO	47.92	105.42	CO (90%)	85.26	187.57
MgO	6.35	13.97	CO_2 (10%)	14.89	32.75
SiO_2	0.53	1.17			
Other	1.65	3.62			
Total Burnt lime	40.78	89.70			
Total Dolo-lime	15.67	34.48			
Oxygen Gas	kg	lb.			
	52.8 Nm^3	1849.7 scf			
	@298K	@70°F			
Total O_2	75.34	165.75			
Total Inputs	1227.8	2701.2	Total Outputs	1227.8	2701.2

9.4.3.2 Determination of Oxygen Requirements

The volume of oxygen gas blown into the converter must be sufficient to oxidize the C, Si, Mn, and P during the blow, and it is computed from an oxygen balance as shown below. For the present

example the oxygen required during the blow is about 52.8 Nm³ (1849.7 scf) per metric ton of steel produced.

$$\left[\text{Oxygen} \right]_{\text{injected}} = \left[\text{Oxygen for the} \right]_{\text{oxidation reactions}} - \left[\text{Oxygen supplied} \right]_{\text{by iron ore}} - \left[\text{Oxygen dissolved} \right]_{\text{in steel at turndown}} \quad (9.4.3)$$

9.4.3.3 Determination of the Weight of Iron-Bearing Materials

In general four distinct iron-bearing materials are involved in oxygen steelmaking: hot metal, scrap, iron ore, and the steel product. Slag and fume are usually considered heat and iron losses. The simultaneous solution of an iron mass balance and an energy balance permits the determination of the weights of two of the iron-bearing materials with a knowledge of the weights of the other two. For the example here, the product weight (1000 kg), and the weight of the iron ore (16.8 kg) are assumed to be known. Then the weights of the hot metal and scrap are computed to be 877.64 kg (1930.8 lb.) and 201.55 kg (443.41 lb.) respectively from the mass and energy balance shown below:

Mass balance for iron: (IRON INPUT = IRON OUTPUT)

$$\text{IRON INPUT} = \left[\text{Weight of Fe} \right]_{\text{in Hot Metal}} + \left[\text{Weight of Fe} \right]_{\text{in Scrap}} + \left[\text{Weight of Fe} \right]_{\text{in Iron Ore}} \quad (9.4.4)$$

$$\text{IRON OUTPUT} = \left[\text{Weight of Fe} \right]_{\text{in Steel}} + \left[\text{Weight of Fe} \right]_{\text{in Slag}} + \left[\text{Weight of Fe} \right]_{\text{in Fumes}}$$

Heat balance: (HEAT INPUT = HEAT OUTPUT)

$$\text{HEAT INPUT} = \left[\text{Heat content in} \right]_{\text{the Hot Metal}} + \left[\text{Heats of} \right]_{\text{reaction}} + \left[\text{Heat of slag} \right]_{\text{formation}} \quad (9.4.5)$$

$$\text{HEAT OUTPUT} = \left[\text{Sensible heat} \right]_{\text{of steel}} + \left[\text{Sensible heat} \right]_{\text{of slag}} + \left[\text{Sensible heat in} \right]_{\text{gas and fume}} + \left[\text{Heat} \right]_{\text{losses}}$$

The heat added to the process comes from the heat content or enthalpy in the hot metal charged into the furnace at about 1343°C (2450°F), the heats of oxidation of elements, such as Fe, C, Si, Mn, P, and S, whose enthalpies are shown in Table 9.9, and the heats of formation of the different compounds in the slag.

Table 9.9. Enthalpies or Heats of Reactions *From Ref. 1.*

Oxidation Reactions	Kilojoule	Heats of Reaction		
		per mole of	BTU	per lb. of
$\text{C} + \frac{1}{2}\text{O}_2 = \text{CO}$	4173	C	3952	C
$\text{C} + \text{O}_2 = \text{CO}_2$	14884	C	14096	C
$\text{CO} + \frac{1}{2}\text{O}_2 = \text{CO}_2$	4593	CO	4350	CO
$\text{Si} + \text{O}_2 = \text{SiO}_2$	13927	Si	13190	Si
$\text{Fe} + \frac{1}{2}\text{O}_2 = \text{FeO}$	2198	Fe	2082	Fe
$\text{Mn} + \frac{1}{2}\text{O}_2 = \text{MnO}$	3326	Mn	3150	Mn

These sources will provide the heat necessary to raise temperature of the steel and slag to the aim turndown temperature, and also to heat up the gases and fumes leaving the furnace. Furthermore, there is enough energy generated to overcome the heat losses during the process, to heat and melt coolants such as scrap and iron ore, and to reduce the iron oxide in the ore.

9.4.3.4 Determination of the Gases and Fumes Produced

The amounts of CO and CO₂ produced from decarburization are determined from a mass balance for carbon. The carbon removed from the bath is converted to approximately 90% CO and 10% CO₂. With the gases about 1 to 1.5 wt.% of iron is lost in the form of iron oxide fumes that exit from the mouth of the furnace.

9.4.3.5 Determination of the FeO in the Slag

The FeO in the slag is generally determined from empirical correlations, developed by each shop, between the slag FeO and the aim carbon and the lime to silica ratio. Other parameters are generally of much lower significance. This empirical relationship is one of the larger error sources in a material and energy balance algorithm, arising from analytical errors of iron oxides and slag sample preparation problems.

9.4.4 Tapping Practices and Ladle Additions

When the blow is completed, the lance is removed from the furnace and the vessel is rotated to a horizontal position towards the charging side for sampling. A steel sample is withdrawn from the bath for chemical analysis, and an expendable immersion-type thermocouple is used to measure the temperature of the melt. The steel sample is analyzed with a mass spectrometer, and the concentrations of the elements present in the steel are determined in approximately three to five minutes. If the steel is too hot, meaning that the measured temperature is higher than the aim temperature, it can be cooled by rocking the vessel, or by adding coolants such as iron ore or limestone. If the steel is too cold, or if the measured concentrations of elements such as carbon, phosphorus, and sulfur are higher than the aim concentrations specified, additional oxygen is blown into the furnace (reblow) for approximately one to three minutes. Once the heat meets the temperature and chemistry requirements, the furnace is rotated towards the taphole side and the steel is tapped or poured into a ladle.

Tapping a 300 ton heat takes from four to seven minutes and the time strongly depends on the conditions or diameter of the taphole. A good tapping practice is necessary to maximize yield, or the amount of steel poured into the ladle. Slag carryover from the BOF into the ladle must be minimized. Furnace slag contains high FeO, which reduces desulfurization in the ladle, and enhances the formation of alumina inclusions. Also, the P₂O₅ present in BOF slags is a source of phosphorus carried into the ladle. Therefore, over the years, extensive work has been done to develop slag free tapping techniques, and the most commonly used are described here. Good tap hole maintenance, combined with the ability of the operator to rotate the furnace quick enough when all the steel has been tapped, will reduce the amount of slag carryover into the ladle. Slag free tapping devices are now commonly used to help the operators reduce slag carryover. Different types of taphole plugs, such as balls and darts, (discussed earlier in section 9.2.2.12) shown in Fig. 9.11, are dropped into the furnace at tap. These Devices float at the slag-metal interface, and plug the taphole when the steel has emptied but before the slag can exit the furnace. There has been much debate over the effectiveness of these devices. Electromagnetic slag detection sensors installed around the taphole will detect the presence of slag in the stream and send a signal to alarm the furnace operator. One of the problems with these devices is that they can give false alarms from slag entrainment within the vortex of the steel stream and they require maintaining a taper in the taphole to work well.

With current steelmaking alloying practices, most of the alloys are added to the ladle. However, large amounts of non-oxidizable alloys such as nickel, molybdenum and copper are usually charged with the scrap as they resist oxidation during the blow. This practice will prevent big temperature

drops in the ladle. In aluminum killed steels aluminum (Al) is used to deoxidize the steel and reduce the dissolved oxygen from approximately 500–1000 ppm to less than 5 ppm, and is generally the first addition made into the ladle during tap. For example, a heat with a Celox reading of 750 ppm of dissolved oxygen requires approximately 365 kg (800 lb.) of aluminum at tap. In semi-killed steels, deoxidation is done with ferrosilicon, and the dissolved oxygen in steel is only lowered to about 50 ppm. Burnt lime is also added with the aluminum to satisfy a lime to alumina ($\text{CaO}/\text{Al}_2\text{O}_3$) ratio of 0.8 to 1.2. This produces a liquid slag over the molten metal that thermally insulates the melt to avoid excess temperature losses, protects the melt from reoxidation from air, desulfurizes the steel, and removes alumina inclusions from the melt.

Ferromanganese is added via chutes located over the ladle, in large quantities, after the steel has been deoxidized by aluminum or silicon. The general rule of thumb is that the aluminum is added when the melt reaches approximately 1/3 of the ladle's height, and all the alloys should be added by the time the melt reaches 2/3 of the full ladle height. Slag modifiers, containing about 50 wt.% aluminum, are added to the slag near the end of tap to reduce the FeO content in the ladle slag originating from furnace slag carryover. Chapter 11 contains a detailed discussion of the refining processes occurring in the ladle after steelmaking.

