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

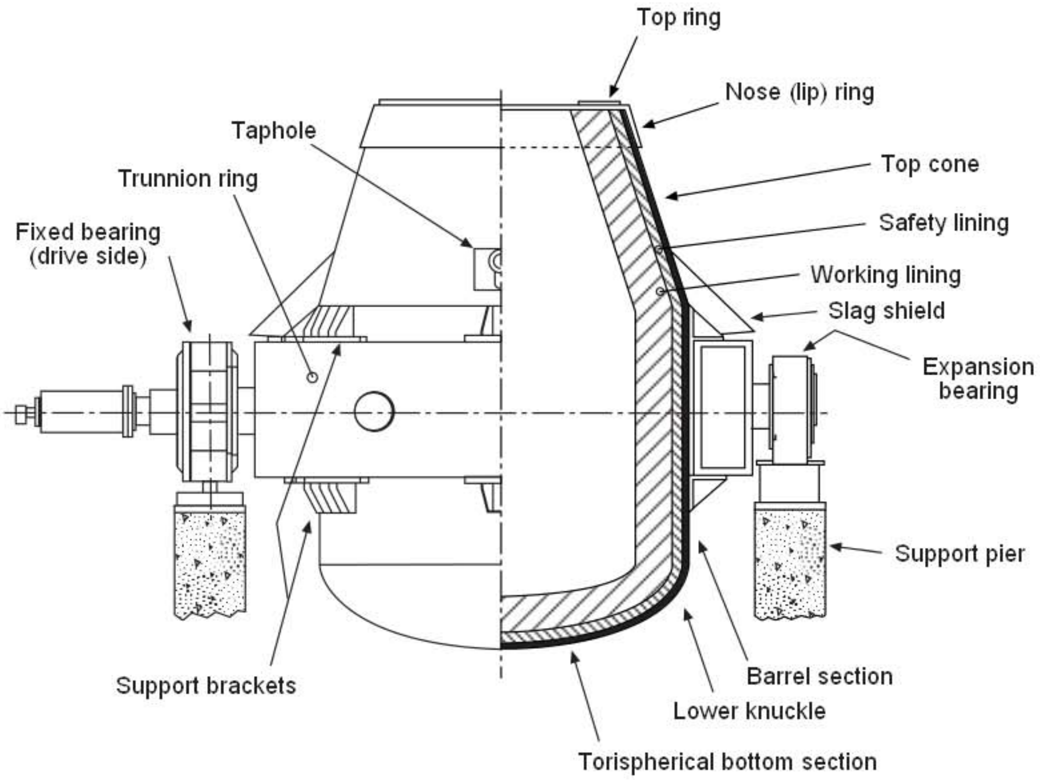
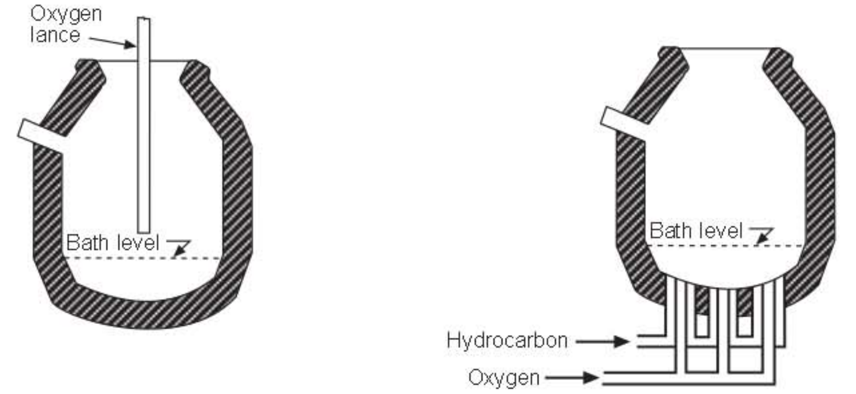


Fig. 8.1 BOF configuration.

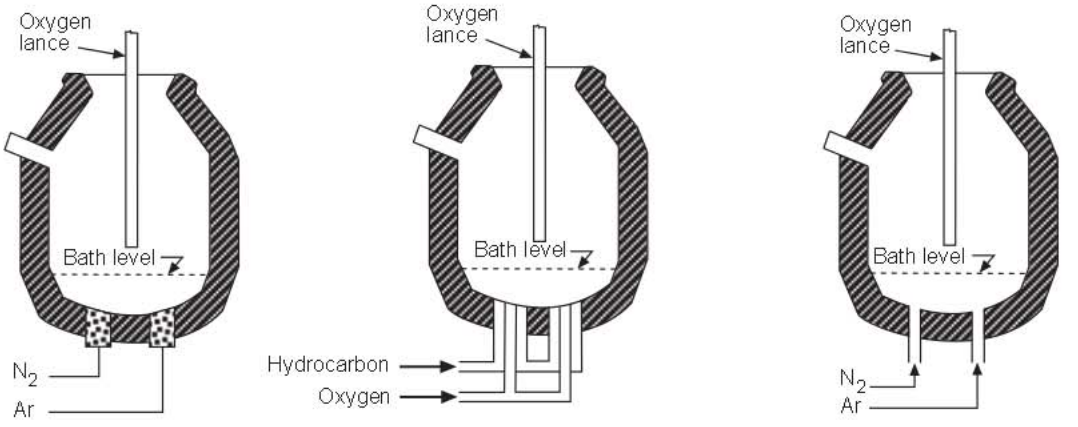


Top-blown (BOF) process

Oxygen of commercial purity, at high pressure and velocity, is blown downward vertically into the bath through a single water-cooled pipe or lance, indicated by arrow.

Bottom-blown (OBM or Q-BOP) process

Oxygen of commercial purity, at high pressure and velocity, is blown upward vertically into the bath through tuyeres surrounded by pipes carrying a hydrocarbon such as natural gas.



Top lance plus permeable elements in bottom

Top lance plus cooled bottom tuyeres

Top lance plus uncooled bottom tuyeres

Combination-blown processes

Oxygen is blown downward into the bath, and oxygen and/or other gases are blown upward through permeable elements or tuyeres.

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

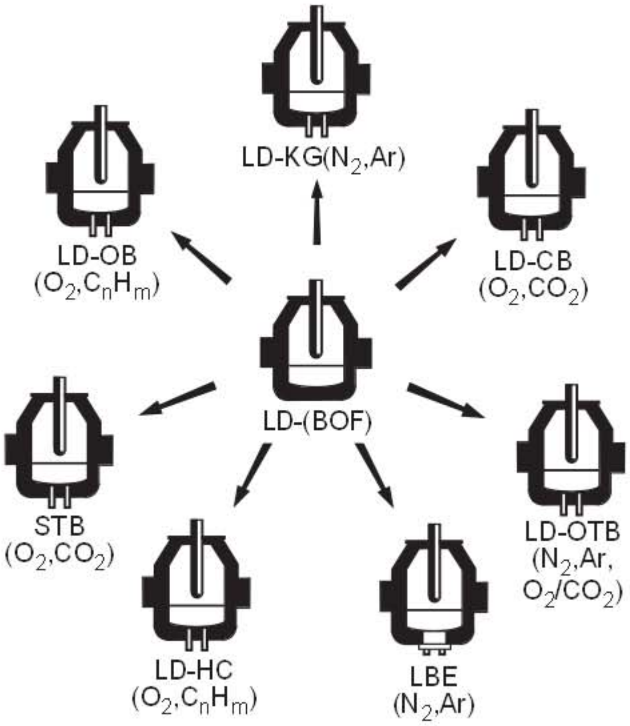


Fig. 8.3 Commercial variations of bottom stirring practices.

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

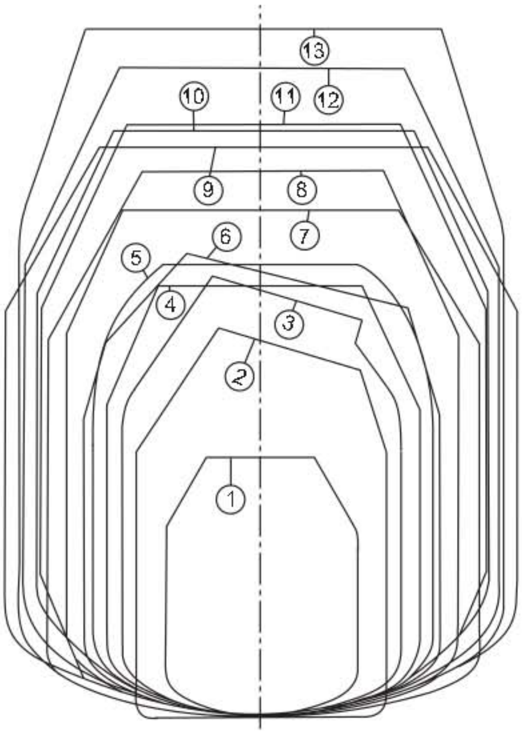
There are generally two methods for the attachment of the top cone of a vessel to its cylindrical section, namely welding or bolting. Welded top cones can be either corner welded or welded with a rounded knuckle. In each case, the inside surface of the shell must be free from offsets because of stress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



	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.

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

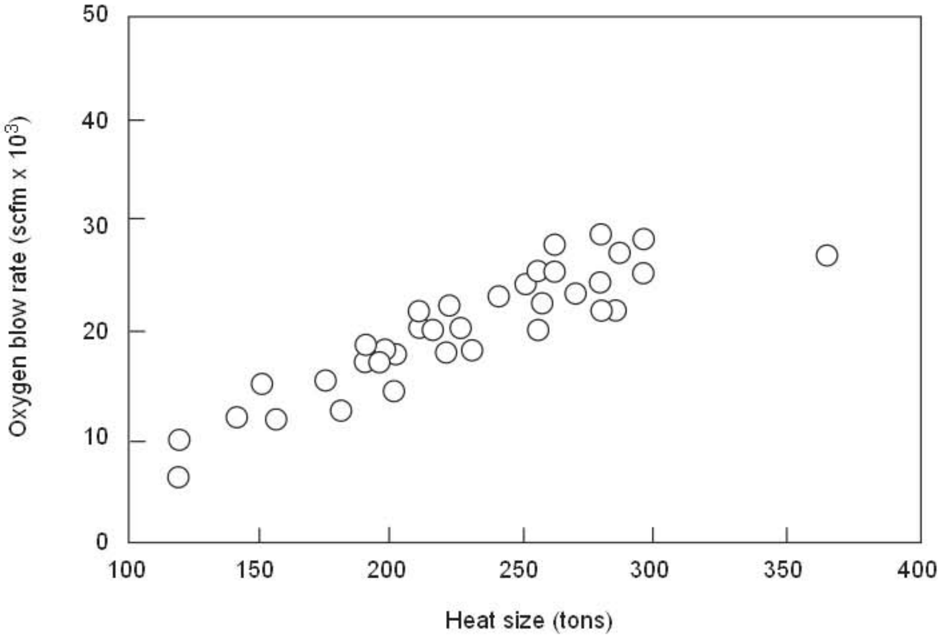


Fig. 8.5 BOF oxygen blowing rate in a sampling of North American shops.

