Chapter 4

Ironmaking Refractory Systems

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4.1 Introduction

Complex refractory systems are used in modern blast furnaces to provide the long, safe lives necessary for furnace availability and to permit nearly continuous furnace operation and casting. To achieve these goals, the best refractory materials are combined with other critical features such as water cooling in the furnace proper or rapid component replacement of the casthouse components. The refractory systems continue to evolve and facets of this evolution are also covered in Chapter 3 on refractory properties, Chapter 9 on furnace construction, and Chapter 10 on pig iron manufacture.

4.2 Blast Furnace Proper

Conditions in the blast furnace vary widely by zone and the refractories are subjected to a variety of wear mechanisms. When selecting refractories for the blast furnace or its auxiliaries, it is imperative that an analysis be undertaken, which includes an evaluation of the wear mechanisms to be encountered, identification of the expected operating conditions which could adversely affect lining life and an evaluation of all external factors which will impact refractory performance. The selection of refractories based solely on properties, will not assure successful refractory performance.

The actual refractory product comprises only one part of a complex, interrelated *system* of components and features and this *system* is affected by many external factors during its lifetime. It is the obligation of the designer to recognize all of the internal and external influences which will adversely affect the refractory.

Some of these external factors are the lining shape or geometry, cooling capability and configuration, operating practices and raw materials, process environment and the impingement of process gases or materials on the lining. The lining thickness and configuration or its composition can also be a major external factor adversely affecting performance, especially in the case of externally cooled conductive refractories. These products require effective cooling and uninterrupted heat transfer, in order to maintain low hot face temperatures. Thus, excessive wall thickness, or configurations which result in heat transfer impediments, will also hamper performance.

Internal factors can include such things as accommodating thermal expansion, differential thermal movements, mechanical and thermal stresses, resistance to wear mechanisms and of course, the obvious, refractory properties.

There is no *ideal* or *perfect* refractory which possesses magical powers to guarantee long life. The very best refractory for a particular application would fail miserably if consideration were not given by the designer, to all of the other internal and external factors which affect performance of the lining *system*.

When considering the *ideal* refractory system for a particular furnace zone, it should be remembered that furnace operations *can still* destroy even the most appropriate material for the application, despite being properly configured and properly cooled. If the furnace geometry (or *furnace lines* as it is called) is incorrect, impingement of high velocity gases with entrained solids will relentlessly attack refractories, essentially sandblasting them into oblivion. This is especially the case in the bosh where raceway action can devastate refractories and prevent protective accretion (skull/scab) formation.

Burden distribution patterns that result in severe wall gas flow in the upper bosh, belly and lower stack can also destroy any properly cooled and configured refractory system. Additionally, poor burden material quality such as coke can affect the cohesive zone and raceway shapes and locations, also resulting in severe process activity at the walls. The shape of the cohesive zone also plays a very important role in the distribution of wall gas flow and can be affected by the type and quantity of tuyere injected fuels. The area of gas flow in the lower part of the cohesive zone is related to its shape and thickness, not to the furnace cross sectional area. Thus, cohesive zone shape can influence central versus wall gas flow and velocities and thus seriously affect refractory life.

Another operating factor that can adversely affect even the most properly configured refractory system is furnace availability. Furnaces that are continually cycled from on-wind to off-wind for maintenance shut-downs or suffer interruptions of full wind because of operational problems can seriously affect refractory performance. These actions submit the refractories to thermal cycling, which can result in thermal shock damage and fatigue to the refractories, shortening their life. The best situation for a refractory system is to be properly dried out, carefully heated to operating temperatures and be maintained at these temperatures, uninterrupted, for as long as possible.

Fig. 4.1 depicts refractory wear mechanisms and their attack severity by furnace zone for typical blast furnaces. As previously mentioned, various refractory geometries, configurations, burden

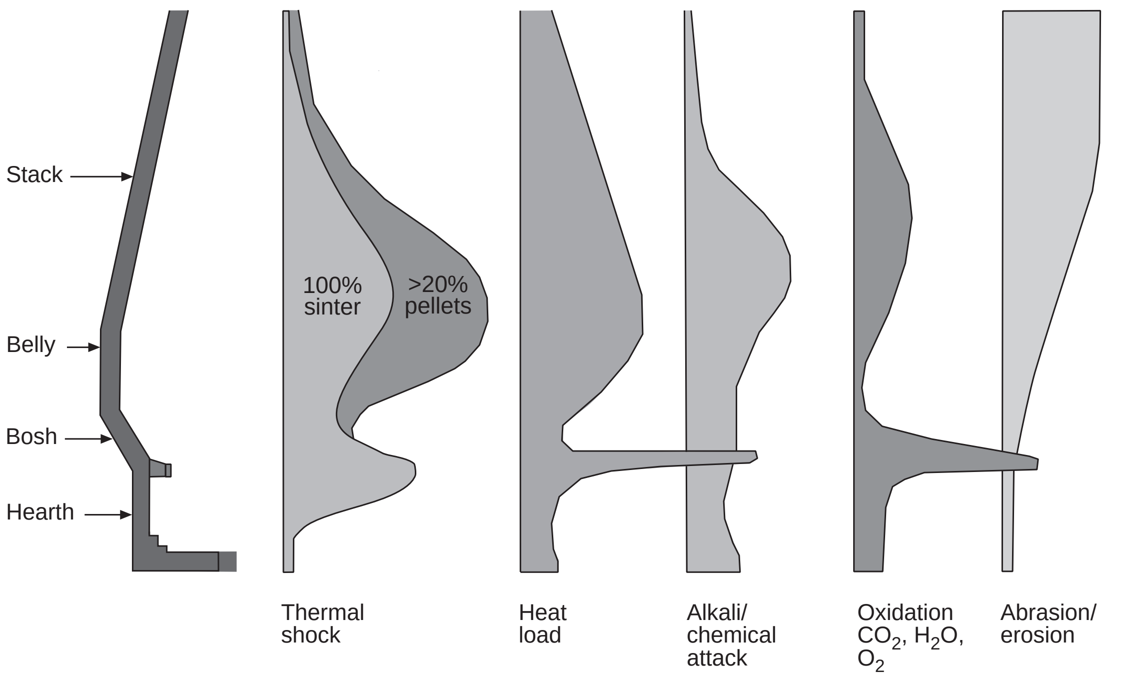

Fig. 4.1 Blast furnace refractory wear mechanisms and their severity by zone.

