Chapter 4

Steelmaking Refractories

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4.1 Refractories for Oxygen Steelmaking Furnaces†

4.1.1 Introduction

The essential goal in the development of refractory practices for basic oxygen furnaces is to obtain a useful lining life that will provide maximum furnace availability for the operators to meet production requirements at the lowest possible refractories cost per ton of steel produced. To this end, the operators and refractories engineers seek to optimize their lining design, maintenance practices, and control of operating practices that are known to affect lining life. In most shops, longer lining life can result in lower refractories cost, but, in high production shops, longer life achieved with minimal downtime for maintenance will also enable increased productivity through increased furnace availability.

To optimize the lining design, most operators try to develop a balanced lining, that is, a lining in which different refractory qualities and thicknesses are assigned to various areas of the furnace lining on the basis of a careful study of the wear patterns. In a balanced lining, the refractories are zoned such that a given segment of lining known to receive less wear is assigned a lower quality or less thickness of refractory, whereas refractories of greater wear resistance and generally of higher costs are reserved for those segments of the furnace that will be subjected to the most severe wear.

The refractory qualities available to use in BOF linings range from pitch-bonded magnesia or dolomitic types to the advanced refractories that are made with resin bonds, metallics, graphites, and sintered and/or fused magnesia that can be 99% pure. Bricks are designed with a combination of critical physical properties to withstand the high temperatures and rapidly changing conditions/environment throughout the BOF heat cycle. A balance of properties such as hot strength, oxidation resistance, and slag resistance are necessary for good performance.

With the wide variety of available brick qualities, there is a wide range of prices; the more expensive brick can cost as much as six times that of a conventional pitch-bonded brick of the type used in many furnace bottoms. As lining designs are upgraded and more of the higher priced products

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are used in a lining, determining if the changes are cost-effective is important. For example, when the cost of a lining is increased by 25% in a shop that is averaging 2000 heats, the lining life will need to increase to 2500 heats for the refractories costs to be maintained. However, in shops where furnace availability is needed for productivity, a lesser increase in lining life and a higher refractory cost may be justified if the furnace availability is greater during periods of high production needs.

As lining designs are upgraded to optimize performance and costs, the effects of operating variables on lining wear are important to know. With this information, the possibility of controlling those parameters that affect lining wear adversely and the economic tradeoffs of increasing operating costs to extend lining life can be better evaluated. In general, the practices that improve process control, such as sub-lances, will benefit lining life. In addition, lining life is helped by charging dolomitic lime to provide slag MgO, minimizing the charge levels of fluorspar, controlling flux additions and blowing practices to yield low FeO levels in the slags. These practices need to be optimized to yield the most cost-effective lining performance.

Even when many operating conditions are improved, lining designs are optimized for balanced wear, and the best brick technology is used, wear does not occur uniformly, and, generally, maintenance practices that involve gunning of refractories and coating with slag are used to extend the life of a lining. See Section 4.2.

The above discussion illustrates some of the many factors that need to be considered in a strategy for BOF lining performance. Some details that are needed for developing the optimum refractories practices are provided in the following sections.

4.1.2 Balancing Lining Wear

4.1.2.1 General Considerations

In theory, linings for oxygen furnaces should be designed by refractory type and/or thickness so that no materials are wasted at the end of a furnace campaign; that is, so that all areas of the furnace are worn to a stopping point such as the safety lining at the same time. In the real case, however, some areas will show higher wear despite the latest brick technology and efforts to use internal maintenance techniques. A continuing and dynamic effort is always in progress in any shop to minimize wear and to provide longer life in these severe wear areas.

4.1.2.2 Areas of Severe Wear

The areas of severe wear are dictated to a large extent by the type of oxygen process involved (top-blown, bottom-blown, combination-blown, bottom-stirred, etc.). In all oxygen practices, the area where scrap and hot metal are charged into the furnace (charge pad) is subject to impact and abrasion. More uniform wear will occur during the oxygen blowing period on top-blown vessels, but bottom-blown vessels will be subject to accelerated bottom wear during the blowing period. On turndown for sampling and tapping, the furnaces (normally to opposite and generally horizontal positions), localized contact with slag will also produce localized wear. Accelerated wear is also experienced in the trunnion areas of any oxygen furnace, mainly because this area is the most difficult to protectively coat with slags or gunning. Other unusual wear areas may result from unique features of a particular oxygen process; for example, cone wear from post-combustion lances or the damage inflicted by deskulling.

Fig. 4.1 shows the different areas of a typical oxygen steelmaking vessel, where different types or thicknesses of refractory may be used to obtain balanced wear.

4.1.2.3 Wear-Rate Measurements

Consistent and predictable lining life is very important to avoid production delays in the steelmaking facility and related operations such as ironmaking, casting, or finishing; predictable life is

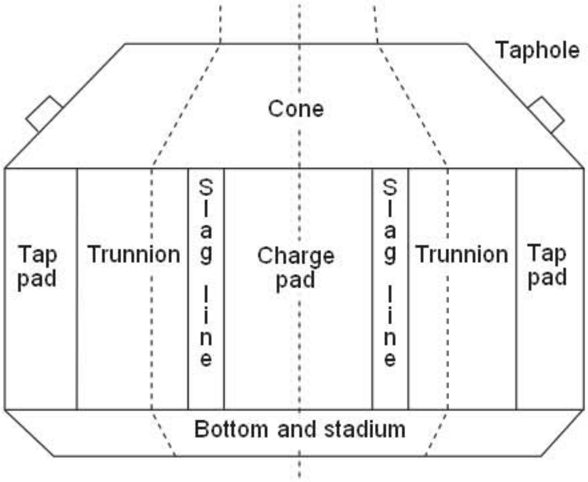


Fig. 4.1 Areas of a basic oxygen furnace.

also a vital part of a safe and stable operation. For these reasons, a variety of tools have been used to determine the condition of the lining at any time and to dictate the maintenance required to balance wear.

The most widely used method currently is a laser-measuring device as illustrated in Fig. 4.2. In this practice, a laser beam is rebounded off calibrated points on the furnace proper and compared to points in the worn lining. A computer analysis is then used to plot the remaining lining thickness. While this information is invaluable in comparing wear rates for different refractories and avoiding shell damage or breakouts, its primary usefulness is in determining and controlling furnace maintenance by gunning. Using the laser as a guide, the areas actually requiring gunning maintenance can be isolated, and the amount of gunning material required can be controlled. Fig. 4.3 illustrates one furnace campaign in which rapid trunnion wear was experienced in the first 500 heats.

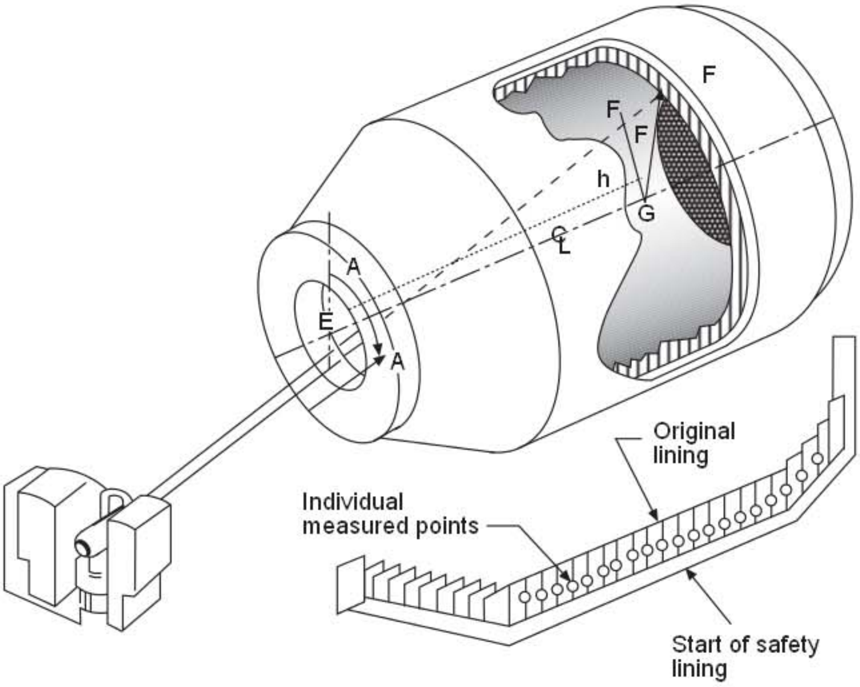


Fig. 4.2 Use of a laser to measure refractory wear.

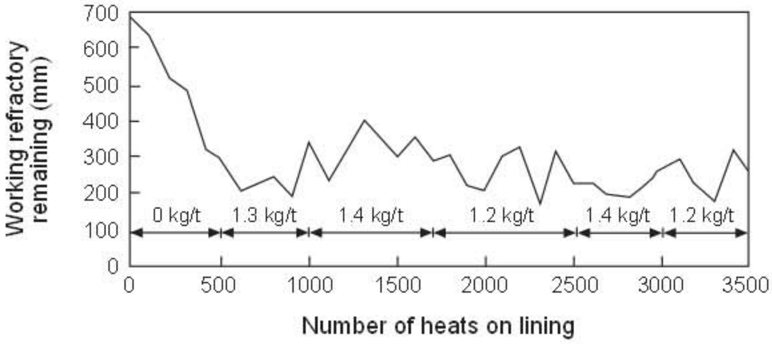


Fig. 4.3 Wear and gunning rate in the trunnion area.

Gunning was initiated at the indicated approximate rate at that time and continued throughout the balance of the campaign.

4.1.3 Zoned Linings by Brick Type and Thickness

The previous chapter on refractories described the types of carbon-bearing basic brick available for use in modern oxygen steelmaking furnaces. The engineers who are responsible for designing today's sophisticated vessel linings now may choose from greater than 30 proven compositions to construct a working lining to meet the service conditions found in a particular vessel. Normally, five to ten compositions have been found to cover most current operating practices and associated wear mechanisms.

Fig. 4.4 and Fig. 4.5 describe the zoning used in two types of operations to provide the optimum refractory behavior. The lining zones may also vary in working lining thickness from some 18 to 30 in. as an additional zoning method.

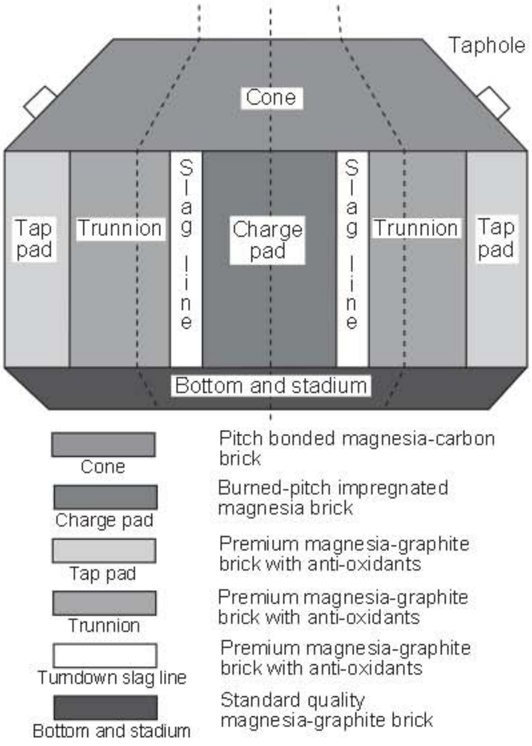


Fig. 4.4 Typical LD-BOF lining.

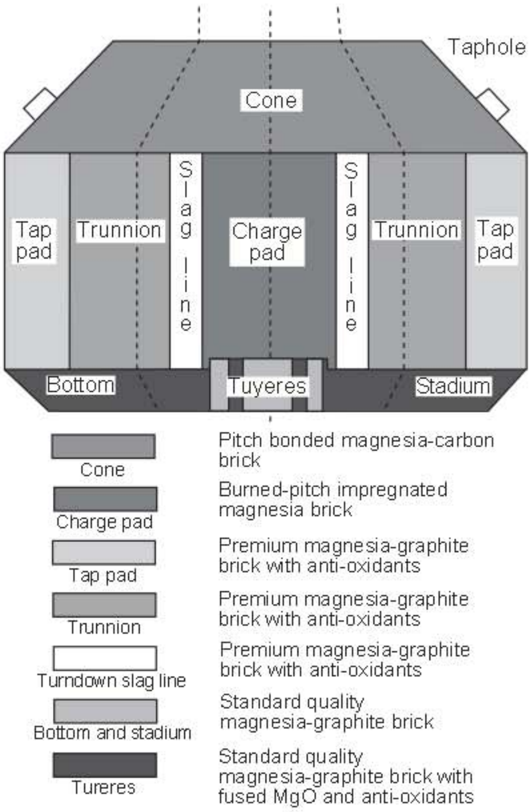


Fig. 4.5 Typical bottom-stirring LBE-BOF lining.

The zoned lining for a particular shop evolves as the operating conditions change and as new refractory types and/or maintenance practices are developed. Table 4.1 is an idealized description of the known wear condition(s) for the several furnace areas along with the best current refractories for each environment.

4.1.4 Refractory Construction

The refractory constructions in oxygen steelmaking furnaces are relatively simple in comparison to other refractory applications in that:

a. Tear-out of the spent working lining can be readily accomplished by mechanical removal of the top brick courses followed by rotation of the furnace to an inverted position.

b. Only two refractory layers are normally used—a thicker working lining (18–30 in.) and a thinner safety lining (6–9 in.) for shell protection. (A large part of the safety lining will last multiple working lining campaigns.)

c. The working lining is installed without mortar while the safety lining is held in place with steel retainer rings and mortar.

d. In principle, the working lining is installed with minimum brick cutting in a ringed-keyed construction where the brick are held in place by the brick taper (smaller hot-face than cold-face).

In reality, the brick construction in actual vessels is more complex as illustrated in Figs. 4.6 through 4.11. Fig. 4.6 and Fig. 4.7 show cross-sections of the refractory construction in typical top

Table 4.1 Furnace Area Wear Conditions and Recommended Materials

Furnace Area	Wear Conditions	Recommended Materials
Cone	Oxidizing atmosphere Mechanical abuse Thermo-mechanical stress High temperature	Standard-quality magnesia–graphite refractories containing anti-oxidants Pitch-bonded magnesia brick Resin-bonded low-carbon refractories with with anti-oxidants
Trunnions	Oxidizing atmosphere Slag corrosion Slag and metal erosion	Premium-quality magnesia–graphite refractories containing anti-oxidants Premium-quality magnesia–graphite refractories containing fused MgO and anti-oxidants High-strength premium-quality magnesia–graphite refractories
Charge Pad	Mechanical impact Abrasion from scrap and hot metal	Pitch-impregnated burned magnesia brick Standard-quality high-strength magnesia–graphite refractories containing anti-oxidants High-strength low-carbon magnesia brick containing anti-oxidants
Tap Pad	Slag erosion High temperature Mechanical erosion	Premium-quality magnesia–graphite brick containing anti-oxidants High-strength low-graphite magnesia brick with metallic additives Standard-quality magnesia–graphite refractories containing anti-oxidants
Turndown Slaglines	Severe slag corrosion High temperature	Premium-quality magnesia–graphite brick containing anti-oxidants Premium-quality magnesia–graphite brick containing fused magnesia and anti-oxidants
Bottom and Stadium (bottom-stirred vessels)	Erosion by moving metal, slag and gases Thermo-mechanical stresses as a result of expansion Internal stresses as a result of thermal gradients between the gas-cooled tuyeres and the surrounding lining	High-strength standard-quality magnesia–graphite refractories containing anti-oxidants Magnesia–graphite refractories without metallic additives characterized by low thermal expansion and good thermal conductivity Pitch-impregnated burned magnesia refractories

and bottom-blown furnaces, respectively. Note that the refractory construction is simple keyed rings for the cone, stadium and barrel sections, but involves other shapes in the furnace bottom areas. These more complex shapes are, however, still layered entirely dry (no mortar) and close dimensional requirements are necessary for all such shapes. Fig. 4.8 shows alternate methods of construction for the area surrounding the removable bottoms of bottom-blown furnaces. The inner rings of these furnace linings are often replaced when bottoms are installed.

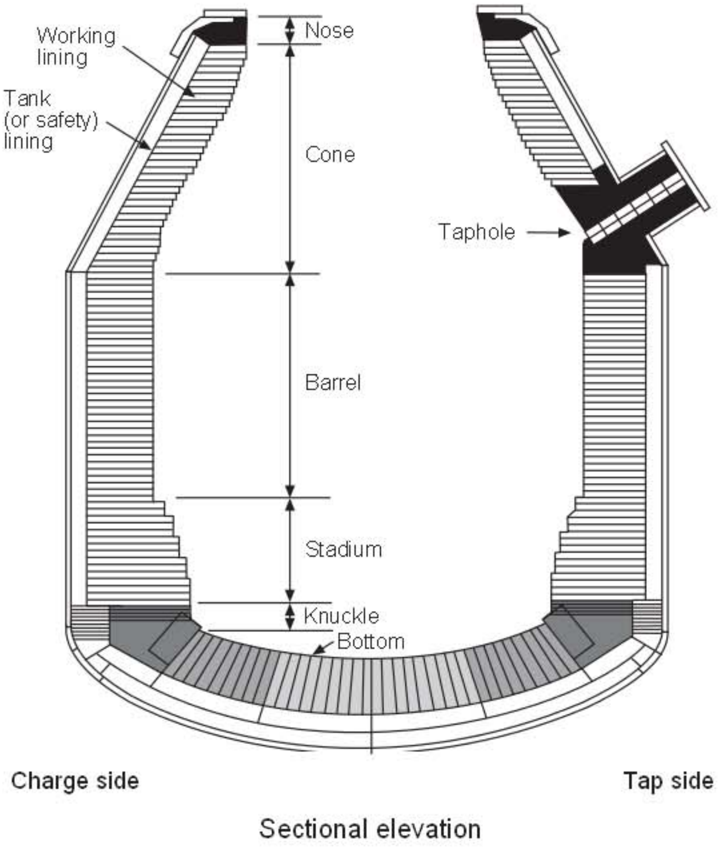


Fig. 4.6 Typical BOF cross-section.

Fig. 4.9 shows the construction of a removable bottom where brick are layered around bottom tuyeres in a manner that only one tuyere is contained in a given brick row to avoid stress buildup in the refractories. As shown in Fig. 4.10, two special shapes are used to obtain a tight fit around the tuyere itself. The construction and operation of tuyeres have been discussed in prior chapters. Similar complex constructions may be required when bottom stirring by inert gas injection is used.

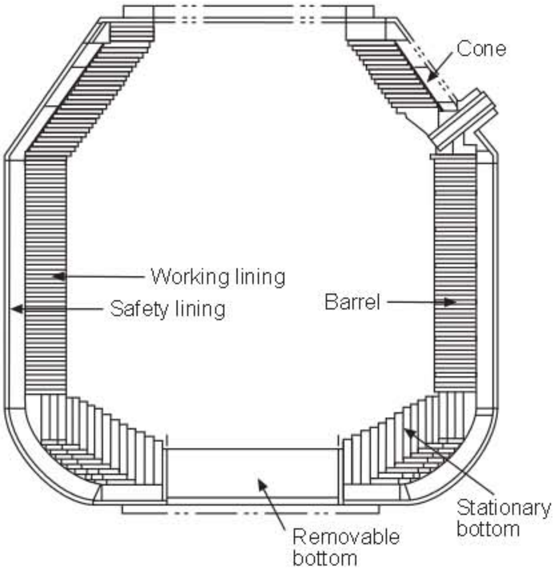


Fig. 4.7 General appearance of OBM/Q-BOP lining.

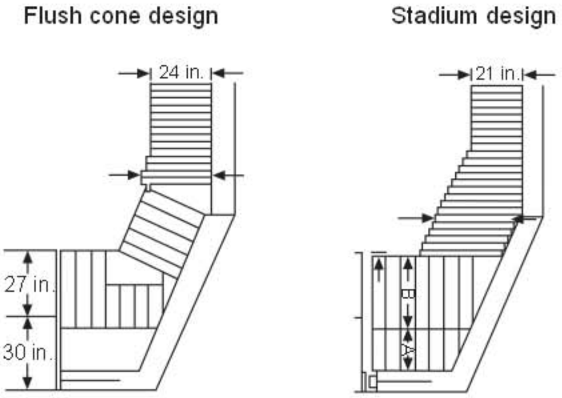


Fig. 4.8 Stationary bottom designs.

Fig. 4.11 shows construction when such inert gas devices (canned bricks, porous bricks, annulus tuyeres, etc.) are employed.

The previous illustrations were presented to give a flavor of the variety of refractory constructions possible in oxygen steelmaking furnaces.

As refractory linings become more complex, the increased thermal rigidity of the newer types of materials resulted in problems with overstressing the refractory and/or steel shell or trunnion support ring. Many modern linings now incorporate thermal expansion allowance on the brick using compressible materials such as special tapes between the brick in a given ring (horizontal expansion) and using compressible fibers between rings (vertical expansion). The amounts of such expansion may be estimated using stress-strain measurements on refractories and computer finite element analysis.

Relines on oxygen steelmaking furnaces are highly organized and planned to achieve furnace turnaround times of four to ten days, depending on other work done on the furnace auxiliaries at the same time.

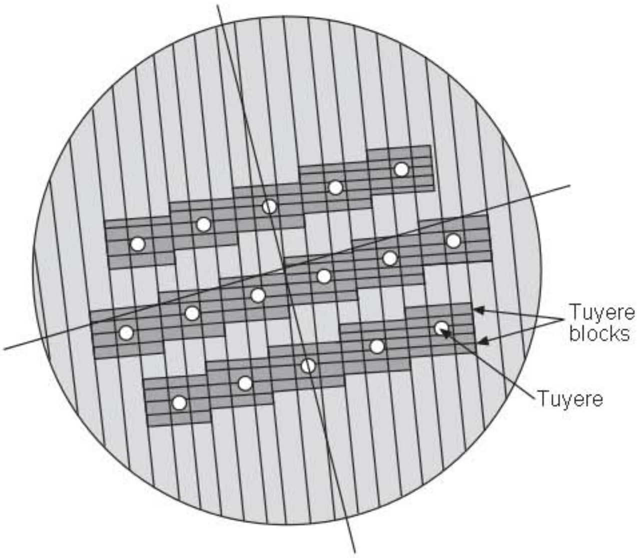


Fig. 4.9 OBM/Q-BOP bottom using bias brick lay-up.

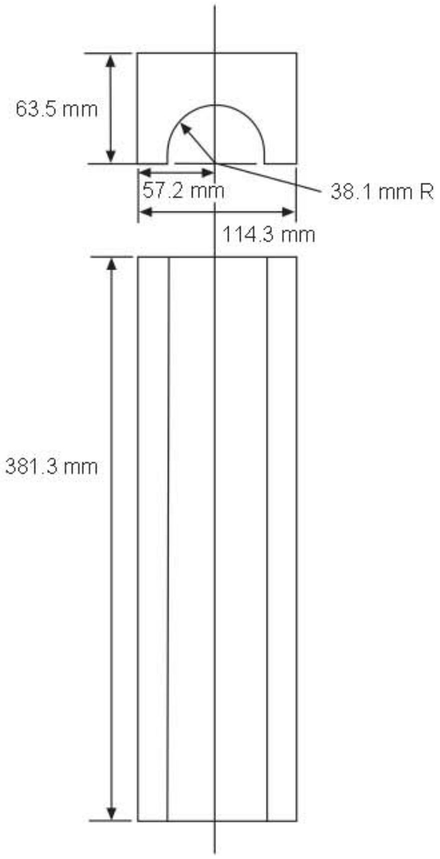


Fig. 4.10 Special shapes used around tuyeres.

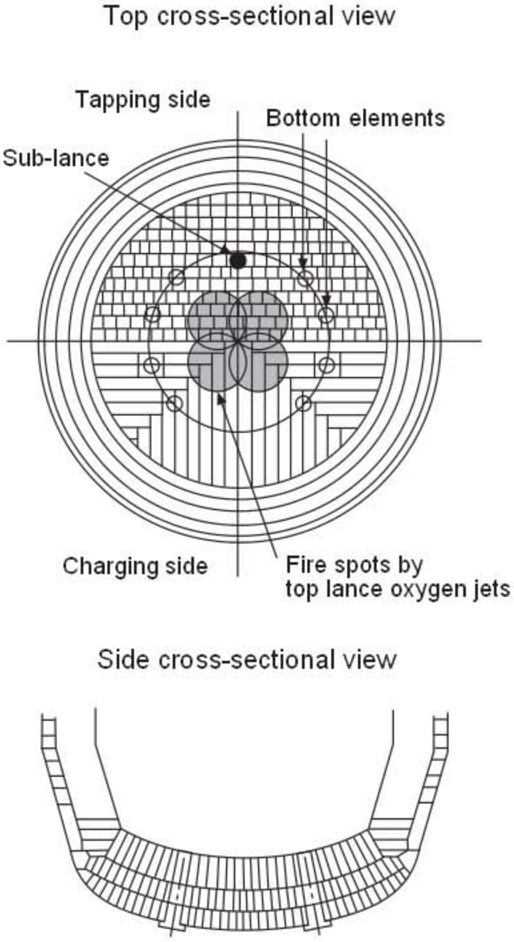


Fig. 4.11 Top and side cross-sectional views of one possible element pattern relative to the top lance oxygen jets and sub-lance sampling point.

4.1.5 Furnace Burn-In

The refractories in all types of oxygen steelmaking furnaces are heated rapidly to avoid unnecessary carbon oxidation from the brick. Fig. 4.12 shows a typical burn-in of four hours followed by immediate charging of the first heat. As described in Chapter 8, fuel for the burn-in is provided by coke charged on the furnace bottom and burned by the oxygen lance and/or by fuels through the tuyeres in a bottom-blown furnace.

4.1.6 Wear of the Lining

Wear of the lining is a complex process as illustrated in Fig. 4.13. As shown, wear may occur by a combination of various physical and chemical parameters and can be expected to differ not only by inherent differences in the process, (for example, top vs. bottom-blown) but also from site-specific parameters such as vessel shape or hot metal composition. The following is a brief discussion of some of the parameters which may affect lining wear.