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

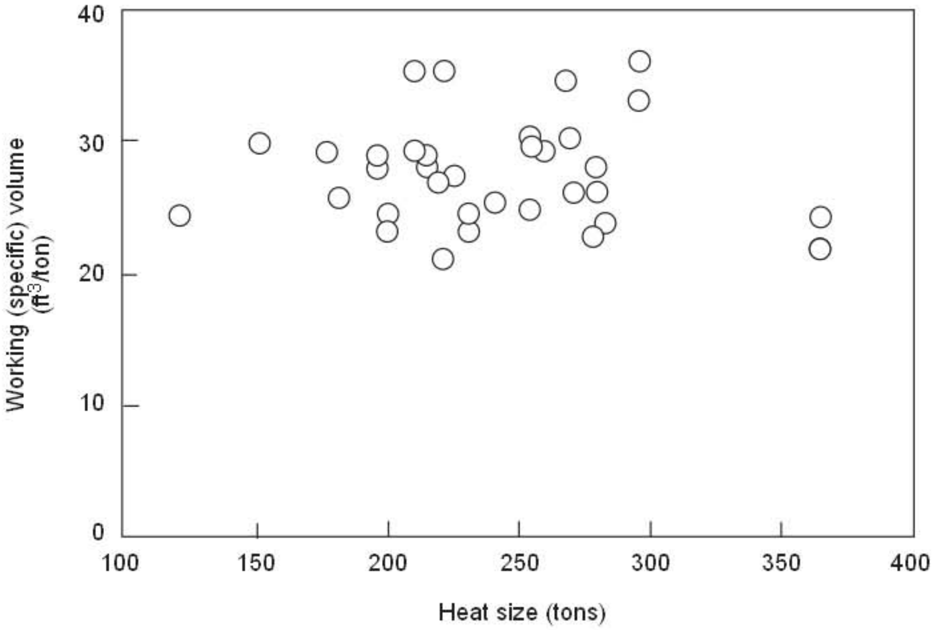
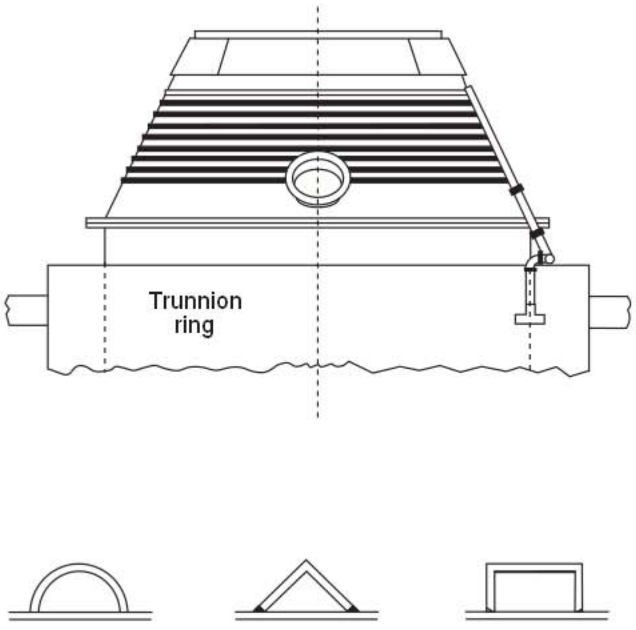


Fig. 8.6 BOF working volume in a sampling of North American shops.

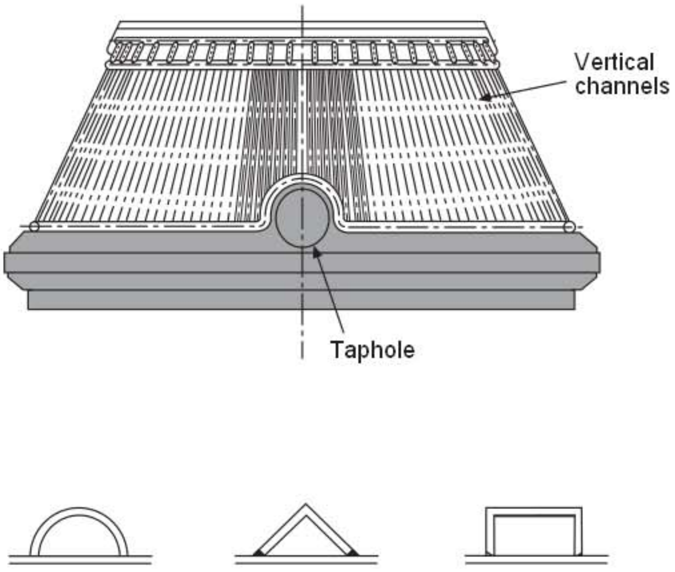


Channel configurations

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

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



Channel configurations

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

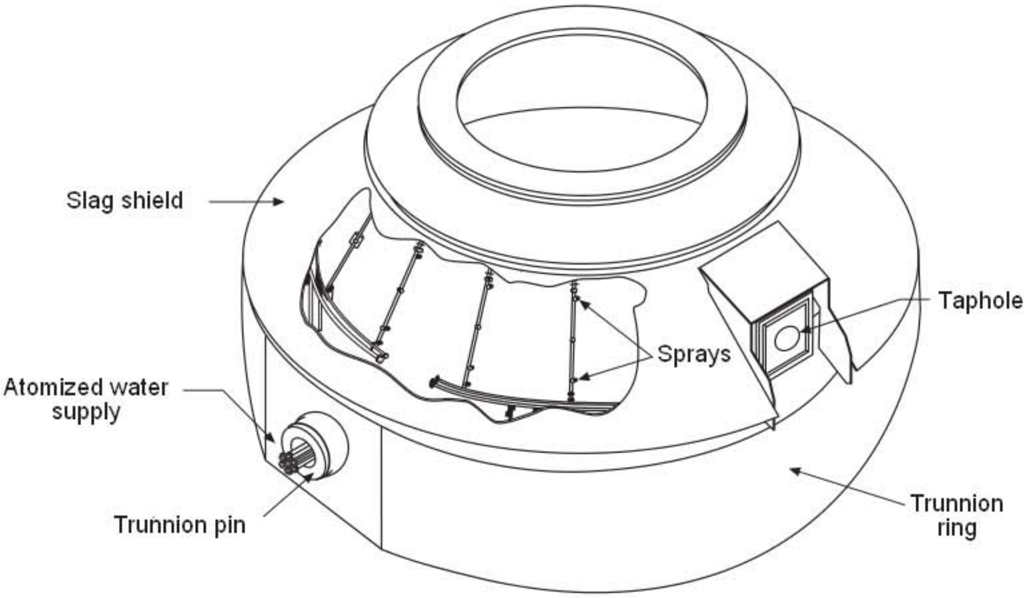


Fig. 8.9 Atomized water supply.

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 reline 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,

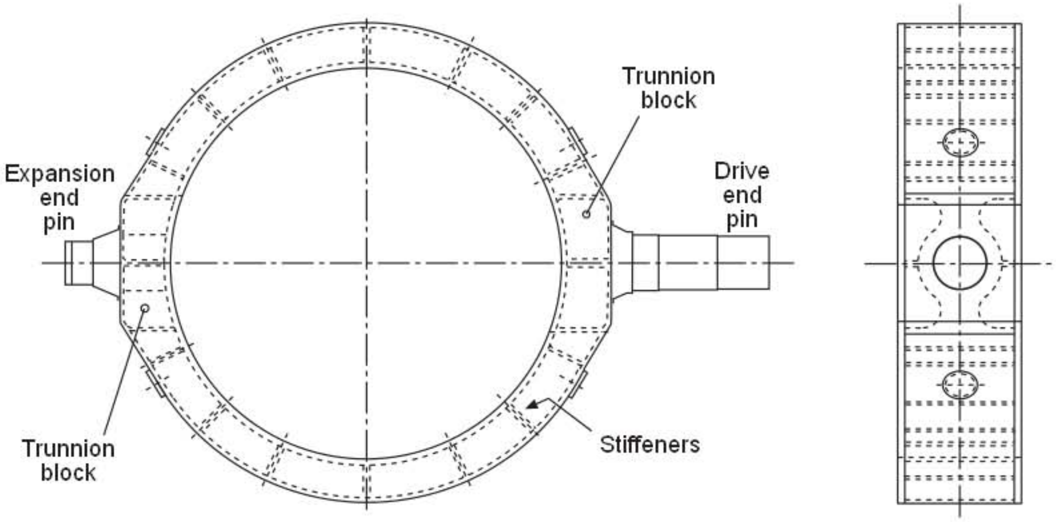


Fig. 8.10 Trunnion ring design.

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 befit 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.