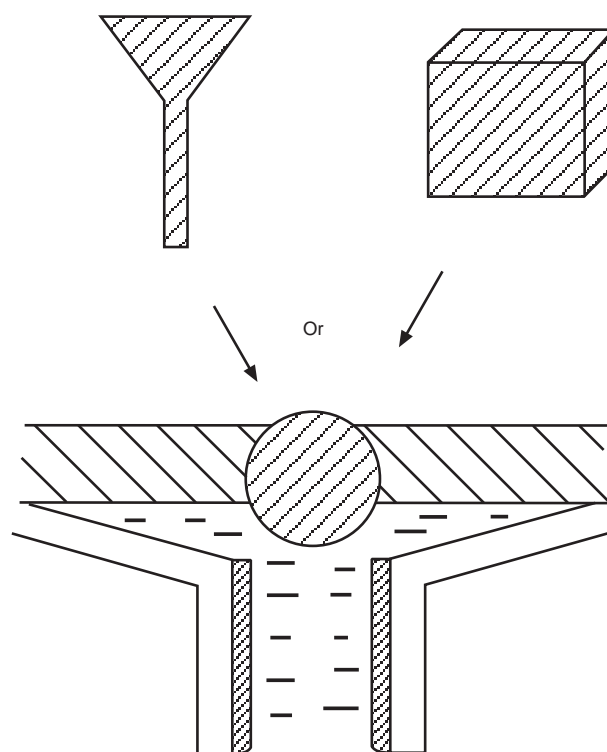


Fig. 9.11 Schematic of taphole plugs for BOF steelmaking. From Ref. 21.

9.5 Process Variations

9.5.1 The Bottom-Blown Oxygen Steelmaking or OBM (Q-BOP) Process

The successful development and application of the shrouded oxygen tuyere in the late 1960s led to the development of the OBM (Q-BOP) process in the early 1970s. Oxygen in this process is injected into the bath through tuyeres inserted in the bottom of the furnace. Each tuyere is made from two concentric tubes forming an inner nozzle and an outer annulus. Oxygen and powdered lime are injected through the central portion of the tuyeres, while a hydrocarbon gas, typically natural gas or propane, is injected through the annular section between the two concentric pipes, as shown in Fig. 9.12. The endothermic decomposition of the hydrocarbon gas and the sensible heat required to bring the products of the decomposition up to steelmaking temperatures result in localized cooling at the tip of the tuyere. The localized cooling is enough to chill the liquid metal and form a porous mushroom on the tip of the tuyere and part of the surrounding refractory. This mushroom reduces the burn back rate of the tuyere, and the wear of the surrounding refractory. The injected lime provides additional cooling to the tuyere, and results in better slag refining characteristics.

Top lances in OBM (Q-BOP) furnaces have also been adopted, mainly for the purposes of increasing the post-combustion of the offgases within the furnace, and to control the buildup of slag and metal in the furnace cone area. Top lances used in OBM (Q-BOP) furnaces are normally stationary, since they are not used for refining purposes. Tuyeres, located in the upper cone area of furnaces with a heat size larger than approximately 150 tonnes have also been used, but typically

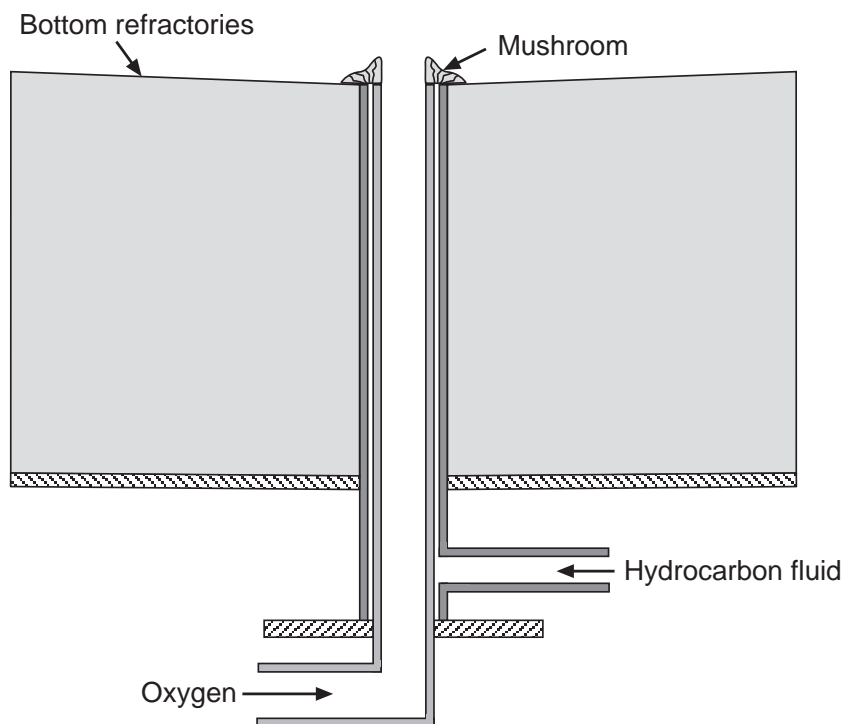


Fig. 9.12 Schematic drawing of an OBM (Q-BOP) tuyere.

result in higher refractory wear. For this reason, their application has been limited to shops which require increased scrap melting capabilities (resulting in shorter lining lives), and with a heat size smaller than 150 tonnes.

9.5.1.1 Plant Equipment

The injection of oxygen through the bottom in the OBM (Q-BOP) process, with a fraction of the total oxygen through a stationary top lance, results in the need for a low building, and consequently in lower greenfield construction costs.

Oxygen, a hydrocarbon fluid (natural gas or propane), nitrogen and argon are gases used in the OBM (Q-BOP) process. These gases are metered and controlled, and introduced through rotary joints located in the trunnion pins. The oxygen, aside from being used as the main process gas, is also used as the transport gas for the pulverized burnt lime. A high-pressure injector contains the burnt lime, which is transported by the oxygen through one of the trunnion pins into a lime and oxygen distributor, and then to the individual tuyeres in the furnace bottom. The hydrocarbon fluid is transported to the bottom of the furnace through the opposite trunnion, to avoid the possibility of leakage and of its mixing with oxygen in the transport line. The hydrocarbon fluid is then distributed to each tuyere. In some instances, the flow of the hydrocarbon fluid is controlled individually for each tuyere prior to entering the rotary joint. Nitrogen is used to protect the tuyeres from plugging during furnace rotation. It can also be used to increase the nitrogen content in the steel. Argon can be used to minimize the nitrogen pickup in the steel, and to produce lower carbon steels than in the BOF process, without excessive yield losses, and with low FeO contents in the slag.

Gas flow through the tuyeres has to be maintained above sonic flow to prevent penetration of steel into the tuyeres, and subsequent plugging. For this reason, the sonic flow is maintained during rotation of the furnace for turndown and for tapping of the steel. The ejections of metal and slag resulting from the injection of this high flow through the tuyeres during rotation, require the complete enclosure of the OBM (Q-BOP) furnaces. Movable doors are used in the charge side for this purpose. The complete enclosure also results in lower fugitive emissions during turndown and tapping than in the BOF furnaces, which usually are not enclosed.

Typically 12 to 18 tuyeres are used in the bottom, depending on the furnace capacity. The tuyeres are located in the refractory bottom on two rows that run from one trunnion to the other. The locations of these two rows are selected so that they are above the slag line during turndown and tapping to allow the reduction of the gas flow during these periods. The inside of the inner pipe of the tuyere is typically lined with a mullite sleeve to prevent excessive wear of the pipe by the burnt lime. The inside diameter of the ceramic liner is 1 to 1.5 inches. Stainless steel is normally used for the inner pipe, and carbon steel for the outer pipe, although copper has also been used.

The higher refractory wear observed in the vicinity of the tuyeres, due to the high temperature gradients experienced by the refractories during a heat cycle and the high temperature generated around them, results in bottom lives of 800 to 2500 heats, depending on tap temperature, turndown carbon content, etc. Since barrel lives approach 4000 to 6000 heats, the furnace is designed to include a replaceable bottom. When the bottom thickness is too thin for safe operation, it is removed and a bottom with new refractories and tuyeres is installed. The furnace can be back in operation with a new bottom in less than 24 hours.

9.5.1.2 Raw Materials

A distinct advantage of the OBM (Q-BOP) process is its capability to melt bigger and thicker pieces of scrap than the BOF process. Sections with thicknesses of up to two feet are melted routinely. This expands significantly the types of scrap that can be used, and lowers their preparation costs. There is no unmelted scrap at the end of the blow in the OBM (Q-BOP) process.

The burnt lime used for slag formation is pulverized and screened to less than 0.1 millimeters. It is sometimes treated to improve its flowability during pneumatic transport with oxygen. The dolomitic lime in the OBM (Q-BOP) process is essentially similar to that used in the BOF process, and is charged through top bins, if available. In shops where overhead bins are not available, a pulverized blend of burnt lime and dolomitic lime is injected through the bottom tuyeres to achieve the desired MgO content in the slag. The rest of the raw materials are the same as for the BOF process.