4.1.6.1 Considerations of Slag Formation

Slags are a necessary part of steelmaking in that they remove impurities, such as sulfur and phosphorus, from hot metal. However, slag attack is the main mechanism of wear to a BOF lining. The

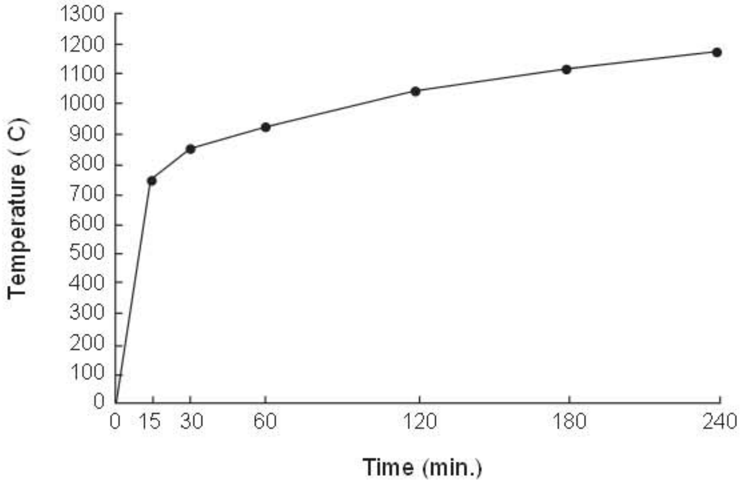


Fig. 4.12 Typical time-temperature curve for burn-in.

considerations of slag formation begin with the scrap and hot metal composition. In the following section, only the hot metal composition, the primary source of many of the oxide constituents in the slag, will be addressed. The components of most concern in the hot metal are: sulfur, phosphorus, silicon, manganese, and titanium. During the blow, liquid slags are formed by the oxidation of the metallic components of the molten metal (including iron), coupled with the addition of fluxes, such as CaO (burned lime), MgO (burned dolomitic lime), and CaF_2 (fluorspar or spar). The fluxes serve two purposes—they aid in achieving the proper chemical composition to remove sulfur and phosphorus from the metal bath, and, except for fluorspar, they protect the lining from attack by FeO and SiO_2.

The main constituents of slag are: SiO_2, CaO, MgO, Fe_xO_y, TiO_2, Mn_xO_y, P_2O_5, and CaF_2. The composition of the slag is shown in Fig. 4.14. The oxidation of silicon to form silica occurs early in the process and is very rapid. The FeO and manganese oxide are also formed early in the blow.

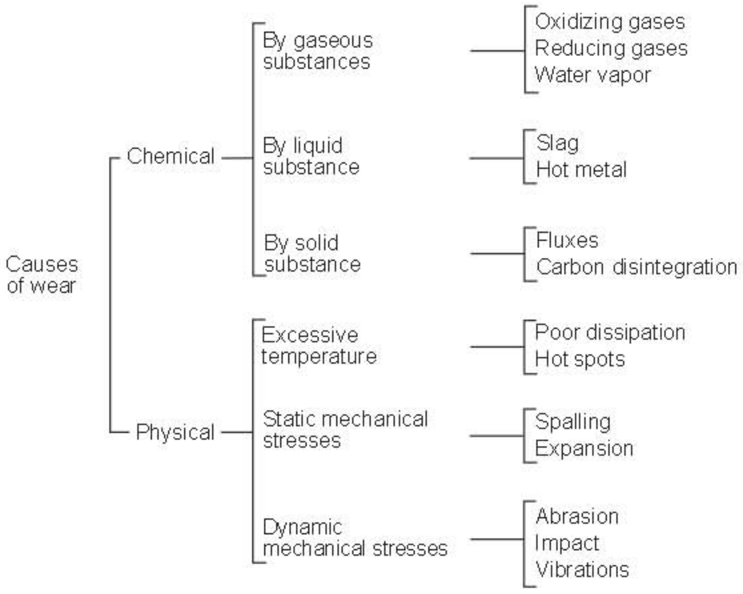


Fig. 4.13 Causes of wear in BOF linings.

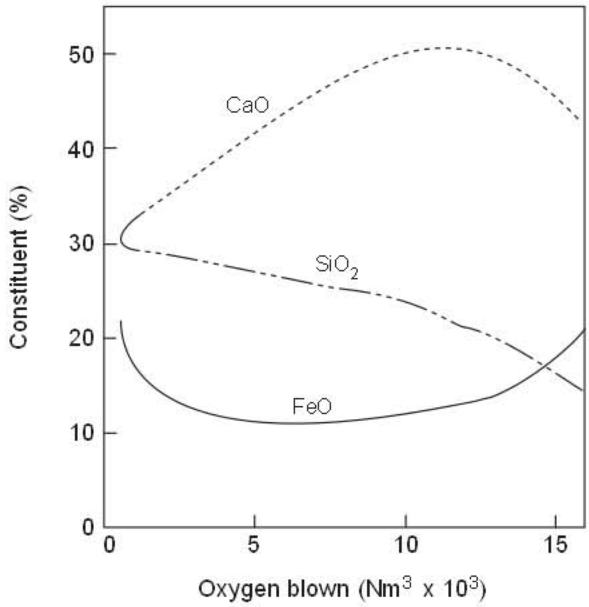


Fig. 4.14 Evolution of slag composition during the blow.

The percentage of FeO decreases as the blow progresses; however, toward the end, when the carbon levels are low, FeO will again increase. Silica reaches a maximum approximately 20–40% into the blow and then decreases while CaO continues to dissolve in the liquid slag. In the final stages, as FeO increases rapidly, the percentages of both CaO and SiO_2 are reduced.

The FeO that is formed both oxidizes the carbon in the carbon-containing refractories and forms liquids with the calcium silicate bonding phases found in the magnesite portion of the brick. The oxidation of carbon is of concern as many BOF refractories are carbon-bonded, and thus become quite weak when the carbon is removed. Also, carbon acts to prevent slag intrusion into the brick structure, and once the bricks are decarburized, the slag resistance of the refractory is diminished significantly.

The silica that is formed early in the blow is very corrosive to the refractory lining and reacts with the MgO to form low-melting compounds. Furthermore, as lime is dissolved into the liquid slag, the early slags, which have a lime-to-silica ratio close to 1.0, are extremely corrosive to the lining.

CaO must dissolve into the slag quickly to protect the lining for the reasons discussed above and to aid in removal of impurities from the molten bath. A limiting aspect of the dissolution of lime is that SiO_2 reacts with the CaO to form a dicalcium silicate shell around the lime particle. This dicalcium silicate layer is very refractory and dissolves slowly.

MgO additions to the slag are well known in reducing slag attack on a BOF lining. Two approaches are used. The first is to add sufficient MgO via dolomitic lime to guarantee adequate saturation of the slag throughout the blow. The second approach, which prevails today, is to add more than enough MgO to saturate the slag. The latter approach results in a buildup on the vessel walls which can greatly extend lining life when properly used.

Very thick layers of MgO-enriched slag may also be frozen on a specific worn area of the furnace such as the charge and tap pads. This practice requires some amount of furnace delay and must be accomplished while the other furnaces in the shop are available.

The reactivity of the lime has an influence on the resulting dicalcium silicate layer formed. A low-reactivity lime forms heavy, coarsely crystalline and adherent rims while a reactive lime produces the opposite results. The amount of fluorspar and other fluxes that must be added to dissolve this rim depends on the reactivity of the lime.

4.1.6.2 Other Factors Affecting Lining Life

A multitude of other factors which may be site or process specific can affect lining life and a brief review of these parameters may be helpful in understanding differences in lining behavior.

4.1.6.2.1 Hot Metal Differences Hot metal with higher silicon or phosphorus content will require the use of different slag practices and will cause more severe lining wear. Metal pre-treatments to reduce sulfur or other impurities greatly simplify slag processing and produce less severe conditions.

4.1.6.2.2 Scrap Variations Processing larger amounts of scrap can complicate slag development and reduce lining life. Some shops have increased damage from scrap charging because of limitations in charging equipment design.

4.1.6.2.3 Tap Temperature Requirements Tap temperature requirements depend on the subsequent processing to be involved before continuous casting (degassing, refining) and the ability to reheat steel in ladles. Higher tap temperatures will significantly lower lining life. Some processes also remove carbon during degassing which can further reduce tap temperatures.

4.1.6.2.4 Reblows and Heat Times An increased number of reblows and/or longer heat times will also have significant effects on lowering lining life. Improvements in processing which reduce these variables (dynamic controls, etc.) will improve lining life.

4.1.6.2.5 Lance/Tuyere Design and Practices Changes in lance practice and design or improved tuyere designs can cause substantial changes in refractory behavior.

4.1.6.2.6 Production Rates Shops operating in a manner to fully utilize furnaces minimize furnace cycling and improve lining life.

4.1.7 Lining Life and Costs

The current life of oxygen steelmaking furnaces varies widely from 1500 to 15,000 heats. The longer lining lives are achieved by extensive use of slag splashing to protect the brick lining as will be described in Section 4.2. Lives of 1500 to approximately 5000 heats can be achieved using brick linings balanced by refractory gunning and slag patching on a periodic basis. In the gunning process, refractory materials ranging in MgO content, from 40% to above 90%, are applied pneumatically to selected areas of the furnace. The so-called "programmed" gunning is designed to extend lining life without increasing overall costs or causing delays which would reduce steel production. Fig. 4.15 shows a typical campaign where gunning was used starting after approximately 1400 heats to extend the overall life to approximately 3500 heats. Note that the lining was removed when overall costs started to slightly increase.

The use of improved brick linings, dolomitic lime to promote slag buildup, programmed gunning and slag splashing or periodic patching have all extended lining lives. These techniques have not

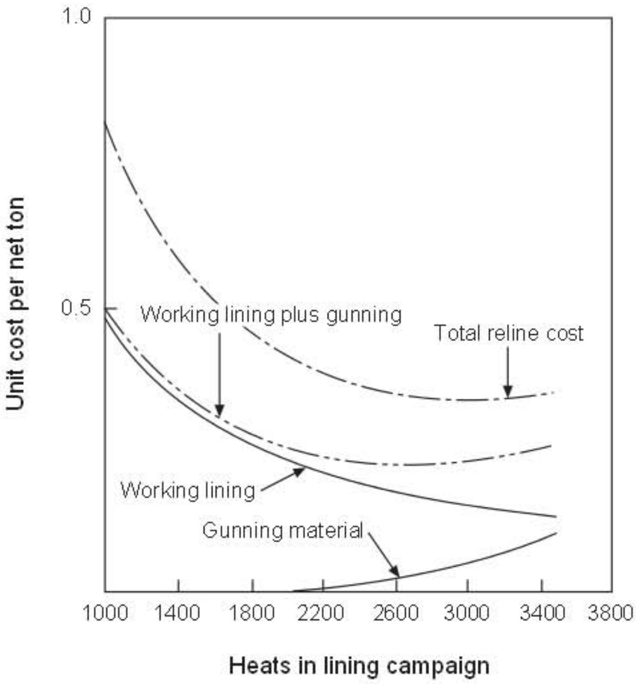


Fig. 4.15 Cost curve showing how gunning material can increase costs in longer campaigns.

proven as successful to-date in shops using the bottom-blown processes. Significant cost reductions have also been achieved so that the current refractory costs of oxygen processes are now only 8–15% of the total refractory costs in the modern steelplant.

4.2 BOF Slag Coating and Slag Splashing

4.2.1 Introduction

For the steel industry, as occurs in other industries, about the time a process appears to plateau in development, a new infusion of technology takes off and another round of experiments and associated technologies are applied to the process. In the past, several areas have been going through these stages simultaneously—bottom stirring in steelmaking, switching from ingot to continuous caster production, and resin-bonded magnesia–carbon brick in the refractory sector. While the emphasis of Section 4.2 is on slag coating and splashing of BOF refractories, the importance of operations and operational changes on refractory performance cannot be stressed strongly enough and have been described in recent publications.[1,2]

4.2.2 Slag Coating Philosophy

Slag coating and splashing substantially contribute to maintaining furnace lining profiles for safety and performance. Slag coating is an art form that requires considerable attention if it is to be done most effectively. Actions that make coating practices successful include: selecting the right slag, making the right and proper amount of additions, rocking the vessels correctly, disposing of the slag when necessary, and coating when it is the best time. These items need to be thought out and well executed.

As in the case of gunning, time to slag coat can often be found, even in most two-vessel operations. A successful slagging program utilizes established rules, and strict adherence to those rules is a key. It should be kept in mind that the vessel does not have to look pretty to accomplish long lining life, Fig. 4.16.

4.2.3 Magnesia Levels and Influences

Magnesia in the slag works against the steelmaking demands such as yield, phosphorus removal, and bottom stirring. The trick, therefore, is to maintain the lowest magnesia level required to accomplish the metallurgical and operational goals and still protect the refractory lining.

The magnesia in the slag is also a very important factor in slag coating technology (with and without slag splashing). It is not desirable to have low magnesia slag on long life vessels. The objec-

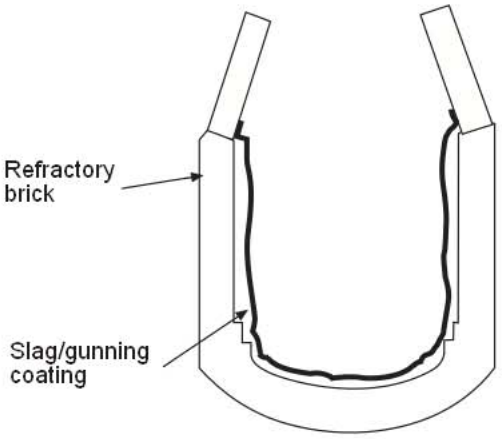


Fig. 4.16 Slag coating techniques by rocking the vessel create a working lining of slag that may be constantly replenished.

tive is to charge more magnesia than the saturation level of the slag to make the slag more refractory. This results in improved coating characteristics of the slag, so when it is thrown on the vessel walls, as with slag splashing, it will resist removal by the following heat. Alternate sources of sized magnesia of +90% are potential materials for slagging pads in combination with the vessel slag. These magnesia sources are typically lower cost magnesia units and possibly solve basic brick recycle problems.

Thus far, magnesia levels (MgO) in the 8–11% range have not adversely affected phosphorus removal in North American melt shops.

4.2.4 Material Additions

Alongside the normal flux charge, there are a number of potential material additions that can be made at different times in a heat, from beginning to end. A cost effective approach is to use low cost materials such as limestone or dolomitic stone, slag, ground brick, etc. Also, BOF slag can be added with the initial flux charge for early slag development. Another early charge technique, called stone-to-foam, is done for trunnion protection. This utilizes a carbonate limestone or dolomite to create CO_2 gas that aids in the foaming of the slag. When using carbonates, care should be taken regarding the effect on the offgas system.

Towards the end of a heat, dolomitic lime, dolomite stone, ground-up recycled brick, and magnesia are used to cool the slag and condition the slag regarding refractoriness and coating characteristics. Other materials (magnesia and carbon) are added at the end of the heat to foam the slag, similar to EAF slagging techniques. A magnesia (MgO) addition may be charged to the slag on extra low and ultra low carbon steels for additional lining protection.

4.2.5 Equilibrium Operating Lining Thickness

The ideal operating mode of a long life vessel is one where a lining wear equilibrium is reached and maintained. From experience, thermal equilibrium appears to be established at a lining thickness of 380 mm (15 in.) from a starting thickness of 762 mm (30 in.). The lining settles in between 127 mm (5 in.) and 381 mm (15 in.) of remaining working lining thickness, Fig. 4.17. In most shops, special attention is paid to the tap pad and the trunnion areas, which may have as little as 25 mm (1 in.) and 76–102 mm (3–4 in.) brick remaining, respectively. These thin areas demand that the lining be laser-measured a minimum of once a day and as often as every turn, with special attention being paid to the worn areas. From an operating perspective, a worn vessel produces heats with increased yield when compared to a new vessel.

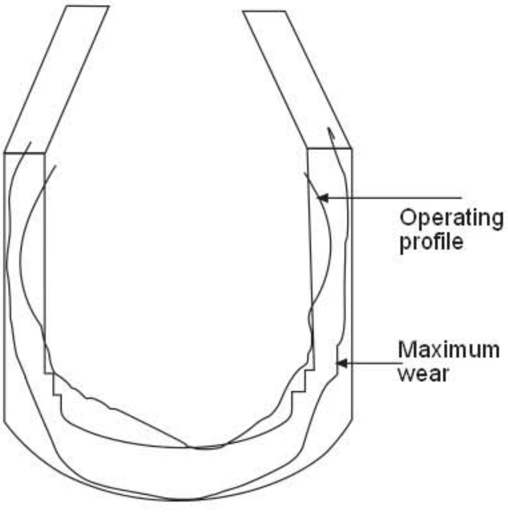


Fig. 4.17 Operating and maximum wear profiles on a extended campaign life of approximately 15,000 heats at a gunning rate of 0.37 kg/tonne.

4.2.6 Other Refractory Maintenance Practices

Those steps, independent of slag splashing, that will aid the maintenance of BOF linings are presented in Table 4.2. Note that these are recommended practices that are beneficial with or without slag splashing as they will extend refractory lining life.

Table 4.2 Additional Steps for Refractory Maintenance

- Slag furnace as often as possible
  - Selectively coat worn areas
  - Space high FeO-slag heats if permissible
  - O_2 wash bottom when needed
  - Use crushed brick, especially for tap and charge pads
- Gun furnace to fill holes in slagged or refractory lining
- Use shooter-type gun
- Keep cone skulls from building up
  - Use proper lance height settings
  - Deskull often, do not let skulls get too large
  - Apply parting agent after deskulling
  - Laser measure vessel daily

4.2.7 Laser Measuring

It is best to laser-measure the lining thickness once per day to establish the lining status (profile) and to distribute color coded copies of the lining profile to the furnace crew, vessel pulpit, and operations management. Areas of the vessel that should be measured daily are the tap pad, the bottom, and the trunnions. When areas of less than 127 mm (5 in.) thickness are noted, an action plan should be implemented. This plan should include gunning as required, the use of a slag conditioner, slag coating the lining after every heat in the vessel from nose to nose, and taking a follow-up laser measurement reading eight hours after the low thickness reading.

Early in the campaign, wear rates on brick can be measured and the influences of the operation can be determined due to the presence of little or no gunning. Once gunning and slag splashing commences, laser readings are best used to maintain lining/slag thickness.

4.2.8 Slag Splashing

The technique of slag splashing has reduced refractory costs and increased productivity by increasing vessel campaign life to years instead of months. This technology was maximized in the early 1990s and has proven to be cost effective.[2] It entails the use of the oxygen lance to blow nitrogen on the residual slag, after tapping a heat, to coat the walls and cone of the converter with slag, Fig. 4.18. The process has greatly reduced the need for gunning of the lining by more than half. Two slag splashing practices are known: (1) with the vessel empty of steel and all the slag remaining in the vessel, as shown in Fig. 4.18, and (2) with the both the molten steel bath and slag in the vessel.[3] The latter method is specific in coating the trunnions and the upper reaches of the furnace. The blowing practices are different for these two techniques.

Slag splashing utilizes the technique of working off a slag coating instead of the working lining brick or its gunned coating. Slag splashing requires only a minute or two to perform and is done while the vessel is in a vertical position after a heat is tapped. The nitrogen flows are often automatic and are based on lance height at the start of a splash. Currently slag splashing refinements are continuing to be optimized, i.e., tuyere cleaning, placing the slag in a specific area, and/or best

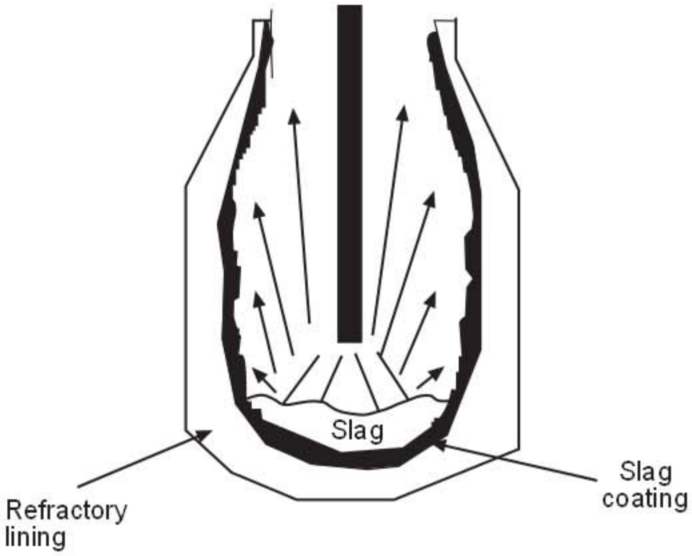


Fig. 4.18 Schematic presenting how nitrogen blowing onto a slag bath produces a slag coating that protects the working lining brick.

slag chemistry for coating. The emissions during the slag splashing period have caused no pollution problems.

4.2.8.1 Lance Buildup

Because slag splashing tosses the molten slag in all directions, the lance is also coated with slag. It is quite important that no steel in the vessel is present as it adds to the difficulty of the lance skull removal. Lance slag buildup removal can be aided by a low pressure water spray that eliminates the slag. Also, alternating lances has been found to be beneficial in slag removal from the lance.

4.2.8.2 Slag Splashing Augmented by Gunning

To attain extended campaign life on a lining, it is necessary to gun areas that encounter severe wear such as the trunnions and slag lines. The best refractory costs, as expressed in cost/ton, Fig. 4.19, are achieved by the selective use of gunning materials.[2] In the past, on long campaigns, gunning material costs could exceed the cost of the original magnesia–carbon lining. Therefore, the use of

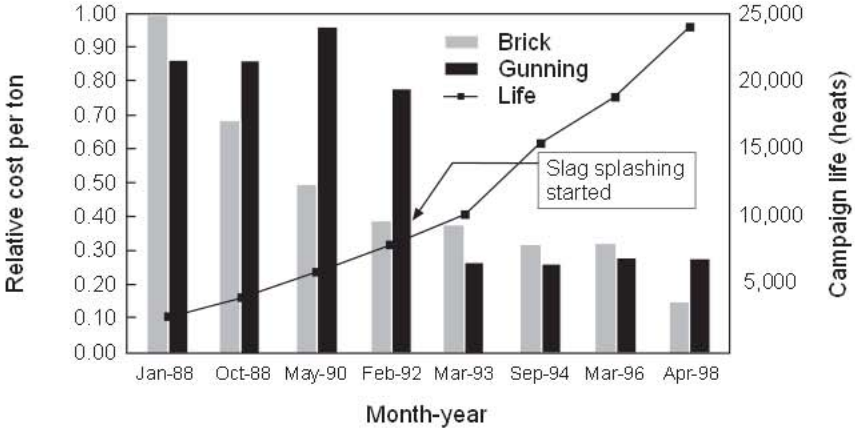


Fig. 4.19 Cost reductions have been considerable with the institution of slag splashing; especially note the reduction of the gunning cost/ton.

the exact amounts of gunning material in the right areas of the vessel, as directed by the laser readings, will yield the overall lowest refractory cost per ton.

Gunning has the potential of being a major improvement area in refractories. It hold great promise as considerable research is being applied to gunning materials. The shooter-type gun has made the application process what it should be under the hostile environment of the hot vessel, and with new gunning materials, it is anticipated that more effective gunning will occur in the future.

4.3 Refractories for Electric Furnace Steelmaking

Refractories for electric arc furnace (EAF) steelmaking are selected based on operating conditions and furnace design features that impact refractory performance. Steelmakers use electric arc furnaces to produce steel from scrap and/or alternative iron units under similar operating conditions. The charge is melted, using fluxes to maintain a basic slag chemistry, tapped at roughly 3000°F, and the furnace is again charged for another heat cycle. These operating conditions require chemically basic refractory products with excellent resistance to high temperature and thermal cycling. Furnace design features of present day electric melting technology require specialized refractory linings. There are various design features, but they are broadly grouped into three areas: tapping design, side tap vs. bottom tap; power source, AC vs. DC power; and the use of supplemental oxygen to increase the melting rate.

4.3.1 Electric Furnace Design Features

Side tapping electric furnaces have a spout extending from their furnace sidewall to transfer the heat to the ladle. The spout is refractory lined, and a taphole through the furnace sidewall connects the furnace interior to the spout. Side tap furnaces tilt approximately 45°, requiring a higher refractory sidewall lining on the tap side of the furnace to contain the molten steel. See Fig. 4.20 for a typical side-tapping electric arc furnace. Bottom tapping furnaces have their taphole through the bottom hearth section of the furnace and require special taphole refractory products. Bottom tapping also enables reduced height refractory sidewalls due to the reduced tapping tilt angle of approximately 15–20°. See Fig. 4.21 for typical bottom-tapping furnace.

Alternating current (AC) power sources require three electrode columns within the furnace for the three electrical phases. These three electrodes have increased arc flare during operation that can

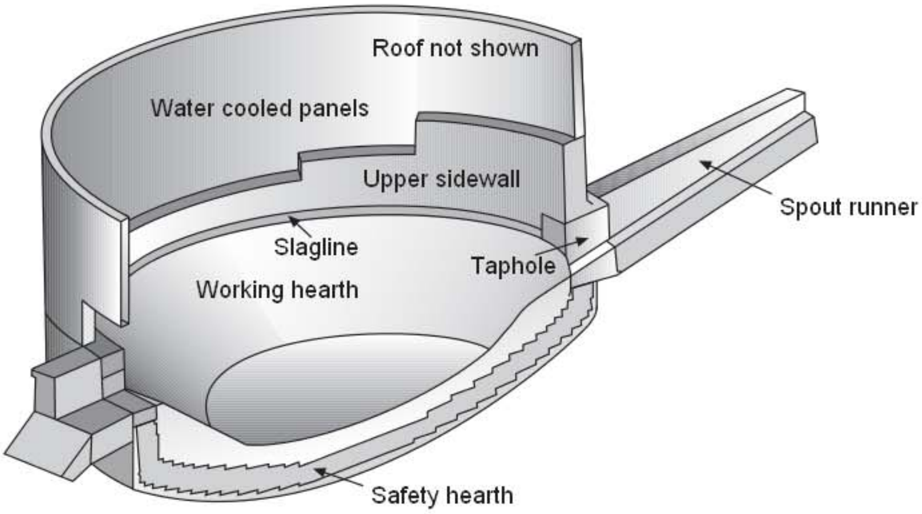


Fig. 4.20 Typical side-tapping EAF.