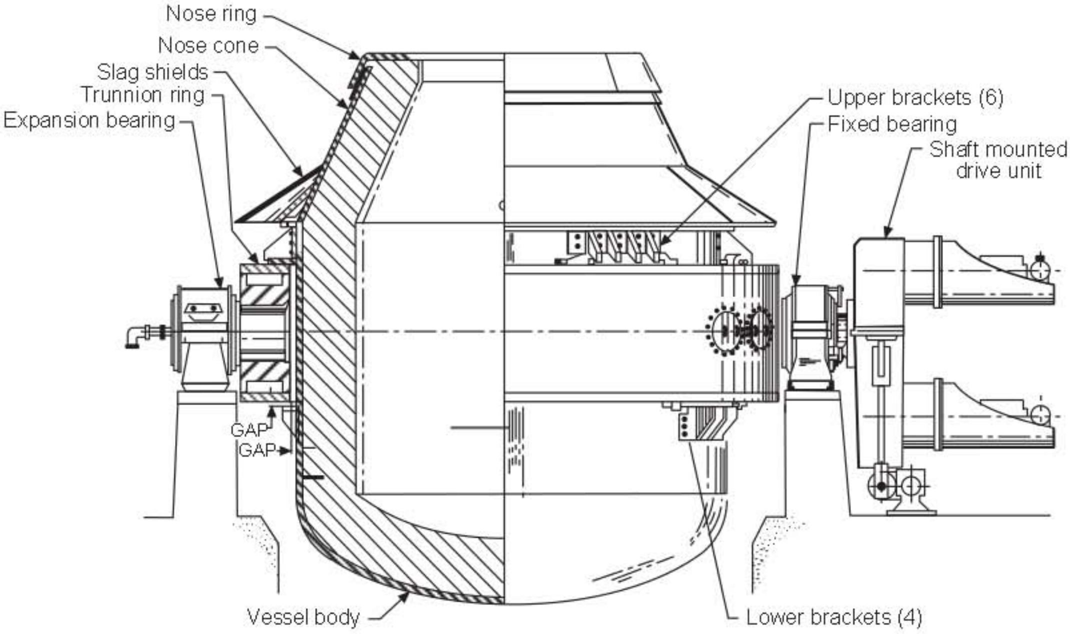


Fig. 8.11 Bracket support system.

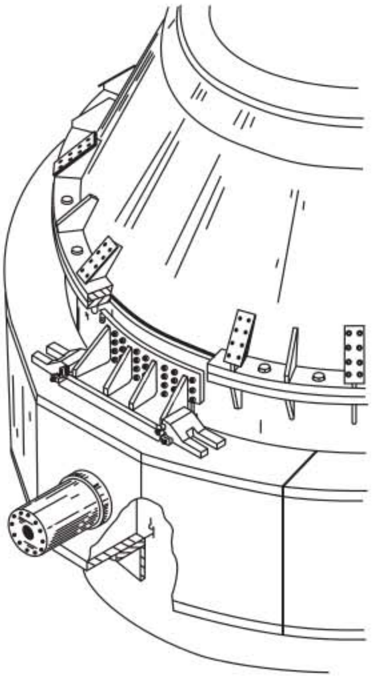


Fig. 8.12 Bracket support system showing detail of gibs.

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.

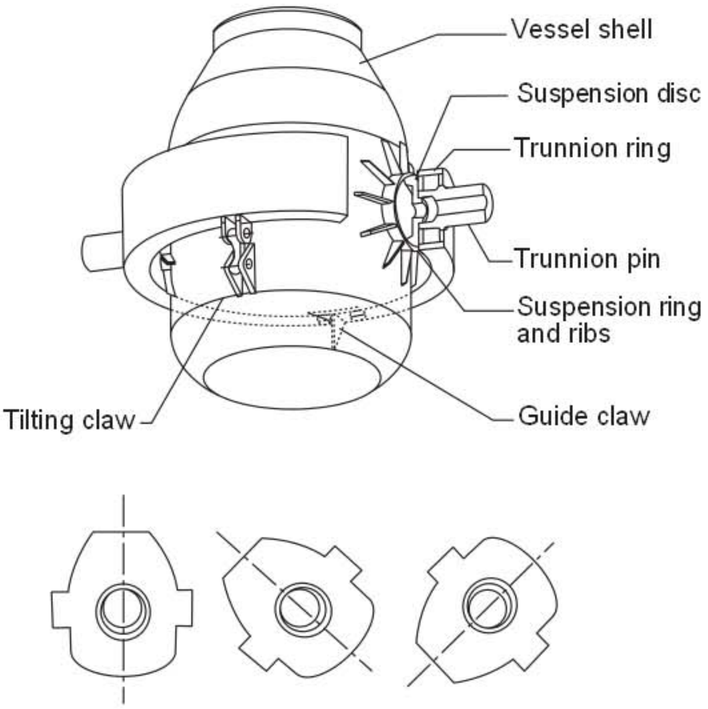


Fig. 8.13 Support disc suspension system.

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

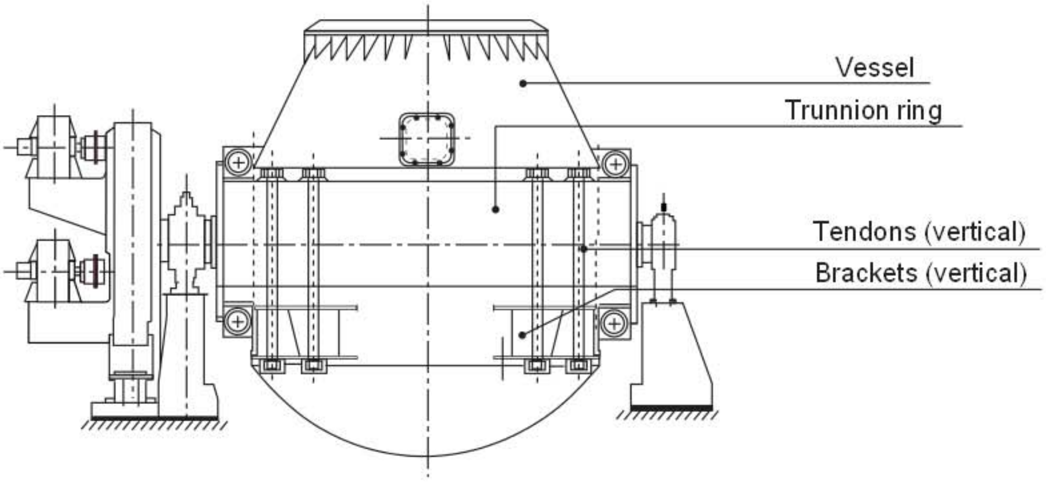


Fig. 8.14 Tendon suspension system, front view.

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,

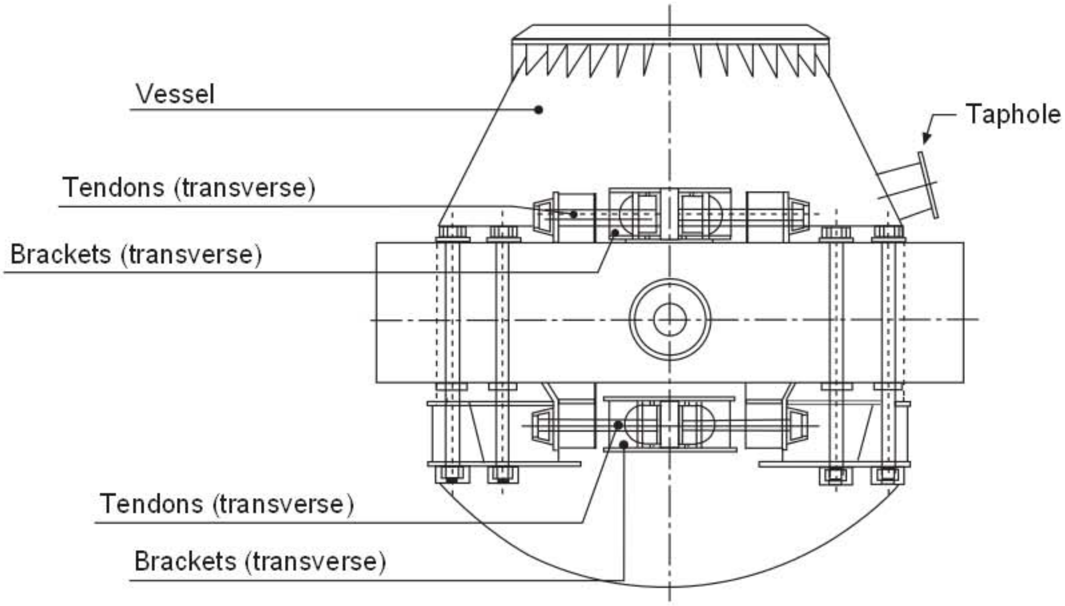


Fig. 8.15 Tendon suspension system, side view.

Fig. 8.16 BOF vessel suspended by lamella plates.

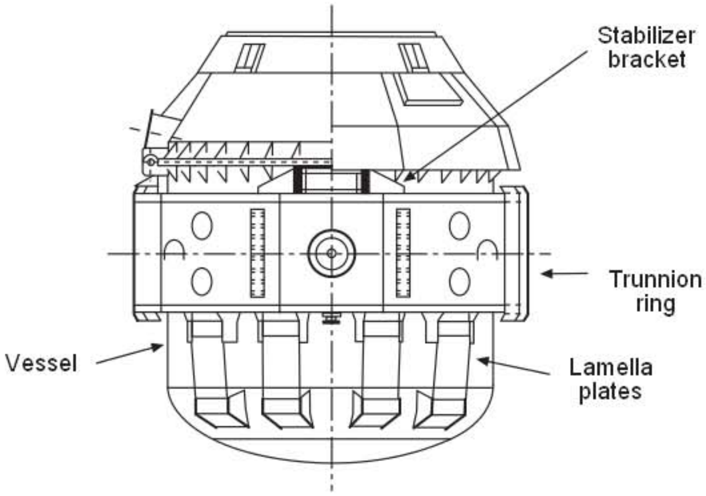


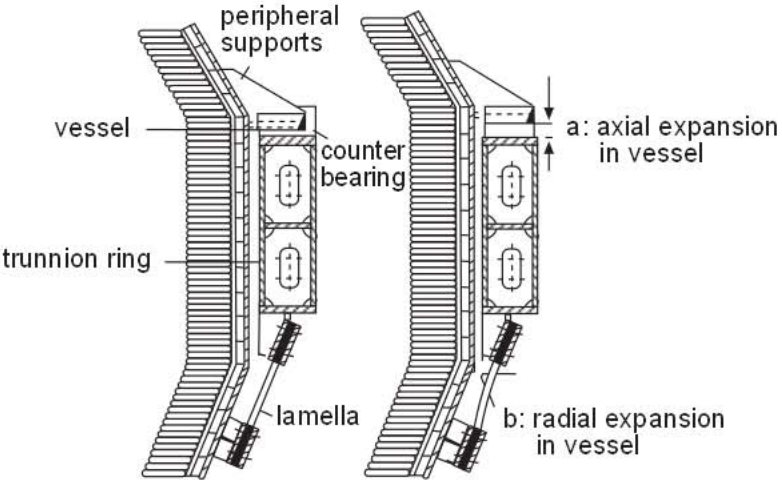
Fig. 8.16 and Fig. 8.17. These plates, called lamellae, are separated from each other by means of a spacer, and enable radial movement of the lower vessel shell against flexural deflection of the two plates about their weak axes. In the direction of their own plane, they possess large strength and stiffness. 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