type, quality and distribution capability and other operating practices can have a direct effect on the severity of these mechanisms for a particular furnace. The change in thermal shock severity in particular, is very sensitive to the percent of pellets in the burden as is shown in Fig. 4.1 It is imperative that the effects on these mechanisms from unusual or unique characteristics and operating practices are considered when analyzing refractory wear potential.

The actual refractory configuration is another external factor which can affect refractory performance, especially when the refractories are cooled from one side. Examples of this type of cooling are jacket sprays, external water panels or staves. If the refractory mass is configured excessively thick, it may be impossible to cool the refractory hot face sufficiently to prevent chemical attack and form protective accretions.

Cooling capability is another important external factor that involves more than cooling type. Good water quality and high velocity can prevent corrosion and build-ups on cooled surfaces and prevent deposits of sediment or organic materials over the many years of operation required. Maintenance practices such as annual acid cleaning and high-pressure water blasting, can be crucial to maintaining effective heat transfer from the refractories. If insulating layers of minerals and corrosion are allowed to occur, refractory temperatures will rise, guaranteeing chemical attack and ultimate loss. Barriers to effective heat transfer such as excessively thick rammed layers, improperly installed rams, air gaps resulting from poor installation practices, etc. must also be eliminated, in order to maintain effective and unchanging heat transfer, for the life of the campaign.

4.3 Blast Furnace Hearth

One of the largest users of refractory materials is the blast furnace hearth. Worldwide, the configuration and design of this large volume refractory system varies considerably, with major differences in performance. This zone of the blast furnace probably exhibits more varied designs, conflicting practices and vastly different performance histories than any other. Technical articles from certain countries continually describe the hearth as the zone of the blast furnace most responsible for the termination or interruption of the campaign. Contrasting this experience are the apparent success stories from other countries of trouble-free, long campaign lives of blast furnace hearths, especially in North America. There are many reasons for this different performance history, especially when the designer analyzes the internal and external factors which affect the hearth refractory *system*.

4.3.1 Refractory Materials

The traditional materials used in hearth construction have been carbonaceous in nature. Various grades of amorphous and hot-pressed carbon, conventionally baked and hot-pressed semi-graphite, semi-graphitized carbon and fully graphitized materials, are the basic refractories used in any modern hearth refractory design. However, the nomenclature of these materials must first be clarified, because they represent an entire family of materials with varying compositions, processing and resulting properties.

The words, carbon and graphite, are often used interchangeably in the literature, but the two are not synonymous. In addition, the words, semi-graphite and semi-graphitic, are also misused. The following briefly describes the major differences and characteristics of the carbonaceous materials used as refractories in the blast furnace.

4.3.1.1 Carbon

The terms, carbon, formed carbon, manufactured carbon, amorphous carbon and baked carbon, refer to products that result from the process of mixing carbonaceous filler materials such as calcined anthracite coal, petroleum coke or carbon black with binder materials such as petroleum pitch or coal tar. These mixtures are formed by molding or extrusion, and the formed pieces conventionally baked in furnaces at temperatures from 800 to 1400°C (1500 to 2550°F) to carbonize the binder. The resulting product contains carbon particles with a carbon binder.

Typically, conventionally baked carbon is manufactured in relatively large blocks. As the binders carbonize and the liquids volatilize, they escape through the block, resulting in porosity. This porosity results in a permeable material that can absorb elements from the blast furnace environment such as alkalies. These contaminants use the same passages to enter the carbon and chemically attack the structure that the volatilizing binders used to escape the block.

Conventionally baked carbon can be densified and thus, permeability improved and pore sizes reduced. This can be accomplished by the introduction of additional binders, impregnated into the baked carbon under a vacuum, and the resultant product rebaked to carbonize the impregnation. Multiple impregnations are also possible to double or triple densify the end product. Each densification, however, adds additional cost and results in a higher priced product.

Some manufacturers also add special raw materials to the carbonaceous mix prior to baking to improve the end productís properties. Silicon carbide or silicon metal can be added to improve permeability, reduce pore sizes and improve abrasion resistance. Artificial or natural graphite can also be added to improve thermal conductivity. Some manufacturers also impregnate the baked carbon with silicon carbide to improve thermal conductivity. However, each of these steps also results in a higher priced product.

4.3.1.2 Hot-pressed Carbon

An American manufacturer developed a unique proprietary method of manufacturing carbon which is called the BP process or hot pressing. In this method of manufacturing carbon which, as previously described, is a product containing carbon particles with a carbon binder, a special pressing/carbonizing operation is utilized.

In this process, carbon particles and binders are mixed, as before, but are then introduced into a special mold. A hydraulic ram then pressurizes the mixture while, simultaneously, an electric current passes through the mold, carbonizing the binders. Unlike conventionally baked carbons that take a period of weeks to bake out the binders, this proprietary process carbonizes the binders in minutes. More importantly, as the liquids volatilize, the hydraulic ram squeezes the mixture together, closing off the pores formed by escaping gases. This forms an impermeable carbon compared to conventionally baked carbon, usually at least 100 times less permeable. This impermeability makes it difficult for blast furnace contaminants, such as alkalies, to enter the hot-pressed brick and makes hot-pressed carbon an ideal hearth wall or bosh lining refractory.