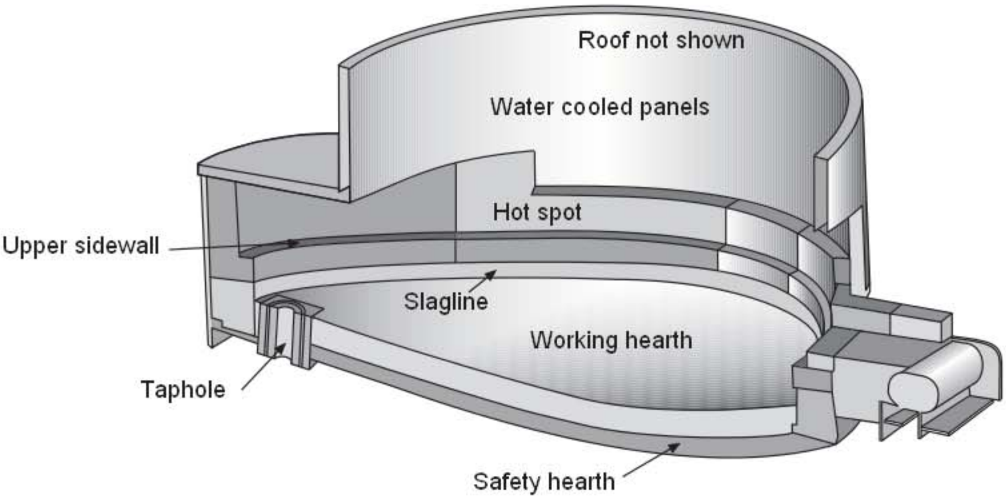


Fig. 4.21 Typical bottom-tapping EAF.

impinge on the refractory sidewalls, resulting in hot spots which must be addressed by refractory design. AC furnaces also require three holes through the refractory roof and the center section of the refractory roof between the electrodes is often an area that limits furnace performance. Direct current (DC) furnaces utilize a single electrode through the roof with the electric arc passing directly to the steel bath that contacts the bottom anode electrode to complete the electrical circuit. DC furnaces have less arc flare to the refractory sidewalls and therefore no hot spots. Roof design is also less complicated with less difficult operating conditions. However, the furnace hearth must contain the bottom electrode, which complicates refractory design there.

The use of supplemental oxygen lances and burners to increase melt rates impacts refractory design and performance. Oxygen directed from lances or burners can be deflected by scrap or charge materials and impinge on the refractory lining, resulting in localized overheating and rapid refractory wear. Localized oxidizing conditions can also occur which cause rapid refractory lining erosion.

4.3.2 Electric Furnace Zone Patterns

Even with the individual differences of operating conditions and furnace features, EAF steelmaking can be broken down into specific zones that have differing refractory requirements. These zones within the furnace, the specific operating conditions for that zone, and the analysis for refractory lining selection are discussed below. Fig. 4.20 shows the zones for side tapping electric furnaces; Fig. 4.21 for bottom tapping furnaces. Key zones of EAF steelmaking furnace are first, the hearth, which contains the molten steel as well as the initial charge materials. The furnace slagline is the transitional area between the hearth and the furnace sidewall. The upper sidewall is the refractory portion of the furnace walls above the slagline and below the water-cooled panels. The taphole is the opening that permits the molten steel to exit from the furnace. The roof has a refractory portion, occasionally referred to as the delta, which provides openings for the electrode(s) to enter the furnace, and an opening for furnace exhaust fume to exit the furnace to a bag house. Relative refractory consumptions by zone are presented in Fig. 4.22.

4.3.2.1 Hearth

The hearth zone of an EAF must contain molten steel at high temperature and resist the impact of heavy charge materials. In addition the hearth must withstand corrosion by molten slag as the furnace is drained. A typical EAF uses a two component refractory hearth of approximately 9 in. of

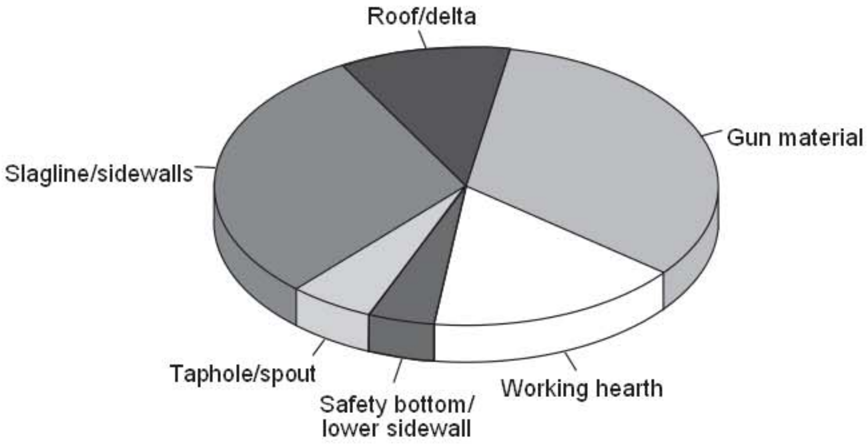


Fig. 4.22 Relative EAF refractory costs by zone, including hearth gunning material.

brick as a safety hearth against the bottom steel shell and 12 to 24 in. of monolithic magnesite as a working hearth. The safety lining brick should be 90–97% MgO content. These brick have the strength and slag resistance capability to contain the molten bath in the unlikely event steel or slag penetrates the monolithic working hearth. The safety hearth brick function as a permanent lining and would be changed infrequently, possibly every year or two. The monolithic hearth material is also a high magnesia product (60–95% MgO) and is a dry granular material. The grain sizing of the hearth material is formulated to compact easily by using vibration equipment during installation. High temperatures from the initial heat of steel causes sintering—bonding, densification and strengthening—in the monolithic hearth product, and the hearth becomes quite strong and penetration resistant. The hearth lining is designed so that approximately the top third of the thickness of the monolithic material is fully sintered, while the middle third of the lining is only partially sintered and the bottom third of the monolithic material against the safety lining brick is unsintered. This layering effect facilitates patching the hearth refractories when steel or slags damage the hearth through penetration or corrosion. The damaged area can be cleaned out by removing the penetrated, sintered magnesite and repaired with new monolithic material, which sinters in place forming an effective patch.

In DC electric arc furnaces the hearth refractory design must incorporate a bottom electrode. Operating conditions for the bottom electrode refractories are severe. Localized high temperatures and extreme turbulence are common at the surface of the bottom electrode. These conditions require refractories with high temperature stability and strength. For DC furnaces using pin or fin bottom electrodes, the same dry vibratable magnesite product can be used; although some steelmakers prefer a more temperature resistant, higher MgO product for the electrode. DC furnaces with bottom electrodes using larger diameter pins or billets often use special brick shapes surrounding each pin or billet to form the bottom electrode. Another design utilizes conductive refractories, either brick or monolith, which are a combination of magnesite and carbon, to carry the electrical current from the bath to the copper electrical connections at the bottom of the furnace. Conductive refractories are a complicated blend of high purity magnesia, graphite, and powdered metals to achieve the required combination of high temperature refractoriness and electrical conductivity to contain the molten steel as well as conducting current. (Bottom tapping electric furnaces also have a taphole through the hearth, but their refractory considerations will be covered in Section 4.3.2.4 on tapholes.)

4.3.2.2 Slagline

The slagline of electric arc furnaces is the transitional area between the hearth and upper sidewall. This area is subject to high temperatures from exposure to the electric arc, oxidation and flame impingement from supplemental oxygen injection, and most importantly, slag attack from high temperature slags containing FeO, SiO_2, and MnO. Slagline refractory design in the electric furnace is a combination of brick and monolithic products. Most common is a slagline 12 to 18 in. in thickness using magnesia–carbon brick with 10–20% carbon content. The carbon phase of the brick is composed of graphite and a carbonaceous resin bond. These carbon materials have excellent resistance to attack by steelmaking slags and have excellent high temperature resistance. However, the carbon is susceptible to oxidation. Often powdered metallic aluminum, silicon, or magnesium are added to the slagline magnesia–carbon brick to protect the carbon from oxidation. These metallics combine with carbon to form carbides which are more oxidation resistant and strengthen the refractory brick as well. Strength is important to resist the erosive action of molten slag and steel washing against the slagline zone in the furnace. Magnesia–carbon brick in the slagline are additionally protected by monolithic refractories. Initial installation of the monolithic hearth usually covers all or part of the slagline brick. However, this hearth material corrodes or erodes rapidly due to the difficult operating conditions in this zone of the furnace. Additional protection for the slagline is afforded by injecting a magnesite gunning mix into the furnace and building up a protective layer on the slagline. Again, this protective layer does not last long and must be replaced at regular intervals depending on the severity of the operating conditions.

4.3.2.3 Upper Sidewall

The upper sidewall zone of electric arc furnaces is lined with magnesia–graphite brick of a similar quality to the brick used in the slagline. The upper sidewall is subject to arc flare (very high temperatures) and impingement by heavy scrap during the charging process. During the tapping process, as the furnace tilts, molten steel and slag contact the upper sidewall brick on the tap side of the furnace. Lastly, upper sidewall brick must be able to withstand corrosion by steelmaking slags and flame impingement from oxygen lances and oxy-fuel burners. Magnesia–carbon brick of 5–20% carbon give cost effective service in upper sidewall linings. Various qualities and purities of magnesite, graphite, and powdered metals are utilized. In AC electric arc furnaces, which have hot spots in the upper sidewall, higher quality brick are used in the hot spots. These higher quality products are based on fused magnesia grain compared to the sintered magnesite grain in standard quality brick products. The fused magnesia brick have improved high temperature resistance but are considerably more costly.

4.3.2.4 Taphole Refractories

Taphole refractories are required for both side tapping and bottom tapping electric furnaces. Operating conditions in both types of furnaces are similar; hot molten steel, and to a lesser degree slag, flowing through a 5 to 8 in. diameter hole at considerable velocity erodes the refractories in the taphole. In the side-tapping furnace the taphole refractories have several alternative designs. The first and simplest design is to leave an opening in the sidewall brickwork while constructing the refractory lining. Then when all brickwork is completed, either a refractory taphole sleeve or a steel pipe is positioned in the taphole opening. Then MgO-based gunning mix is used to fill in the void between the sleeve or pipe and the adjacent brickwork. A second alternative is to use a large taphole assembly with a pre-formed taphole. This assembly is set in place in the furnace prior to installing the sidewall brickwork. Once the taphole assembly is properly positioned, the adjacent brickwork is completed, creating a tight fit between sidewall brickwork and the taphole assembly. Refractory products are always high quality in the taphole. If the taphole is constructed with gunning mix sprayed around a steel pipe mandrel, the highest quality magnesia gunning mix is used. This product has maximum strength and erosion resistance to minimize the erosive action of the molten steel. If a taphole assembly is used or a refractory sleeve, these are also of high quality magnesia brick with carbon and metals. Metallic additions to magnesia–carbon taphole brick assemblies provide added strength and oxidation resistance in this critical application. The side-tapping furnace has a spout extending from the taphole to enable the molten steel to flow into the ladle. The spout is a precast monolithic runner shape placed in the runner steel shell during lining construction. This precast runner shape is made from a magnesia based castable if furnace operating practices result in slag entering the taphole and the furnace runner; the slag resistance of MgO is required to counteract slag attack. On the other hand, if furnace operating practices limit the introduction of slag into the taphole and runner, then high strength, high alumina castables are used for the precast runner. These high alumina runners generally last longer due to improved thermal shock resistance and higher strength as compared to magnesite precast runners.

Bottom-tapping electric arc furnaces require specially designed taphole sleeves and an end block to comprise the taphole design. The taphole sleeves sit within the hearth in a taphole seating assembly. The assembly can be constructed from either brick shapes or precast shapes which result in a roughly 18 in. diameter hole through the furnace hearth refractories. The taphole sleeves are centered within the taphole seating assembly and a basic castable or ramming mix is tamped in the annular opening between the sleeves and the seating blocks. Taphole sleeves are magnesia–carbon shapes made from high purity magnesia or fused magnesia grain and with 10–15% carbon content. Powdered metals are used as a strengthening agent to maximize erosion and oxidation resistance. The bottom of the taphole extends beyond the furnace shell utilizing a shape called an end block. This end block is a similar magnesia–carbon brick that is held in place by an end block casting attached to the furnace. The end block is exposed to the atmosphere outside the furnace and must have excellent oxidation resistance as well as maximum erosion resistance to withstand the erosive action of the taphole stream. The end block is most often the limiting factor in taphole performance. As refractory erosion occurs the tap stream begins to flare, increasing reoxidation of the steel. It is necessary to then do a hot repair to replace the end block and taphole sleeves. Typical taphole life in bottom tapping furnaces is 5–10 days of operation.

4.3.2.5 Roof

Electric arc furnace roof refractories for both AC and DC furnaces are generally high strength, high alumina (70–90% Al_2O_3) precast shapes. Because the roof lifts and swings away from the furnace body during the charging process, refractories in the roof experience excessive thermal shock. The lesser thermal expansion of high alumina castables compared to basic castables offer an advantage in withstanding thermal shock. In addition, high alumina castables are much stronger than basic castables; therefore high alumina roofs are better able to resist the stresses developed as the roof is lifted and moved during furnace operations. Electric furnace roof refractories last anywhere from less than a week to up to ten weeks in some steelmaking operations. The roof also enables furnace exhaust fumes to exit the furnace and be transported to a baghouse for dust control. While the immediate exit from the furnace is usually water cooled, there is a refractory lined zone in the duct system. Refractories in the exhaust ductwork must be capable of withstanding slag carryover and slag abrasion from particulate-laden gases moving at high velocity. Refractories in the ductwork are 50–70% alumina brick or fireclay/high alumina gunning mix (40–60% Al_2O_3). Both of these materials have the required combination of thermal shock resistance and slag resistance to withstand the operating conditions.

4.3.3 Electric Furnace Refractory Wear Mechanisms

4.3.3.1 Corrosion

Electric furnace refractories are subject to a variety of wear mechanisms which must be understood to properly design and manage electric furnace refractory systems. The most important wear mechanism is corrosion. This is the chemical reaction of metallic oxides in the slag, iron oxide (FeO), silica (SiO_2), or manganese oxide (MnO), with the refractory products. Magnesia from the refractory lining is soluble in the steelmaking slag, with saturation levels varying from 6 to 14%, depending on temperature and FeO content. These chemical corrosion reactions result in wearing away the furnace refractory lining; the products of reaction become part of the slag. Corrosion reactions can be minimized by neutralizing FeO with fluxes and controlling the oxygen content of the slag. Another way to control corrosion is to use refractory brick that contain carbon. This carbon in the refractory lining deoxidizes corrosive slag at the refractory/slag interface, minimizing lining corrosion.

4.3.3.2 Oxidation

A second critical wear mechanism in electric arc furnace linings is oxidation. In this process, carbon in the refractory lining is oxidized by reacting with oxygen or FeO in the slag. As the carbon in the refractory lining reacts, the brick loses its strength and is washed away. This carbon oxidation mechanism also occurs at the cold face of the brick if there are holes in the steel shell. Oxygen from the air reacts with the brick s carbon, and the back part of the brick lining turns to powder.

4.3.3.3 Erosion

Erosion is another prevalent refractory wear mechanism. This is the physical wearing away of the refractory due to molten steel or slag moving over the face of the refractory lining and physically abrading or eroding the lining. Erosion is most common in electric arc furnace tapholes, slaglines, roof electrode openings, and in the offtake ductwork.

4.3.3.4 Melting

Melting is also a common wear mechanism in the electric arc furnace. The unshielded electric arc generates temperatures that are well beyond the melting point of all commercial refractories. Melting is the simple phase change of the refractory from solid to liquid, and the liquid phase is easily washed away. Melting is a serious problem in electric arc furnace linings if not detected and corrected immediately.

4.3.3.5 Hydration

Because water cooling is used extensively in modern electric arc furnaces, there are occasional water leaks. Refractories are easily damaged by water or steam due to hydration of the magnesia or lime phases in the refractory product. Hydration results in expansion of the individual grains comprising the refractory lining. These grains grow and burst, disrupting the lining.

4.3.3.6 Spalling

A more subtle refractory wear mechanism is known as spalling. In this type of wear, rapid heating or cooling of the refractory lining cause stresses in the refractory lining. These stresses often exceed the inherent strength of the refractory material, resulting in cracking. As these cracks intersect, chunks of refractory fall out of the lining. This condition is most common on furnace roofs that are opened and closed to expose the refractory portion of the roof to cold air.

4.3.4 Conclusion

Refractory lining systems for EAF steelmaking are selected using a thorough knowledge of both operating conditions in the furnace and the impact of electric arc furnace design features. Refractory wear mechanisms can be minimized by a similar understanding of furnace operating conditions and their interaction with the available refractory products. As electric melting technology advances, refractory systems must be improved or developed which can counteract the increasingly difficult operating conditions.

4.4 Refractories for AOD and VOD Applications

4.4.1 Background

In the past 30 years, the AOD and similar type processes (CLU, ASM, K-OBM-S etc.) and the VOD, have become the dominant methods for the production of stainless steels throughout the world. In 1995, the total worldwide production of stainless steels was reported to be 14.9 million metric tons.[4] Over 85% of the stainless steel produced was through the AOD vessel or related processes. The balance was produced via various VOD ladle processes.

Dolomite and dolomite–magnesia brick are the most common (> 75% worldwide) refractory lining for the AOD vessel, but with significant magnesia–chrome and small amounts (< 2%) of magnesia–carbon brick also being used. In VOD ladle applications the same types and grades of refractories are used, but with more equal amounts of magnesia–chrome and dolomite–magnesia based brick, with the worldwide consumption estimated at 45% magnesia–chrome, 40% dolomite–magnesia and 15% magnesia–carbon brick. Monolithic refractories are not currently used as primary linings in AOD or VOD applications.[5]

4.4.2 AOD Refractories

4.4.2.1 Introduction

The types of refractories used in the AOD have evolved since the first AOD was put into commercial operation at Joslyn Stainless Steel, Ft. Wayne, Indiana in 1968. Magnesia–chrome refractories were initially used in the AOD, ranging from 60% MgO direct-bonded magnesia–chrome for use in the barrel to rebonded fused grain 60% MgO tuyere pads. In the early 1970s, the first dolomite based bricks were used in Europe.[6] The first dolomite lining used in the U.S. was in 1976. Since those initial trials, dolomite refractories have become predominant in AOD applications for three main reasons: economics; longer lining life—experience with dolomite based linings has shown that most vessels achieve or exceed lining life obtained with other basic refractories; and metallurgical benefits—the very basic nature of dolomite refractories allows the steelmaker to operate with higher basicity ratio slags, $(CaO + MgO)/(SiO_2 + Al_2O_3) > 1.4$, which improves chrome recovery, and desulfurization.[7,8] Dolomite bricks are chrome-free, enabling the steel producer to make both stainless and low alloy or chrome-free steel in a single AOD.

For those AOD applications which run at lower basicities, magnesia–chrome refractories may give lower overall costs. The factors governing the choice of magnesia–chrome over dolomite are generally lower slag basicities (< 1.4), extensive use of alternative alloy sources (recycled high-alloy slag, or direct reduction of chrome or manganese ore in the vessel), high process temperatures (> 1800°C), and local availability of competitively-priced magnesia–chrome refractories.

4.4.2.2 Life and Wear Rates

Each area of the vessel is subjected to different types of wear mechanisms. The primary wear mechanisms for AOD refractories can be classified as follows: corrosion by decarburization and reduction slags that can vary widely in basicity; erosion as a result of turbulence created in the tuyere region; thermal shock due to temperature variations during and between heats; and metal attack resulting from chemical reactions with strong reductants and fuels (Si, Al).

Life in the AOD vessel is partially a function of vessel size, due to turbulence effects, and ranges from 30–50 heats in vessels under 50 tons in size to greater than 120 heats in 90 ton and larger vessels. Consumptions range from 5–15 kg of refractory/ton of steel. Typically the highest wear/failure area is in the AOD sidewall tuyeres, or bottom tuyeres for a CLU type vessel. Side-blown vessels experience tuyere area wear rates of 2–8 mm/heat, with 5 mm/heat being typical. Bottom-blown vessel tuyere wear rates vary from 8–12 mm/heat. In the balance of both vessels, wear rates are typically 1–4 mm/heat.[5]

4.4.2.3 AOD Lining Construction and Zoning

4.4.2.3.1 Safety Lining AOD safety linings are constructed using standard grade, see Fig. 4.23, Table 4.3 and Table 4.4, fired magnesia–chrome or rarely, dolomite brick. Magnesia–chrome is used in 76–100 mm thick, fully mortared arch or bevel construction laid against the shell without insulation. When dolomite brick are used, special non-aqueous mortars must be employed. The cone usually is constructed without a safety lining in vessels less than 90 tons. Alumina brick or monolithics are not used for AOD safety linings because they lack sufficient resistance to the operating conditions to allow a heat to be completed on the safety lining without a breakout.

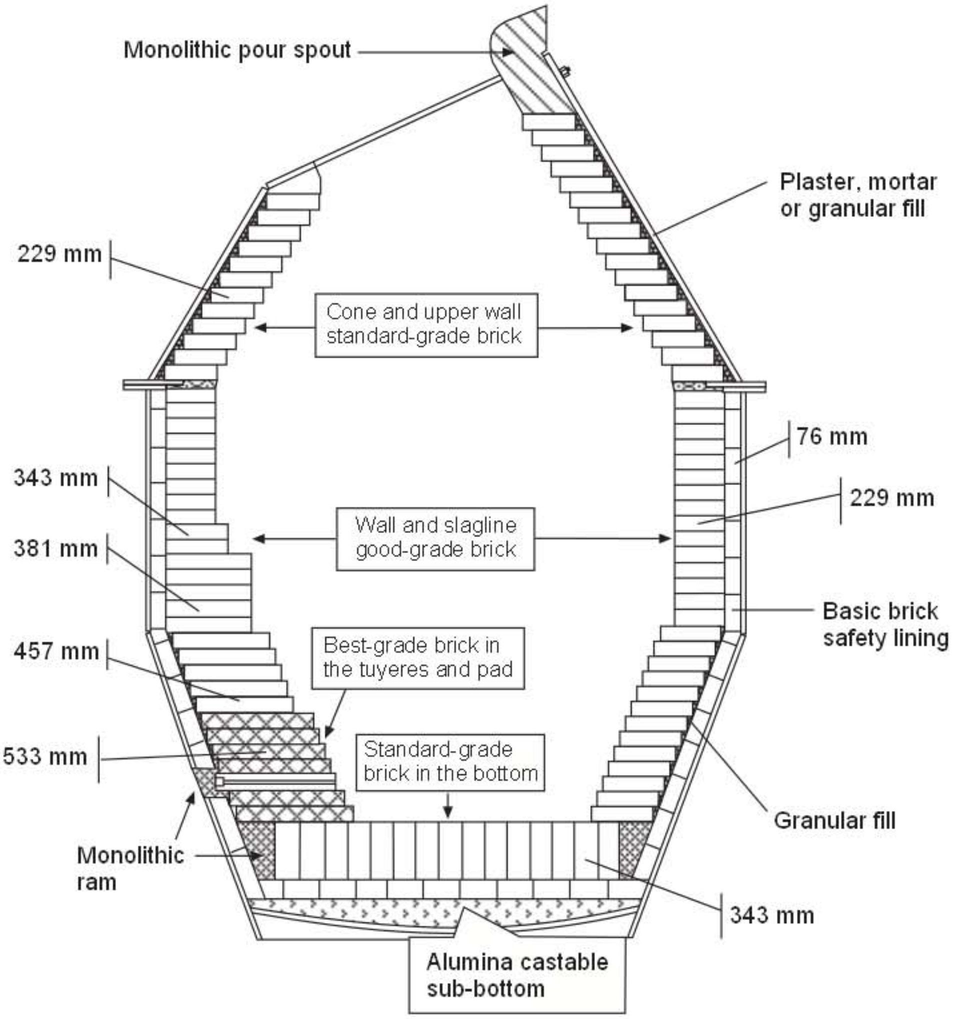


Fig. 4.23 Typical 45-ton flat bottom, side tuyere AOD vessel, showing quality zoning and relative brick thicknesses.

4.4.2.3.2 Working Lining One key to balancing AOD refractory wear patterns and reducing refractory cost per ton is careful attention to zoning and tight construction of the working lining. Zoning options include zoning the refractory lining by brick thickness, composition, or a combination of both thickness and composition. Fig. 4.23 illustrates the typical zoning of an AOD vessel. Dolomite working linings are typically constructed of straights and keys, laid dry (without mortar) and tight against the safety lining without expansion allowance. Backfill is only used where small gaps exist between the working and safety linings, especially in the stadium area. Sizing tolerances for dry dolomite linings must be tighter than ±1 mm, and are commonly ±0.8 mm. Magnesia–chrome linings frequently use mortared construction. If mortared construction is not used with magnesia–chrome, expansion allowances may be needed.

4.4.2.3.3 Bottoms Two types of bottom refractory construction are used in AOD vessels, flat and dished. Flat bottoms are simple to install, usually requiring only one size of straight sided brick. Dished bottoms require two to three keys and/or straight shapes, see Fig. 4.24. The main advantage of using the dished bottom design is that several tons of increased volume can usually be gained. The keyed construction also helps to retain the bottom refractories in position as the brick wears. Dolomite bottoms are laid dry, and dusted with dolomite fines. Magnesia–chrome bottoms are usually laid with mortar. The perimeter of the bottom (under the sidewalls) is rammed with monolithic

Table 4.3 Simplified Chemical and Physical Properties of Typical Dolomite AOD and VOD Bricks

	Grade						
	Standard	**Standard**	**Standard**	**Good**	**Good**	**Best**	**Best**
AOD Applications	Cone, barrel and bottom	Barrel and bottom	Barrel and bottom	Intermediate wear areas	Slagline	Tuyere and tuyere pad	Tuyere and tuyere pad
VOD Applications	Freeboard and bottom	Wall, bottom and impact pad	Freeboard, wall and bottom	Upper and lower slagline	Slagline	Slagline and stir pad	Slagline and stir pad
Brick Type	Resin-bonded dolomite	Resin-bonded dolomite	Fired dolomite	Fired MgO-enriched dolomite	Fired MgO-enriched dolomite	Fired MgO-enriched dolomite	Fired MgO-enriched dolomite
				Chemical Analysis (%)			
MgO		>38		~50	~60	~60	65–70
CaO		55–60		~45	~40	~40	~30
SiO_2							
Al_2O_3							
Fe_2O_3 + MnO				Total typically 2.3–2.8			
Cr				Typically <5 ppm			
B				2–10 ppm			
ZrO_2	—		—	—	—	<1	<1
C	2–3	4–6	—	—	—	—	—
				Physical Properties			
Bulk Density (g/cm^3)			>2.95			2.98	>3.0
Porosity (%)	<13*	<15*		11–15			<11
MOR As-received (MPa)			>13			>9	
MOR As-coked (MPa)	>2		—	—	—	—	—
Permanent Linear Change (after 1600°C)	—	—		–0.1 to –0.2		0	
Hot MOR at 1371°C (MPa)	>3				3–4		>5

Table 4.4 Simplified Chemical and Physical Properties of Typical Magnesia–Chrome AOD and VOD Bricks

	Grade				
	Standard	Good	Good	Best	Best
AOD Application					
VOD Application					
Brick Type					
Chemical Analysis (%)					
MgO	~50	~60	60–70	~60	~60
CaO			<1		
SiO_2	<2.5	<2	<2	<2.5	<2.5
Al_2O_3			7–14		
Fe_2O_3			6–11		
Cr_2O_3	>20	>16	>11	>19	>19
Physical Properties					
Bulk Density (g/cm^3)		>3.1		>3.2	>3.25
Porosity (%)	18	17	16	15	13
MOR As-received (MPa)		>5		>10	>14
Permanent Linear Change (after 1700°C)			+0.1 to +0.3		
Hot MOR at 1482° (MPa)	1	>2	>2	>4	>5

material. A typical non-aqueous basic monolithic used with dolomite linings is shown in Table 4.5. Alumina or chrome-based monolithics are used with magnesia–chrome linings, and should have a continuous service rating of >1700°C.