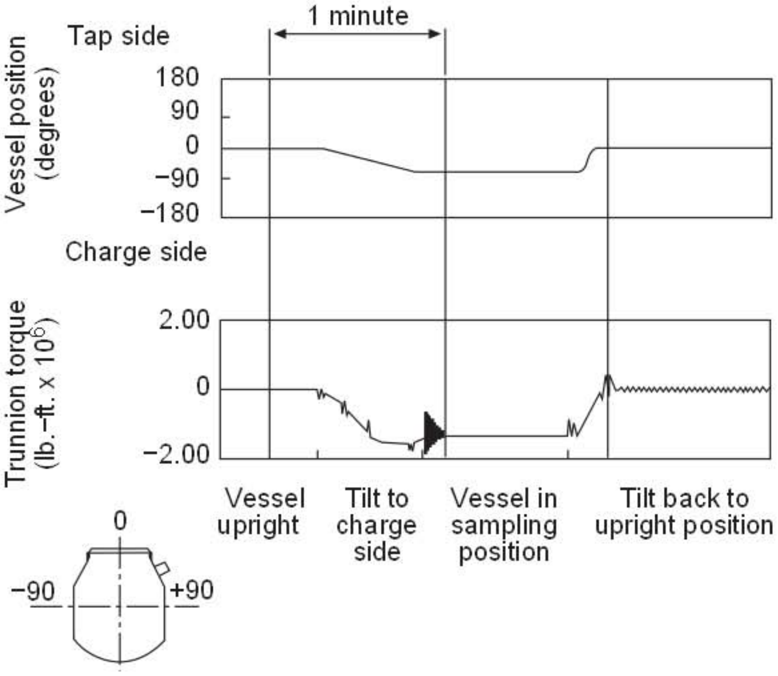


Fig. 8.18 Vessel position and tilt drive torque for a 200 ton BOF.

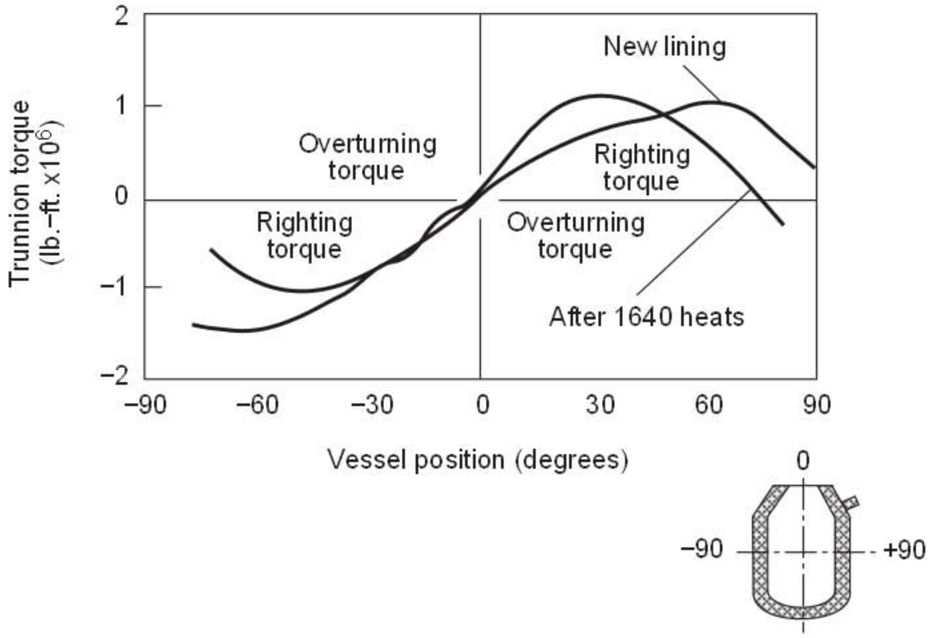


Fig. 8.19 Effect of vessel lining wear on tilt drive torque.

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.

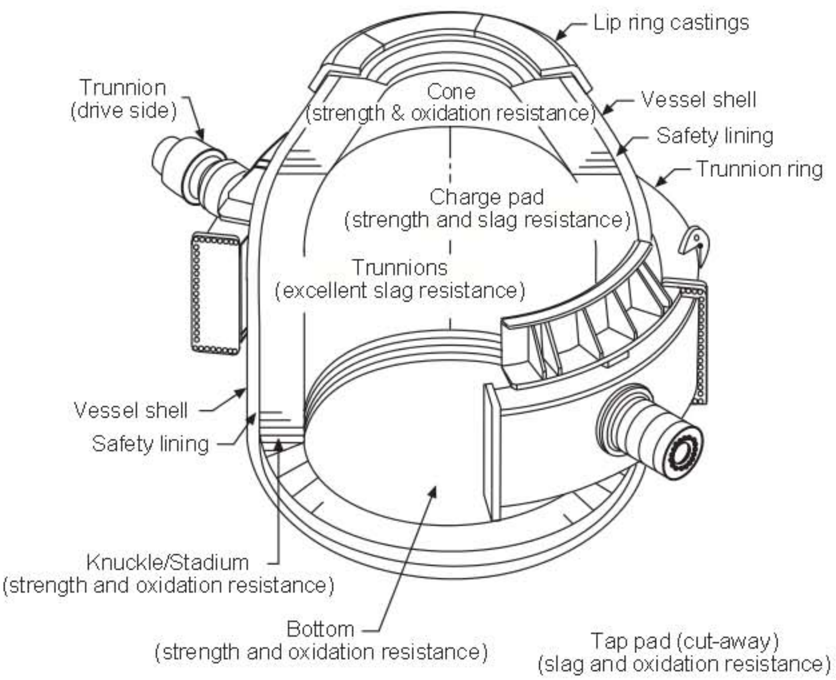


Fig. 8.20 Areas of the refractory lining.

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.

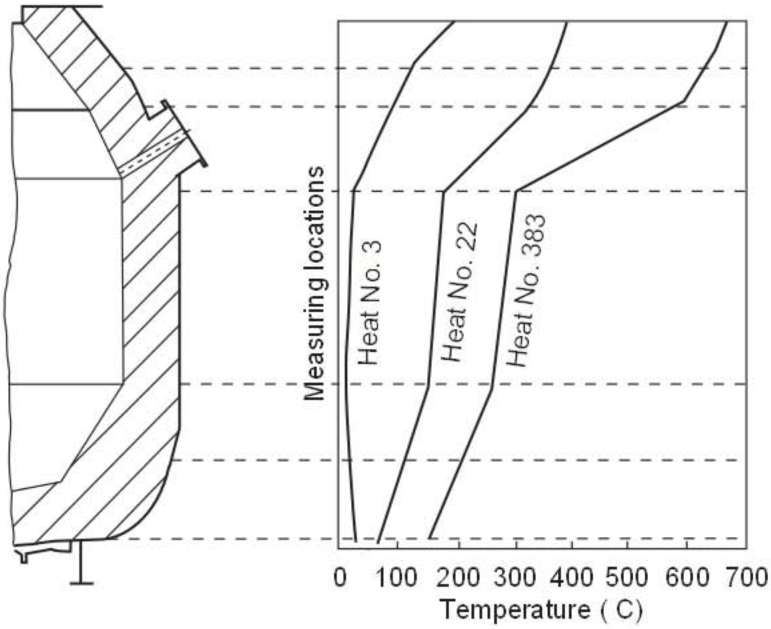


Fig. 8.21 Shell temperature measurements on a 220 ton BOF.

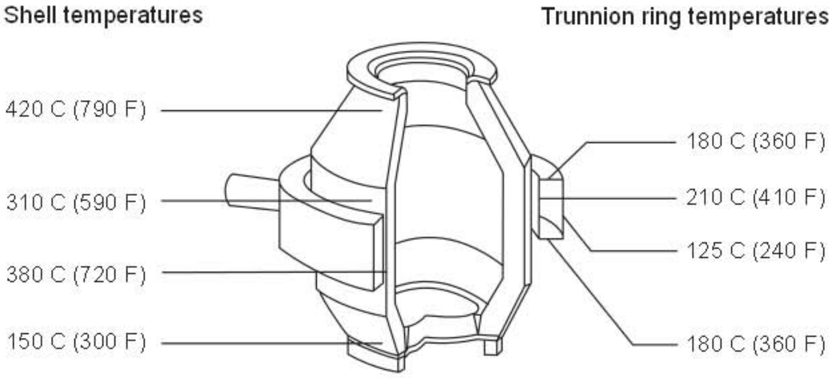


Fig. 8.22 Temperature measurements on a converter shell and trunnion ring.

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.

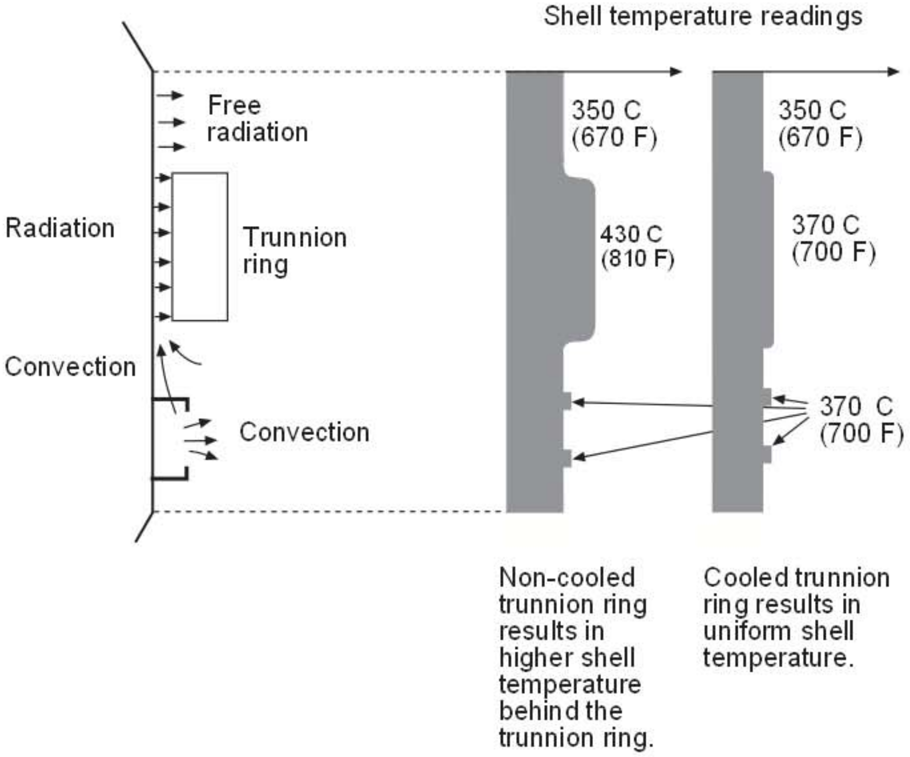


Fig. 8.23 Influence of trunnion ring cooling on BOF shell temperature.