9.5.1.3 Sequence of Operations

After the steel is tapped, the furnace is rotated to the vertical position, and nitrogen is blown to splash the slag onto the furnace walls. This results in a coating that extends the life of the furnace barrel. The furnace is also rocked to coat the bottom with slag. This operation can be done with the slag as is, or with conditioned slag. The furnace is then ready to receive the scrap and hot metal. Nitrogen is injected at sonic flow to protect the tuyeres during the hot metal charge. The furnace is rotated to its vertical position, and the bottom and top oxygen blow are started. Burnt lime is injected with the oxygen through the bottom, and the dolomitic lime is added through the top at the beginning of the blow. Typically the lime is injected within the first half of the oxygen blow. When the calculated oxygen amount has been injected, the gas is switched to nitrogen or argon and the furnace is rotated for sampling. A sample for chemical analysis is taken, and the temperature and oxygen activity are measured. If the desired temperature and chemistry have been obtained, the heat can then be tapped. If necessary, small adjustments in temperature and chemistry can be made by injecting additional oxygen through the bottom, by injecting more lime, or by cooling the heat with ore or raw dolomite. Since the process is very reproducible, the heat is normally tapped after these adjustments, without making another temperature measurement or taking another sample for chemical analysis. Shops so equipped can take a sample for chemical analysis, temperature and carbon content measurement with sub lances a few minutes before the end of the oxygen blow. Any necessary adjustments can be made during the blow to obtain the aim steel temperature and chemistry. The turndown step can thus be avoided, decreasing the tap-to-tap time, and increasing the productivity of the shop.

9.5.1.4 Process Characteristics

The injection of the oxygen and hydrocarbons through bottom tuyeres results in distinct process characteristics. The oxygen reacts directly with the carbon and silicon in the liquid iron melt, resulting in

lower oxidation levels in the metal and slag at the end of the blow. The bottom injection also results in very strong bath mixing. Steel decarburization is enhanced by the strong bath agitation, particularly during the last portion of the blow, when mass transfer of the carbon in the melt controls the rate of decarburization at carbon contents below 0.3%. This results in less iron being oxidized and lost to the slag, as shown in Fig. 9.13, and in less dissolved oxygen in the steel at turndown, as shown in Fig. 9.14. The manganese content at turndown is also higher than in the top-blown vessels, as shown in Fig. 9.15, due to the lower bath and slag oxidation. The variability in blow behavior introduced by the top lance in top-blown vessels is eliminated. By injecting the oxygen and lime through the bottom tuyeres in a controlled manner, a highly reproducible process control is obtained.

9.5.1.5 Product Characteristics

In general, the same steel grades that can be produced in top-blown vessels can be produced by the OBM (Q-BOP). Additionally, the better mixing attained in the bath allows the production of steels with carbon contents of 0.015–0.020% without excessive bath and slag oxidation and without vacuum decarburization. The slightly higher hydrogen contents obtained at turndown can be lowered by flushing the bath with nitrogen, argon, or a mixture of argon and oxygen at the end of the blow. For the production of low-nitrogen steels, argon can be used to minimize the nitrogen pickup during rotation, or by flushing the bath at the end of the blow. Nitrogen can also be alloyed into the steel by purging the melt with nitrogen at the end of the oxygen blow.

9.5.2 Mixed-Blowing Processes

Virtually every company has invented or modified a version of the oxygen steelmaking process to suit its own situation. Consequently, there are many designations for fairly similar processes. Table 9.10 attempts to translate and relate some of the more common acronyms. This table is divided into four broad categories: top blowing, mixed blowing with inert gases, mixed blowing with bottom oxygen, and bottom blowing.

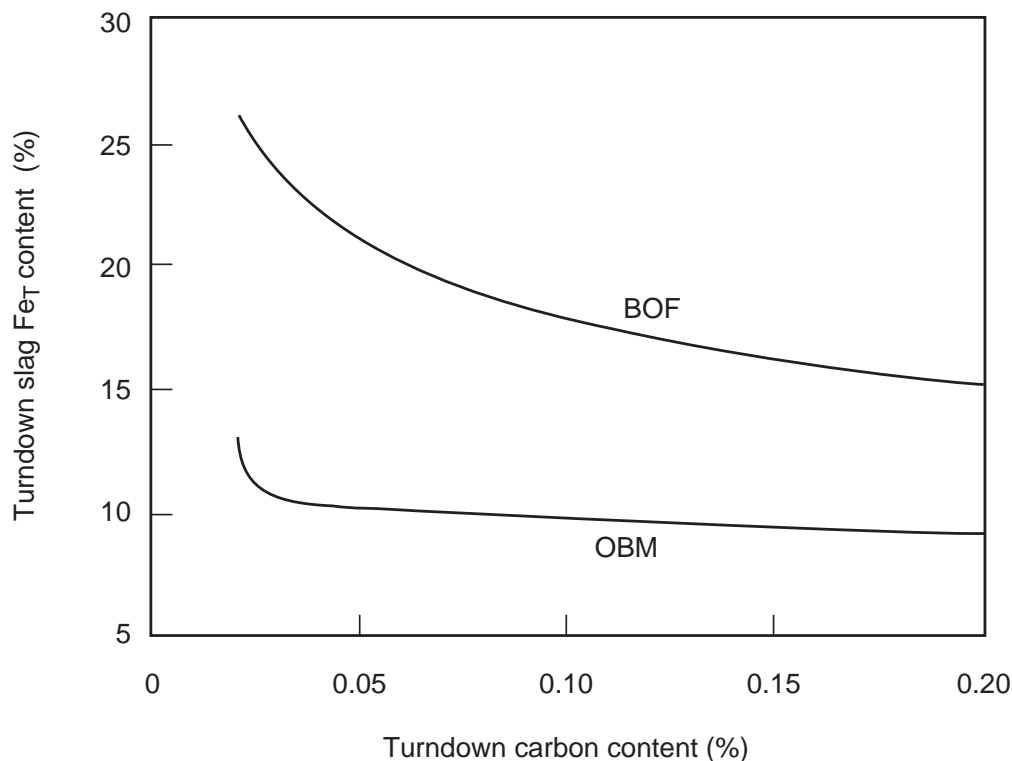


Fig. 9.13 Slag Fe_T content as a function of the carbon content at turndown in the U.S. Steel Gary Works BOF and OBM (Q-BOP) shops.

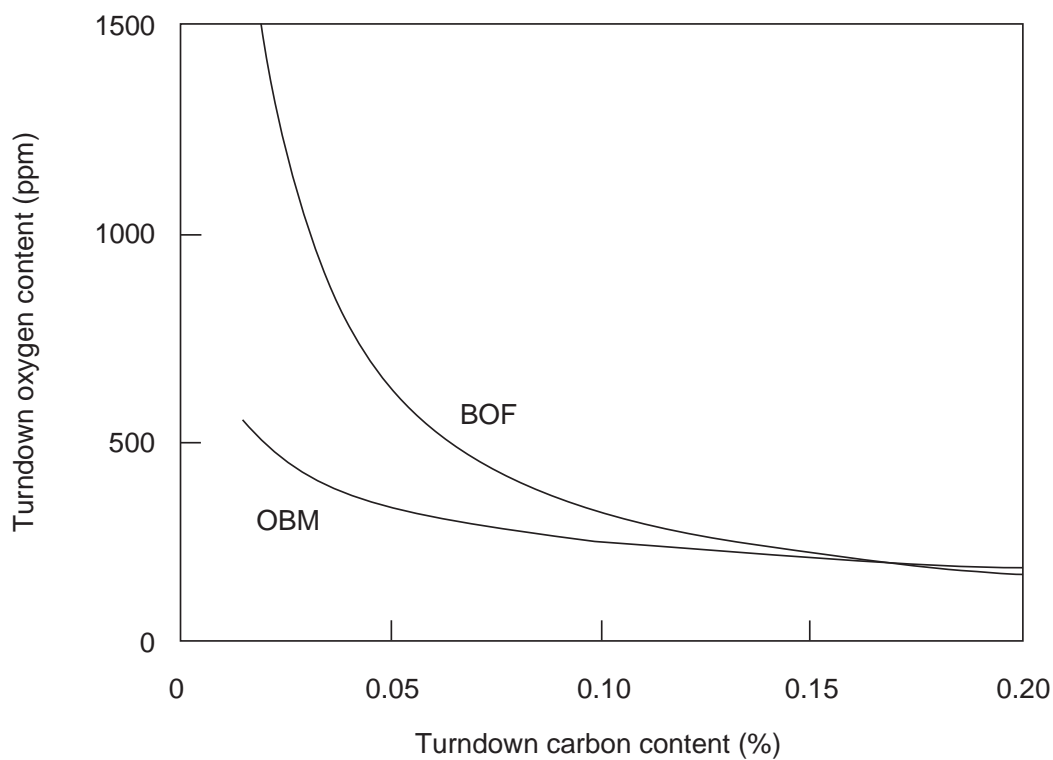


Fig. 9.14 Dissolved oxygen content as a function of carbon content at turndown in the U.S. Steel Gary Works BOF and OBM (Q-BOP) shops.