To make this product even more alkali resistant, special silica and quartz additions are also added. These additions are made because sodium or potassium in the blast furnace react preferentially with silica, forming compounds that do not swell in the carbon. Normally, the reaction of these alkalies with carbon would form lamellar compounds which do swell, causing volume expansion spalling of carbon. Thus, the combination of hot pressing and raw material composition results in a superior alkali-resistant carbon.

Hot pressing also results in a higher thermal conductivity than conventional carbon, which makes this product a desirable bosh or hearth wall lining. This is because the higher thermal conductivity promotes the formation of a protective skull of frozen materials on its hot face because of its ability to maintain a hot face temperature that is below the solidification temperature of iron and slag. The protective skull protects the wall from chemical attack and erosion from moving liquids.

Because of the special manufacturing process required for hot pressing, the product is restricted to sizes not exceeding approximately 500×250×120 mm (20×10×5 in.)

4.3.1.3 Graphite

The term, graphite, also called synthetic, artificial or electrographite, refers to a carbon product that has been further heat treated at a temperature between 2400 and 3000°C (4350 and 5400°F).

This process of graphitization, changes the crystallographic structure of carbon and also changes the physical and chemical properties.

Graphite is also found in nature in flake form, and, if used in a refractory product, usually forms part of a mixture of ceramic materials for the binder. This ceramic bonded, natural graphite containing refractory is considered a ceramic product, however.

Artificial or synthetic graphite refractories begin as a baked carbon material, similar in manufacture to the carbon refractory material described previously. However, after carbonizing of the binder is completed, this baked carbon is then loaded into another furnace to be graphitized at a high temperature. Graphitization changes the structure not only of the carbon particles but also the binder. The resulting product contains graphitized particles as well as a graphitized binder.

There is no industry-wide system for designating the various grades of graphite that are commercially available. Each manufacturer has a method and nomenclature to describe the available grades and varieties which are made for specific purposes or properties. These grades differ with regard to raw materials, grain sizes, purity, density, etc. For denser versions, the porosity of the material can be filled with additional binder materials such as tar or pitch by impregnation under a vacuum. Then, the impregnated material is regraphitized, forming a less porous product. Multiple reimpregnations/graphitizations can be performed to provide additional densification.

Purification can be utilized to reduce the ash levels of graphite for high purity requirements. In addition, proprietary manufacturing methods and techniques can also be used to minimize ash or iron contamination of graphites. Since iron is a catalyst for oxidation of graphite in a blast furnace, graphites intended for use as a refractory should contain relatively low iron.

Graphite products are manufactured in large blocks or rounds and must be cut and machined into blocks for use as a refractory. Tight tolerances can be maintained with machined graphite components due to its easy machinability.

4.3.1.4 Semi-graphite

The term, semi-graphite, is used to describe a product that is composed of artificial graphite particles mixed with carbonaceous binders such as pitch or tar and baked at carbonization temperatures of 800 to 1400°C (1500 to 2550°F). The resulting product is composed of carbon-bonded graphite particles in which the graphite particles had previously been manufactured at temperatures close to 3000°C (5400°F) but with binders that have only been baked in the 800 to 1400°C (1500 to 2550°F) range. The resulting product, a true carbon-bonded graphite, exhibits higher thermal conductivity than the carbons but, because of the carbon binder, not as high as 100% graphite. Thermal conductivities will vary with baking temperature and can be increased by rebaking at higher temperatures.

These products are also conventionally baked (as described for carbon), which results in a relatively porous material. However, these conventionally baked semi-graphites can also be densified and rebaked to carbonize the impregnated binder. Thus porosity and, consequently, permeability can be reduced. Some conventionally baked semi-graphites are also impregnated with or combined with silicon metal and silicon carbide for greater abrasion resistance and lower permeability. These products, however, are intended for use in the bosh and stack.

4.3.1.5 Hot-pressed Semi-graphite

One American manufacturer also utilizes its proprietary hot-pressing method to make a true semi-graphite refractory product. The resultant product is considerably less permeable and has a higher thermal conductivity than conventionally baked semi-graphites.

Different products are available for a variety of applications. One grade is composed of crushed graphite particles, which were previously processed at graphitization temperatures, with a carbonaceous binder and the addition of silica and quartz materials for alkali resistance (as previously described for hot-pressed carbon).

Another grade is a silicon carbide containing hot-pressed semi-graphite refractory. It is composed of the same graphite component as the first product and the same carbonaceous binder. However, silicon carbide is substituted for the silica and quartz. The resultant product is more abrasion resistant and even less permeable than the first product. It has proven especially resistant to thermal shock and cyclic operation.

Another grade is a hot-pressed semi-graphite developed for use as a bosh and stack refractory. Like the first two grades, it is composed of graphite particles with a carbonaceous binder with a smaller addition of silicon carbide. This results in a product that is a true, low-ash, semi-graphite but with improved properties that hot pressing provides, compared to conventionally baked semi-graphites.

Because of the special manufacturing process required for hot pressing, the resultant products are restricted to sizes not exceeding approximately 500×250×120 mm (20×10×5 in.).

4.3.1.6 Semi-graphitized

The term, semi-graphitized material, refers to a baked carbon that has been further heat treated at a temperature between 1600 and 2400°C (2900 and 4350°F). This process only begins to change the crystallographic structure of the carbon and alters its physical and chemical properties. However, because this additional heat treating occurs at temperatures below graphitization temperatures, the product is considered to be semi-graphitized. It contains carbon particles with a carbon binder, which are both semi-graphitized. (This is different than a semi-graphite product which is composed of true graphite particles with a carbon binder.) It has a higher thermal conductivity and resistance to chemical attack (alkali or oxidation) than carbon or semi-graphite. This is because the binder is usually attacked first and the semi-graphitized binder is more resistant to attack than the carbon binder of a semi-graphite.

These semi-graphitized products are also manufactured in large blocks or rounds and must be cut and machined into blocks for use as a refractory. However, because of their semi-graphitized bonding, they are more difficult to machine than a true graphite.