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.

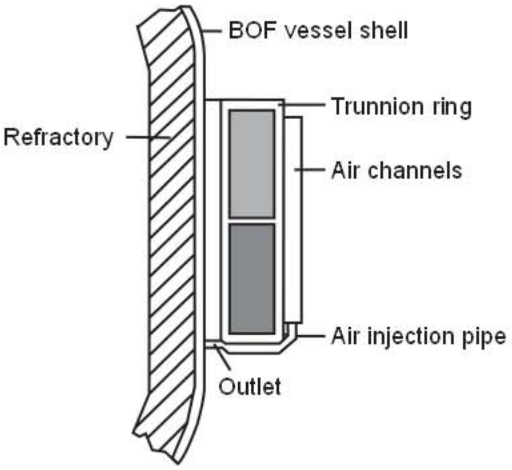


Fig. 8.24 Method of cooling vessel shell with air jets, U.S. Patent No. 5,039,067.

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

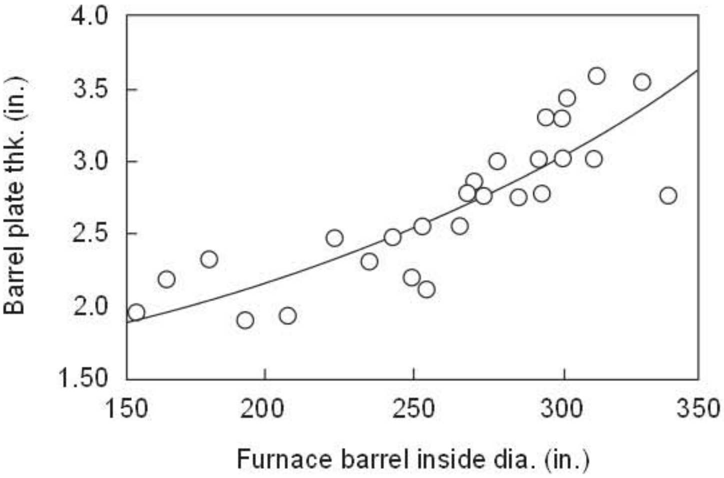
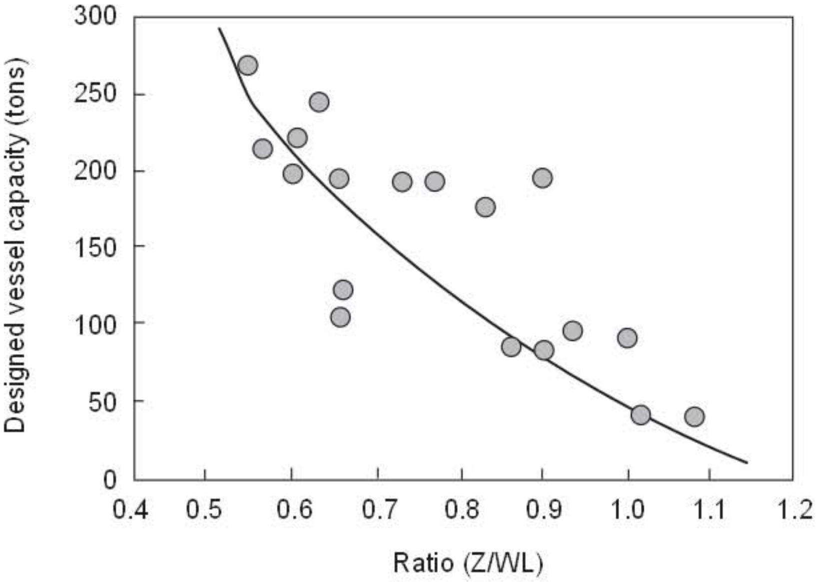


Fig. 8.25 Historical design data for BOF barrel plate thickness.

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.



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.)

Fig. 8.26 Historical design data for BOF trunnion rings.

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.

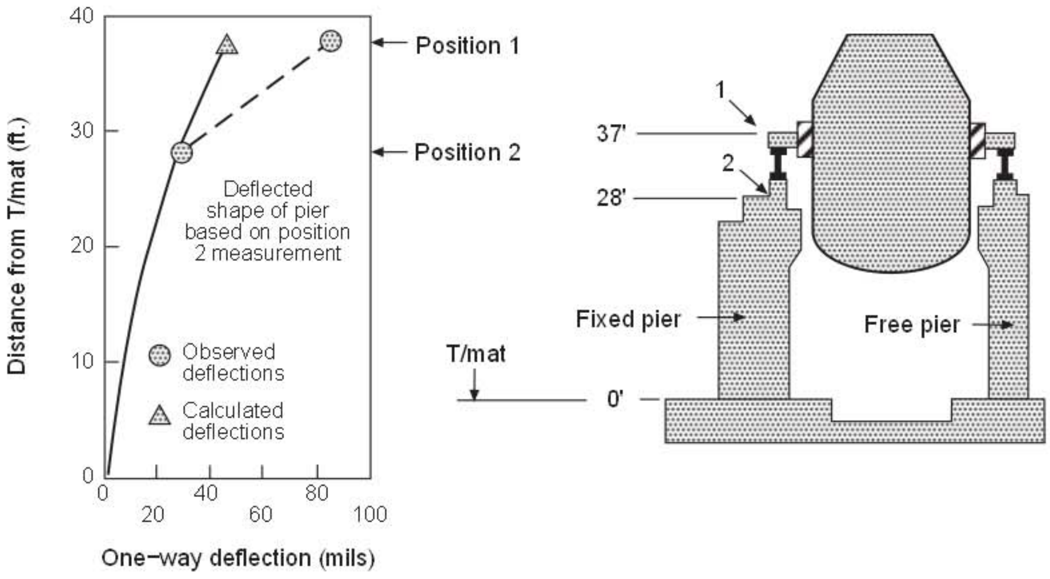


Fig. 8.27 OBM (Q-BOP) support vibration.

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.

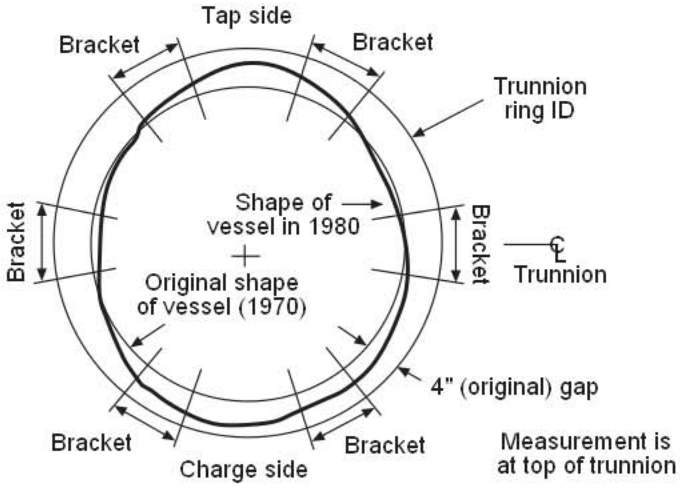


Fig. 8.28 BOF vessel distortion.

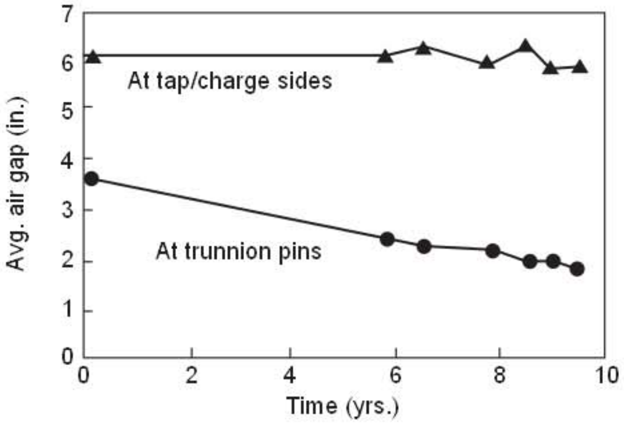


Fig. 8.29 Change in vessel-to-trunnion ring air gap in a water-cooled trunnion ring system.

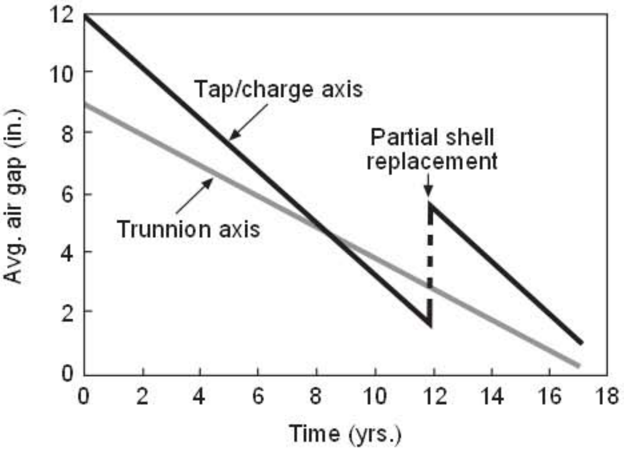


Fig. 8.30 Monitoring of vessel-to-trunnion ring air gap in a non-water-cooled trunnion ring system.