4.4.2.3.4 Tuyere Zone—Knapsacks Because of the high wear rate in the tuyere area, increasingly longer refractories (up to 1000 mm) are being used to extend vessel campaign life. However, longer tuyere pads in standard AOD shell designs can result in unexpected side effects, such as a reduction in vessel volume, increased slag splashing and changes in lining wear patterns. One method to increase the tuyere length without sacrificing vessel volume is the use of the knapsack. Also referred to as a doghouse or pod, an example is shown in Fig. 4.9. In the stadium section, notice the use of two bricks, one in front of the other. Using this construction technique allows a greater total tuyere pad length.

The tuyere brick and pad experience thermal shock from gas cooling, erosion from turbulence, and extremes in temperature from oxidation reactions. Corrosion from the reaction products may also contribute to wear. In this area the best grade of available refractory is used. In dolomite linings, the tuyere brick are usually high-density, low permeability with increased MgO levels and additions of ZrO_2 for thermal shock resistance. The one or two guard bricks immediately surrounding the tuyere are frequently of the same composition. The balance of the tuyere pad is usually constructed using slightly less premium brick to save costs. The tuyere pad typically extends up to the vessel slagline and encompasses 160–180 degrees of circumference. Magnesia–chrome tuyere/pad compositions employ either fused-grain or chrome oxide enriched bricks fired to temperatures >1750°C.

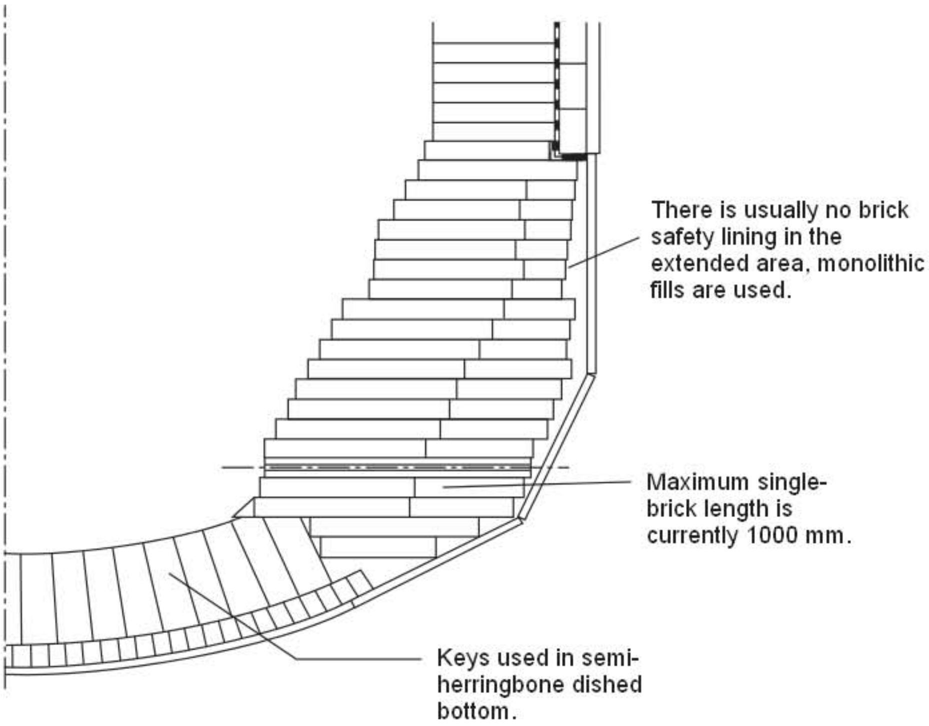


Fig. 4.24 Close-up view of a knapsack-extended tuyere pad design, and also of a dished bottom.

Table 4.5 Simplified Chemical and Physical Properties of Typical Non-Aqueous Basic Monolithic AOD and VOD Refractories

Product Type	Resin-Bonded Dolomite–Magnesia	Magnesia–Carbon	MgO-Enriched Dolomite–Carbon
Use	Monolithics for AOD cone seal, behind and around tuyere, VOD/AOD bottoms well-stir blocks	Pre-formed AOD lip rings VOD well and stir blocks	
	Chemical Analysis (%)		
MgO	38–95	88.0	55.0
CaO	balance	2.1	43.2
SiO_2	<3 Total	<1	
Al_2O_3		8.8	0.4
Fe_2O_3 + MnO		<0.7	
C	—	~8	~3
	Physical Properties		
Bulk Density (g/cm^3)	>2.7	2.75	2.80
Coked Porosity (%)	<18	17	17
MOR As-cured (MPa)	>9	>15	>15
MOR As-coked (MPa)	>3	>4	>4

4.4.2.3.5 Walls and Slagline The second highest wear area of the AOD vessel is the slagline, especially in the trunnion area. This area is under constant contact with slag in all vessel positions. If the slag chemistry is less than optimum, wear will occur from chemical corrosion combined with some erosion. Dolomite linings use a good grade of MgO-enriched brick in this area. The balance of the wall is constructed with standard grade brick.

4.4.2.3.6 Vessel/Cone Flange and Seal Several techniques are used for sealing the joint between the vessel and cone flange, see Fig. 4.25. The method used depends on flange design, the height of the last barrel course and whether the cone is bricked separately. If a basic monolithic seal material, see Table 4.5, is used between bricks, as shown in Fig. 4.25, the seal thickness at the brick hot face should be 25–75 mm. Fig. 4.25 also shows the use of a cut flange brick. Magnesia–chrome linings may use either the dolomite material from Table 4.5 or a 90% alumina plaster.

4.4.2.3.7 Cone The cone is the lowest wear area and frequently may be reused on a second vessel with minor repairs to the tapping side. The cone is constructed with standard grade keys using corbelled construction, being dry for dolomite and mortared for magnesia–chrome. Large dolomite-lined vessels often use a double-chamfered (or parallelogram key) lining in the cone. This construction is faster and more stable than standard keys. Vessels <15 tons in size may use cast magnesia or alumina monolithic cones.

4.4.2.3.8 Pour Spouts Fig. 4.23 shows an example of a monolithic pour spout. Pour spouts help to concentrate the metal stream and help to reduce nitrogen pickup in the steel during tapping. Other benefits of monolithic pour spouts include increased metal yield, optimized slag-off, easy slag deskulling and reduced cone steelwork maintenance. Table 4.5 lists the properties of some basic monolithic spout compositions.

4.4.2.4 Preheating of Linings

Fig. 4.26 shows the recommended preheat curve for all AOD linings. The preheat begins with a temperature rise of 60°C per hour up to 650°C. At this point the lining is soaked for four hours, after which heating should continue at 65°C per hour up to 1100°C. If time does not permit a soak period, the cycle can go to 65°C per hour after 650°C has been reached. Linings should be held at 1100°C for >4 hours prior to being placed in service. Reheating of a used lining can be at a rate of 65° to 95°C per hour up to 1100°C.

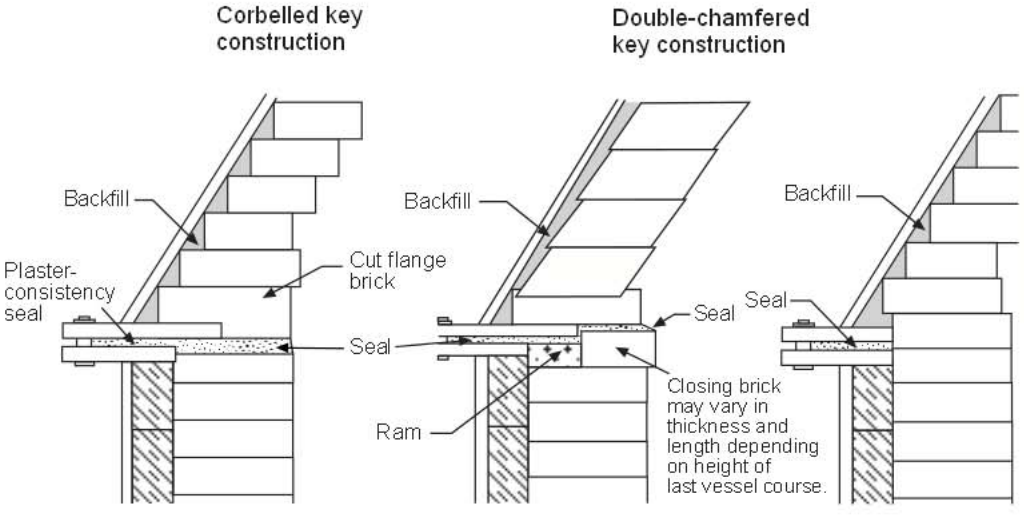


Fig. 4.25 Examples of common cone/vessel sealing methods, also illustrating the use of double-chamfer cone keys.

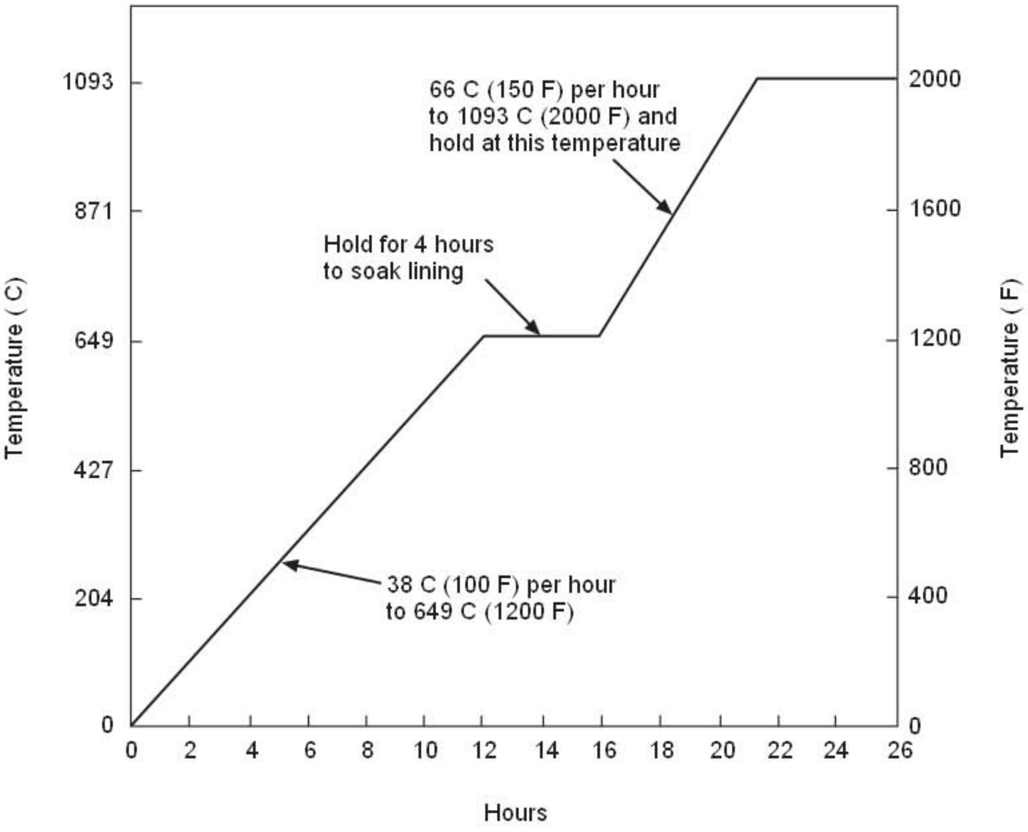


Fig. 4.26 Recommended AOD preheat schedule for all refractory linings.

4.4.2.5 Process Variables Significantly Affecting Life

It is necessary to optimize certain process variables in order to maximize the performance of AOD refractories. Slag chemistry and fluidity control in the AOD during all refining steps is important to maintain good refractory life. This requires that sufficient levels of lime and magnesia are present in the slag. The optimum slag conditions are similar for all three major refractory types, although dolomite and magnesia–carbon are more tolerant of high basicities. Slags with V-ratios >1.4 are compatible with basic AOD refractories and can be important with regards to metallurgical considerations. Other operational parameters that need to be controlled in order to improve refractory life include process temperatures <1700°C, tuyere and knurdle control, and short average heat times. With improper control of tuyere and slag conditions, tuyere area wear rates can exceed 20 mm/heat.

4.4.2.5.1 Slag Control The control and predictability of the slag chemistry throughout the AOD process is critical for optimizing refractory wear and metallurgical control.

The type of refractory used in the AOD will influence the slag practice. If a magnesia–chrome refractory is used, good refractory life is generally obtained if V-ratios are in the range of 1.2 to 1.5. Operating with higher slag basicities will have a detrimental affect on these refractories due to chemical corrosion of the chrome component of the brick.

In comparison, a dolomite-lined AOD vessel requires slags having higher basicities (V-ratios 1.4 to 2.0). One of the reasons for the extensive use of dolomite linings in the AOD is that several metallurgical benefits can result by operating with higher slag basicities. These benefits include better desulfurization potential and alloy recovery. In Fig. 4.27, the effect of higher reduction slag basicities on chrome recovery is shown.

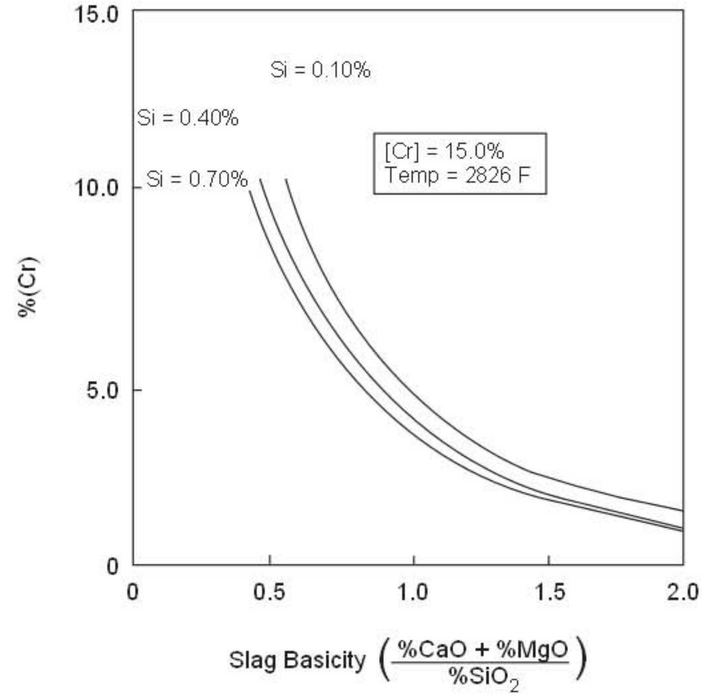


Fig. 4.27 Estimated equilibrium chromium content in slag versus basicity.

The following is a synopsis of AOD slag practices with dolomite linings.

4.4.2.5.1.1 Transfer Slag Control of transfer slag chemistry and volume brought to the AOD is important if proper slag control is to be maintained. Highly variable transfer slags make it difficult to calculate the proper amount of flux additions necessary in the vessel. If possible, the transfer slag should be CaO and MgO-saturated, so that the initial slag in the vessel is basic and can neutralize the acidic oxides generated during the oxygen blow. If the transfer slag is acidic and the amount of slag is variable, erosion of the AOD refractory lining will start at the beginning of the process.

4.4.2.5.1.2 Decarburization Slag Slag control during the decarburization blow is critical if maximum refractory life is to be obtained. At the beginning of this stage, corrosive slags with high levels of SiO_2, Fe_2O_3 and Cr_2O_3 are generated. In order to neutralize the acidic oxides, CaO and MgO should be added as a pre-charge material, or very early in the blow. The role of MgO is to react with the metallic oxides of Cr, Mn, Fe and Al. Their reaction with MgO forms solid or near-solid complex spinels during decarburization and limits corrosion of the lining. It is recommended that the CaO source be in the form of dolomitic lime. Part or all of the MgO can come from dolomitic lime, however this can result in additional slag volume. Decarburization slags that are fluid have insufficient CaO and MgO levels and can be corrosive to dolomite linings. Typical MgO content of stainless decarburization slags is in the 10 to 20% range.

4.4.2.5.1.3 Reduction Slag During the reduction stage, the AOD slags change considerably. The solid MgO spinel phases disappear as the metal oxides of Cr, Mn, etc. are reduced by silicon or aluminum back into the bath. The SiO_2 and Al_2O_3 generated during reduction must be neutralized with CaO to minimize corrosion of the dolomite lining. The lime also serves to tie up the SiO_2 and effectively reduce any reaction with the transition metals. Reduction slags for silicon-killed practices should target V-ratios of 1.6 to 1.8, with an MgO content of 8 to 12%. Better refractory life, desulfurization and alloy recovery can be achieved with V-ratios >2.0.

If aluminum is used during reduction or as a fuel, maintaining CaO saturation is critical if Dolomite refractory wear is to be minimized. Slags with high Al_2O_3 content can dissolve more lime and will do so from the dolomite refractory lining unless enough lime is added. Table 4.6 shows the effect of Al_2O_3 content in the slag on lime demand. If CaO saturation is not possible, higher MgO levels in the slag are required for refractory protection.

Table 4.6 Aim V-Ratios used with Dolomite Linings as a Function of Al_2O_3

Al_2O_3 Content	V-Ratio*
0–10%	1.55
15%	1.65
20%	1.78
>25%	1.82

*V-ratio = $(CaO + MgO)/(SiO_2 + Al_2O_3)$

4.4.2.5.2 Tuyere Knurdle Control Consistent control of knurdle length and shape is essential for preventing premature failure of the refractory tuyere zone. Knurdle size is controlled by making adjustments to shroud gas pressure and/or flow. A large knurdle, indicating excessive shroud pressure, can become plugged and misdirect the gas stream toward the refractory lining. A small knurdle or no knurdle at all, resulting from low shroud pressure, will not protect the tuyere and can result in tunneling of the tuyere brick. Optimum knurdle size depends on the individual shop conditions, but generally, 25 to 75 mm is best.

If as little as 2% oxygen is present in the shroud gas, the cooling effect can be reduced and tuyere brick tunneling may begin to occur.

4.4.2.5.3 Temperature Temperature can have a significant impact on the amount of CaO and MgO needed to saturate slags during reduction. Higher CaO and MgO levels are needed if processing temperatures are higher. If adjustments are not made, dissolution of the refractory lining by the slag will occur. In Table 4.7, the affect of temperature on lime and MgO requirements for saturation is shown.

Table 4.7 Effect of Temperature on CaO and MgO Demand for Slag Saturation

Temp (°C)	CaO (%)	MgO (%)	SiO_2 (%)	CaO/SiO_2
1600	44.3	17.3	38.4	1.15
1700	48.5	16.1	35.4	1.37
1750	51.6	15.1	33.3	1.55
1800	55.1	14.0	30.9	1.78

The bath temperature becomes elevated under normal conditions by metallic oxidation of the bath as the carbon content reduces to lower levels. The temperature of the bath can also be increased by oxidation of fuels (aluminum or silicon) during a reblow. A reblow to achieve temperature increases of 20°C or higher, however, is equivalent in refractory wear to making another heat on the lining. Temperature control is best accomplished by keeping transfer metal temperature and chemistry levels consistent and controlling the peak temperature at the end of the oxygen blow by varying the O_2/inert gas ratios.

An excessive inert gas stir for temperature reduction can also adversely affect refractory performance. Extended stirs can form long, pipe-like knurdles that will sag from their own weight. When these long knurdles bend over, the injected gases are directed downward during the early stage of the next heat, and tuyere pad or bottom erosion may occur.

4.4.2.5.4 Back Tilt Gas injected through the tuyeres tend to roll back and up along the sidewall, carrying the products of oxidation with it. The gas stream creates localized high temperature and turbulence resulting in a high wear area. Back tilting the vessel during blowing keeps the gas stream further away from the wall, helping to reduce wear. Optimum back tilt is usually between 5° to 7°. A fan shaped wear pattern, starting around the tuyere and extending upward and outward, generally indicates an improper back tilt practice.

4.4.3 VOD Refractories

4.4.3.1 Introduction

As mentioned in the Section 4.4.1, the VOD process uses more linings of fired magnesia–chrome brick than of fired or resin-bonded dolomite–magnesia primarily because of the use of highly variable multiple slag processes, and secondarily because of much more thermal cycling than in the AOD. Some of these slags are very fluid or insufficiently basic, $(CaO + MgO)/(SiO_2 + Al_2O_3) \ll 1.4$, for optimum life with dolomite refractories.

The choice of brick composition, especially in the slagline, is controlled by the acceptable carbon pickup during processing, the acceptable bath chrome pickup, and slag chemistries. Where carbon pickup from the brick in the range of ~0.2 ppm per minute (under vacuum) is tolerable, magnesia–carbon slaglines are preferred for their wide range of slag compatibility, and have been used to produce steel as low as 15–30 ppm carbon.[9] If carbon pickup is not acceptable, then fired brick must be used, and for chrome-free alloys, fired magnesia–dolomite brick is the only choice. Where chrome pickup is allowable, the choice of fired magnesia–chrome or magnesia–dolomite is determined primarily by slag chemistry.

VOD slags have the requirement of high fluidity, because of the relatively small slag volume, and the limited stirring energy usable in the ladle. This fluidity may be obtained by having slags with V-ratios $\ll 1.4$, or with higher V-ratio slags by using fluorspar or alumina as fluidizers. Magnesia–chrome brick generally give better slagline performance against slags having V-ratios <1.2 or having Al_2O_3 contents $>15\%$, while magnesia–dolomite is preferred for V-ratios >1.4 and for slags containing $>10\%$ fluorspar.

The effect of slag on the wall refractories is less than in the main slagline, and with the increasing use of magnesia–carbon slaglines, compatible with a wide range of slags, and tighter control over the process, and especially thermal cycling, the choice of magnesia–chrome or dolomite-based wall and bottom linings is becoming primarily economic.

4.4.3.2 Lives and Wear Rates

Life is typically equally short for either type of lining, ranging from 15–25 heats. The primary wear/failure areas are the slagline, the stirring pad and the stir plug/block itself. Refractory consumption is similar for all refractories, is highly variable between shops and may be as low as 10 kg/ton or over 30 kg/ton of steel. In the severe areas, slagline and stir pad, wear rates are 7–15 mm/heat. In the lower wear areas of the walls and bottom, typical rates are 3–7 mm/heat.

4.4.3.3 VOD Lining Construction and Zoning

The selection of refractories for VOD applications should consider the conditions of aggressive fluid slags, high temperatures (>1750°C), long process and stirring times (>3 hr), and the effects of vacuum on reducing heat transfer and increasing shell temperatures where the VOD ladle is in a vacuum tank. Because of the very wide range of processing conditions encountered in VODs, there is considerable variation in safety and working lining construction. The following typical design, Fig. 4.28, should be considered the minimum requirement in the absence of a shop refractory history.

4.4.3.3.1 Safety Lining The safety lining in a VOD ladle is intended to prevent a steel breakout if there is a failure of the working lining during the processing, and the quality and construction must be sufficient to allow one complete heat to be made directly on the safety lining. A VOD ladle safety lining is generally similar to the safety linings used for ladles used for severe ladle furnace or tank degasser applications, see Section 4.5.3.

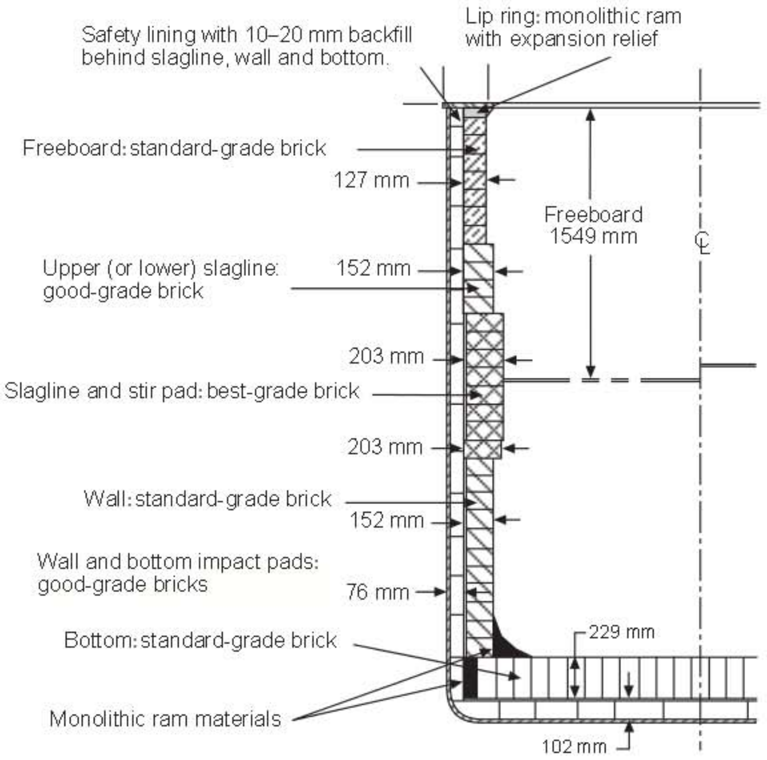


Fig. 4.28 Typical 45-ton VOD lining showing quality zoning, relative brick thickness, and large freeboard.

Total thicknesses of 75–150 mm are used consisting of primarily of 70–85% alumina fired brick in the walls and bottom, with fired 95% magnesia or direct-bonded magnesia–chrome brick commonly used in the slagline area for their better slag resistance. The entire brick safety lining should be installed fully mortared, using arch brick or bevels with a maximum joint thickness of 2 mm. Monolithic safety linings are also used based on both castable and dry-vibratable alumina or magnesia materials of similar quality to bricks. All safety lining materials for VOD ladles should be volume stable, be resistant to cyclic oxidation-reduction, and have a continuous service rating >1650°C.

Where insulation is required to hold shell temperatures below 400°C, 5–8 mm of non-compressible insulating panels are most frequently used between the shell and the main safety lining. Where less insulation is needed, 20–30 mm of clay or forsterite brick has been used in place of the insulating panels. This requires a corresponding reduction in the thickness of the main safety lining, but is less expensive. The maximum permissible in-service compression or shrinkage of insulating materials for VOD ladle applications is ~2 mm. A continuous service rating of >800°C is suggested for VOD insulating materials.