4.3.2 Discussion

These groups of carbonaceous material form the basis for a full range of specialized products to enhance their performance in the blast furnace. As discussed, various additives such as graphite particles, alumina, silicon carbide or other ceramics are included by some manufacturers to improve properties, or multiple impregnations are used to improve permeability or reduce pore sizes. However, the general characteristics of each material classification do not change. For convenience, these classifications are summarized in Table 4.1.

Currently, there is a large variety of carbonaceous refractory material on the market produced by different manufacturing techniques with various properties. It is difficult to provide material properties

Table 4.1 Classifying Carbonaceous Materials

Product Classification	Baking Temperature, °C	Particles	Binder
Carbon	800–1400	Carbon	Carbon
Hot-pressed Carbon	~1000	Carbon	Carbon
Graphite	2400–3000	Graphite	Graphite
Semi-graphite	800–1400	Graphite	Carbon
Hot-pressed Semi-graphite	~1000	Graphite	Carbon
Semi-graphitized	1600–2200	Semi-graphitized carbon	Semi-graphitized carbon

Table 4.2 Representative Carbonaceous Hearth Material

Property	Proprietary hot-pressed carbon brick	Conventionally baked, big beam carbon	Conventionally baked, big block carbon	Conventionally baked, big micropore carbon	Semi-graphitized carbon, big block	Conventionally baked, big block semi-graphite	Low ash, low iron graphite
Bulk density (g/m3)	1.62	1.6	1.57	1.6	1.65	1.62	1.67
Crushing Strength (kPa)	30,500	17,900	35,500	44,000	27,000	25,000	28,000
Ash (%)	10[a]	8	4.8	13[a]	0.4	0.4	0.2
Permeability (m'Darcys)	9	800	~200	~21	~150	~150	N.A.
Thermal conductivity							
(W/m°K)							
at 600°C	18.4	10.4	4.3	11	45	42	120
at 800°C	18.8	10.4	5	15.4	N.A.	38	N.A.
at 1000°C	19.3	10.5	5.5	16.5	32	32	70
at 1200°C	19.7	10.9	N.A.	N.A.	N.A.	N.A.	N.A.

[a] Contains deliberate non-carbonaceous additives.

for these products without referring to specific manufacturer's grade designations, because each manufacturer produces products that are unique to that manufacturer and thus, exhibit unique properties. A representative listing of some of these materialsí properties are summarized in Table 4.2.

In general, carbon or semi-graphite materials are used for the hot face lining materials that will be in contact with molten iron. Usually, graphite materials are reserved for a backup lining to take advantage of their high thermal conductivities and because they are more easily dissolved by the iron. In addition, many ceramic materials such as high alumina, mullite and chrome corundum are used in the hearth pad as a wearing surface to minimize exposure of the carbonaceous materials of the hearth to molten materials. Some designers are even providing a lining of ceramic materials on the face of the hearth walls for wear protection and to minimize heat losses, mainly because of poor historical performance with some large, conventionally baked, carbon block designs.

Ceramic materials for the hearth pad can be inexpensive super-duty fireclays of 40–50% alumina or a variety of high alumina products in the 60% range. The objective is to provide a lining that will melt and vitrify (or fuse together) on its hot face in the presence of liquid iron, effectively sealing the surface to penetration.

In another philosophy, refractory materials such as artificial mullites or chrome corundum are chosen which are resistant to melting. These materials however, do require elaborate jointing techniques such as interlocking, tongue and groove or roll-lock interfacing to prevent joint penetration by molten materials and resultant flotation of bricks.

Whichever ceramic materials are utilized in the pad, the effect is that the iron remains in contact with the ceramic which is more resistant to abrasion from moving liquids. The carbonaceous material in the pad thus forms a cooling member instead of a crucible, until late in the campaign when the ceramic may totally wear away by abrasion. The high conductivity of carbonaceous materials, especially if underhearth cooling or a graphite cooling course is utilized, enables penetration of the iron into the pad to be arrested in the ceramic layer. This provides a long-wearing hearth design, combining the properties of two or more different refractory materials to optimize the performance of each, in the zone to which they are most suited.

Representative properties of some of these ceramic materials are shown in Table 4.3. They can be combined in various layers such that the more economical materials are located on the hot face, where they will be consumed more easily until thermal equilibrium is reached. The more expensive, hot metal resistant materials can then be located next to the carbonaceous materials where they can be more easily cooled for longevity. The tendency is to utilize specific grades of refractories in each hearth zone that can best withstand the attack mechanisms prevalent in that zone. The result is a hearth lining composed of not just one grade of refractory but, sometimes, even four or six different types of materials, both carbonaceous and ceramic.

Table 4.3 Representative Ceramic Hearth Materials

Property	Hard-Burned Superduty Fireclay	Alumina 60%	Artificial Mullite	Chrome Corundum
Bulk Density (g/m^3)	2.24	2.40	2.45	3.43
Crushing Strength (kPa)	31,000	35,000	85,000	78,000
Porosity (%)	13	22	19	8
Thermal Conductivity (W/m°K)				
at 500°C	1.9	2.0	N.A.	N.A.
at 1000°C	0.9	1.7	1.8	2.3

4.3.3 Wear Mechanisms

In the hearth, refractory survivability depends upon proper, uninterrupted cooling. The hearth bottom pad and walls are cooled on their cold faces and almost exclusively utilize various conductive refractory materials such as carbon, semi-graphite, semi-graphitized carbon and artificial graphite along or in combination with each other or combined with ceramic materials. The performance of the hearth lining system is totally dependent upon effective and uninterrupted heat transfer through the refractory configuration, because it is cooled on its cold face. The only way that the refractory hot face temperature can be maintained below the *critical reaction temperature* for the various wear mechanisms encountered, is to provide an efficient and unchanging heat transfer path from the hot face to the cold face.