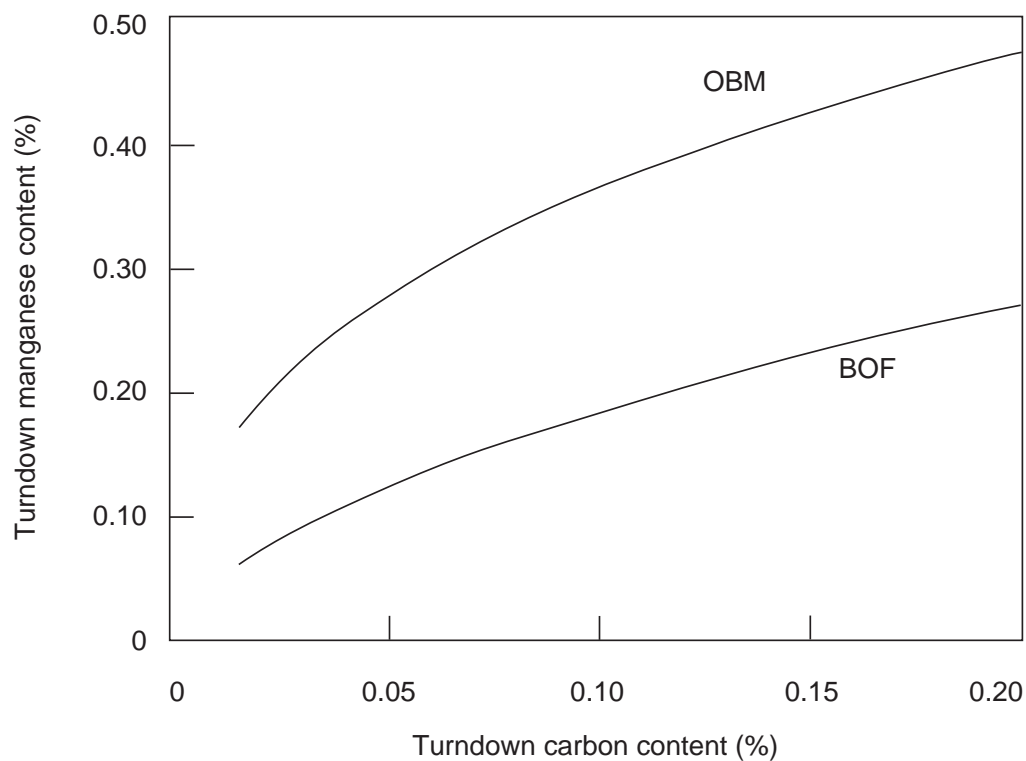


Fig. 9.15 Manganese content in the steel as a function of carbon content at turndown in the U.S. Steel Gary Works BOF and OBM (Q-Bop) Shops.

Table 9.10 Various Oxygen Steelmaking Process Designations
From Ref. 8, updated from Refs. 31–36.

Process Name	Origin	Description
Obsolete bottom-blown processes that preceded modern furnace configurations:		
Bessemer Converter		An early bottom-blown converter developed by Henry Bessemer in 19th Century England, blowing air through simple tuyeres using acid refractories.
Thomas Converter		Similar to bessemer but using basic refractories in US.
All Top Blowing:		
LD	Voest, Austria	Linz-Donawitz. First top-blown process with water-cooled lance, lump lime.
BOF	Worldwide	Basic Oxygen Furnace. Common term for LD top lance-blown, lump lime.
BOP	USX and others	Basic Oxygen Process. Same as LD and BOF
LD-AC	ARBED/CRM Luxembourg; France	Similar to LD with powdered lime added through lance, for high P hot metal.
LD-CL	NKK, Japan	LD but lance rotates.
LD-PJ	Italsider	LD with pulsed jets, not in current use.
ALCI	ARBED, Luxembourg	LD basically with Ar/N ₂ through lance. Post combustion ports and coal injection from top for higher scrap melting.
LD-GTL	Linde/National Steel, USA	LD with Ar or N ₂ through top lance to limit over-oxidation, lump lime.
AOB	Inland, Union Carbide	Similar to LD-GTL.
Z-BOP	ZapSib Russia	Basically LD or BOF. Various process methods of adding additional fuels to increase scrap melting. Some include preheat cycles. Can melt 100% scrap.
Mixed Blowing, Inert Stirring Gases:		
LBE	ARBED, Luxembourg IRSID, France	Lance Bubbling Equilibrium. LD with permeable plugs on bottom for inert gas. Lump lime.
LD-KG	Kawasaki, Japan	LD with small bottom tuyeres Ar and/or N ₂ .
LD-KGC	Kawasaki, Japan	LD with number of small nozzles using Ar, N ₂ CO for inert gas bottom stirring. Unique in that it uses recycled CO as a stirring gas. Lump lime.
LD-OTB	Kobe, Japan	Similar to LD-KG
LD-AB	Nippon Steel, Japan	LD with simple tuyeres to inject inert gas. Lump lime
NK-CB	NKK, Japan	Top-blown LD with simple bottom tuyere or porous plugs to introduce Ar/CO ₂ /N ₂ , lump lime

continued

Table 9.10 Various Oxygen Steelmaking Process Designations (*continued*)
Mixed Blowing with Oxygen and/or Inert Bottom Gases:

OBM-S	Maxhutte, Germany Klockner, Germany	Mostly bottom OBM type with top oxygen through natural gas shrouded side tuyere, powdered lime through bottom.
K-BOP	Kawasaki Japan	Top and bottom blowing. Natural gas shrouded bottom tuyeres, powdered lime through tuyeres.
TBM	Thyssen, Germany	Top and bottom stirring with bottom nozzles and N ₂ /Ar.
LET	Solmer, France	Lance Equilibrium Tuyeres. Top blowing with 15 to 35% bottom-blown with fuel oil shrouded tuyeres.
LD-OB	Nippon Steel, Japan	OBM tuyeres (natural gas shrouded) on bottom with top lance, lump lime.
STB	Sumitomo, Japan	Mostly top-blown with lance, with special tuyere on bottom. Inner pipe O ₂ /CO ₂ , Outer pipe CO ₂ /N ₂ /Ar. Lump lime.
STB-P	Sumitomo, Japan	Similar to STB except powdered lime through top lance for phosphorus control.

All Bottom Blowing:

OBM	Maxhutte, Germany	Original 100% bottom-blown. Natural gas shrouded tuyeres, powdered lime through tuyeres
Q-BOP	USX, USA	OBM type 100% bottom-blown. Natural gas shrouded tuyeres, powdered lime through tuyeres.
KMS	Klockner, Germany	Similar to OBM. Early trials of oil shrouded tuyeres, now use natural gas. Can inject powdered coal from bottom for more scrap melting.
KS	Klockner, Germany	Similar to KMS only modified for 100% scrap melting.

(Note: **Bold** lettered processes are still in regular use today.)

The BOF is the overwhelmingly popular process selection for oxygen steelmaking. The usual reason to modify the BOF configuration is to lower the operating cost through better stirring action in the steel bath. It has been found by a number of companies and investigators that additional stirring of the bath from the furnace bottom reduces FeO in the slag. Lower FeO results in higher yield, and fewer oxidation losses of metalics. Bottom stirring increases slag forming, particularly if powdered limes are injected into the bath.

9.5.2.1 Bottom Stirring Practices

Inhomogenities in chemical composition and temperature are created in the melt during the oxygen blow in the top-blown BOF²⁵ process due to lack of proper mixing in the metal bath. There is a relatively dead zone directly underneath the jet cavity in the BOF.

Bottom stirring practices using inert gases such as nitrogen and argon are being used extensively to improve the mixing conditions in the BOF. The inert gases are introduced at the bottom of the furnace by means of permeable elements (LBE process) or tuyeres. In a typical practice, nitrogen gas is introduced through tuyeres or permeable elements in the first 60 to 80% of the oxygen blow, and argon gas is switched on in the last 40 to 20% of the blow. The rapid evolution of CO in the first part of the oxygen blow prevents nitrogen pickup in the steel.

Some of the effects of bottom stirring and the resulting improved mixing include:

- (a) *Decreased FeO content in slag.* Better mixing conditions in the vessel causes the FeO in the slag to be closer to equilibrium conditions, which results in lower concentrations of FeO in the slag. Plant studies have shown that for low carbon heats, bottom stirring can cause a reduction in the FeO level in slag by approximately 5%. This results in better metallic yield, lower FeO level in the ladle slag and reduced slag attack on the refractories. Improvements in iron yield by as much as 1.5% or more have been reported.²⁶ Lower levels of FeO in the steelmaking slag reduces the amount of heat generated during the oxygen blow, and hence reduces the maximum amount of scrap that can be charged in a heat.
- (b) *Reduced dissolved oxygen in metal.* A study shows that bottom stirring can reduce the dissolved oxygen level in a low carbon heat by approximately 225 ppm. This lowering of dissolved oxygen leads to lower aluminum consumption in the ladle. Studies have shown aluminum savings of about 0.3 lb./ton due to bottom stirring.
- (c) *Higher manganese content in the metal at turndown.* An increase of approximately 0.03% in the turndown manganese content of the metal has been shown. This leads to a reduction in the consumption of ferro-manganese.
- (d) *Sulfur and Phosphorus removal.* Bottom stirring has been found to enhance desulfurization due to improved stirring. However, phosphorus removal has not been found to improve substantially in some studies. Although bottom stirring drives the dephosphorization reaction towards equilibrium, the reduced levels of FeO in steel-making slags tend to decrease the equilibrium phosphorus partition ratio ($(\%P \text{ in slag})/[\%P \text{ in metal}]$).

9.5.2.2 Bottom Stirring Maintenance Problems

The price for the bottom stirring benefits is in maintaining a more complicated process. This complexity varies depending on the type of bottom stirring devices installed. Generally, the simpler the device is to maintain, the lesser is the benefit obtained.