4.4.3.3.2 Backfill Backfills are sacrificial granular monolithic materials used between the safety and working linings to absorb working lining thermal expansion, capture metal penetration, and reduce reactions between the working lining, slag, and safety linings. They generally protect the safety lining and make removal of the working lining easier. More than 90% of dolomite–magnesia lined VOD ladles use backfill. Magnesia–chrome lining customarily have no backfill.

Backfill thicknesses of from 10–20 mm are used by placing the working lining brick a desired distance from the safety lining, and pouring and tamping the backfill into the gap every second course. Compositions are most commonly 80–85% alumina, with >90% magnesia sometimes used in the slagline areas. Dolomite-based backfills are also used. Backfills should have a continuous service rating of 1650°C.

4.4.3.3.3 Working Lining The primary zones of a VOD working lining, Fig. 4.28, are: the bottom, including well blocks, stir plug, and impact pad; walls; sidewall impact and stirring pads; slagline and hotspots; and the freeboard. These zones do not vary significantly between magnesia–chrome or dolomite linings. Because of the fluid slags and metal, and extensive stirring, tight sizing tolerances are needed for VOD brick. Sizing ranges for resin-bonded compositions are typically less than ±0.5 mm, and for fired brick are typically less than ±1.0 mm.

> Note: Magnesia–chrome, alumina-based and dolomite-based refractories are normally not mixed in a single VOD working lining. Under vacuum, destructive interactions may occur between the CaO in dolomite and the spinels in magnesia–chrome or alumina–silica phases in alumina refractories. Where the two types of brick are used together, an interface layer of magnesia–carbon brick should be used. An interface may also be required if the stir plug block or well block, and their surrounding monolithics, are not of a refractory type (basic vs. acid) compatible with the adjacent brick. Table 4.5 shows monolithics suitable for use with dolomite linings. Because VOD conditions greatly increase the potential for incompatibility reactions, refractory suppliers should be consulted prior to mixing compositions.

4.4.3.3.4 Bottoms Standard grades of magnesia–chrome and dolomite straight bricks, see Tables 4.3 and 4.4, are used in thicknesses of 187–250 mm. Recently, limited amounts of alumina–magnesia–carbon (AMC) brick have been used in bottoms. Any of the common brick patterns, (rowlock, soldier, semi-herringbone, herringbone), may be used with magnesia–chrome, AMC, or resin-bonded dolomite for the convenience of fitting around the stir plug and well block. Fired dolomite brick are usually laid in a semi-herringbone pattern. Bottom brick may be installed under the sidewalls or as a plug bottom. Plug bottoms are easier to repair and/or replace, but expose the monolithics used around the bottom perimeter. Fig. 4.28 shows the most common construction, with the bottom installed under the sidewalls. The bricks are typically laid dry, with finish grouting or dusting to fill any minor open joints.

4.4.3.3.5 Bottom/Wall Impact Pads Usually the good-grade of brick is employed in the bottom/wall impact pad, frequently slightly thicker than the main lining. For dolomite linings, the impact pads are often made of resin-bonded brick. VOD ladles duplexed with BOFs or EBTs may require either the best-grade brick or metals-containing magnesia–carbon brick in the bottom pad, because of more concentrated tap streams.

4.4.3.3.6 Stir Plug/Blocks and Well Blocks VOD ladles use plug and block compositions similar to those required in severe LMF and degasser operations, see Section 4.5.5. The conditions of very fluid slags, high temperatures, and long stirring times cause these areas to be one of the main limitations on VOD life. A very wide range of compositions are being used, often requiring magnesia–carbon brick as an interface layer or window to maintain compatibility with the main lining. The current trend (1998) is to increase the use of basic compositions (magnesia–carbon, magnesia–spinel, magnesia–zirconia, and magnesia–dolomite) for the blocks, and to use slotted or directional porosity plugs.

4.4.3.3.7 Walls Standard-grade bricks from 114–250 mm thick are used in the walls. Key or arch construction is preferred over semi-universals for greater stability when bricks wear thin. Magnesia–chrome is frequently mortared, while dolomite is laid dry. A majority of dolomite linings use 10–20 mm of backfill behind the walls.

4.4.3.3.8 Main Slagline plus Sidewall and Slagline Stir Pads The best grade of brick is used in these critical wear areas. Selection of the refractory type is governed by the metallurgical/slag conditions as discussed above. The use of metals-containing, large crystal size and fused grain magnesia–carbon brick in slaglines is increasing, even in otherwise carbon-free linings. For VOD applications, carbon levels are commonly 7–10%, to minimize oxidation and carbon pickup, and anti-oxidants must be carefully chosen for slag compatibility. Magnesia purity and large crystal size are more critical in VOD ladles than in other ladle applications.

4.4.3.3.9 Upper Slaglines As a result of foaming under vacuum, VOD ladles must have an extended slagline zone. Where a typical LMF ladle may have a 700–1000 mm high slagline, a VOD will use

1000–1500 mm of slag zone. Most of the additional height is in the upper slagline, which is in intermittent contact with the low-density foamed vacuum slag. This area typically uses either 20–50 mm thinner brick and/or one grade lower brick than the main slagline. Even when the main slagline is magnesia–carbon, the upper slagline frequently is fired brick because of the greater oxidation potential in this zone.

4.4.3.3.10 Freeboard Fired standard-grade brick are used, and are chosen for their oxidation and thermal cycling resistance. In this low wear area, thickness may be as little as 114 mm. Construction is usually keys or arches, laid dry and tight against the safety lining without backfill. In ladles with <800 mm of freeboard, this zone will see some minor slag attack and is usually of a composition similar to the wall brick. In VOD ladles with >1000 mm freeboard, the upper portion sees little slag and may even be of 85% alumina brick. The freeboard is an area where dolomite brick may be used in a magnesia–chrome lining and vice versa.

4.4.3.3.11 Lip Rings For VOD ladles, the lip ring design is determined by whether the vacuum seal is on the lip or the ladle is tank degassed. In most VODs, the large freeboard allows the use of alumina brick or castables and pre-formed shapes with alumina-based monolithics. These lip materials should be rated for continuous service at >1700°C. With mortared magnesia–chrome linings, vertical thermal expansion allowances are not usually needed, but with dolomite–magnesia linings, vertical expansion allowances of approximately 0.5% should be incorporated in the lip construction. Many dolomite linings use a dolomite or magnesia-based resin-bonded ram, Table 4.5, which is temporarily thermoplastic on heatup to provide this relief.

4.4.3.4 Preheating of Linings

Fig. 4.29 presents a schedule that is suitable for all lining types. When there are no carbon-containing brick in the lining, slower preheat rates and longer soaks may be used. Preheat and/or soak temperatures above 1100°C are not recommended because of brick reactions with the relatively low melting point VOD slags.

4.4.4 Acknowledgments

The author acknowledges the significant contributions of Lowell Johnson, Nobu Mimura, and Eugene Pretorius, all of Baker Refractories, and Don Moritz, retired from Baker Refractories and Eastern Stainless Steel. And also wishes to thank Victor Ardito, retired from Allegheny Ludlum Corp., and Richard Choulet, of Praxair, Inc. for their helpful suggestions.

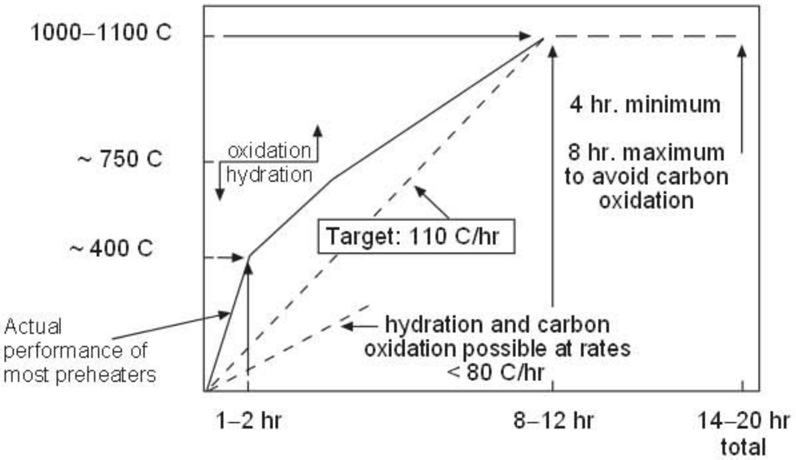


Fig. 4.29 Preheat schedule for fired and resin-bonded VOD brick.

4.5 Refractories for Ladles

4.5.1 Function of Modern Steel Ladle

The modern steel ladle is used in a significantly more complex manner than the older ingot ladles used simply to transport steel from a furnace to ingot molds. Table 4.8 lists typical functions of the modern steel ladle.

Table 4.8 Functions of Modern Ladles

Metal transport from furnace to caster
Metal processing/treatments—minimum wear
Minimize O_2 pickup from refractory
Minimize heat loss
Safety/reproducibility
Environmental effects minimized—in use and disposal
Low cost/ton

While the overall purpose of the ladle is still to deliver steel for a caster, steel processing between the furnace and caster may occur by a complex combination of steel and slag treatments. These includes furnace slag skimming and the introduction of a new artificial slag, steel alloying and stirring from porous plug and lances, steel reheating using electric arcs, and degassing by various procedures. These steps must be accomplished without significant refractory wear or influence on any of the refining processes. Fig. 4.30 illustrates the process steps in one shop where both bloom and slab heats are produced in degassed or regular grades. The increased number of process steps in ladles means that, in essence, they function as traveling components of skimming, stirring, reheating, and degassing processes. Also the exposure time for a given heat has expanded from two to five times of that for ingot teeming.

The ladle lining can also influence the quality of the steel produced in the lining if oxygen is picked up from the lining during any stage of processing. Linings containing SiO_2 in uncombined forms

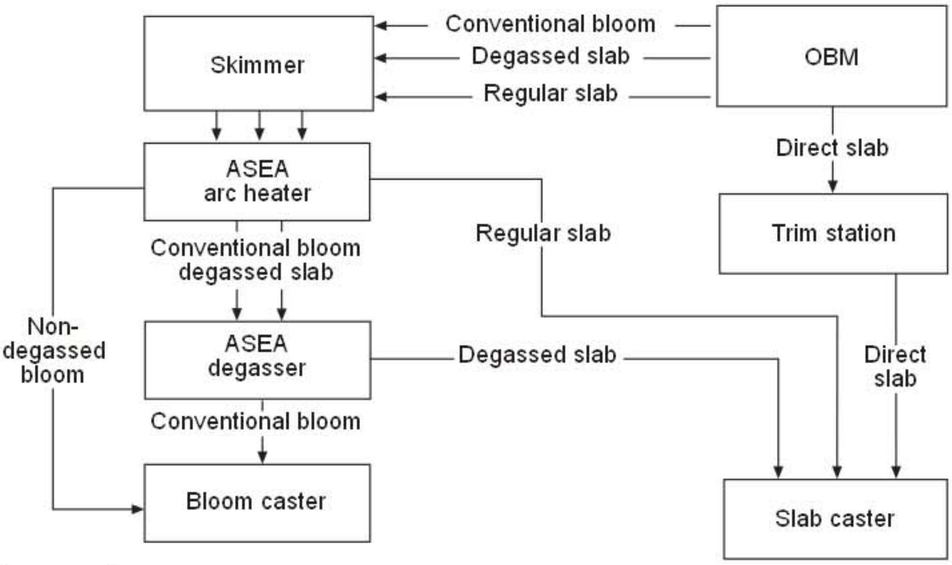


Fig. 4.30 Process routes.

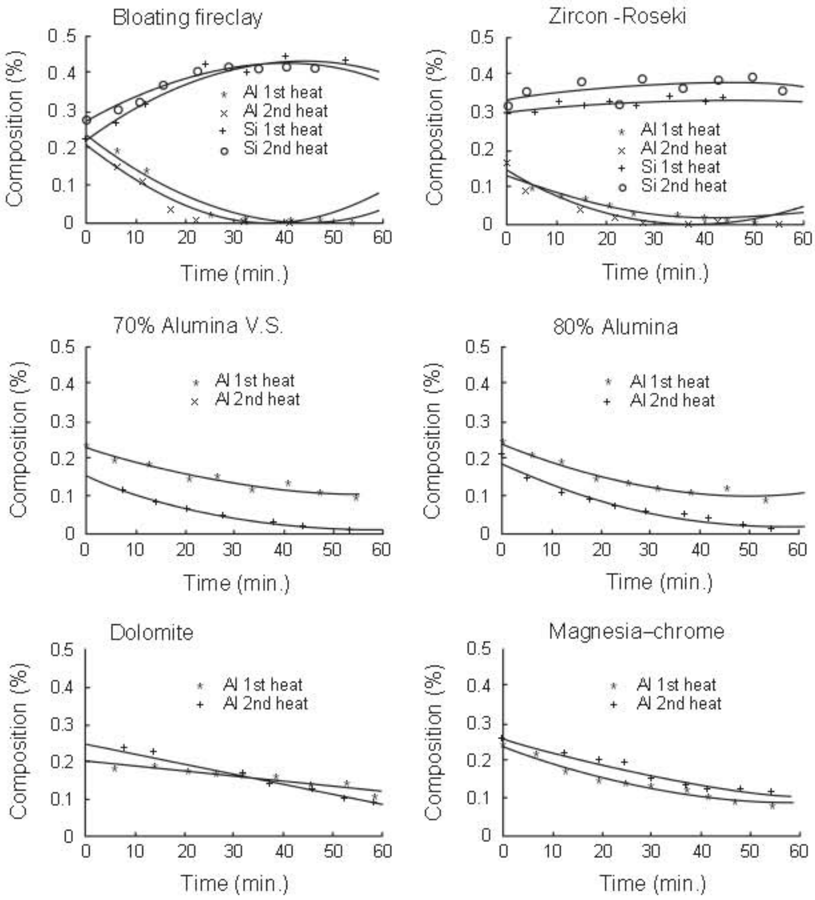


Fig. 4.31 Aluminum loss and silicon pickup on holding steels in a laboratory furnace.

can cause problems in modern ladles as illustrated in Fig. 4.31. In those laboratory tests where Al-killed steels were held in various lining materials, fire clay or zircon-Roseki linings gave rapid Al loss (and Si pickup) in comparison to significantly less Al loss with high alumina refractory linings where the lower levels of SiO_2 were largely combined as mullite. Refractories with very low levels of SiO_2 (dolomite, magnesia–chrome) obviously perform well in such tests. In actual service, the ladle surface is clean only on the first heat, and oxygen pickup is influenced by the amount and oxidation state of the coating remaining on the lining from the prior heats.

Ladles must also conserve heat by minimizing heat loss during transport and the various process steps. In this regard, significant developments have been made to properly preheat ladles prior to the first heat, and to cycle ladles on subsequent heats in a manner to minimize heat losses. Fig. 4.32 shows a ladle cycling procedure for one plant. Fig. 4.33 shows some ladle temperatures for this plant for the first and subsequent heats. In this case, the first heat was tapped into a ladle preheated to 1900°F, and later heats were tapped in a cycle of approximately three hours. While every effort is made to reuse ladles without delay and to provide covers on ladles between heats, processing of ladles between heats is necessary to remove ladle slag and provide for ladle well cleanout, slide-gate inspection and repairs and ladle well sanding.

Ladle preheat and cover devices have improved significantly in recent years, and many types of preheaters (ladle horizontal or vertical) are available, Fig. 4.34. Table 4.9 lists some of the benefits of proper ladle preheating and cycling, including longer refractory life by minimizing thermal shock. The actual ability to rapidly cycle ladles and make the most efficient use of preheaters can vary significantly between operations, depending on shop layout and ladle transfer ability.

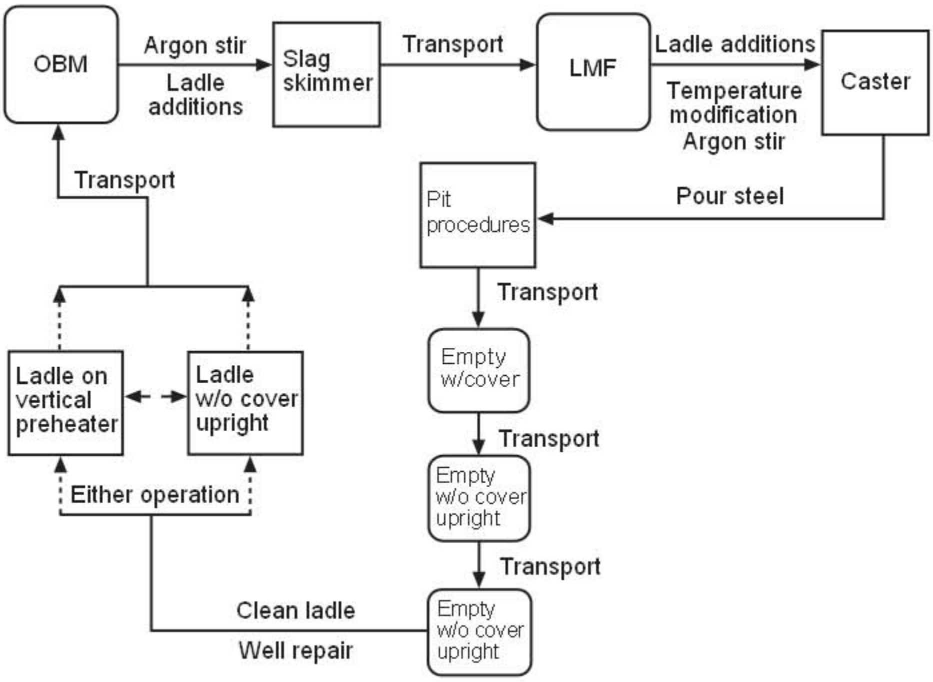


Fig. 4.32 Ladle cycling procedure.

Ladle life must be very predictable and reproducible for safety reasons and to avoid process delays. As a result, ladles are often removed from service to provide an adequate supply of ladles. The cost of ladle refractories can be significant ($1–4 per ton of steel) and disposal costs of spent linings must also be considered.

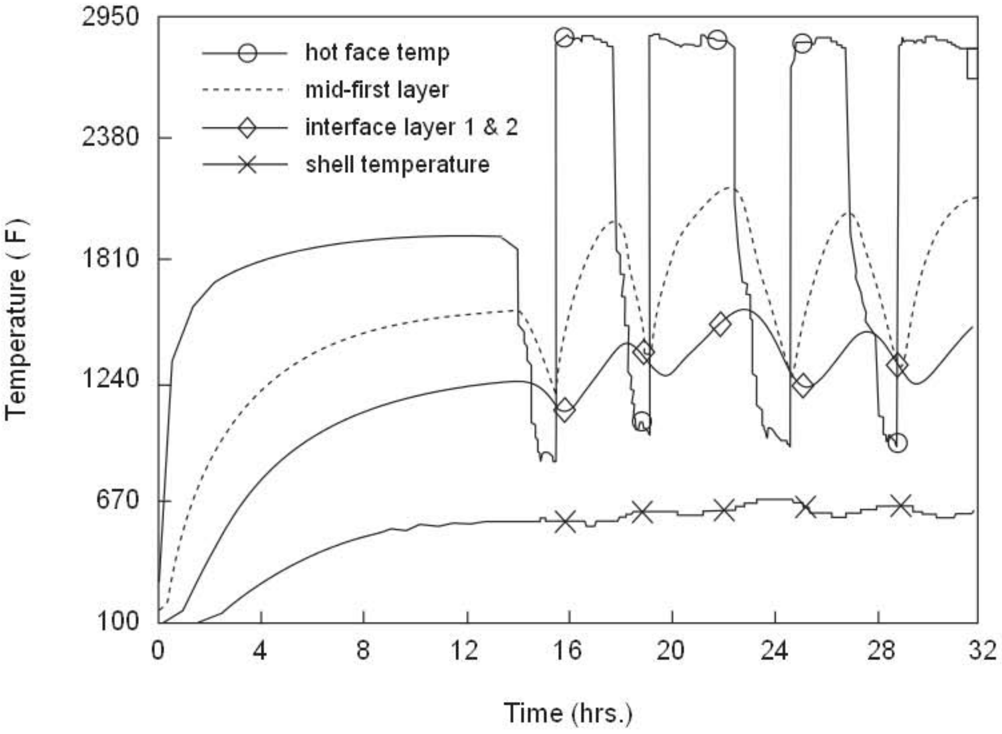


Fig. 4.33 Transient phenomena in ladle cycling.

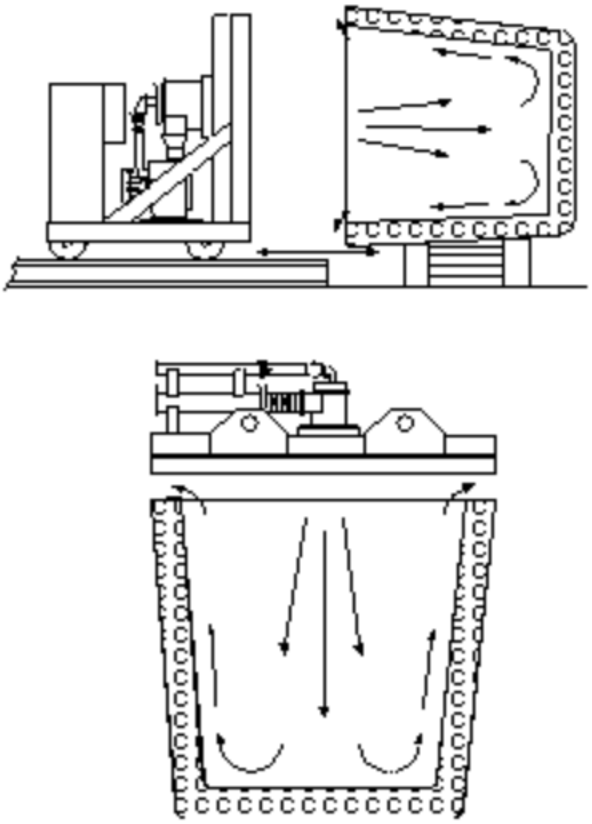


Fig. 4.34 Horizontal and vertical preheat systems for ladles.

4.5.2 Ladle Design

Steel ladle shells must be constructed to allow safe transport of very heavy loads by transfer cars, cranes, and other devices. For example, a typical full ladle could involve 200 tons of molten steel in a lining and steelwork weighing 100 tons. The design of such a structure is highly complex as

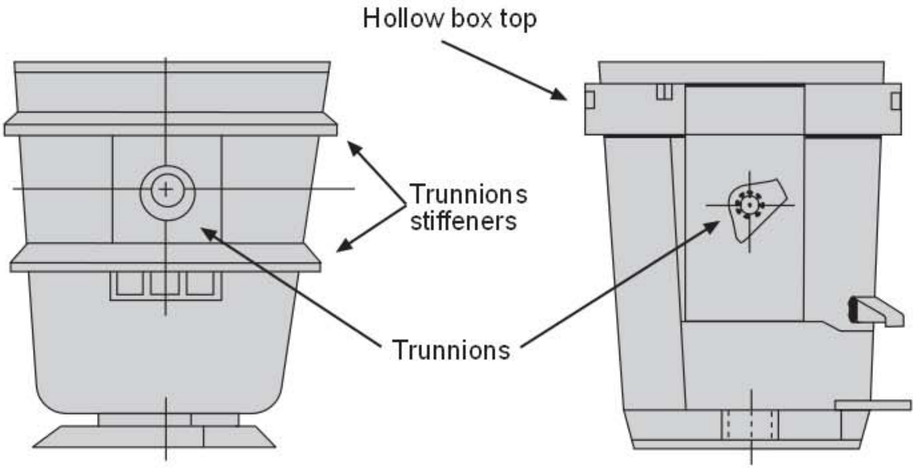
Table 4.9 Ladle Preheating: Goals and Benefits

Goals

Provide ladles with consistently high refractory heat content to the BOF for tapping heat after heat
  a. less tap temperature biasing for cold/hot ladles
  b. consistent first heat practice

Benefits

Reduction in average steel temperature loss in the ladle
  a. lower tap temperatures
  b. less arcing required at the LMF
Reduction in refractory costs
  a. reduced thermal shock to ladle refractories
  b. increased steelmaking furnace refractory life
  c. reduced ladle slagline wear through less reheating at the LMF
Provide more consistent steel temperature to the caster
  a. less temperature related terminations
  b. increased productivity and quality by maintaining optimum tundish temperatures



Conventional

Induction-stirred

Fig. 4.35 Appearance of steel ladles.

shown by the design criteria of *AISE Technical Report No. 9, Specifications for Design and Use of Ladles*.[10] Fig. 4.35 shows the general appearance of some steel ladles indicating the trunnion supports for ladle lifting and rotation and stiffeners to provide lining structural support. In reality, ladle structures are often even more complex because of shop specific criteria. For example, Fig. 4.36 shows an obround ladle in which a flat section was added to a round ladle to increase ladle capacity while using existing crane facilities.

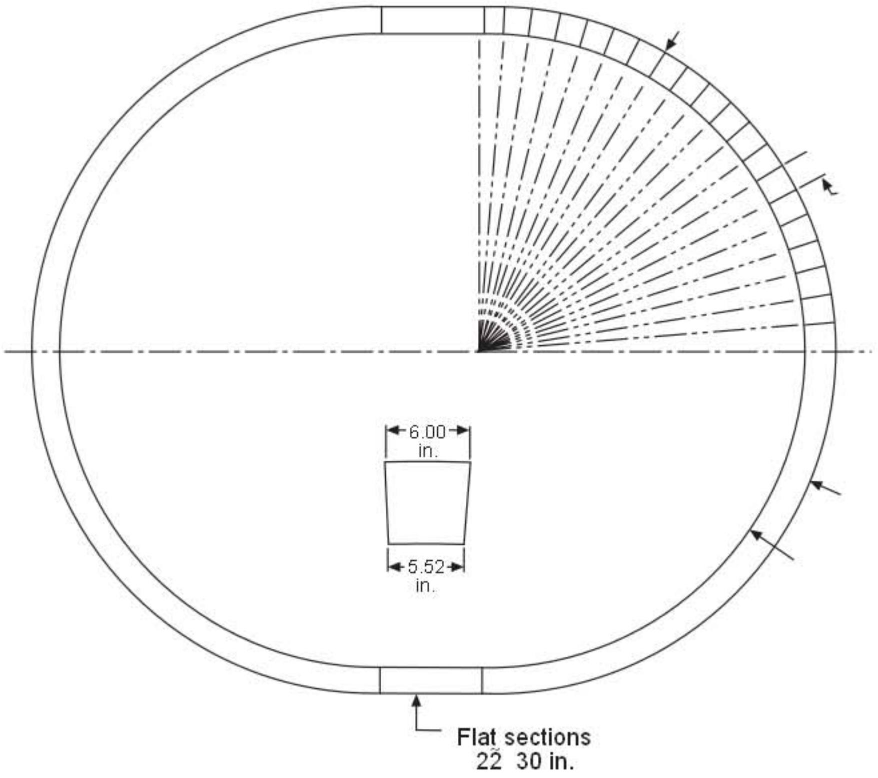


Fig. 4.36 Obround ladle section.