If conductive refractory hot face temperatures are allowed to exceed approximately 1150°C (2100°F), these carbonaceous materials will be chemically attacked by dissolution by the iron and will be subjected to erosion and wear by the movement of molten materials. This is because the refractory hot face temperature would be above the solidification temperature of the iron and thus would be in constant contact with the molten materials. Consequently, these molten materials may also be forced into the pores of the refractories, due to ferrostatic head and high furnace operating pressures.

If conductive refractory temperatures are allowed to exceed approximately 870°C (1600°F), these carbonaceous materials will be chemically attacked by alkalies and zinc, which first destroy the refractory binder system. As the binder system is attacked, material strength and properties are destroyed, most notably thermal conductivity. Thus, as chemical attack progresses, the ability of the refractory to transmit heat is lost, which then results in even higher hot face refractory temperatures.

Blast furnace designers generally utilize computer modeling techniques to locate the isotherms in the hearth lining. The location of these isotherms then permits an evaluation of the potential chemical attack zones or *salamander* penetration into the hearth due to thermal considerations. As noted earlier, the 1150°C (2100°F) isotherm will define the limit of dissolution of the carbon by iron and the 870°C (1600°F) isotherm will define the limit of alkali and zinc attack. Additionally, the 1250°C (2250°F) isotherm will define the melting zone of some ceramics, that would be expected to be eroded away by molten material movement. This computer modeling tool can therefore be utilized to provide an estimate of chemical attack zones and iron penetration, once the hearth refractory mass reaches thermal equilibrium.

However, actual hearth pad penetration and wall deterioration is a function of more than thermal effects. Mechanical stress, lack of thermal expansion provisions and erosion from molten material movement also contribute to hearth wear. For this reason, many computer models utilize historical wear line data to establish boundary conditions.

These boundary conditions allow the computer model to simulate hearth wear, in the profile that it normally occurs for that particular lining concept. However, a particular hearth model may have no significance for a different hearth concept or configuration, or for a furnace exhibiting a different historical wear pattern. For example, hearth computer models that are developed to estimate the inverted mushroom shaped wear pattern or *elephant's foot*, with severe wall material loss at the wall/pad interface, will not accurately predict the expected wear pattern of a furnace that exhibits a bowl-shaped wear pattern, with little or no wall material loss. Therefore, the designer must consider the concept, historical wear performance and other *internal* and *external* factors which affect refractory performance, when designing a hearth.

4.3.4 Design Considerations

Hearth wall problems can be traced to a combination of factors: lack of thermal expansion relief; high thermal gradients across the wall block; and inability to accommodate differential thermal expansion. All of these factors promote cracks with subsequent hot metal and chemical attack. Attack of the wall by hot metal and chemicals most often is a result of the cracking problem.

Proper wall design requires a high thermal conductivity refractory that would minimize thermal gradients through the wall and, consequently, promote the formation of a protective layer of solidified materials on its hot face. Proper wall design also incorporates provisions for radial thermal expansion of the wall but, more importantly, incorporates provisions to accommodate differential thermal expansion of the wall thickness.

Differential expansion occurs because the wall hot face temperature is higher than the wall cold face temperature. This differential is at least 1450°C (2650°F), especially when an accretion of solidified materials is absent. As a result, the hot face of the wall is growing at a faster rate than the cold face. The differential induces high stresses in the blocks which are restrained from bending or bowing. Cracks result parallel with the hot face.

Thermal spalling and cracking of the hot face can also be induced by the rigors of a blow-in, especially when the wall design cannot accommodate radial expansion and the refractory thermal conductivity is low. This type of cracking also occurs parallel to the refractory hot face.

Cracks interrupt the ability of individual blocks to convey heat and facilitate cooling because each crack acts as an air gap which is a barrier to effective heat transfer. Once the ability to convey heat away is lost, the protective accretion can no longer form and, therefore, carbon will be attacked by the hot metal and chemicals. This is because the carbon temperature will be above the critical reaction temperature for attack by these mechanisms.

In addition, the rammed layer required between the shell (or stave) and the cold face of a large block carbon wall, also insulates the carbon from the cooling system. This is because ramming materials shrink when cured and possess thermal conductivities that are significantly lower than baked carbon. The lower conductivity and shrinkage combine to provide additional barriers to heat transfer and result in high hot-face carbon temperatures above the solidification temperature, so that skulls cannot form on block walls, until their thickness is usually substantially reduced by erosion and dissolution by iron.

Proper wall design not only accommodates thermal growth and expected differential movements, and utilizes a carbon refractory with high thermal conductivity, but also uses a carbon refractory possessing an extremely low permeability. The low permeability prevents chemical and hot metal attack by preventing penetration into the refractory.

It has also been demonstrated that a hearth refractory that possesses a low elastic modulus, combined with a low coefficient of thermal expansion, results in low mechanical stress at the important pad/wall interface. American big beam blocks and hot-pressed carbon as well as graphite and semi-graphite, fulfill these requirements. Because of the elastic properties of hot-pressed carbon, expansion stresses are easily accommodated, which prevents cracks from occurring in the wall. The opposite is true for the strong large blocks that have recently been used in Europe and Asia in an attempt to increase the life of the hearth wall.

Because of differential expansion and bending, and tight fit due to precision machining and lack of thermal expansion provision, these stronger blocks are prone to stress cracking, pinch spalling and thermal shock. Thermal shock is particularly size dependent so that, the larger the exposed hot face cross-section, the more likely thermal shock is to occur. Walls composed of smaller cross-section pieces are unaffected by thermal shock.

Expansion relief is also a requirement for preventing pinch spalling and stress cracking. This relief can be provided by specially designed expansion joints between blocks or by the use of special, heat setting, carbonaceous cements. Ideally, these cements should be installed in a sufficiently thick layer to provide expansion relief before curing. After curing, they should provide a strong carbonaceous bond to seal the joint. Multiple layers and rings provided by small brick also permit differential expansion without cracking.