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

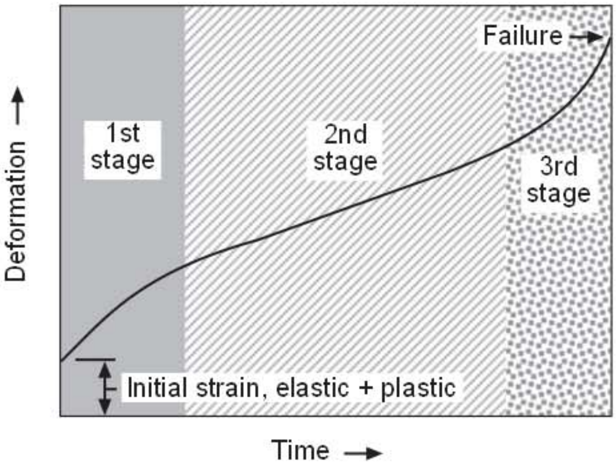


Fig. 8.31 Classical creep life cycle.

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.

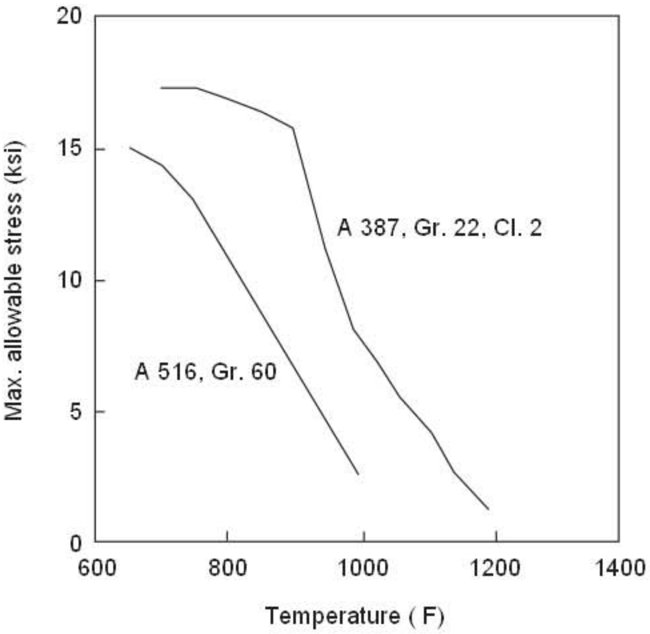


Fig. 8.32 Effect of service temperature on strength of BOF vessel steels.

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.

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.

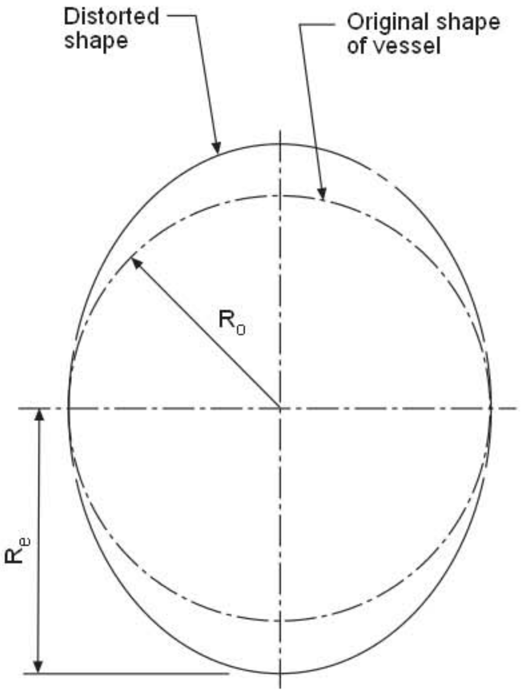


Fig. 8.33 Simulated distortion in a BOF vessel due to creep.

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

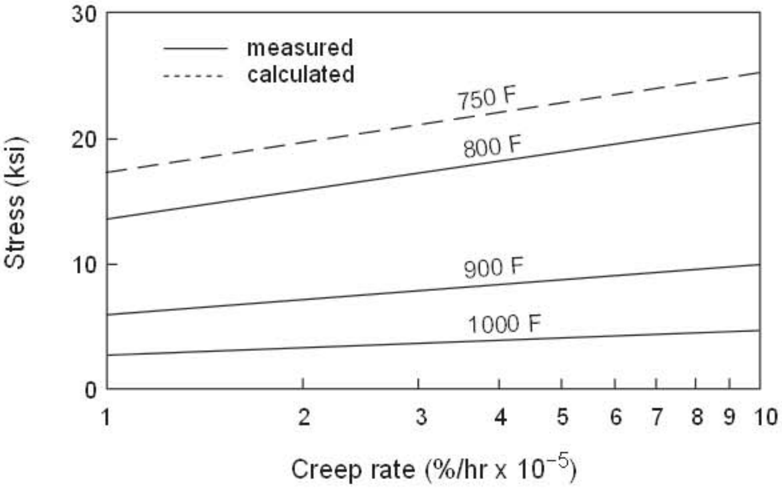


Fig. 8.34 Creep rate curves for medium carbon steel.

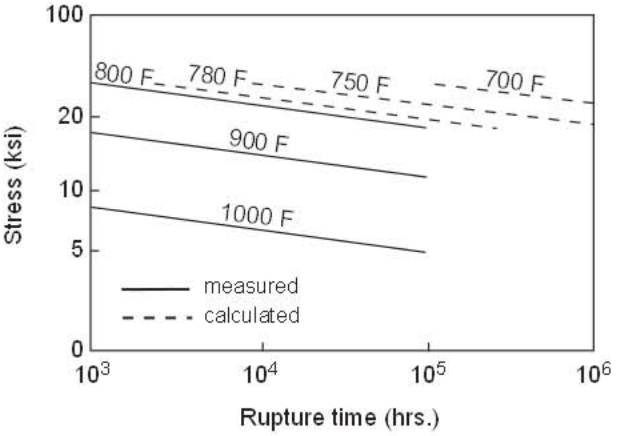


Fig. 8.35 Stress rupture curves for medium carbon steel.

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

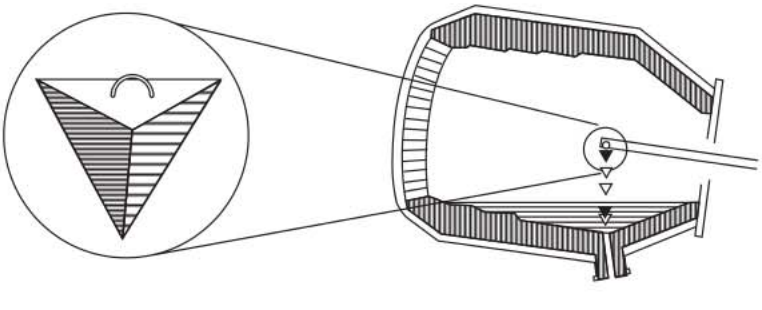


Fig. 8.36 Refractory plug used for slag retention in the BOF vessel.

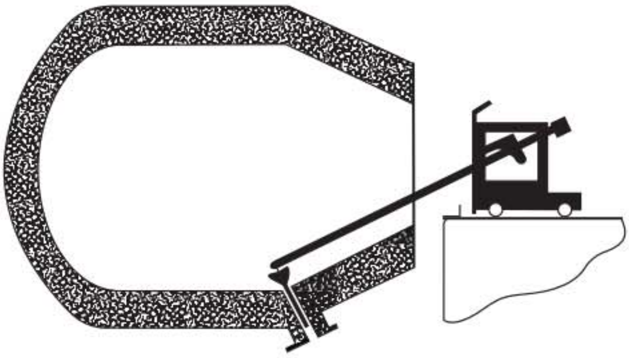


Fig. 8.37 Method of positioning the dart-type slag stopper in the taphole.

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.

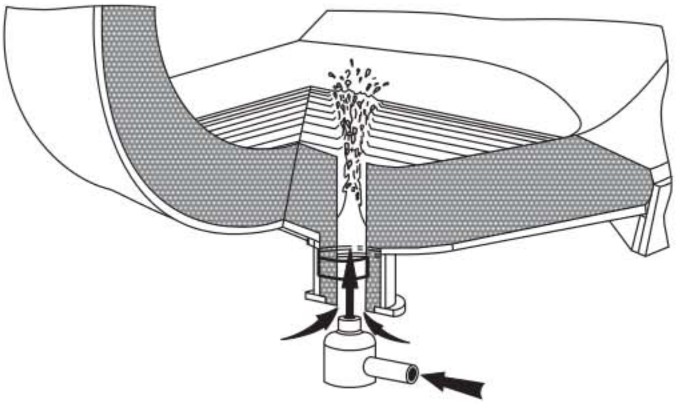


Fig. 8.38 Pneumatic slag stopping device.

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 CO_2 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)
$C\ 1\ {}^{1}/_{2}O_{2}\ 5\ CO$	66
$2CO\ 1\ O_{2}\ 5\ 2CO_{2}$	57.4
$Si\ 1\ O_{2}\ 5\ SiO_{2}$	137.5
$Mn\ 1\ {}^{1}/_{2}O_{2}\ 5\ MnO_{2}$	58.5
$2P\ 1\ {}^{5}/_{2}O_{2}\ 5\ P_{2}O_{5}$	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:

$$F = W\frac{V_e}{g} \tag{8.5.1}$$

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 steelmaking 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

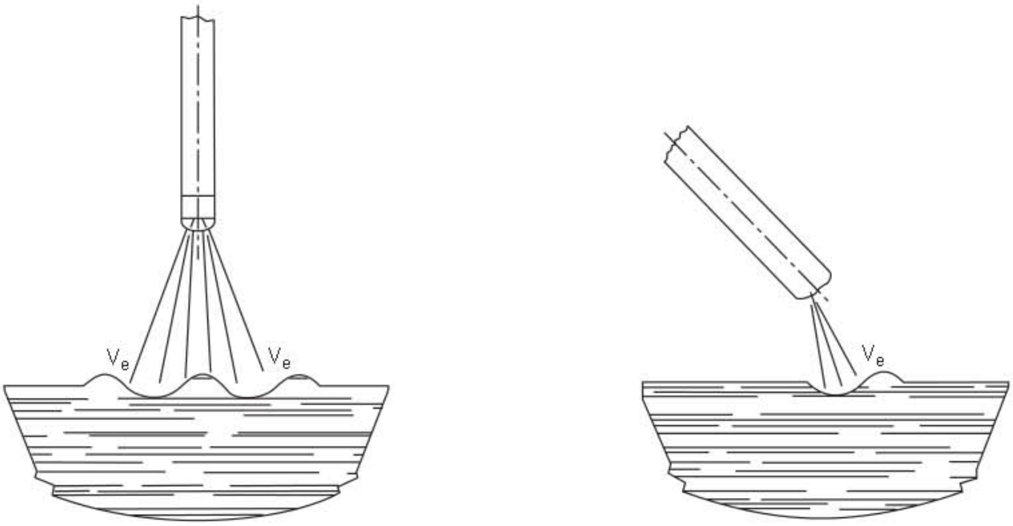


Fig. 8.39 Effect of nozzle design on impact angle and jet thrust.