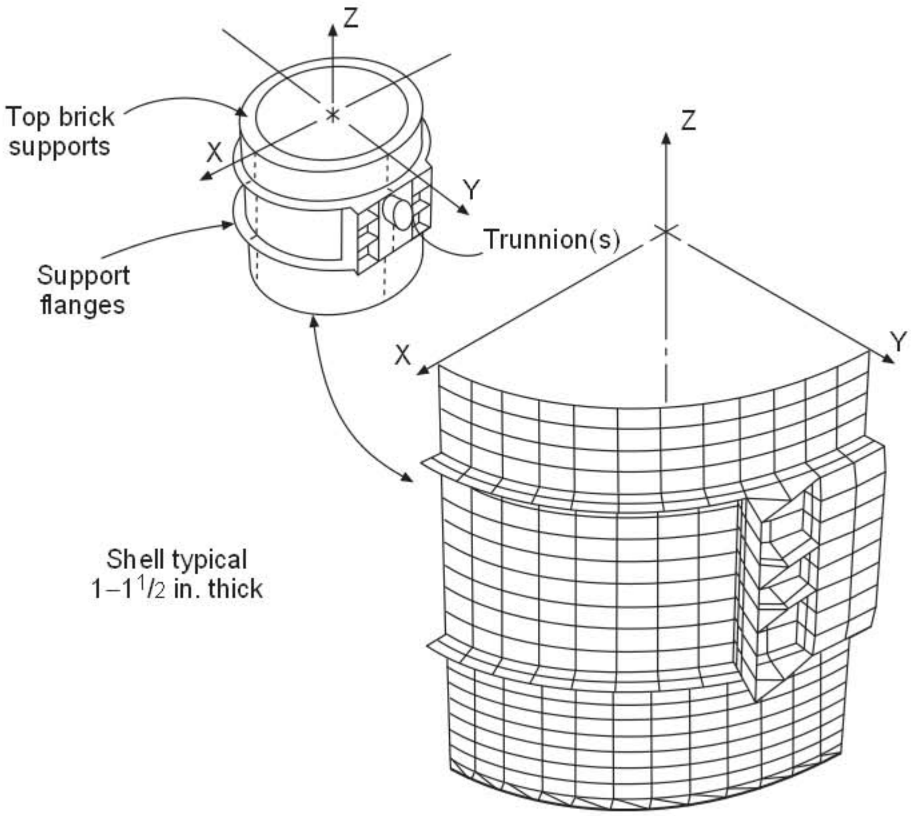


Fig. 4.37 Shell model of ladle for finite element analysis.

In recent years, finite element analysis using non-linear refractory properties and transient temperature regimes are being employed to study the behavior of refractories in steel ladles, Fig. 4.37. While highly complex, the studies essentially endeavor to maintain the proper degree of compression on the ladle refractory during all phases of their use in modern ladles. Excessive compressive forces can result in refractory cracking and/or buckling in areas such as the ladle flat section. Lower than desirable compressive stresses can cause joints or gaps to form, which may permit metal or slag penetration.

The properties of refractories may be adjusted to provide proper behavior in ladles. For example, Fig. 4.38 and Fig. 4.39 show the use of specific refractories to either increase or decrease refractory expansion to more desirable levels. In Fig. 4.38 a refractory with higher reheat expansion is

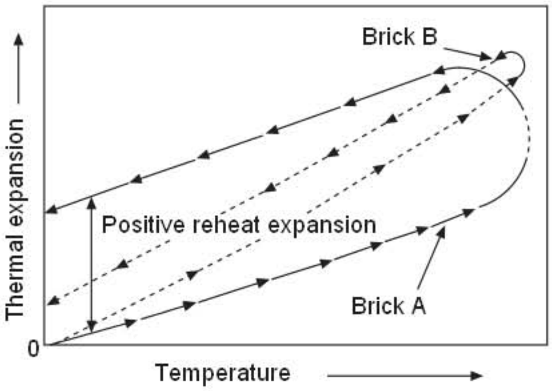


Fig. 4.38 Thermal expansion characteristics of high alumina brick. Brick A, with a positive reheat expansion, will keep joints tighter during cooling than the Brick B, with the higher thermal expansion.

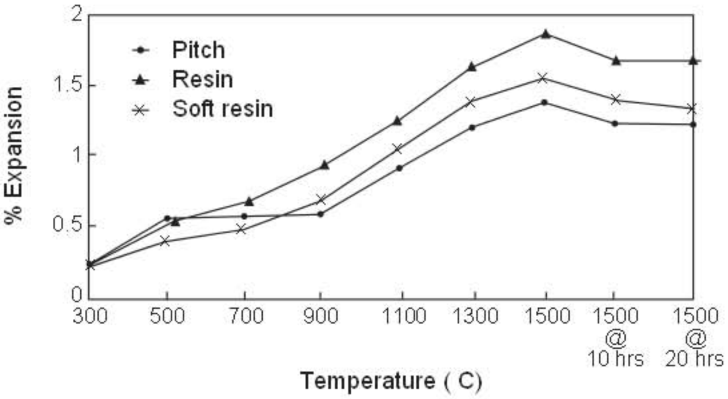


Fig. 4.39 Thermal expansion under load. In oval ladles, pitch or soft resin bonded magnesia–carbon brick are desirable over resin due to their thermal plastic behavior that relieves expansion stresses. From 500 to 900°C expansion forces in pitch and soft resin brick are relieved.

used to prevent joint openings in the high alumina section of a ladle. The same ladle might use a pitch or soft resin brick in the slagline section to reduce expansion and prevent brick cracking or movement. Ladle finite element analysis has provided valuable guidance for refractory service trials to improve behavior.

4.5.3 Ladle Refractory Design and Use

The refractories in steel ladles are zoned in type and thickness to provide maximum service minimum cost. Fig. 4.40 shows a typical ladle to illustrate the overall size and style of a ladle and some ideas of refractory thickness. Table 4.10 shows ranges of refractory thickness used in ladles. Linings are relatively thin to meet ladle capacity and weight requirements.

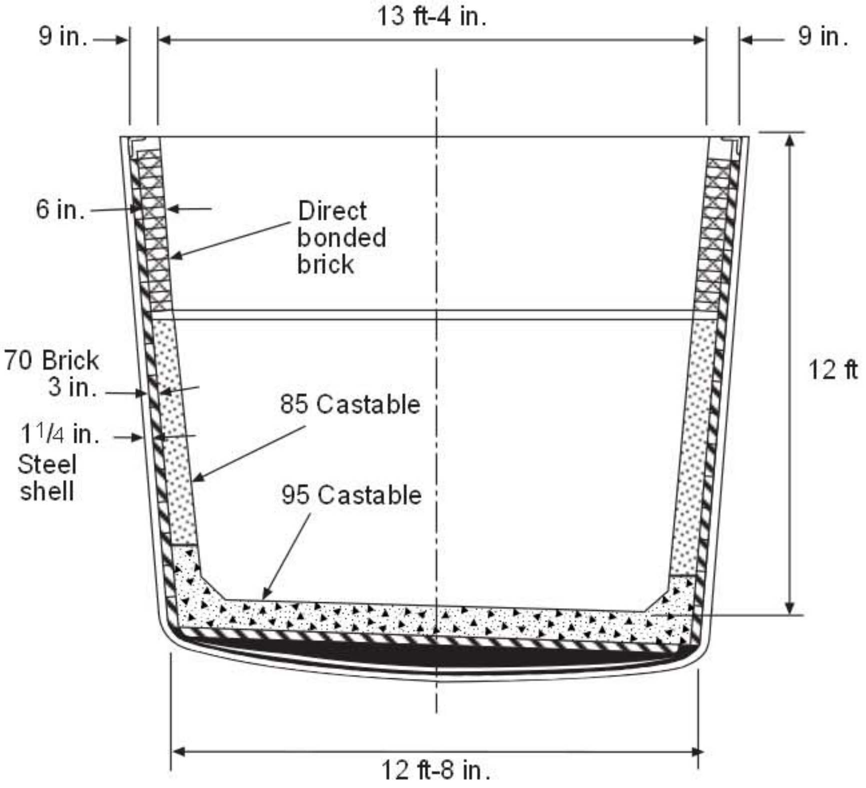


Fig. 4.40 Lining in a caster ladle using a castable barrel and bottom.

Table 4.10 Refractory Thickness by Area

Area	Thickness range, in.
Working Lining	
Slagline	5–7
Upper Barrel	6–7
Lower Barrel	6–9
Bottom	9–12
Safety Lining	2–6

The types of refractory construction vary widely depending on the caster operating conditions and on the ability to cycle ladles rapidly. Table 4.11 presents some of the more widely used working lining combinations.

Table 4.11 Working Lining Combinations

Construction	Slagline	Balance of Working Lining
A	Magnesia–carbon brick	High-aluminum brick
B	Magnesia–carbon brick	High-aluminum castable
C	Dolomite brick	Dolomite brick
D	Magnesia–chrome	High-aluminum brick
E	Magnesia–carbon brick	Aluminum carbon brick

Safety linings function to hold steel or slag for limited time periods, but essentially provide shell insulation. Multiple component safety linings may be used to further lower shell temperatures as illustrated in Fig. 4.41. In this illustration, the 4 in. thick safety lining has now changed from all

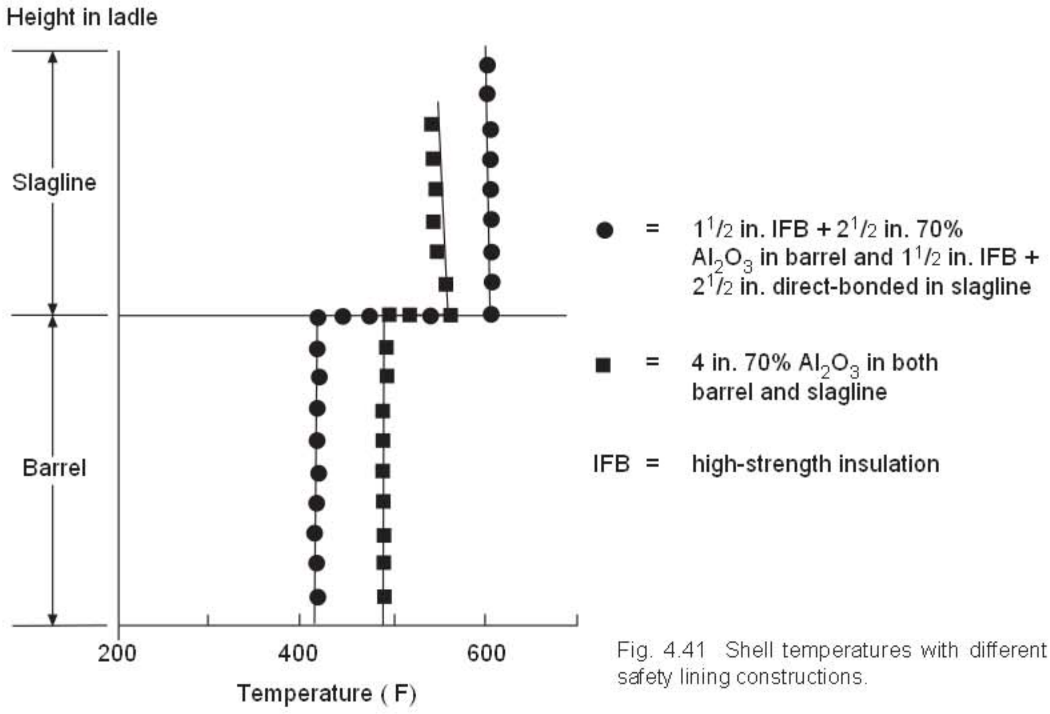


Fig. 4.41 Shell temperatures with different refractory safety lining constructions.

high-alumina brick to a composite with a high-strength insulation brick to lower the shell temperature. The higher shell temperatures in the slagline are caused primarily by the higher thermal conductivity of the slagline working lining brick. In general, few ladles use true insulating materials as part of safety linings because of reduced safety lining life and/or increased danger of steel penetration and possible breakouts.

The particular refractory constructions used are under constant change in each operating shop. The following will comment briefly on the factors and refractory properties important in each area of the ladle.

4.5.3.1 Stream Impact Pad

As illustrated in Fig. 4.42, wear in this zone occurs as the high-momentum steel stream strikes the ladle bottom (and in some cases the lower sidewall) during the initial moment of tap. The severity of this wear is quite shop-specific and requires that additional thickness or quality of refractory be used. In general, refractories for the stream impact are selected to have maximum erosion resistance based on hot-strength. Fig. 4.43 shows the temperature–hot strength relation for several refractories used in impact pads where the 96 Al_2O_3 castable provides improved performance.

4.5.3.2 Bottom and Lower Barrel Refractories

As shown in Fig. 4.44, wear occurs in this area from erosion during stirring or reheating and from physical damage during deskulling between heats. In some cases, slag remaining in this area in the

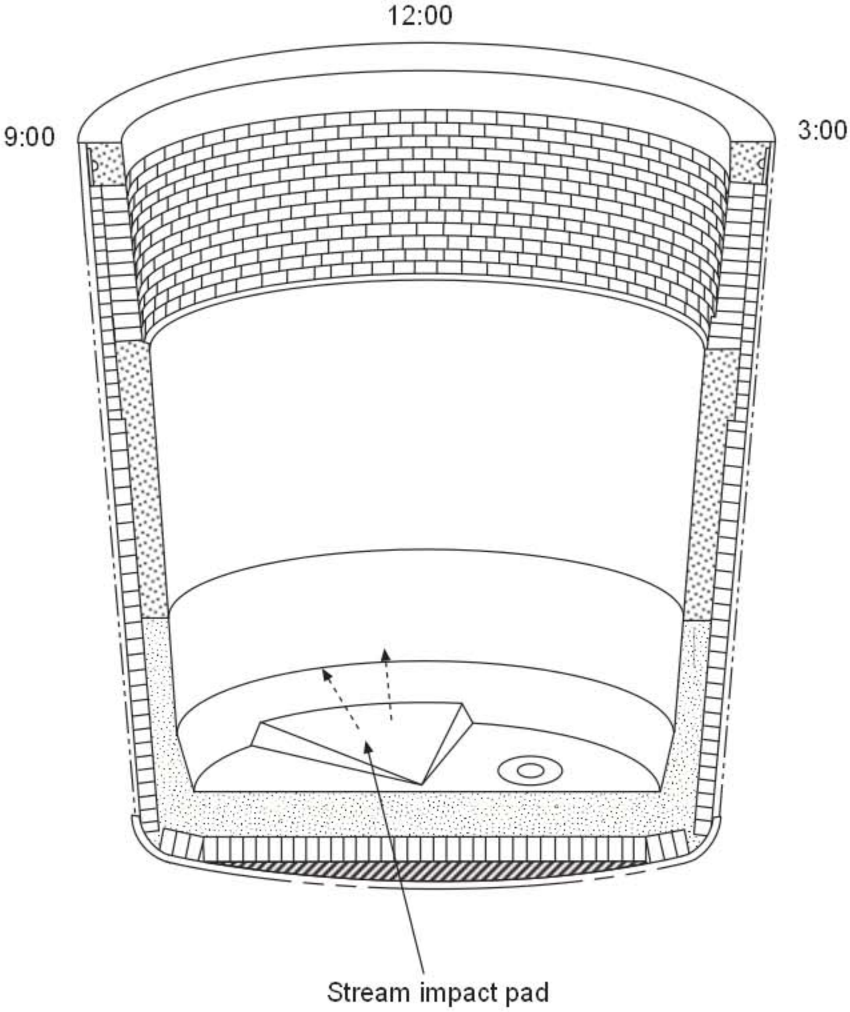


Fig. 4.42 Primary causes of wear in stream impact area of ladle are: 1. metal (and slag) erosion, 2. thermal cycling.

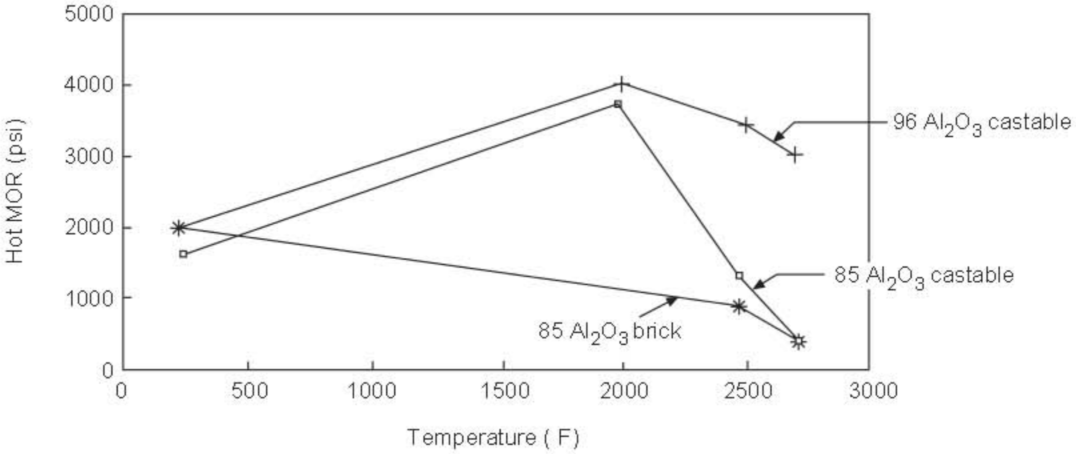


Fig. 4.43 Property comparison for refractories in stream impact pad.

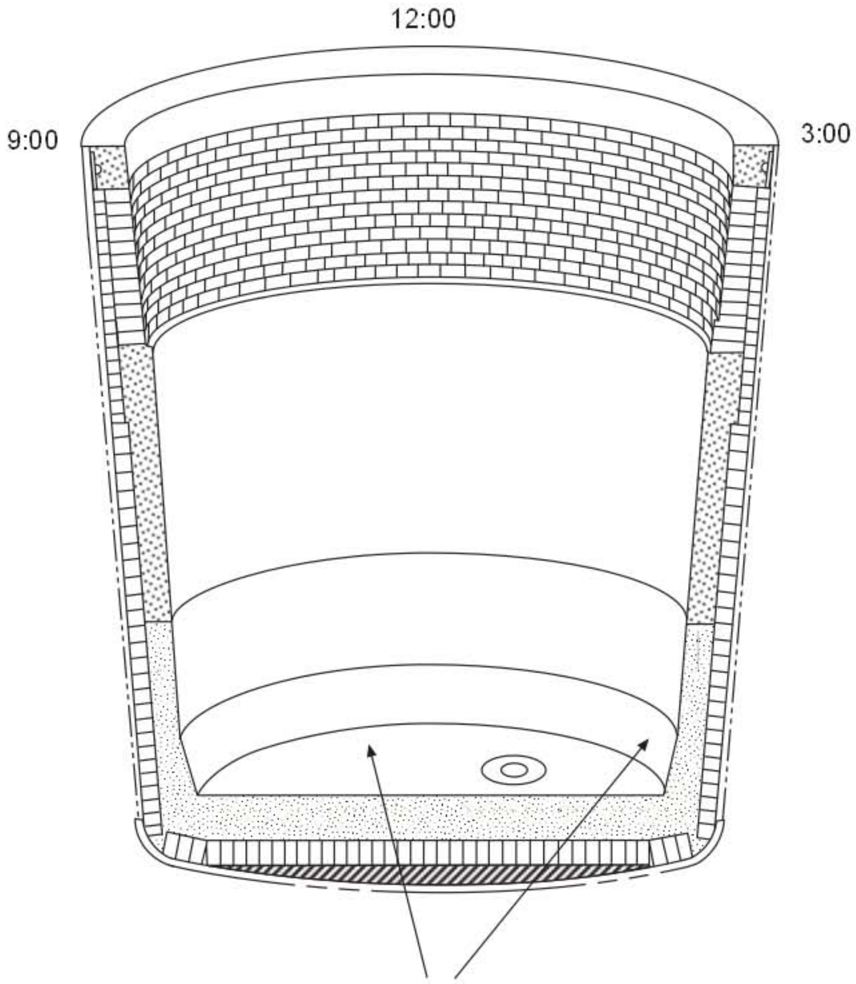


Fig. 4.44 Primary causes of wear in the bottom and lower barrel area of the ladle include: 1. erosion during stirring and other processing, 2. damage during deskulling, 3. slag attack during transport back from caster, and 4. thermal cycling.

time between steel shutoff at the caster and slag dumping can cause slag erosion problems. In general, the slag erosion in this area is not sufficient to zone for, except to provide for additional refractory thickness. Damage from skull removal can occasionally be sufficiently enough severe to require bottom repairs.

4.5.3.3 Barrel

The barrel normally has the least severe wear in the ladle and can be zoned for quality and/or thickness. Fig. 4.45 shows a ladle in which the barrel castable lining is zoned with a lower quality (lower Al_2O_3) castable.

4.5.3.4 Slagline

The most severe wear area of most modern ladles occurs in the ladle slagline where the refractory is subject to severe corrosion, Fig. 4.46. The slags encountered vary widely, and include high iron oxide slag carried over from the furnace, artificial slags introduced after partial slag skimming, slags added or formed during specific metallurgical purposes such as stirring or injection, and slags formed or circulated during degassing. As the slags are generally basic in nature, basic refractories are required in ladle slaglines. Fig. 4.47 shows the range of erosion resistance between high-alumina and various basic refractories. The high-alumina refractories are suitable for most areas of the ladle other than the slagline proper. Table 4.12 shows the wide range of slag compositions experienced in one shop producing a wide range of Al-killed caster products.

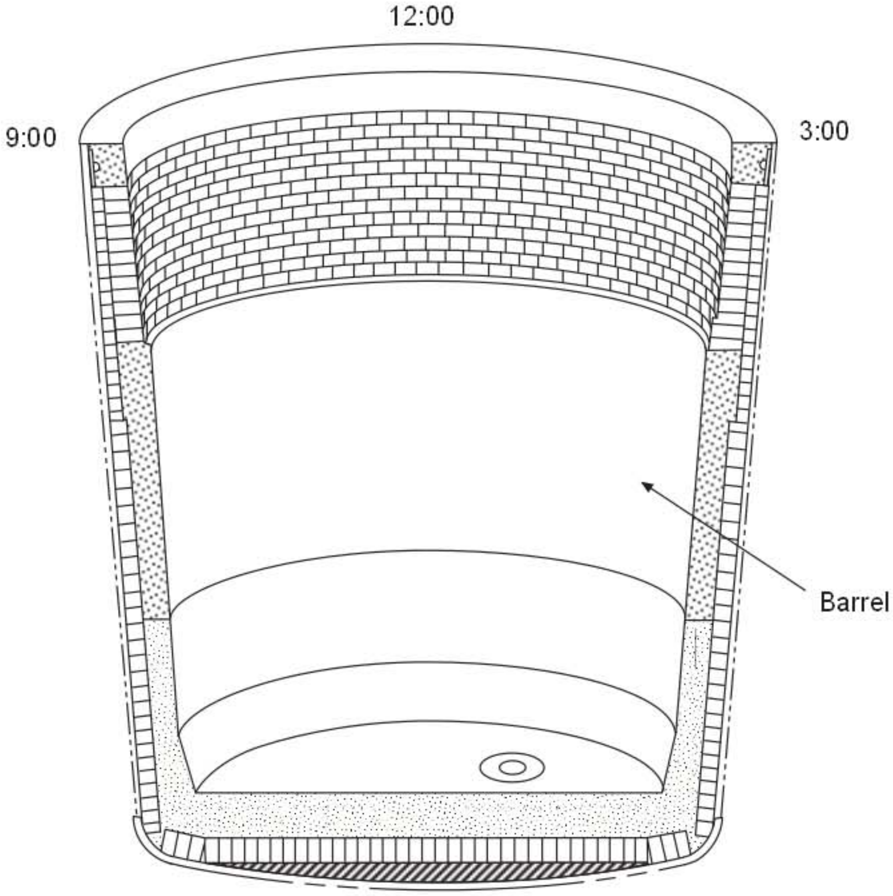


Fig. 4.45 Primary causes of wear in the barrel area of the ladle include: 1. metal erosion with some slag erosion, 2. thermal cycling.

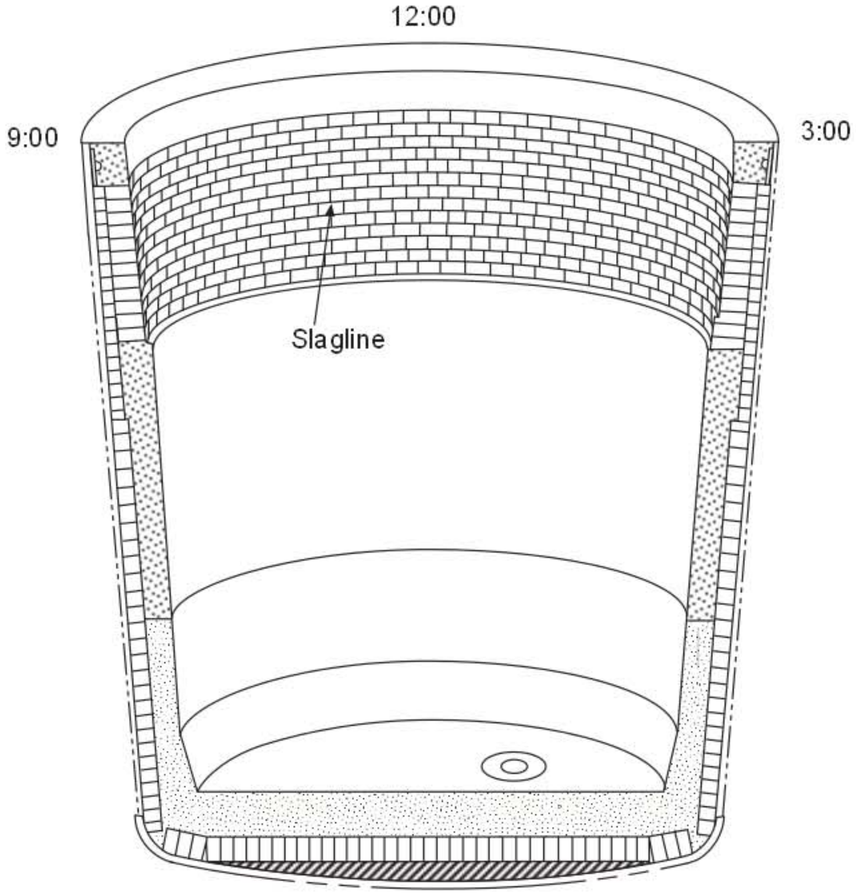


Fig. 4.46 Primary causes of wear in the slagline area of ladles include: 1. slag corrosion, 2. arc damage, 3. thermal cycling, and 4. ladle flexing.