High thermal conductivity hot-pressed carbon and semi-graphite refractories promote the formation of a protective skull of frozen material on the hot face of the walls. This protective skull prevents wear of refractories due to erosion from gases or molten materials. Additionally, rammed layers are not utilized, to maximize heat transfer to the stave or shell.

A single, full-thickness block cannot accommodate the differential growth experienced and, consequently, it cracks, thus interrupting heat transfer. The cracks prevent the hot face of the block from being cooled below the solidification temperature so that a protective skull cannot form. Thus, the large block carbon is continually exposed to molten materials at high ferrostatic pressure and high gas pressure. These high pressures tend to force the molten materials into the pores of the big block materials. Hot metal impregnation results in damage to the carbon and additional cracking and spalling.

In an attempt to prevent hot metal impregnation of large carbon blocks, many manufacturers have introduced densified or reimpregnated carbon blocks with low porosity and minimal pore size. These micropore carbon refractories are designed to limit the amount of molten materials that can enter the structure of the block through its porosity. This solution is contrary to that employed with hot-pressed carbon or semi-graphite concepts which utilize high thermal conductivity and the prevention of cracking to promote a hot face temperature that is maintained below solidification temperature. Thus, in the case of the latter, cooler wall concept, a skull quickly forms on the wall hot face and impregnation by molten materials is prevented. The resulting skull thickens over time to form an insulating layer once thermal equilibrium is achieved. Wall hot-face temperatures in these systems at the back of the skull are typically in the range of 200 to 600°C (400 to 1100°F). Another advantage that this cooler wall provides is that other temperature dependent reactions, such as oxidation, alkali and zinc attack, cannot occur as long as the wall temperatures remain below their critical reaction temperatures in carbon. Typically, these critical reaction temperatures are between 870 and 1100°C (1600 and 2000°F). As long as the wall hot face temperature can be maintained below these critical reaction temperatures, attack by these mechanisms cannot occur. However, if stress-induced cracking, deterioration of ram layers or any other disruption of heat transfer occurs, wall temperatures will increase, usually above these critical reaction temperatures. This results in chemical attack of the wall material in the zone of the wall that is in the range of 870 to 1100°C (1600 to 2000°F). Usually, these chemical reactions do not occur above 1100°C (2000°F) in carbon so that a deteriorated band of material is found within the wall thickness. This brittle zone is usually sandwiched between sound carbon on both the hot and cold faces.

As previously mentioned, some designers are utilizing a ceramic hot face layer on the carbon walls to prevent wall erosion. In addition, because of the low thermal conductivity of these materials, it is believed that wall heat losses will be reduced. Several furnaces have been lined using this concept with mixed success. The longevity of the ceramic is dependent on good thermal contact with the carbon and maintaining uninterrupted heat transfer capability through the large block carbon for the life of the ceramic. For reasons previously discussed, large block carbon walls are prone to cracking and loss of heat transfer capability. Thus, if cracking does occur, high temperatures in the ceramic result, hastening their demise.

In Europe and especially Japan, it is also common practice to create hearth protection by adding significant amounts of titanium bearing ores in the burden or directly injected through the tuyeres. This addition allows the formation of a protective layer of titanium to temporarily form on the hearth walls, as long as the material is charged into the furnace. Once injection is stopped, the protective layer quickly wears away. This is a very expensive method of hearth preservation since the titanium bearing ore is expensive and the furnace coke rate increases since energy is required to release the titanium from the ore. However, often this operating cost penalty is smaller than the huge financial penalty that would be incurred if the protection layer were not induced and the hearth refractory failed. Thus, some operators are forced to add these titanium ores to artificially induce accretions on their linings, as a result of the failure of the lining *system* to provide the longevity required. Often, however, these titanium accretions fail to form or form in areas where they are not needed, so they may be ineffectual at prolonging campaign life in some cases.

The composition of many carbonaceous products such as hot-pressed brick and micropore materials, are resistant to chemical attack as long as they are properly cooled. However, because all hearth wall cooling is dependent on heat transfer through the entire wall thickness and then to a stave or furnace shell on the wall cold face, it is imperative that contact be maintained with the cooling system at all times. Often, high-conductivity grouting materials must be injected between the shell and wall to reestablish contact with the refractories, thus assuring heat transfer. Otherwise, the small air gap that forms between the shell and wall, will result in high wall temperatures and, consequently, chemical and hot metal attack will occur. When rammed layers are used between the cooling elements and refractories, care must be taken to insure that materials are utilized with little or no shrinkage and with the highest thermal conductivities possible. No rams should be used if possible, because a rammed layer is never as good as the refractory material adjacent to it. This is because the density, porosity and thermal conductivity of the ramming material will always be inferior when compared to the carbonaceous refractory product.

Also, shrinkage of the rammed layer over time will result in a loss of heat transfer capability of the wall, again shortening its life. When combined with other problems such as block cracking or low thermal conductivity, this combination of problems results in severe hearth wall erosion, cutback in an inverted mushroom shape and ultimate failure.

4.3.5 Summary

Blast furnace hearth design concepts, materials, configuration and wear patterns vary greatly throughout the world. Hearths are generally composed of varying grades of carbonaceous and ceramic materials, zoned to take advantage of the properties of each grade, to minimize wear. Historically, severe hearth wall erosion problems are nonexistent in North America, but are a major source of downtime and termination of campaigns in Europe and Asia.

Solutions to this severe wall wear problem must consider the wear mechanisms that are responsible such as thermal shock and stress, mechanical stress, differential thermal expansion as well as traditional mechanisms such as chemical attack and erosion. A variety of design concepts and materials, that withstand these wear mechanisms, eliminate hearth problems and maximize life, are available to the blast furnace user.