Starting at the simple end, porous plugs or permeable elements do not require maintaining gas pressure when the stirring action is not required. While gas under pressure can permeate these devices, steel does not penetrate, even when the gas is turned off. The disadvantage of the porous plugs is that they are not very effective stirrers. Two factors influence their poor performance. First, only a relatively small amount of gas can be introduced per plug. More gas flow requires more plugs thus adding complexity. Secondly, if the furnace bottom tends to build up, the plugs are covered over with a lime/slag mush and gas does not stir the steel bath. Rather, it escapes between the bricks and the protective mush. Another problem is at higher flow rates, the originally installed plugs do not last very long (1500 to 3000 heats) and replacements are shorter lived (200 to 2000 heats). The reasons for the shorter replacement plug life is not clear.

The use of the bottom stirring tuyeres (rather than plugs) can lead to stirring reliability and effectiveness problems. The tuyeres are known to get blocked early in the lining campaign when there is a buildup at the bottom of the furnace. The tuyere blockage can be prevented by maintaining proper gas flow rates through the tuyeres at different stages of the heat, by using high quality refractory bricks in the area surrounding the stirring elements or tuyeres, and by properly maintaining the bottom of the furnace by minimizing buildup.

9.5.2.3 Bottom Plug/Nozzle Configurations

There are basically three types of tuyeres used for mixed blowing. First, there is a refractory element that behaves much like porous plugs. This unit is made of compacted bricks with small slits. Like most tuyeres, it needs sufficient gas pressure to prevent steel penetration. This unit is more penetrating than porous plugs. Second, an uncooled tuyere is used to introduce large amounts of inert gases per nozzle. This results in local heavy stirring, which can more easily penetrate the buildup. Air or oxygen cannot be used because there is no coolant and the heat generated would make tuyere life too short to be practical. The third type is a fully cooled tuyere similar to the OBM (Q-BOP). Here, either inert gas or oxygen can be blown, causing very strong stirring and almost no problems penetrating bottom buildup.

In all cases the gas piping is routed through the furnace trunnions using rotary joints or seals to allow full rotation of the furnace.

9.5.3 Oxygen Steelmaking Practice Variations

9.5.3.1 Post-Combustion Lance Practices

Post combustion involves burning the CO gas produced by the reaction of carbon in the metal with jet oxygen, to CO₂ within the furnace. The heat generated as a result of this oxidation reaction can be used for any of the following purposes: (1) to increase the scrap-to-hot metal ratio, (2) to minimize the formation of skulls formed at the mouth of the vessel, (3) to minimize the formation of lance skulls and (4) to reduce the formation of “kidney” skulls in the upper cone region inside the BOF.

In a normal BOF operation, the percentage of CO in the off gas is approximately 80 to 90% during the middle portion of the blow, when the rate of decarburization is maximum, Fig. 9.16.²⁷ The oxidation of the CO gas to CO₂ generates 12 Mcal per Nm³ CO (1260 BTU per scf CO)), which can melt more scrap and/or reduce skulling problems.

Post combustion lances have primary nozzles as well as secondary nozzles which typically are located at about nine feet from the tip of the lance, Fig. 9.17. The primary nozzles in PC lances are identical to those of the standard lances. They consist of four or five nozzles at the tip of the lance with inclination angles varying from 10 to 14 degrees. Usually, there are eight secondary nozzles above the primary ones, directed out, at an angle of about 35 degrees from the vertical. The oxygen flow rate through the secondary nozzles is considerably less than through the primary ones, usually 1.5 to 15% of the total oxygen flow.

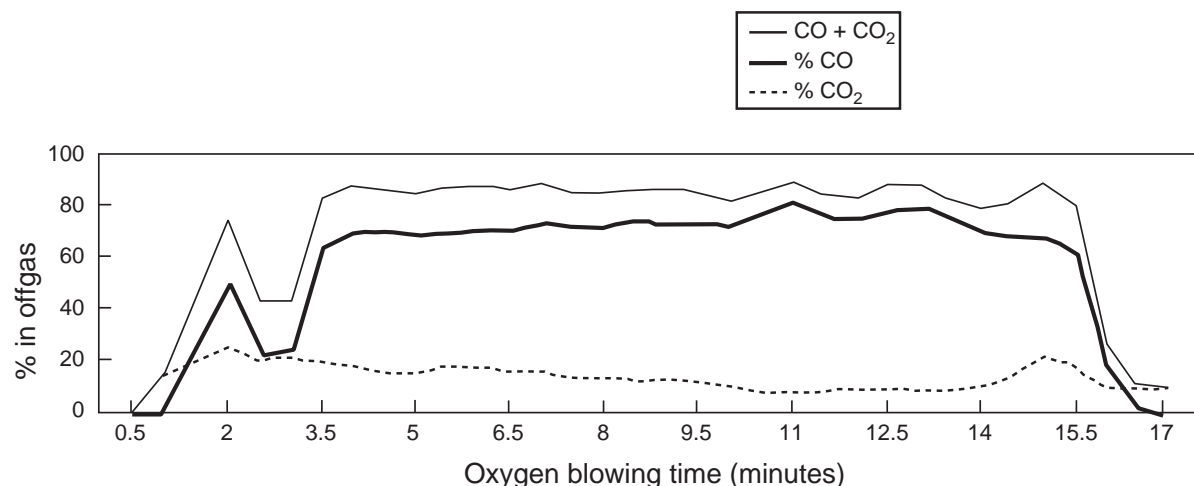


Fig. 9.16 The percentage of CO and CO₂ gases in the BOF offgas. From Ref. 27.

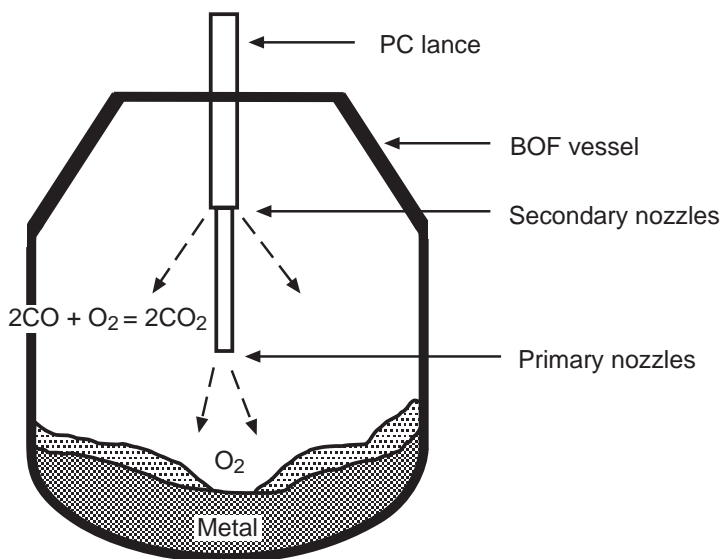


Fig. 9.17 Schematic of a post combustion lance in a top-blown BOF.

Studies show that post combustion has been successfully used to melt additional scrap in the BOF (achieving scrap-to-hot metal ratios of 25% or more), and to reduce lance and furnace mouth skulling problems. It has been found to increase the turn-down temperature, if additional scrap or coolant is not added, to compensate for the extra heat generated. No effect on slag FeO^{28} and turndown manganese in metal has been found. There has been no effect on refractories when post-combustion is used at low flow rates in the skull control mode. However, if post-combustion is used in high flow, scrap melting mode, some care in design and operating parameters must be observed to avoid damaging the cone.

9.5.3.2 High Scrap Melting Practices

The ability to vary the scrap-to-hot metal ratio in a BOF is important because of the variations in scrap prices and the possibility of having hot metal shortages from time to time due to problems in the blast furnace. Several shops add anthracite coal early in the oxygen blow as an additional fuel to melt more of scrap. Such processes can be used in conjunction with post combustion lances.

A recent example of the scrap stretch is a series of steelmaking processes called Z-BOP that were developed in Russia to melt higher scrap charge.^{29,30} These processes include Z-BOP-30, Z-BOP-50, Z-BOP-75 and Z-BOP-100, where the numbers indicate the percentage of scrap charge in the BOP. The Z-BOP-100 process utilizes 100% scrap charge with no hot metal, using the conventional BOP with virtually no equipment modifications.

In the Z-BOP processes, the additional energy required to melt scrap comes from lump coal (anthracite and high volatile bituminous), which can be fed using a bin system. In the Z-BOP-100 process, the first batch of scrap is fed into the furnace using a scrap box, and coal is added in small batches while blowing oxygen. This process continues with additional scrap being charged. The number of scrap boxes charged can vary from three to five. The main blow commences when all the scrap is charged in the furnace, and small additions of coal are made throughout the main blow.

The typical tap-to-tap time for the Z-BOP-100 process is 64 to 72 minutes. No one has used these high scrap percent processes on a sustained basis because of damage to the furnace linings. Typical iron yield of the Z-BOP 100 process is about 80%, (91–92% is normal for the BOF) and the slag FeO content is very high (45 to 72%; normal for the BOF is approximately 25%). The sulfur content of tapped steel was not found to be higher than that of the scrap itself.

The major disadvantages of this process include decreased yield, increased slag FeO which can adversely affect the refractory lining, presence of tramp elements similar to EAF, and presence of fugitive emissions (SO_2 and NO_x). This process may be used during hot metal shortages, but is not proven for continuous use. Some shops have used a 70% or 80% scrap charge to accommodate a blast furnace reline and stretch a limited amount of hot metal from the remaining blast furnace(s).