The corrosive effect of ladle slags is particularly severe when arc reheating is used to control and add steel temperature by superheating the ladle slag. Fig. 4.48 shows the degree of superheat added to the slag for various slag thicknesses and stirring conditions. As shown, the temperature of the slag can be expected to be 100–300°F above the steel temperature. Laboratory tests show that slag erosion rates can increase two to five times for such changes in temperature. Field tests have shown that slag erosion can be reduced by control of slag basicity, Al_2O_3 content, and additions of MgO to the slag as illustrated in Fig. 4.49. Significant control over the amount of erosion during arc reheating can therefore be obtained using controlled slag obtained using compositions with added

Table 4.12 Range of Slag Compositions for a Specific Shop

	Range	Median
CaO	20–55	42
SiO_2	5–18	10
Al_2O_3	12–50	26
MgO	6–12	8
MnO	1–10	5
FeO	1–15	5

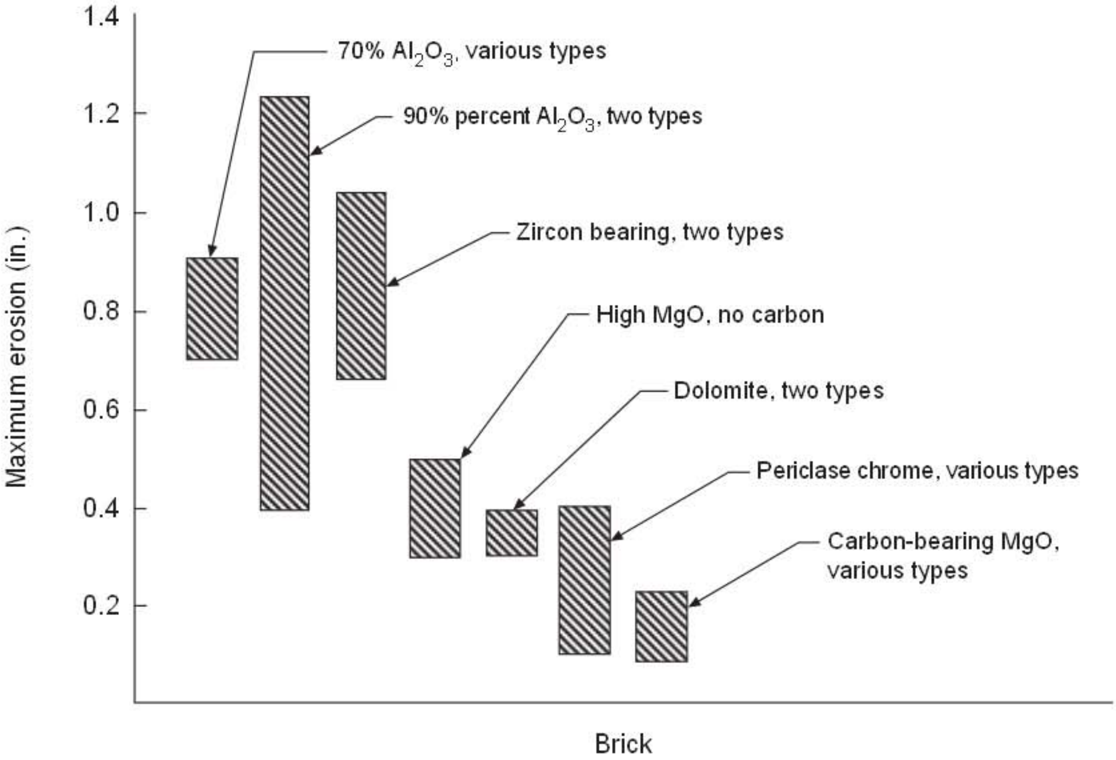


Fig. 4.47 Range of slag erosion values for various types of brick tests with various basic ladle slags.

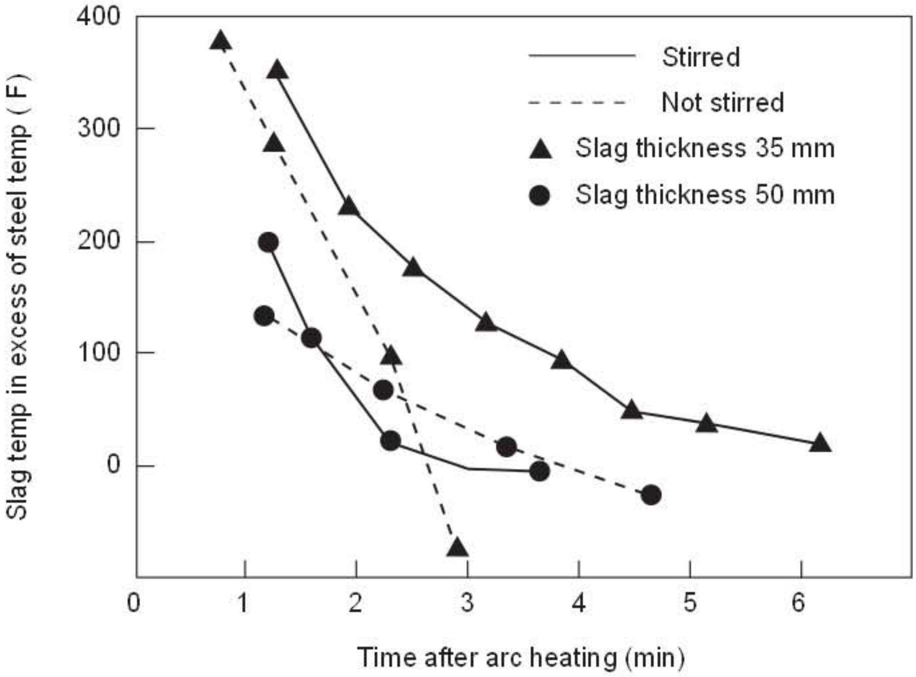


Fig. 4.48 Effect of slag thickness and stirring on slag superheat.

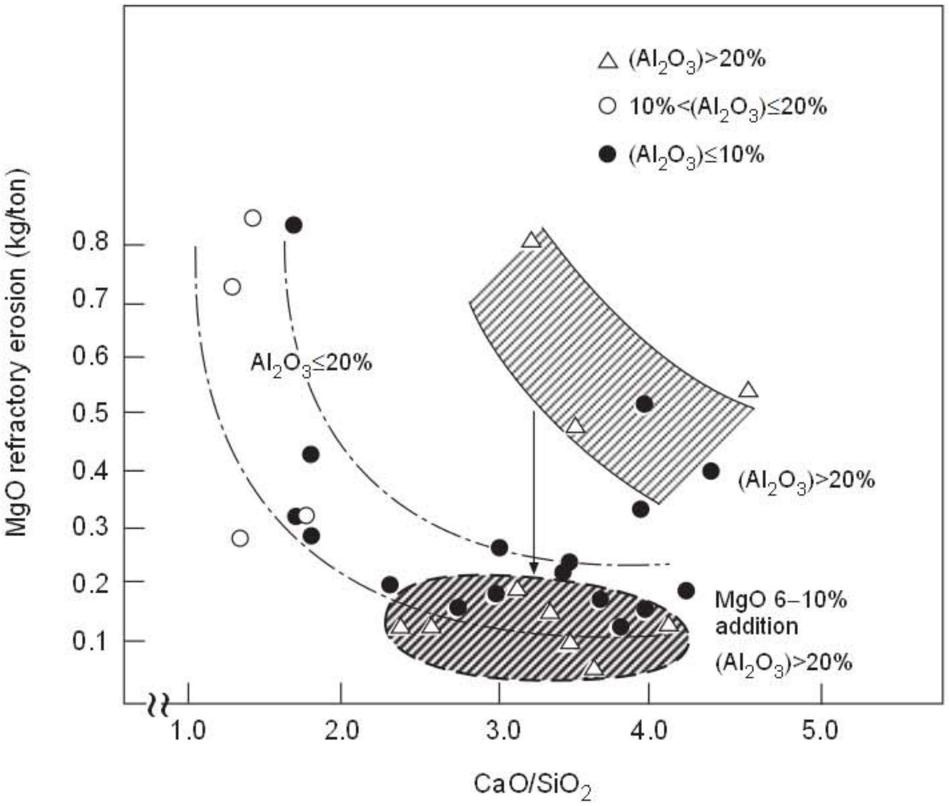


Fig. 4.49 Effect of slag basicity on MgO refractory erosion.

MgO and the use of consistent slag stirring to control slag superheat. Reference should also be made to sections on electric furnace operations which clearly illustrate the importance of arc heating conditions such as arc length and slag submergence on refractory wear.

Table 4.13 shows the properties of various MgO–C brick for slaglines and how specific properties may be improved. Higher purity raw material (sintered or fused MgO and graphite) and metal additions can be used to enhance the properties of magnesia–carbon brick. Table 4.14 shows some of the properties of these bricks for ladle slaglines with bricks ranging from 5–15% carbon.

Table 4.13 Properties of Various MgO–C Brick for Ladle Slaglines

Property	Better Resistance Obtained by
Arc Resistance	More graphite Higher purity graphite
Oxidation Resistance	Metal Metals
Hot Strength	Metal Metals Metals and higher purity graphite
Corrosion Resistance	High purity sintered grain High purity graphite Fused grain Combinations of above

Table 4.14 Properties of Some MgO–C Brick for Ladle Slaglines

%C	5	5	10	10	10	10
Density (lb/ft^3)						
as received	188	187	183	182	186	179
% Porosity						
as received	4.5	5.0	6.0	6.0	4.5	6.5
coked	11	11	11	11	9.5	12
ignited	18	19	24	22	21	28
MOR (lb/in^2)						
70°F	4000	3500	500	1900	2500	1800
2200°F	2800	2700	1200	2700	1800	1500
2820°F	2000	2000	—	2200	1600	1300
Relative oxidation						
2200°F	0.41	0.63	0.91	0.62	0.74	0.97
2700°F	0.39	0.45	0.79	0.43	0.51	1.26
%MgO	85	85	84	79	79	76

Direct-bonded magnesite–chrome or dolomite refractories may also be used in steel ladle slaglines. Dolomite refractories provide lower initial cost and excellent performance if ladle cycles can avoid long delays. Magnesite–chrome refractories can provide lower cost operations if arc reheating conditions are not severe.

It should be noted that thermal cycling damage was listed as a wear mechanism in all areas of the ladle. The extent of such damage has been greatly minimized in recent years with the proper use of preheating and more extensive use of ladle covers. Experience in each shop to use the minimum possible number of ladles at any time and to cycle those ladles as rapidly as possible has also minimized the extent of thermal cycle damage.

Ladle flexing on lifting and during other parts of the ladle cycle is known to influence ladle life. Efforts to combat this effect with improved design in the ladle and lining are continuing.

4.5.4 Ladle Refractory Construction

The majority of ladles in North America are lined with brick construction using semi-universal shapes as illustrated in Fig. 4.50. This construction allows the use of an upward spiral of brick

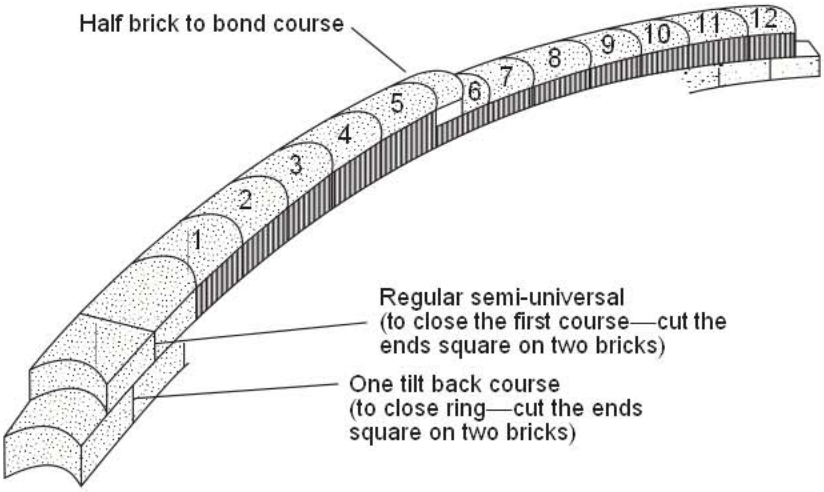


Fig. 4.50 Semi-universal brick construction for ladle side-walls.

Table 4.15 Cast Steel Ladle Advantages and Disadvantages

Advantages	Disadvantages
Labor	**Costs**
Reduced labor hours per ladle	Total costs of labor, material, ladle availability difficult to quantify High startup costs due to equipment Changes in mandrel design can be costly
Technical	**Technical**
Joint-free lining, less steel penetration Physical properties equal to brick No void between working and safety lining Can zone castables in high wear areas with no joints Portions (25%) of castable is reused	Low-moisture castables require controlled installation Vertical dryers with controls are required Technology for slagline castable does not exist

against the sloping sides of a ladle. Brick locking is produced by the curved mating surfaces. Other types of brick construction (arch-wedge or keyed) are more widely used in other parts of the world. In all cases, tight construction with very thin (or no) mortar joints are necessary to keep the lining under compression and prevent joint penetration. Certain operations have converted to cast ladles in the barrel and bottom sections, Fig. 4.40, but efforts to cast basic slaglines have not proven successful. Table 4.15 summarizes the advantages and disadvantages of cast ladles under present conditions. In general, castables provide an excellent joint-free construction and many offer cost advantages where a portion of the spent lining can be reused. Castable ladles do require special equipment, including space, and must be very carefully installed and dried. Future changes in material and labor costs or environmental changes may require reexamination of castable ladles for specific shops. At present, ladles are being used where combinations of brick and castable are employed to obtain the best technical and economic combination of castable and brick approaches to ladle lining. For example, Fig. 4.51 shows construction in a ladle bottom using a precast impact pad with the balance of the bottom cast. This construction improves life due to the jointless construction, but avoids most of the special equipment and space requirements required for a fully cast ladle.

4.5.5 Refractory Stirring Plugs

Refractory stirring cones or plugs are used in ladle bottoms to introduce gas, mainly argon, for ladle rinsing or stirring in the various metallurgical processes. Fig. 4.52 shows cross sections of three types of plugs using different directional mechanisms to provide controlled argon flow.

Argon flow may be controlled by the space between a solid refractory cone and its metal casing, through a permeable refractory cone, or through and solid refractory cone with pre-formed holes or other channels. The amount of flow required will vary widely from rinsing (low flow) to mixing during arc reheating or other processes. Fig. 4.53 shows the relation between flow and pressure for several plug types.

The reliable performance and life of plugs is very important in producing consistent steel product quality. To insure proper flow, it is often necessary to clean the plug surface after a given heat by oxygen burning or mechanical cleaning. Fig. 4.54 shows the sequence of wear of the plug when a penetrated plug surface is cleaned to restore flow. The refractories for plugs are high-Al_2O_3 or burned MgO materials, designed specifically for this application, and are installed from outside the ladle by mechanical or manual devices such as the bayonet system shown in Fig. 4.55. This system

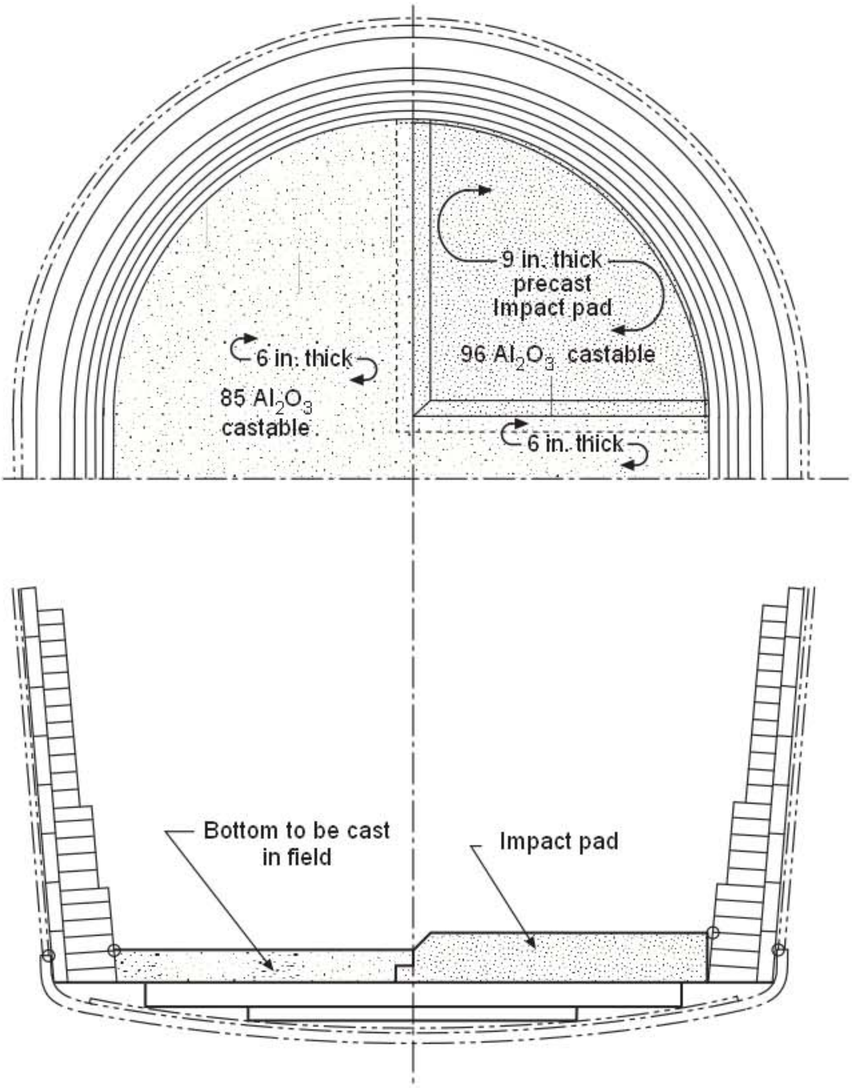


Fig. 4.51 Castable refractory in ladle bottoms.

permits a quick plug exchange in a hot ladle. Plugs are removed from service after a predetermined number of minutes of use or when visual wear indicators built into the plug are overused. Because of wear in the refractory seating block around the plug, hot repairs of the area around the plug may be required using pneumatic refractory placement or from inside the ladle using a diving bell.

The control of steel flow from ladles to caster molds is accomplished by one of a variety of sliding gate systems. Fig. 4.56 shows the concept of steel flow by a sliding gate, where refractory plates held under pressure by springs or other devices are moved to control flow. The design and construction of the various slidegate systems vary widely according to the steel pouring demands of the particular caster. For example, spring location and method of cooling differ between the various gate systems and the movement of plates may be accomplished by hydraulic or other mechanisms. All the slidegate systems provide a rapid means of removing pressure from the plates between heats to allow inspection of the refractories and to permit rapid replacement of plates or the lower nozzle.

The refractory construction of a typical gate system is illustrated in Fig. 4.57. Included are refractories in the seating block and upper nozzle in the ladle bottom, the fixed and sliding plates (in this

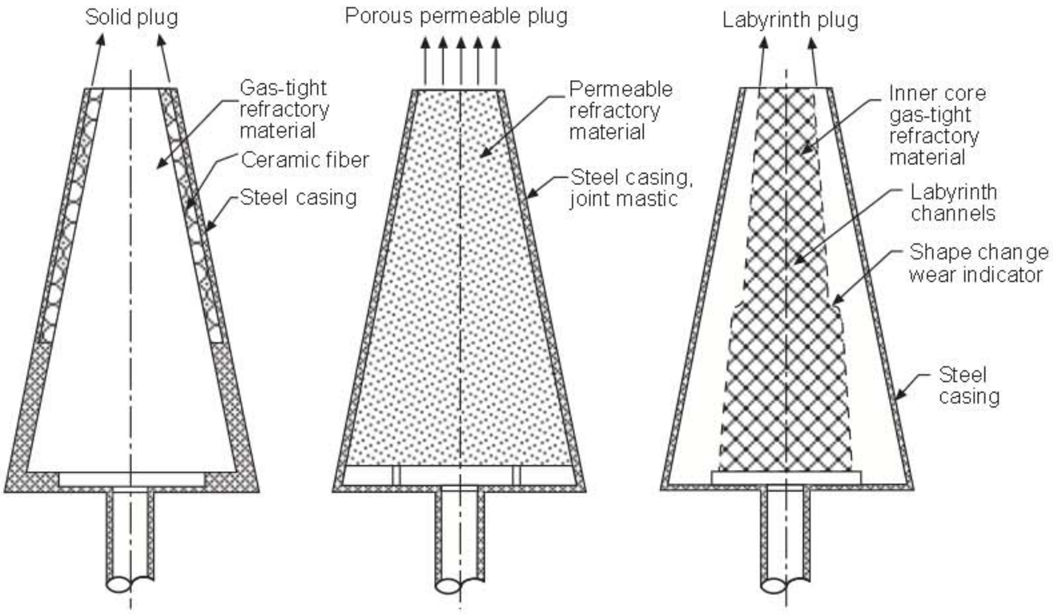


Fig. 4.52 Standard gas stirring plugs.

case a three plate system) and a lower nozzle connection for a tube or shroud into a caster tundish. Table 4.16 and Table 4.17 give refractory properties of the upper and lower nozzles and seating blocks, respectively, which are selected to balance the overall life of the gate system.

The sliding and fixed plates are among the most unique and durable refractories used in any steelplant application. These plates must withstand severe thermal shock and steel erosion for long

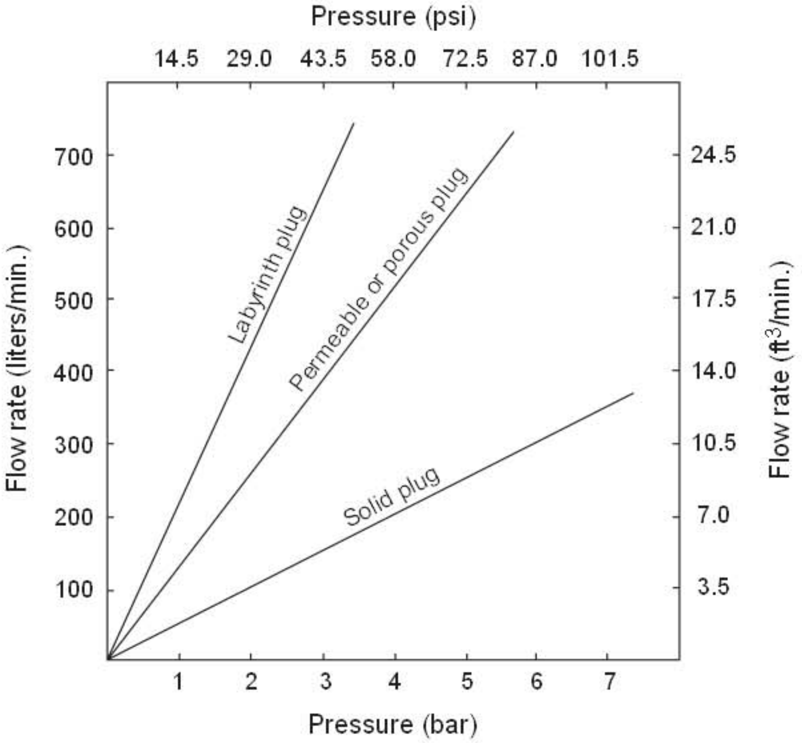


Fig. 4.53 Gas flow of standard gas purging cones.

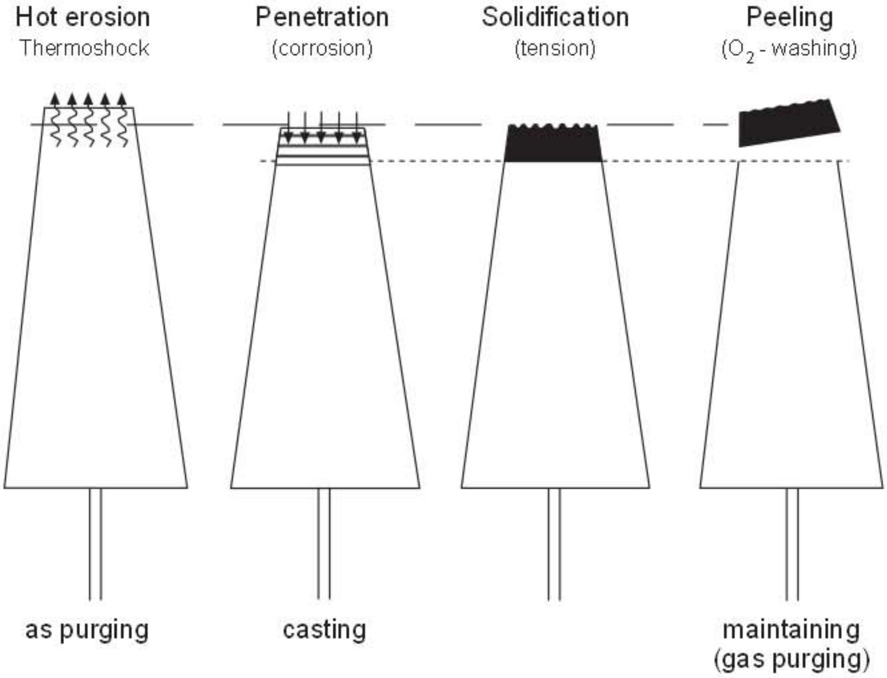


Fig. 4.54 Wear behavior of a porous purging plug.

periods of operation. The composition of these plates may vary from simple alumina to zirconia in the oxide system, Table 4.18, to complex oxide–carbon systems, Table 4.19. The exact plates used depend largely on the steel compositions to be cast and the frequency of plate replacement. Such plate replacement can be accompanied after inspection of the plates. Such inspection is performed after each cast or less frequently based on experience. Fig. 4.58 shows the appearance of plates after use with either erosion or erosion/cracking requiring the plates to be replaced. Plates may be changed after only one heat or may have lives of 10 to 20 heats, depending on steel grades and/or the refractory quality used.