4.4 Bosh, Belly and Stack

The refractory systems comprising the bosh, belly and stack of the blast furnace proper, probably are the most critical in terms of their impact on the operating capability of the ironmaking complex. No other refractory systems in the ironmaking plant have a greater effect on the day-to-day survivability and integrity of their process containment vessel. Indeed, if the furnace must shut down because of bosh, belly or stack lining problems or failures, iron production ceases and the need for any other refractory lined system in the complex ends.

As was discussed previously, any refractory lining is a system of complex, interrelated components and features, affected by many internal and external factors. One such external factor for the bosh, belly and stack which can have a dramatic effect on refractory performance, is the quality, effectiveness and type of cooling system employed. Some experts have even claimed that "cooling water is the best refractory." However, in evaluating this claim, it should be recognized that cooling water removes heat energy from the process and that properly engineered lining/cooling *systems*, provide a way to optimize performance and minimize wall heat losses over the full campaign.

The cooling aspect of the lining/cooling *system* is a most critical external factor which can determine the success or failure of any refractory product. Consequently, the intimate contact between the cooling system elements and the refractory products is a critical feature which can be the weak point of any lining/cooling system. If you lose contact with the cooling element, refractory temperatures rise above their *critical reaction temperature* for the attack mechanisms. If the refractory configuration results in a hot face location too far away from the cooling effect, the critical reaction temperatures will also be exceeded, thus assuring chemical attack. Thus, it is imperative for the refractory designer to consider not only the type of cooling method employed, but also how to integrate the lining with the cooling and to maximize the cooling effect on the refractory hot face. Products such as high conductivity ramming materials with expanding characteristics and non-shrink properties can assist in this critical endeavor.

4.4.1 Refractory Materials

Bosh linings are comprised of various conductive refractories such as carbon, semi-graphite and graphites, varying types of ceramics or sometimes combinations of both.

Traditionally, in the belly and stack, lining materials have been comprised of varying types of ceramics. However, conductive refractories such as graphite and semi-graphite have found favor, used alone for their excellent chemical attack and thermal shock resistance or to take advantage of their cooling capability, used in combination with various ceramics.

4.4.1.1 Carbonaceous Refractories

Table 4.1 in Section 4.3 lists the classifications of the various types of conductive carbonaceous refractories. It is difficult to present material properties of these products, without referring to specific manufacturer's grade designations. That is, because each manufacturer produces products that are unique to him and thus exhibit unique properties. Tables 4.4 and 4.5 however, present a representative listing of some of these materials' properties.

4.4.1.2 Ceramic Refractories

The properties and characteristics of all ceramic refractories depend on the raw materials utilized and their size consist. The fine particles in the mix form the ceramic bonding of the larger particles as the material is fired at high temperature. The fired refractory contains larger crystalline particles bonded together with glass or other smaller crystalline particles, that have fused together during firing.

Crystals composed of silica or alumina form strong bonds in materials such as fireclay or high alumina. Glass bonded refractories tend to have good strength but soften and deform under load. Additionally, impurities such as iron oxide or lime promote the formation of glass. Therefore, manufacturers try to limit the amount of impurities in these types of products.

When designing ceramic lining *systems*, one significant refractory property is the bulk density, which reflects the heat carrying capacity of the refractory. Porosity or permeability are also important and provide a means to determine the ability to resist penetration by molten materials and gases and have an influence on thermal conductivity and the chemical resistance of the brick to such wear mechanisms as alkali, carbon monoxide degradation and slag or hot metal attack.

Table 4.4 Graphite Materials Properties

	Graphite Material Description			
Property	**Standard Density Standard Ash**	**Standard Density Low Ash**	**Medium Density Low Ash**	**High Density Low Ash**
Bulk Density (g/m^3)	1.63	1.67	1.72	1.80
Porosity (%)	21	16	14	12
Cold Crushing Strength (kPa)	20,000	28,000	40,000	51,000
Thermal Conductivity (W/m°K)				
at 20°C	150	140	150	160
at 1000°C	70	70	75	80
Ash (%)	0.5	0.2	0.2	0.2

Table 4.5 Semi-graphite and Semi-graphitized Material Properties

	Semi-graphites		Semi-graphitized		Hot Pressed Semi-graphites		
Property	**High Fired, Conventional, Med. Density**	**High Fired, Conventional, High Density**	**High Fired, Conventional, Med. Density**	**High Fired, Conventional, High Density**	**Graphite With Silica Addition**	**Graphite With Small SiC Addition**	**Graphite With Large SiC Addition**
Bulk density (g/m^3)	1.62	1.73	1.65	1.75	1.82	1.84	1.87
Porosity (%)	19	15	18	15	16	16	16
Permeability (m' Darcys)	–	–	–	–	5	4	3
Cold Crushing							
Strength (kPa)	25,000	36,000	27,000	38,000	30,000	29,000	35,000
Thermal conductivity (Wm° K)							
at 20°C	45	45	50	50	60	70	60
at 600°C	32	32	25	25	40	48	48
Ash, %	0.4	0.2	0.4	0.2	9[a]	10[b]	17[b]

[a] Ash content includes quartz and silica addition to control alkali attack.
[b] Ash content includes silicon carbide.

Refractory service temperature is probably the most important issue in any ceramic refractory system. For each chemical attack wear mechanism, there exists a *critical reaction temperature* for that refractory grade, which defines the point at which chemical attack commences. If refractories can be cooled below this critical reaction temperature, chemical attack could be prevented. This is because all chemical attack mechanisms are thermochemical reactions and as such, the rate of reactions are temperature dependent. Therefore, the refractory designer must provide a *system* that provides refractory temperatures consistently below the critical reaction temperature for each grade of refractory in the system. Cooling enhancement or highly conductive refractory components can assist with this effort.