9.5.3.3 Slag Splashing Refractory Maintenance

Any improvement in the furnace lining life is a boon for steelmakers due to the increased furnace availability and reduced refractory costs. Slag splashing is a technology which uses high pressure

nitrogen through the oxygen lance after tapping the heat, and splashes the remaining slag onto the refractory lining, Fig. 9.18. The slag coating thus formed cools and solidifies on the existing refractory, and serves as the consumable refractory coating in the next heat.

Slag splashing is currently being used by several BOF shops, and has extended refractory lining life to record levels. A typical slag splash operation following the tapping of a heat is as follows:

1. The melter observes the slag, and determines whether any conditioning material such as limestone, dolomite or coal must be added. High FeO levels in the slag (estimated by a simple correlation with turn-down carbon and manganese values) are undesirable, and these slags are either not splashed or are treated with conditioners to make them more viscous.
2. The vessel is rocked back and forth to coat the charge and tap pads. The furnace is then uprighted.
3. The nitrogen blow is started when the oxygen lance is lowered in the furnace to a predetermined height. The positioning of the lance and the duration of the nitrogen blow are determined by the melter, and depend on the condition of the slag and the area of the furnace that has to be coated.
4. At the end of the nitrogen blow, the furnace is tilted and excess slag is dumped into the slag pot.

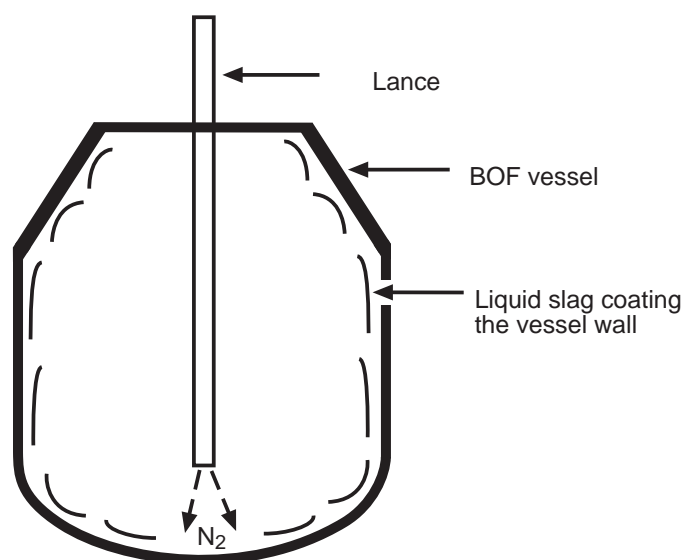


Fig. 9.18 Schematic of slag splashing in the BOF.

Not only has slag splashing been successful in increasing the furnace lining life, but it has also significantly reduced the gunning costs. One major company has reported a reduction in gunning cost by 66%, and an increase in furnace availability from 78 to 97%. No detrimental effects on the turn-down performance (chemical and thermal accuracy) of the furnace have been found.

Slag splashing has reduced the frequency of furnace relines considerably. This creates a problem in maintaining hoods, which is normally done during long furnace reline periods. Now, planned outages are needed for hood maintenance without any work on the furnace lining.

9.5.3.4 Effects of Desulfurized vs. Non-Desulfurized Hot Metal

Generally, heats that are made for sulfur sensitive grades of steel (0.010% or lower) must be desulfurized. Grades that do not have stringent sulfur specifications (approximately 0.018%) may not require hot metal desulfurization. The high sulfur content of the hot metal (approximately 0.06%) has to be reduced to acceptable levels in the hot metal desulfurizer, the BOF and/or in the ladle. The hot metal desulfurizing station can reduce the sulfur levels in the hot metal to as low as 0.001% through injection of lime and magnesium.

The BOF is not a very good desulfurizer because of the oxidizing conditions in the furnace. Heats using non-desulfurized hot metal can be desulfurized to approximately 0.012% sulfur in the BOF. However, heats using desulfurized hot metal may pick up sulfur if the slag in the desulfurizer was not skimmed properly or if a high sulfur scrap was used.

Some shops desulfurize virtually 100% of the hot metal to enable the blast furnace to run with a lower flux charge. This practice also reduces the heat burden on the blast furnace and saves coke. The net effect is a reduction in hot metal costs that is larger than the expense of desulfurizing.

9.6 Process Control Strategies

9.6.1 Introduction

Process control is an important part of the oxygen steelmaking operation as the heat production times are affected by it. Several steelmaking process control strategies are available today, and steel plants use strategies depending on their facilities and needs. Process control schemes can be broadly divided into two categories: static and dynamic. Static models determine the amount of oxygen to be blown and the charge to the furnace, given the initial and final information about the heat, but yield no information about the process variables during the oxygen blow. Static models are basically like shooting for a hole-in-one on the golf course: there is no further control once the ball leaves the face of the club. Dynamic models, on the other hand, make adjustments during the oxygen blow based on certain in-blow measurements. The dynamic system is like a guided missile in a military situation; there is provision for in-flight correction for better accuracy to hit the target.

Lance height control is an important factor in any control scheme as it influences the path of the process reactions. Detailed descriptions of static and dynamic models currently in use by the steel industry, along with a brief discussion of lance height control, follow.

9.6.2 Static Models

A static charge model is normally a computer program in an on-site steelmaking process computer. Plants have static models that depend on the type of operation and product mix. The static charge model uses initial and final information about the heat (e.g. the amount of hot metal and scrap, the aim carbon and temperature) to calculate the amount of charge and the amount of oxygen required. The relevant information is collected in the process computer, and a static charge model calculation is performed at the beginning of the heat. The output from the model determines the amount of oxygen to be blown and the amount of fluxes to be added to attain the desired (aim) carbon and temperature for that heat.

Performance of the charge model depends on a number of factors: the accuracy of the model; the accuracy of the inputs (aims, weights, chemistry of charge ingredients) to the process computer; consistency in the quality of materials used and of practices; and conformance to the static charge model.

The objective of the static charge model is to have improved control of carbon, temperature, sulfur and phosphorus. An accurate control over these variables using the model will result in fewer reblows and steel bath cooling, which are time consuming and expensive. Improved control will also result in better iron yield, greater productivity, better refractory lining life and an overall lower cost of production. The OBM (Q-BOP) static charge model is essentially the same as the BOF model, except for slight modifications arising out of differences in slag chemistry and natural gas injection. Most of the static charge models have an OK-to-tap performance of approximately 50 to 80%.

There is one BOF shop in Europe that achieves over 90% OK-to-tap performance. It is a two-furnace LBE type shop with inert gas bottom stirring. They use only one furnace at a time while the other is being relined. Their success is attributable to discipline, attention to detail, pushing the one furnace very hard which results in consistent heat losses, almost zero furnace maintenance with resultant short lining lives, and well-developed computer models. Their resulting tap-to-tap times are very short and production rates are very high. There is no dynamic control system nor sensor sub-lance.

9.6.2.1 Fundamentals of the Static Charge Model

The charge model consists of a comprehensive heat and mass balance involving different chemical species that participate in the steelmaking reactions. The hot metal poured into the steelmaking

vessel typically contains 4.5%C, 0.5%Si, 0.5%Mn and 0.06%P, apart from other impurities. These elements, along with Fe, get oxidized during the blow to form gases and slag, and these reactions generate the heat required to run the steelmaking process.

The static model also contains information on the heat of oxidation of different elements, such as carbon and iron, as a function of the oxygen blow. This information, along with a comprehensive mass balance involving different chemical species, determines the amount of heat generated from the steelmaking reactions as a function of total oxygen blown.

The primary coolants used in oxygen steelmaking processes are scrap, iron ore (sintered or lump), DRI and limestone (or dolomitic stone). The heat generated from the oxidizing reactions must be balanced with the use of these coolants to achieve the temperature aim of the heat. The model determines the amount of hot metal and scrap to be charged in the furnace, depending on the size and the type of heat to be made.

The rate of decarburization as a function of oxygen (available from the lance as well as from the ore) must be known to determine the duration of the blow, so that the heat turns down at the desired carbon level. The model also computes slag basicities (normally in the range of two to five) for effective dephosphorization and desulfurization. The amount of silica in the slag is calculated from hot metal silicon, assuming that it gets oxidized entirely to silica. The amount of lime (CaO) to be added is calculated from the desired basicity and the amount of silica formed from oxidation.

The charge model also determines the amount of dolomitic lime (CaO–MgO) to be charged into the furnace from an estimate of the overall slag chemistry. It is important to saturate the steelmaking slag with MgO to protect the furnace refractory lining.

9.6.2.2 Operation of the Static Charge Model

Many different kinds of charge models exist. In one typical model, charge calculations are made in three separate steps at the beginning of a heat. In the first step, called the hot metal calculation, the steelmaking operator makes a charge calculation of the amount of hot metal and scrap needed for the heat, given the product size, and the aim carbon and temperature of the heat. The hot metal analysis may or may not be available at this time. If not, an estimate based on previous hot metal analysis is used.

Having fixed the hot metal and scrap weight, the operator runs the second part of the calculation, which is called the product calculation. For this, the hot metal analysis is required. The amount of fluxes to be added and the amount of oxygen to be blown are determined. This part of the calculation takes place before the start of the oxygen blow.

The third part, the oxygen trim calculation, takes place during the early stages of the oxygen blow and after the fluxes have been added to the furnace. In this step, the charge model utilizes the actual amounts of fluxes added to the furnace (which can be different from the calculated amounts), and provides the new trimmed value of total oxygen. This step is required to correct for any variations in the process due to weighing inaccuracies in the amount of flux charge.