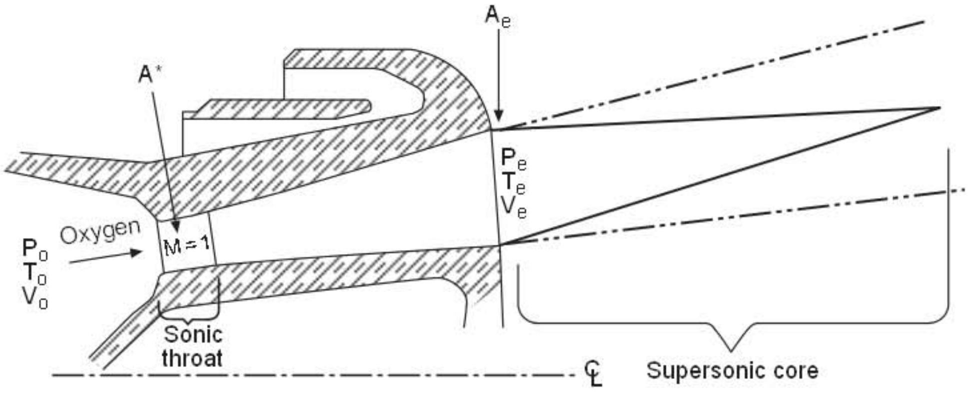


Fig. 8.40 Mechanics of supersonic jet formation.

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

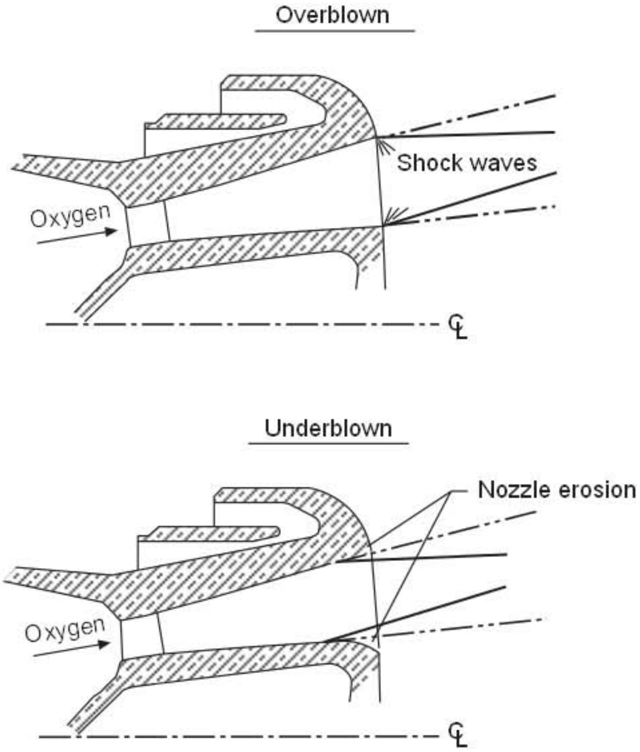


Fig. 8.41 Overblown and underblown conditions at the nozzle tip.

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.

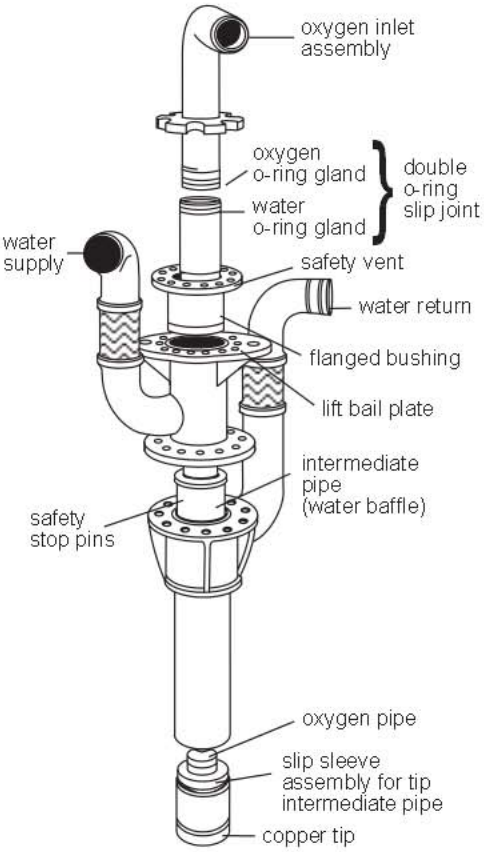


Fig. 8.42 Top adapter assembly of the BOF oxygen lance.

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. 8.43 Various types of BOF lance tips.

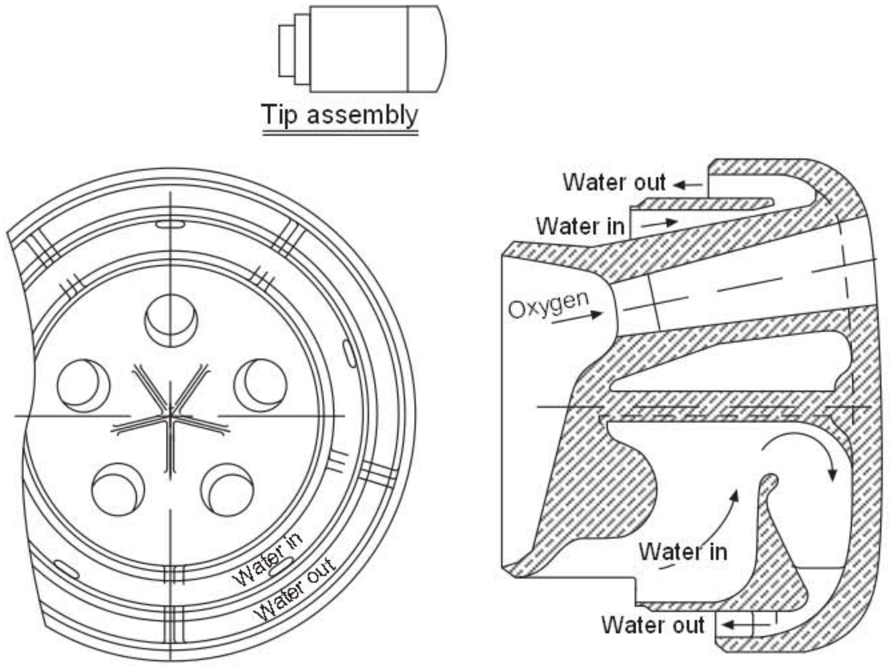


Fig. 8.44 Schematic of a typical 5-hole BOF lance tip.

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.

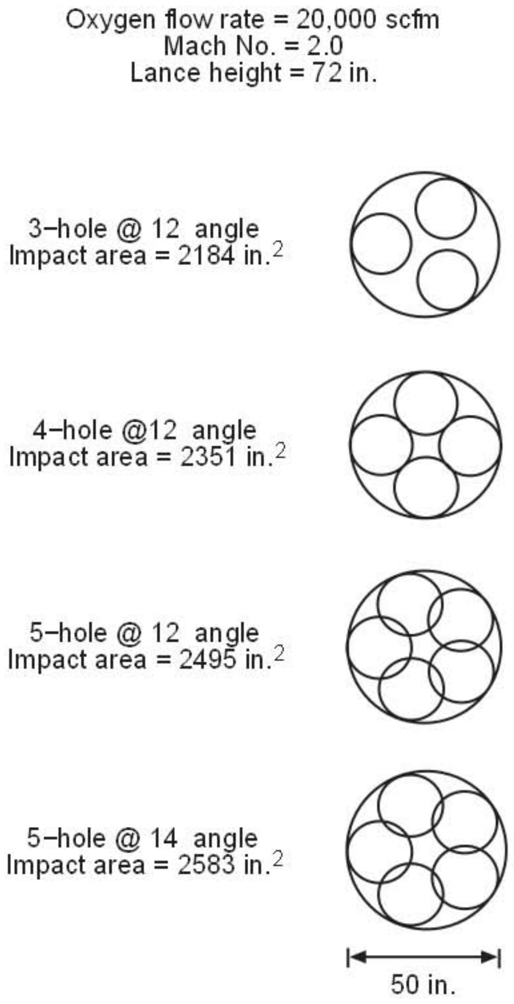


Fig. 8.45 Impact area as a function of number of nozzle holes and nozzle angle.

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

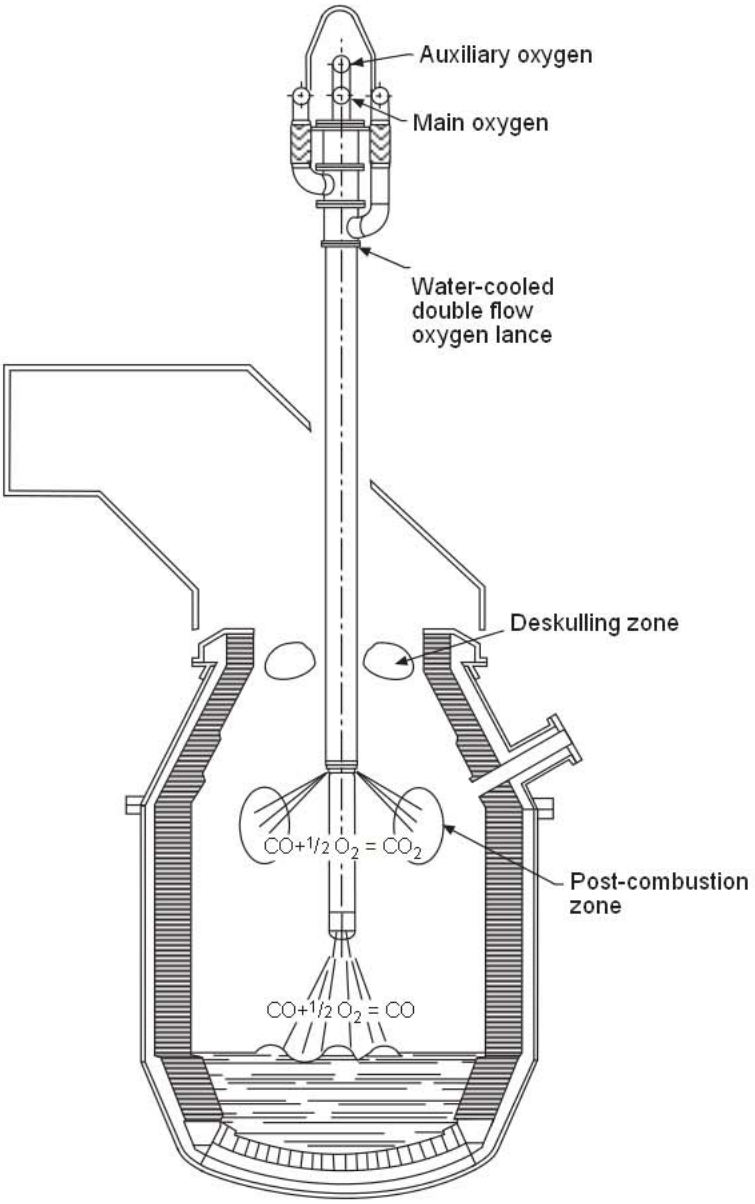


Fig. 8.46 Schematic of a post-combustion oxygen lance.