Table 4.16 Typical Properties and Refractory Compositions for Upper and Lower Nozzles

Brand	A	B	C	D	E
Physical Properties					
Bulk density (g/cm^3)	2.25	2.57	2.77	2.86	3.01
Apparent porosity (%)	13.5	8.5	7.0	7.5	7.0
Cold crushing strength (psi)	6500	9000	13,500	11,500	11,500
Chemical Composition (wt.%)					
Al_2O_3	44	60	74	82	90
SiO_2	45	31	16	2	4
ZrO_2	—	—	—	4	—
C	4	4	4	7	4
Corrosion Resistance	———	———	Increasing	———	——→
Thermal Shock Resistance	←——	———	Increasing	———	———
Main Application	Erodable lower nozzle	Lower nozzle	Lower nozzle	Upper and lower nozzle	Upper nozzle

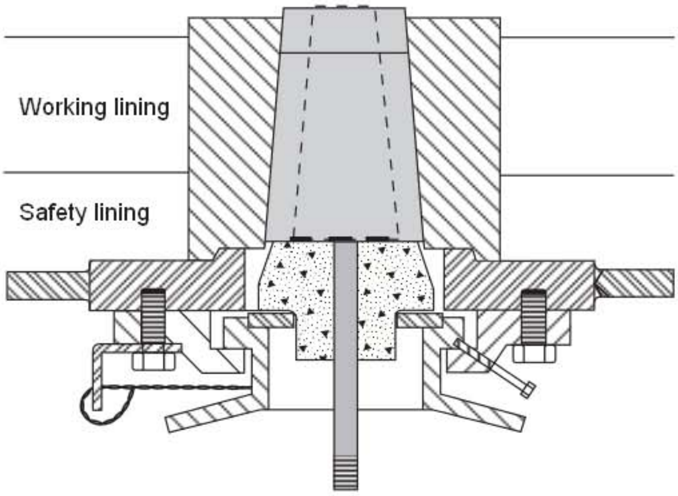
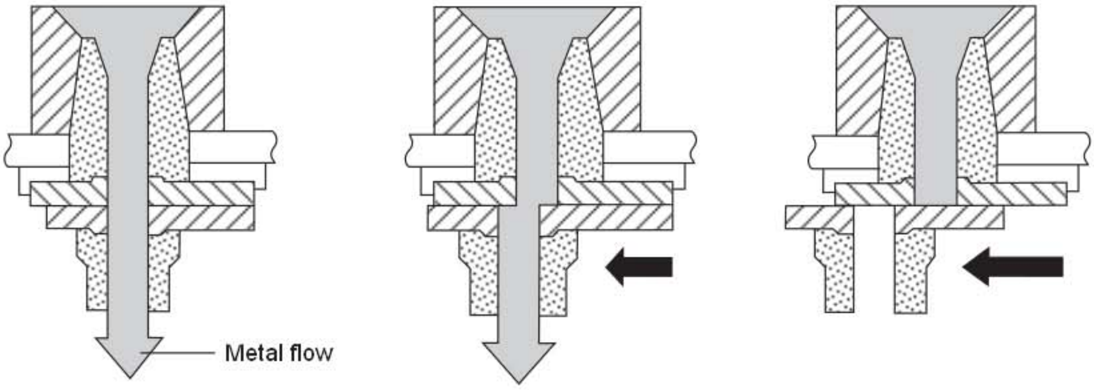


Fig. 4.55 Bayonet system for installing stirring plug.



Open position **Throttle position** **Closed position**

Fig. 4.56 Slidegate operation concept. In a typical installation, the upper nozzle and plate are stationary in relation to the ladle lining and ladle bottom. Coil springs, used to apply face pressure, prevent molten metal leakage without restricting movement of the lower plate. In a sliding motion, nozzle openings in the upper and lower plates are brought into or out of alignment to initiate or terminate metal flow. Intermediate positions, with partial alignment of nozzle openings, provide a throttling action and a range of reduced controlled flow rates.

After each heat, the entire gate system must be cleaned of residual metal and slag by oxygen lancing and a granular refractory filler installed before the next heat. As illustrated in Fig. 4.59, this filler (ladle sand) prevents molten metal from entering the gate system before the gate is opened at the proper time at the caster. The ladle sands may be silica, zircon, or other refractory combinations, Table 4.20, which will flow freely from the slidegate when opened without requiring mechanical probing or lancing.

4.5.6 Refractory Life and Costs

The life of ladle refractories will obviously vary widely between shops, but historically show significant improvement during the first one to three years of operation. These initial improvements occur from the development of standardized operating conditions and the increased ability to control ladle cycling. After this initial period, life will improve at a moderate rate from changes in refractory type and construction. In most cases, slagline life will be less than that for the remaining ladle, with slaglines being replaced one or more times during a ladle campaign. Safety lining

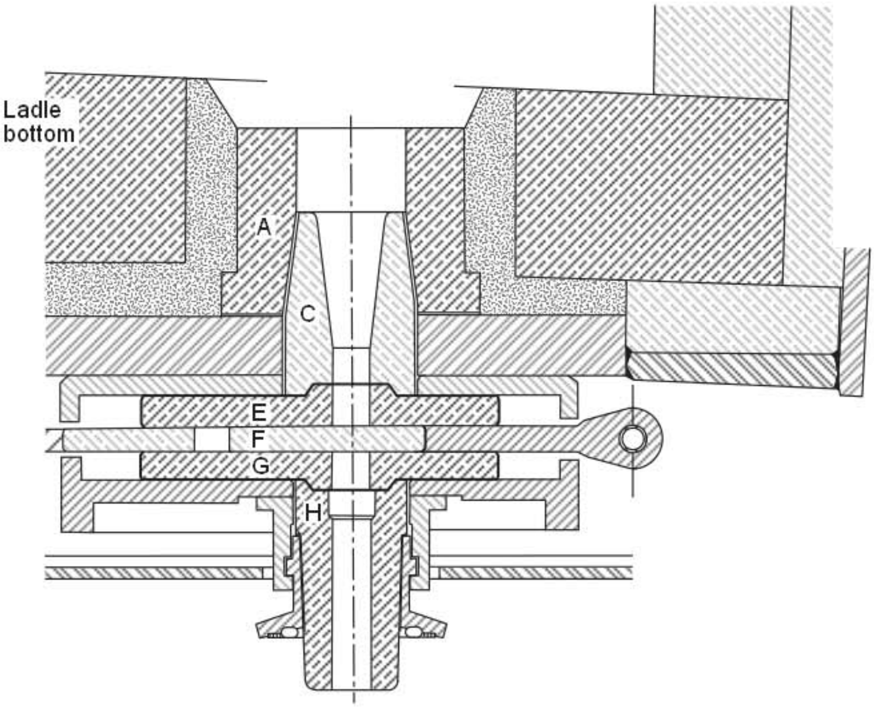


Fig. 4.57 Typical refractories in a slidegate system.

A = Seating block
C = Upper nozzle
E = Upper plate
F = Middle plate (sliding plate)
G = Lower plate
H = Lower nozzle

Table 4.17 Typical Properties and Refractory Compositions for Seating Blocks

Type	Cast		Pressed			
Material	High Alumina		Alumina–Carbon			
Physical Properties						
Bulk density (g/cm^3)	2.64	2.98	>2.15	2.60	2.80	3.00
Apparent porosity (%)	23	16.5	<16.0	9.50	6.00	8.00
Cold crushing strength (psi)	—	—	>4000	9000	14,500	14,000
Chemical Composition (wt.%)						
Al_2O_3	82	94	>40	50	80	90
SiO_2	11	—	<50	31	13	4
ZrO_2	—	—	—	—	—	—
C	—	—	4	4	4	4
Corrosion Resistance	Increasing →					
Main Use	Large one-piece blocks for thick ladle bottoms		Lower blocks	Upper, lower and one-piece blocks	Upper and one-piece blocks	Upper and one-piece blocks

Table 4.18 Oxide Refractories for Slidegate Plates

Properties	Standard Alumina	High Purity and Density Alumina	Magnesia	Zirconia
Chemical Composition (%)				
Al_2O_3	89.3	96.0	—	0.4
SiO_2	9.7	1.0	0.3	0.7
ZrO_2	—	3.0	—	94.8
MgO	—	—	98.0	0.1
Apparent Porosity (%)	15.2	2.1	16.0	14.6
Bulk Density (g/cm^3)	2.98	3.98	2.92	4.80
MOR (lb/in^2)				
at room temperature	2900	13,340	2980	6000
at 1480°C	1680	11,280	1320	
Thermal Shock Resistance	Good	Very Poor	Very Poor	Good
Steel Erosion Resistance	Poor	Excellent	Excellent	Excellent
Performance	1.0	3.0	2.0	3.0

Table 4.19 Carbon Bonded Refractories for Slidegate Plates

Properties	Brand A	Brand B	Brand C	Brand D	Brand E
Chemical Composition (%)					
Al_2O_3	75.8	83.3	72.6	71.6	0.4
SiO_2	8.2	3.3	4.5	6.0	0.6
ZrO_2	—	4.8	8.0	7.0	83.4
Carbon	12.7	8.6	13.6	11.8	12.0
Apparent Porosity (%)	6.5	1.7	6.0	4.0	5.0
Bulk Density (g/cm^3)	2.92	3.26	3.07	3.20	4.40
MOR (lb/in^2)					
at room temperature	4700	4470	4830	4550	4000
at 1480°C	1010	2410	3270	2540	2000
Thermal Shock Resistance	Poor	Fair	Fair	Fair	Fair
Steel Erosion Resistance	Fair	Good	Good	Good	Very Good
Performance	1.5	2.0	3.0	3.5	4.0

will last multiple working campaigns with some localized repairs. Fig. 4.60 shows the ladle life history of a caster during the first two years of its operation, where ladle life improved from 50 to 86 heats. This shop used two slaglines per ladle campaign. At present, ladle lives from 50 to 200 heats are being experienced with slagline lives from 30 to 200 heats. For a given shop, analysis of process data can usually be used to explain differences in the life for a given ladle or a given time period. For example, one could predict or explain the life of individual ladles by the frequency of heats with abnormal wear parameters such as long ladle arc times, long steel holding times during caster delays, and unusual situations where ladles were taken out of service of repairs to slidegates or plugs.

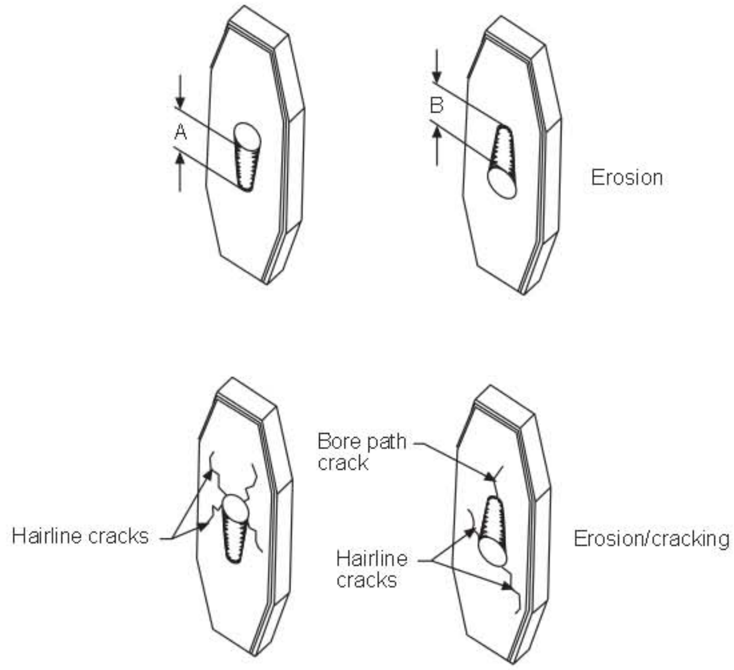


Fig. 4.58 Appearance of slidegate plates after use.

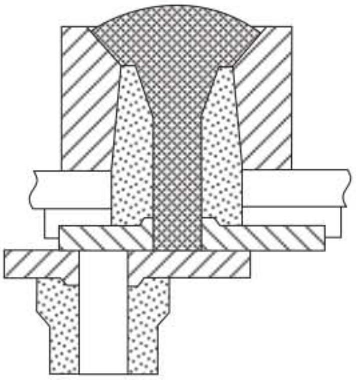


Fig. 4.59 Nozzle plugging agents prevent molten metal from entering slidegate before it is opened and assure free opening of the slidegate after long ladle hold times.

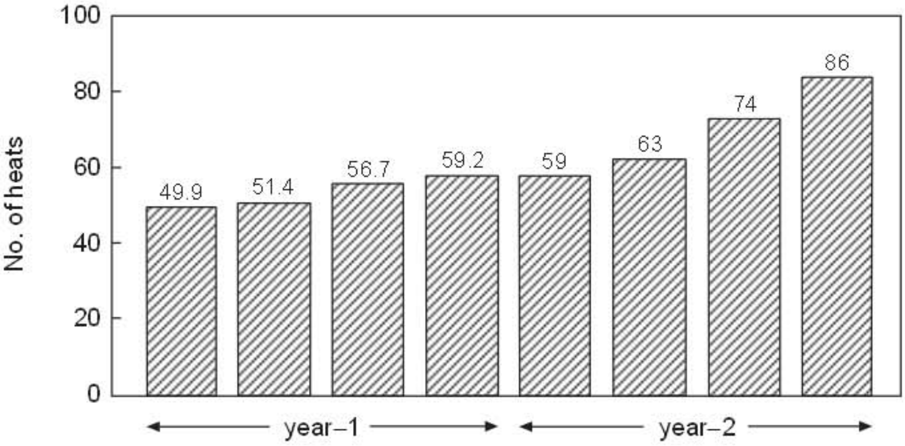


Fig. 4.60 Ladle life during startup of a caster operation.

Table 4.20 Characteristics of Nozzle Plugging Agents

Properties	Silica	Zirconia
Chemical Composition (%)		
SiO_2	95.3	0.2 max
Al_2O_3	2.4	2.0 max
R_2O_3	1.7	—
C	—	—
TiO_2	—	0.35 max
ZrO_2	—	65.0
Fe_2O_3	—	0.05 max
Grain Size (%)		
>2.00	1.0	—
2.00–1.00	47.0	—
1.00–0.50	51.0	—
0.50–0.21	1.0	<1.0
0.21–0.15	—	13.0
0.15–0.10	—	48.0
0.10–0.08	—	36.0
<0.08	—	<3.0
Bulk Density (g/cm^3)	1.4	2.8
Refractoriness (SK)	33	>34
Sinterability		
at 1200°C	Slight	None
at 1300°C	Moderate	None
at 1400°C	Significant	Slight
Features	Large grains, low alkali content to prevent excessive sintering	Small round grains, high melting point, low alkali content to prevent excessive sintering

4.6 Refractories for Degassers

The wear of refractories in degassers can present limitations to equipment availability and cost and affect steel quality in producing low carbon, hydrogen, and nitrogen steel for modern requirements. The refractory use and maintenance technologies vary widely with location in a given degassing unit and between operations.

Fig. 4.61 through Fig. 4.63 illustrate a typical vessel degasser (RH or RH-OB) and refractory construction. Table 4.21 lists refractories used for each area. The RH degasser is a recirculating type degasser. The snorkels are immersed into a ladle held steel bath. Evacuation of the degasser causes metal to rise through the legs into the lower vessel. Circulation of the liquid steel results from injecting argon into the steel in the snorkel of one of the legs (called the lifting leg or up leg) thus lowering the steel density and causing flow upward. The degassed steel in the lower vessel, now considerably denser, returns to the ladle through the other leg (appropriately call the return leg or down leg), descending in fact to the ladle bottom. Steel flow rates, or circulation rates, can be quite high (e.g., 80,000 kg/min) and depend on argon flow rates and snorkel inside diameter. RH degasser treatment times generally range between 15 and 30 minutes, the longer times for attaining low hydrogen levels. While originally used primarily for hydrogen removal, alloying, and

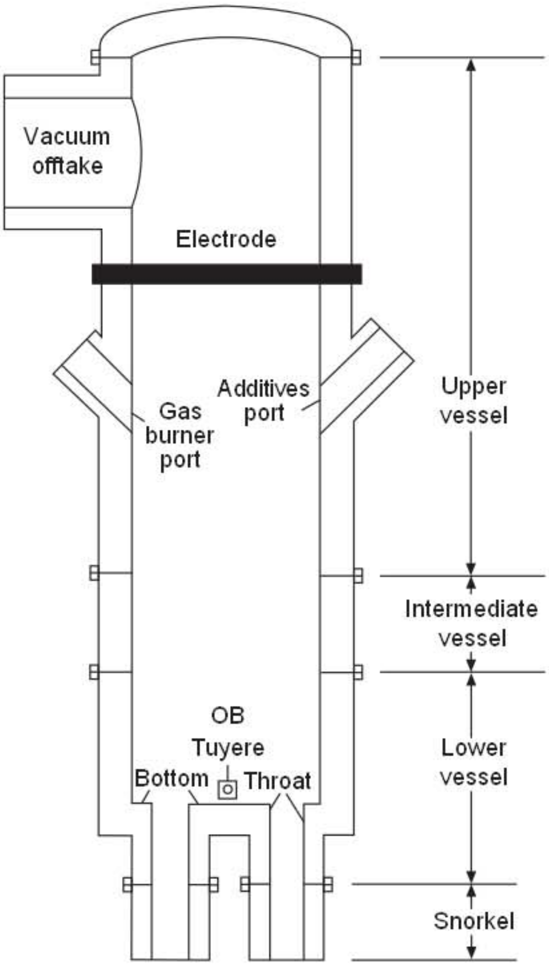


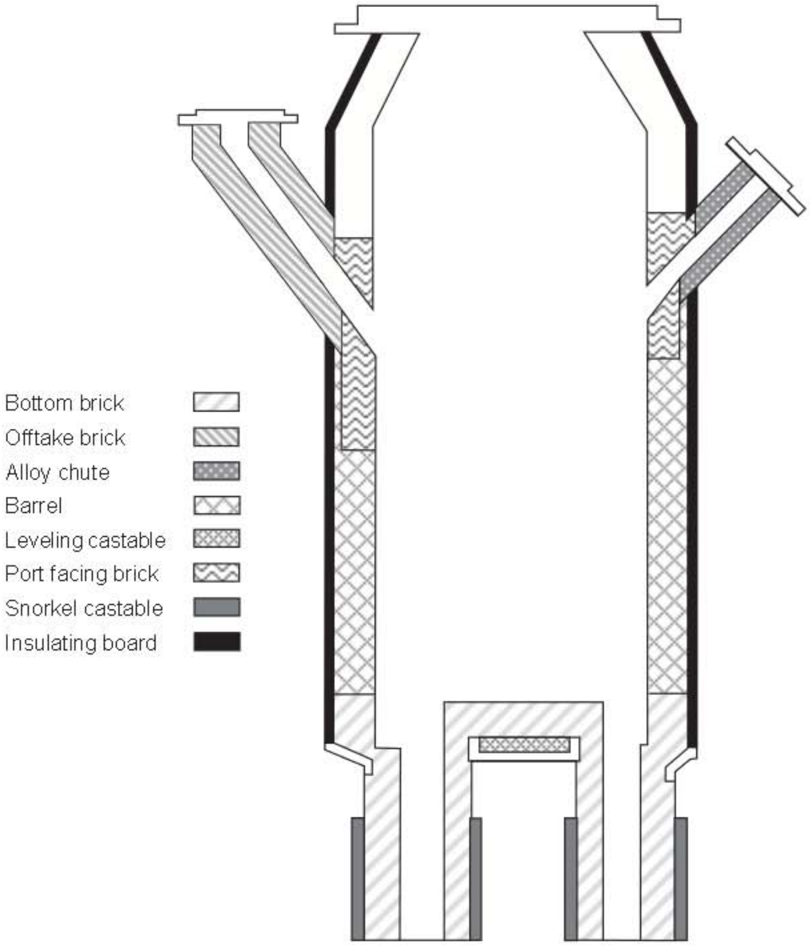
Fig. 4.61 Typical configuration of RH/RH-OB degassers.

inclusion flotation, the RH degasser is now also used for decarburization, nitrogen removal, and desulfurization.

RH-OB adds oxygen blowing capability to the RH process. With oxygen blowing, heats with higher furnace tap carbons can be decarburized, and some reheating can be done by aluminum burning.

Table 4.21 Vessel Degasser Refractory Use by Area (Refer to Fig. 4.62 and Fig. 4.63.)

Area	Refractory Description
Bottom Brick	Magnesia–chrome brick containing fused grain
Offtake Brick	60% Al_2O_3 brick
Alloy Chute Brick	90% Al_2O_3
Barrel Brick	Magnesia–chrome brick
Leveling Castable	Magnesia–chrome
Port Facing Brick	Magnesia–chrome brick with fused grain
Dome Brick	50–60% Al_2O_3 brick
Snorkel Castable	Tabular alumina or spinel castable
Insulating Board	High-strength insulting board



* Drawing not to scale

Fig. 4.62 Refractory areas of a vessel degasser.

Working lining refractories are exposed to a variety of conditions depending on vessel location. All locations are exposed to thermal and atmospheric cycling. Use of auxiliary heating between treatments can significantly reduce the severity of thermal cycling, but rapid temperature changes can range from 200 to 600°C depending on the adequacy of that heating. Atmospheric cycling can range from ambient down as to low as 0.5 Torr. Besides being exposed to liquid steel at temperatures as high as 1650°C, snorkel and lower vessel (particularly throat and bottom) refractories are subjected to the erosive action of high velocity, turbulent steel flow. Refractories in these locations are also exposed to contact with slags, which include ladle carryover slags (despite precautions to exclude them) and those generated during treatment (especially if the treatment includes desulfurization). These refractories may also suffer iron oxide alteration from oxidation of skulls left on their hot faces and from skull oxide melt runoff from higher vessel locations. Tuyere area refractories of RH-OB degassers experience greater erosive bath action than do lower vessel sidewall refractories in RH degassers. Aluminum burning may also cause localized heating. Upper vessel refractories, spared from erosive bath action, are coated with metal and slag splash accompanying the violent bath agitation and gas evolution. Subsequent oxidation of the adherent metal results in major alteration.

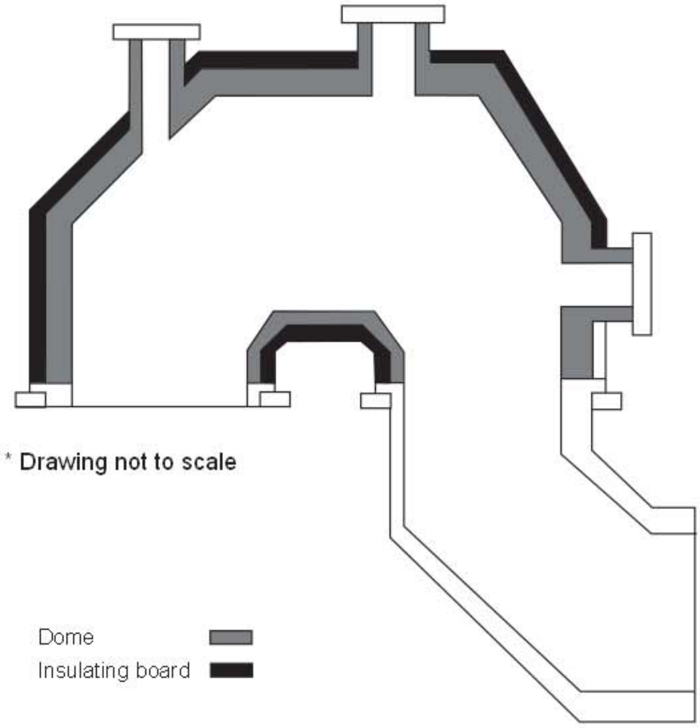


Fig. 4.63 Refractory areas of a degasser offtake.

Knowledge of the service conditions and nature of the refractory alterations as described above provide insight into wear mechanisms. In those areas experiencing the greatest steel bath circulation rates, such as snorkel, throat, bottom, and OB tuyere, the likely primary mode of wear is erosion of the disrupted hot face refractory structure. Structural disruption or weakening occurs by a variety of processes, such as: thermal shock damage resulting from rapid heating or cooling of the hot face between preheating and steel processing (the less the difference between the temperatures involved, the less the damage); Fe^{2+}/Fe^{3+} oxide cycling because of oxygen pressure and/or temperature changes (both refractory chrome ore and chromite spinel phases and absorbed iron oxide zones will be affected); and slag infiltration with dissolution of the normal refractory bonding (silicate bonds are particularly susceptible). Also lost to erosion in these lining areas will be the iron-oxide-rich immediate hot face portion of the iron oxide absorption zone. Considering the temperatures involved, wherever the iron oxide content exceeds roughly 80%, appreciable amounts of liquid are formed. Even in those lining areas subjected to less aggressive contact with the circulating steel (e.g., upper portion of lower vessel sidewall exclusive of OB tuyere areas), the partially liquefied hot face zone will be washed away.

Finally, some wear is likely the result of loss of partial hot face from spalls, as the hot face wear front approaches internally formed cracks. For a given brick, these losses are probably relatively discontinuous (as opposed to an essentially continuous erosion–corrosion loss of material). The loss rate of spalls would be greater in high erosion areas due to more rapid movement of the wear front and the stripping power of the flowing steel.

RH and RH-OB degasser working linings are commonly direct-bonded magnesia–chromite brick. To counter the different exposure conditions, linings are often zoned by product quality.

Table 4.22 shows some properties of various types of magnesia–chrome brick. The more corrosion-resistant products would obviously be selected for the snorkel and lower vessel areas where more severe conditions are encountered. Similarly, castables for the outside of the snorkel must be selected for maximum hot-strength and high-temperature stability so that only the most high purity materials prove successful.

Table 4.22 Properties of Various Magnesia–Chrome Brick used in Vessel Degassers

		Rebonded Fused-Grain	
	Regular	A	B
Composition (wt%)			
MgO	60	60	60
Cr_2O_3	15	19	24
CaO	6.7	6.6	0.5
SiO_2	1.4	1.6	1.5
Porosity (%)	16–18	13–14	12–14
Modulus of rupture			
at 1300°C, MPa	12–13	16–17	15–18
at 1500°C, MPa	3	4–6	6
Corrosion index (Low = less erosion)	100	50	45–50

Table 4.23 Refractory Life for Areas of Vessel Degasser

Area	Life (number of heats)
Snorkel	150–200
Throat/bottom	150–200
Sidewalls	400–600
Balance of degasser	About one year

Refractory life obviously varies with the location in the degasser as illustrated below in Table 4.23 for one typical degasser. The degasser lining must be designed to facilitate rapid replacement of the higher wear sections.

Acknowledgment

The information on oxygen steelmaking refractories presented in Section 4.1 is excerpted, with permission, from the Iron & Steel Society publication titled *Pneumatic Steelmaking, Vol. 3, Refractories.*

This comprehensive reference text, consisting of six chapters, provides an understanding of the underlying principles of refractories for oxygen steelmaking and presents information on improving, both technically and economically, the steelmaking process.

To obtain more information about this publication, contact the Iron & Steel Society by writing to 410 Commonwealth Drive, Warrendale, PA 15086.

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