9.6.3 Statistical and Neural Network Models

Over the last few years, a significant amount of attention has been given to statistical methods designed to improve the performance of the static charge model. The turn-down performance of the static model does not only depend on the accuracy of the mass and thermal balance of the steelmaking system, but also on the inherent variability of the process which arises out of a number of factors that cannot be accurately quantified. Steelmaking melters use the concept of bias adjustments to correct for unexplained inconsistencies in temperature or carbon performance. For example, if the melter finds a series of heats that were hot for unexplained reasons, he makes a temperature bias correction for the following heat, hoping that it will turn down close to the aim temperature. This bias correction, in effect, alters the aim temperature of the following heat for the purpose of charge calculation. The problem here is that different operators may react to a given situation differently and

therefore the manual adjustments lack consistency. In addition, many operators are tempted to tamper (make adjustments too frequently), thereby introducing another variable.

Statistical models, in effect, use the same concept of bias to make adjustments in the charge calculation for a heat but do so with better consistency. The model tracks the turn-down performance of heats, and by statistical means, determines the amount of unexplained deviations in the performance of carbon, temperature etc. The model, then instructs the charge model to make appropriate modifications in the inputs for charge calculation for the following heat, so that these unexplained deviations may be countered. Studies indicate that the statistical models have been successful in fine tuning the static models to some extent.

Neural network algorithms are also being developed and used to improve the turndown performance. In this technique, the dependent variables (such as turndown carbon and temperature) are linked to the independent variables of a heat (such as the amount of hot metal, scrap and ore) through a network scheme. The network may consist of a number of layers of nodes, connected to each other in a linear fashion. As the input signals enter the network, they are multiplied by certain weights at the nodes and the products are summed as these signals are transferred from one layer to the next. The weights are determined by training the neural network model based on available historical data. The outputs from the model are calculated by adding the product of the weights and the signals in the last layer of the model.³⁷

Researchers have obtained reasonable success in estimating process variables using neural network modeling.³⁸ However, the success of this technique depends on the quality and quantity of input signals that are fed into the model. In simple terms, the old computer proverb is still valid: “garbage in, garbage out.”

9.6.4 Dynamic Control Schemes

Several steelmaking shops are currently using dynamic control schemes in combination with static models to improve their turndown performance. Dynamic control models use in-blow measurements of variables such as carbon and temperature, which can be used in conjunction with a static charge model, to fine tune the oxygen blow. A few dynamic control schemes are discussed in the following sections.

9.6.4.1 Gas Monitoring Schemes

This scheme is based on a continuous carbon balance of the entire BOF system. A gas monitoring system, which normally consists of a mass spectrometer, continuously analyzes dust free offgas samples for CO and CO₂ and determines the amount of carbon that has been oxidized at any given stage of the blow. Given the amount of carbon present in the system at the beginning of the heat (calculated from hot metal and scrap), one can calculate the level of carbon in the metal dynamically during the oxygen blow.

Although this method has a sound theoretical basis,⁴⁰ it has not been very successful at the commercial level. One problem is that it is not possible to accurately determine the initial amount of carbon present in the hot metal and scrap. Even a small amount of error in determining this initial carbon content could result in serious process control problems.³⁹ Another problem is the difficulty in continuous and accurate determination of the amount of CO and CO₂ exiting the system as offgas. Often the volume of filtering apparatus and tubing and the time to analyze a sample causes a delay of more than 60 seconds before the result is displayed or available for control.

9.6.4.2 Optical and Laser Based Sensors

A few shops in North America have started using light sensors to dynamically estimate carbon levels in the low carbon heats. The light meter system continuously measures the intensity of light emitted from the mouth of the steelmaking vessel during the oxygen blow.⁴³ The system then correlates characteristics of the light intensity curve with the carbon content towards the end of the oxygen blow when the estimated carbon is around 0.06%. This system has been quite successful in dynamically estimating carbon levels in low carbon heats (0.06% or less), and adjusting

the oxygen blow for improving the turndown carbon accuracy. However, this system cannot be used for heats with aim carbon greater than 0.06%.

A few oxygen steelmaking shops have tried using laser based sensors to dynamically estimate the bath temperature. Some laboratory researchers have attempted to devise a probe that would take in-blow metal samples and provide instant chemical analysis. However most of these techniques are still in the developmental stage and are not yet commercially available.

9.6.4.3 Sensor or Sub-Lances

Sensor or sub-lances are effective tools for controlling both the carbon and temperature of the metal.⁴¹ In this technique a water-cooled lance containing expendable carbon and temperature sensors is lowered into the bath about two or three minutes before the end of the oxygen blow. The sensor determines the temperature of the metal bath at that time of blow and the carbon content of the steel by the liquidus arrest temperature method. The carbon and temperature readings thus taken are fed into the process computer which determines the additional amount of oxygen to be blown and the amount of coolants to be added.

The sensor lance has proven to be an extremely effective process control tool, with an OK-to-tap performance of 90% or more. The drawbacks of using sensor lances are substantial capital costs and engineering and maintenance problems. There are many oxygen steelmaking shops in Japan, and a few in North America, that are currently using the sensor lance technique to improve their turndown performance.

9.6.4.4 Drop-in Thermocouples for Quick-Tap

Drop-in thermocouples or bomb thermocouples are effective tools for measuring the temperature of the metal bath without turning down the steelmaking vessel. The thermocouple is contained in a heavy cylindrical casing, which is dropped into an upright vessel from the top of the furnace. The thermocouple probe has a sheathed wire attached to it which can convey a reliable emf reading before it burns up. The generated emf is conducted to a converter card and a computer, which converts the analog emf signal to a temperature value. The temperatures recorded by drop-in thermocouples have been found to be in good agreement with those measured using immersion thermocouples.

Drop-in thermocouples can be used to quick-tap heats, i.e. tap heats without turning the furnace down for chemical analysis. Certain grades of steel do not have stringent requirements for phosphorus or sulfur. In such a case, all that the steelmaking operator has to worry about at the end of the blow is temperature and carbon. If the operator feels confident that the carbon level in the bath is below the upper limit as specified by the grade (by either looking at the flame at the end of the oxygen blow, or by reading light meter carbon estimates, or by any other means), then he can use a drop-in thermocouple to determine the temperature of the metal bath without turning the vessel down. If the temperature recorded by the drop-in thermocouple is close enough to the aim temperature, then the heat can be quick-tapped.

Quick-tapping is becoming increasingly popular in North America with the advent of better devices for measuring in-blow carbon and bath temperatures. Quick-tapping has the obvious advantage of saving the production time that is otherwise consumed in turndowns. However, there is an obvious risk that a quick-tapped heat may be later found to have one or more of the elements present above their specification limits, in which case the heat may have to be regraded or scrapped. Another disadvantage is that the sensors cost between \$0.05 to \$0.10 per ton of steel.

9.6.4.5 Sonic Analysis

Several studies have been carried out in the past to correlate the audio emissions from the steel-making furnace to the decarburization reaction and slag/foam formation. Investigators found an increase in the sound intensity at the beginning of the blow due to the establishment of the decarburization reaction.⁴² The sound intensity reportedly decreased with the onset of slag and foam

formation in the slag. The sonic device can be used to control carbon and slag formation, which in turn can be used to control dephosphorization. These units can be affected by extraneous noise. Control is done by altering lance height or blow rate.

9.6.5 Lance Height Control

Lance height is defined as the vertical distance between the slag-metal interface in the furnace and the tip of the oxygen lance. The consequences of poor lance height control were discussed earlier in Section 9.2.2.6 on Oxygen Blow. It is an extremely important parameter as the height from which oxygen is blown affects the overall fluid flow of metal and slag during the blow. It is important to be able to measure it and to keep it consistent to achieve good process control of the furnace.

9.6.5.1 Measurement of Lance Height

Measurement of lance height was also discussed earlier. However, the best practice in measuring lance height is to do it often. If the furnace bottom rapidly changes, due to either excess wear or to rapid bottom buildup, the lance height should be measured frequently (once per shift). If the furnace lining shape is stable, then less frequent determinations (once per day) will suffice. Lance height has a significant effect on slag formation, furnace and lance skull formation and decarburization rate. Generally, the safest, reasonably accurate method is calculating the bath height from refractory wear laser data.

9.7 Environmental Issues

9.7.1 Basic Concerns

Environmental or pollution control issues are becoming increasingly difficult and costly. State jurisdictions are setting increasingly stringent standards for new site permits or for significant modification to existing processes. Nearly every process has become a source of emissions. Usually, these must be controlled to a legal standard which is measured in pounds or tons per unit time. Sometimes, tradeoffs are permitted as long as a net major improvement or emissions reduction is achieved.

There are at least five major characteristic sources of environmental pollution. These include airborne emissions, water borne emissions, solid waste, shop work environment (usually burning and welding) and safety, and noise. Air emissions are the major issues in a BOF shop. Water borne pollutants, generated by the scrubber system, are clarified by settling and then the clean water is recirculated. Solid waste is generated by oxide bearing materials collected from the scrubber, electrostatic precipitators or baghouse. While much solid matter is recycled, the rest is put into long range storage for byproduct use (i.e., aggregate) and future recycle (for example, Waste Oxide Briquettes). Noise generally is not a major concern in a BOF (i.e., compared to an arc furnace). Shop environmental and safety is always a major concern for personnel protection and employee morale. This discussion will concentrate principally on issues of air pollution.