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

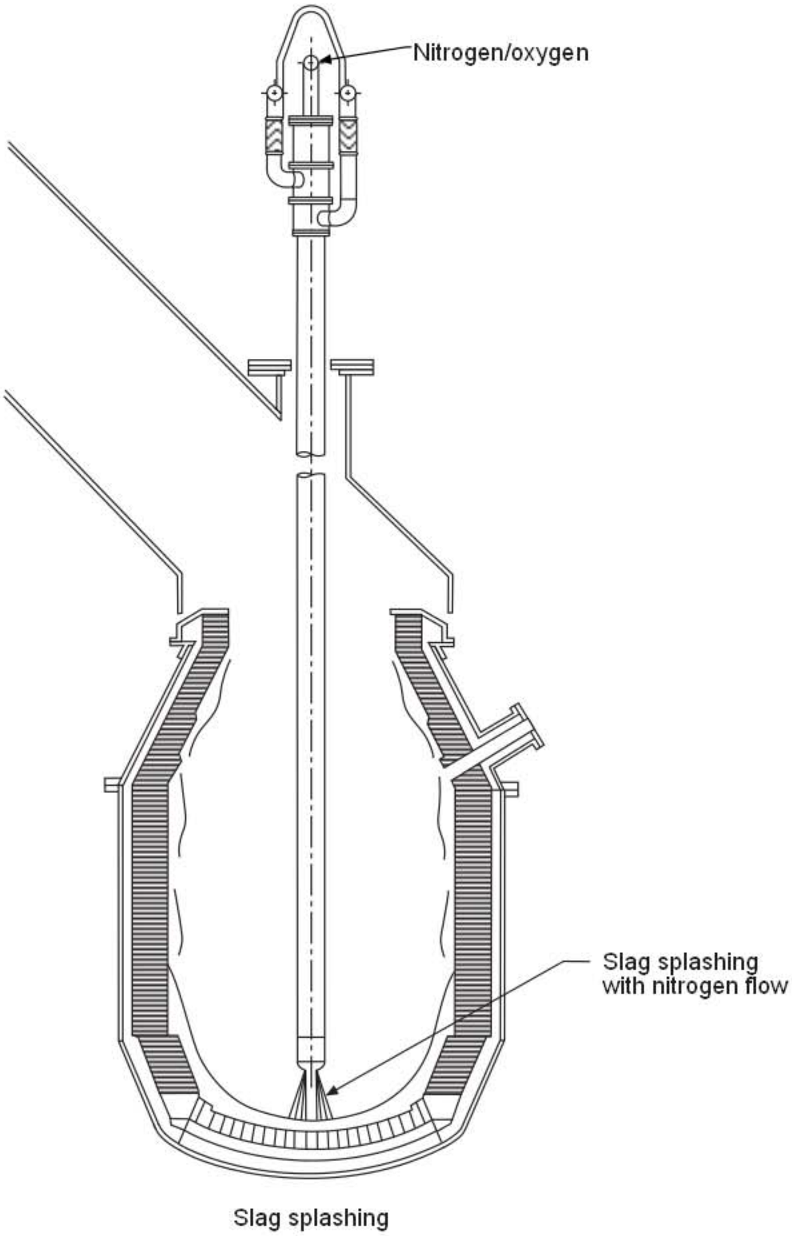


Fig. 8.47 Schematic of a slag splashing oxygen lance.

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

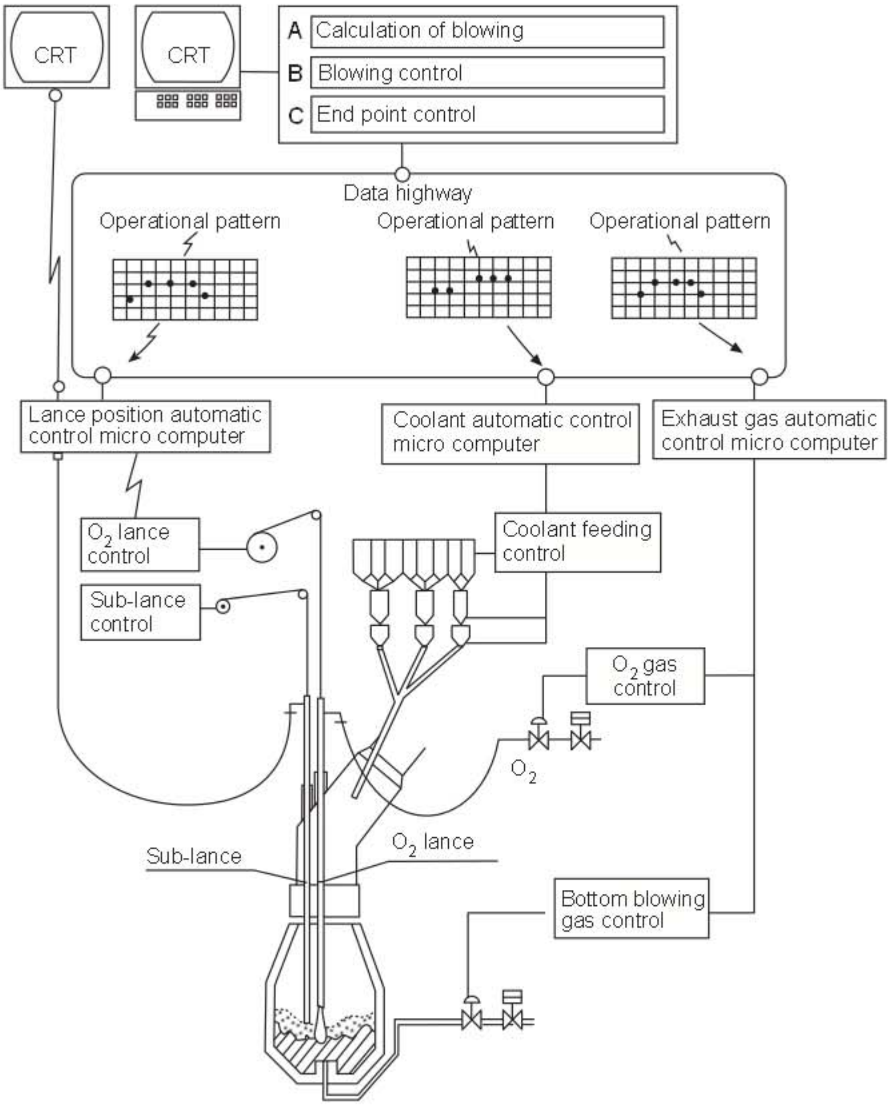


Fig. 8.48 Schematic of process control outputs generated from sub-lance measurements.

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

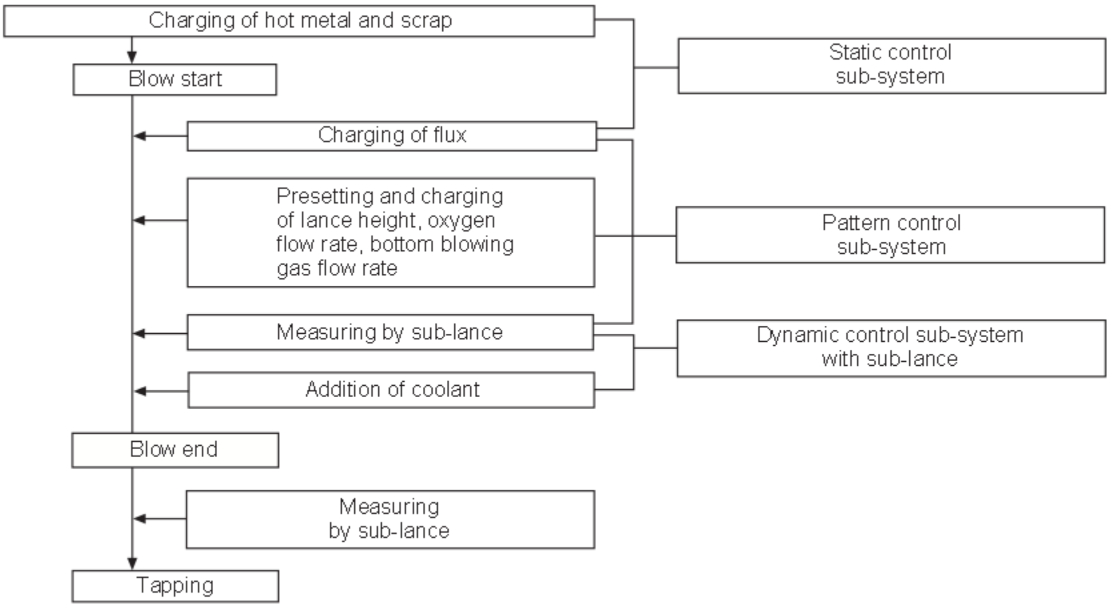


Fig. 8.49 Heat cycle with in-blow and end-blow sub-lance measurements.

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.

References

1. "Design and Maintenance of Basic Oxygen Furnaces," *AISE Technical Report No. 32* (Pittsburgh, PA: Association of Iron and Steel Engineers, 1996).
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