9.7.2 Sources of Air Pollution

There are two broad areas: undesirable gases such as CO, fluorides or zinc vapors; and particulates such as oxide dusts. A brief summary of the various sources is discussed below.

9.7.2.1 Hot Metal Reladling

Pouring of hot metal from the torpedo car into the transfer ladle results in plumes of fine iron oxides and carbon flakes. This mixture, called kish is the major source of dust and dirt inside the shop. The graphite particles are generated because the liquid hot metal is saturated with carbon and when the temperature drops during pouring into the ladle, the carbon precipitates out as tiny

graphite flakes. The usual method of control is to pour inside an enclosure (hood) and to collect the fume in a baghouse.

9.7.2.2 Desulfurization and Skimming of Hot Metal

Pneumatic injection of the liquid iron with nitrogen and magnesium with a lance stirs the metal and generates a fume similar to that of reladling. Often, the reladling hood is designed to accommodate the desulfurizing lance operation. During slag skimming, the splash of slag and metal is collected in a vessel (usually a slag pot) which also generates fine oxide fume. This is frequently collected in a separate hood over the skimming collection pot.

9.7.2.3 Charging the BOF

There is some fume generated when the scrap hits the bottom of the furnace. However, the major emission is generated while pouring hot metal into the furnace. Here, very dense oxide clouds, kish, and heavy flames rise quickly. Some shops have suction hoods on the charging side above the furnace that collect fume and divert the heat away from the crane. However, many shops are not so equipped and must rely on slow-pouring to limit the fume emission from the roof monitors to comply with regulations. Pouring too fast results in heavy flame reactions that have been known to anneal the crane cables, causing spillage accidents.

9.7.2.4 Blowing (Melting and Refining)

By far the largest mass of fume is generated during the main blow. Approximately 90% by weight of total sources is generated at this point. The fume consists of hot gases at temperatures, over 1650°C (3000°F) and very heavy concentrations of iron oxide particles. The particulates can contain heavy metal oxides such as chromium, zinc, lead, cadmium, copper and others, depending on the scrap mix. The gas composition is approximately 80 to 95% CO and the rest is CO₂. In open combustion hoods, where air is induced just above the furnace into the cleaning system, the temperatures can be as high as 1925°C (3500°F) because of further combustion of CO. The fume is mostly fine iron oxides with some other oxides and dusts from flux additions.

The collection systems for this fume are of two types. Open hoods draft enough air to completely burn the CO before it hits the filtering device. Closed or suppressed combustion hoods either eliminate or reduce the induction of air to very low levels (<15%). This reduces the required fan horsepower and filtering capacity. However, consistent sealing between the furnace and hood is required to prevent the generating and igniting of explosive mixtures. Generally, the capital and operating costs for closed systems are less than for open systems. Thus, the most recently built shops are characterized by closed hood systems.

Another controlling characteristic is the filtering device. Two types have been successful in BOFs: electrostatic precipitators and venturi scrubbers.

The electrostatic precipitator draws the gas and fume into chambers. These are used only with open combustion hoods. These contain many parallel plates or alternating plates and wires spaced closely together within a few inches. Alternate elements (usually wires) are charged to a high potential. As the fume nears or contacts the highly charged element it becomes charged and is attracted to the other element (of opposite charge). Periodically the charge is dropped and the elements are vibrated, which releases the fume into a hopper and transport system below. Precipitators require gas temperatures less than 370°C (700°F) and some moisture (>6%) to be efficient. A common problem is plate warpage, due to excessive heating, which results in electrical short-circuits.

The venturi scrubber, used with either open or suppressed combustion hoods, induces the gas/fume through a violent spray which washes and separates the fume from the gas. The oxide laden water is then subjected to a series of separation processes, which are a combination of centrifugal, chemical and settling operations. The settled filter cake is dredged and dried for recycling. Most facilities now use venturi scrubbers.

9.7.2.5 Sampling and Testing

Turning the furnace down for testing and temperature sampling generates fine oxide fumes at a relatively low rate. Most of this fume is drafted into the hood above. However, many shops running on limited fan capacity close off suction in the hood on the testing furnace and start blowing the next heat on the other furnace. The sampling/testing fume rates for a bottom-blown process are much heavier than top-blown furnaces due to continued blowing through the tuyeres to keep them clear. Most bottom-blown facilities use a charge-side enclosure, or doghouse, to effectively collect these emissions into the main hood. In effect, the doghouse is a set of doors that extends the hood down to the charging floor.

9.7.2.6 Tapping

Some fume comes directly from the furnace but most comes from steel colliding with the bottom of the ladle or other liquid steel. The addition of alloys increases the smoke during tap. Some fume is collected in the main hood, but much escapes through the roof monitors. Some shops use a tap collection hood and route the fume to a baghouse.

9.7.2.7 Materials Handling

The handling of fluxes, alloys and treatment reagents can be a significant source of fume. Often the handling facilities are equipped with a collection system that leads to a baghouse. Materials used in small amounts per heat can be transported in bags or super sacks to eliminate fugitive dust during transfer. Sometimes materials quality control specifications are required to control the generation of dust during handling and transfers. Reducing burnt lime fines specification is an example.

9.7.2.8 Teeming

Ingot teeming generally does not require special collection systems unless a hazardous element, such as lead, is involved. Free machining bar stock and plates alloyed with lead are common examples. Here lead is added while teeming ingots. A mobile hood collects the lead laden fume while teeming each ingot. It is both a hazardous material for the workers (vapors and particulate) and a solid waste. Further, workers' lead contaminated protective clothing and equipment are collected in special containers for proper disposal.

9.7.2.9 Maintenance and Skull Burning

The BOF operations generate skulls on equipment such as the furnace mouth, ladles, oxygen lances, metallic spills etc. These must be processed or removed by oxy-propane burning or oxygen lancing. Generally, this is a small emission source.

9.7.3 Relative Amounts of Fumes Generated

Most of the fume in the overall process is generated during the main blow. Table 9.11 summarizes the relative amounts of fume generated from various BOF sources. Overall, about 31 lbs of fume are generated per ton of steel. Over 90% is from the main oxygen blow and reblows. The OBM (Q-BOP) and other major bottom blowing processes generate somewhat lesser amounts of fume with larger particle sizes which are easier to collect than the case of 100% top-blown. Desulfurizing and tapping each generate about one pound per ton.

Table 9.11 also shows how much is removed by a reasonably good filtering system. A well designed system will reduce the fugitive emissions in a shop to less than 0.2 lbs/ton, or by 99.4%

There is at least one consultant who has developed an effective modeling technique to test and optimize emission collection designs. A test is done in a water tank using small jets of salt water as pollution sources. The salt water is more dense than fresh water, and when put into a fresh water tank and modeled upside down, it generates a plume startlingly like the real thing. This technique has been very successful for both conformance to emission standards and for improving shop work

Table 9.11 Summary of Major Emission Sources of a BOF Shop. From Ref. 44

Emission Source	Approx. Amt. (lb/ton, steel)
BOF hot metal transfer, source	0.190
Building monitor	0.056
Hot metal desulfurization, uncontrolled	1.090
Controlled by baghouse	0.009
BOF charging, at source	0.600
Building monitor (roof top)	0.142
Controlled by baghouse	0.001
BOF refining, uncontrolled	28.050
Controlled with open hood, scrubber	0.130
Controlled with closed hood, scrubber	0.090
OBM (Q-BOP) refining, closed hood scrubber	0.056
BOF tapping, at source	0.920
Building monitor	0.290
Controlled by baghouse	0.003
Total at source or uncontrolled, BOF	30.850
Total controlled (scrubber, baghouse)	0.158
Total controlled (scrubber, monitors)	0.497

environment. Most jurisdictions look favorably on such modeling to check the viability of candidate collection system designs.

9.7.4 Other Pollution Sources

9.7.4.1 BOF Slag

BOF slag is generated at a rate of approximately 240 pounds per ton of steel. Currently about half of this quantity gets recycled within the plant to the sinter plant or is used directly in the blast furnace. Such in-plant slag recycling has been declining because of higher steel quality demands, e.g., lower phosphorus. Other uses such as aggregate and agricultural purposes are being explored.

9.7.4.2 BOF Dust and Sludge

BOF dust and sludge is generated at a rate of approximately 36 pounds per ton of steel. Small amounts are sold to other industries, such as the cement industry, while small amounts are recycled to the sinter plant for metal recovery. There is a growing interest in using this material in the BOF as an iron source and coolant, in the form of WOBs or waste oxide briquettes.

The major driving forces for recycling come from government mandated pressures to reuse byproducts and not to land fill them. In many cases there is an economic opportunity to use a low cost iron or coolant source. Problems to be overcome are buildup of phosphorus during recycling, zinc content, moisture, and the use of safe and suitable binders to improve handling characteristics.

9.7.5 Summary

Studying emission sources is a way to understand the process from another point of view. It is of increasing social and legal importance. Different jurisdictions do not always agree on acceptable levels, but they are all headed toward tougher environmental standards in the future. Accordingly, pollution control measures and evolving technologies will increasingly influence the design, capital, work environment, and operating costs of shops. Considerable thought by the steel industry is now being given to controlling emissions through engineering.

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