Thermal shock resistance is also a critical issue when investigating refractory system design. Thermal shock or *spalling* is caused by thermal stresses which develop from uneven rates of expansion and contraction within the refractory, caused by rapid temperature changes. There are no standard tests for evaluating thermal shock resistance because shock is also a function of size and shape. A qualitative prediction of the resistance of materials to fracture by thermal shock can be expressed by the factor

$$ks/\alpha E \tag{4.4.1}$$

where:

k = thermal conductivity

s = tensile strength

α = coefficient of thermal expansion

E = modulus of elasticity

The higher the value of this factor, the higher the predicted thermal shock resistance of the material.

Erosion of refractory particles results when the bond of the refractory is destroyed by impact or impingement of process materials or dust-laden gases. The higher density materials exhibit higher resistance to abrasion or erosion.

4.4.1.2.1 Fireclay Fireclay refractories consist of hydrated aluminum silicates and minor proportions of other materials. Examples of fireclay refractories are superduty, high duty or medium duty. These materials contain between 18–50% alumina and 50–80% silica, depending on the grade.

Superduty fireclay refractories exhibit good strength and volume stability and have an alumina content of approximately 40–50%. Often, superduty fireclays can be high temperature fired to enhance the high temperature strength of the brick, stabilize volume and prevent damage by carbon deposition. These materials are often used as economical bosh, belly and stack linings in low production facilities or as a sacrificial lining material on the hot face of the refractory wall. Tar impregnation can be used to reduce porosity and permeability to resist chemical attack.

High duty or *medium duty* fireclays are normally utilized in areas subjected to moderate attack mechanisms. In the bosh, belly and stack, they are often used as a blow-in protection lining and as a low cost sacrificial hot face lining material.

4.4.1.2.2 High Alumina High alumina refractories are available with alumina contents of 45–99+%. They are limited to a maximum service temperature of approximately 1800°C (3300°F). They exhibit high refractoriness and chemical resistance at high temperatures. Mullite and corundum materials are also considered as high alumina refractories. These materials are often used as a bosh, belly and stack refractory in low to moderate production facilities or where budgets are limited. They can also be utilized as the hot face or cold face lining layers in *sandwich* lining configurations. These materials also can be tar impregnated to improve permeability and thus improve chemical attack resistance. Some high alumina refractories utilize special bonding systems such as sialon to improve chemical attack resistance or carbon bonding to improve thermal shock resistance.

4.4.1.2.3 Silicon Carbide Refractories comprised of silicon carbide are used in the bosh, belly and stack due to their higher resistance to chemical attack, abrasion and thermal shock, as compared to fireclay or high alumina refractories. Silicon carbide refractories can utilize several different bond types which change the physical properties of the refractory.

In general, silicon nitride (Si3N4) bonded silicon carbide has proven to be preferred over various direct bonded, self-bonded or carbon silicon bonded materials. Sialon ($Si_{6-x}A1O_xN_{8-x}$) bonded silicon carbide (as well as sialon bonded high aluminas) have also been used in the bosh, belly and stack for their improved alkali resistance.

The bonding system used in silicon carbide refractories can be affected by the various wear mechanisms encountered in the blast furnace. For example, oxidation can be a problem to the self-bonded or direct bonded silicon carbides, which causes a *swelling* of the material. For this reason, most ironmakers utilize either silicon nitride bonded or sialon bonded silicon carbide for the bosh, belly and stack.

Silicon carbide refractories, because of their abrasion resistance, can also be utilized in the stockline area, where impact from falling charge materials is severe. Phosphate bonded high alumina materials also are successfully utilized in this erosion-prone zone.

4.4.2 Ceramic Properties

Historically, many different grades of ceramic refractories have been used in the bosh, belly and stack with varying degrees of success. Often, the choice of cooling system and its capabilities limits the choice of refractories. Sometimes, very economical grades of refractories are chosen for their *sacrificial* use as a blow-in protection lining or for a stave cooling system, that is intended to operate *naked*, that is, without a refractory lining. Sometimes, budgetary limitations preclude the use of exotic ceramics or silicon carbide refractories that could improve performance. However, there are a large and varied group of ceramic refractories available, at varying price levels, to achieve the intended lifetime goals. A representative listing of some of these materials' properties are summarized in Table 4.6.

The many permutations possible from the range of different materials available, offer the designer challenging opportunities for optimizing the lining design. The key of course, is to recognize that the success of the *system* will depend upon how the many internal and external factors which affect the refractory product, are addressed. Additionally, lifetime improvements can also occur if various grades and types of refractories are combined in one system, to take advantage of the best properties or characteristics of each of the products used.

4.4.3 Wear Mechanisms

The severity of attack by the mechanisms of wear in the bosh, belly and stack, can be different from furnace to furnace, even in the same plant, due to variations in furnace geometry, burden materials

Table 4.6 Representative Bosh, Belly and Stack Ceramic Materials

Property	Superduty (≈48%Al_2O_3)	High Alumina (≈60% Al_2O_3)	High Alumina (≈90% Al_2O_3)	Silicon Carbide (Si_3N_4 Bonded)	Silicon Carbide (Sialon Bonded)
Density (g/m3)	2.4	2.55	2.95	2.58	2.72
Crushing Strength (kPa)	60,000	80,000	120,000	140,000	180,000
Porosity (%)	11	15	15	15	14
Thermal Conductivity (W/m°K) at 1000°C	1.7	1.9	2.9	13	12

Table 4.7 Comparison of Furnace Wear Mechanism Severity by Zone

	Severity of Attack					
Wear Mechanism	**Bosh**	**Belly**	**Lower Stack**	**Middle Stack**	**Upper Stack**	**Stockline**
Thermal Shock	Moderate–High	Extreme	Extreme	High–Very High	Low–Moderate	Low
Heat Load	Moderate–High	Very High	Low–Very High	Low–High	Low–Moderate	Low–Moderate
Slag Attack	Extreme	Very High–Extreme	Moderate–Low	Low	None	None
Alkali/Zinc Attack	High	Moderate–High	Very High	High	Moderate–High	Low–Moderate
Oxidation	Low–Moderate	Low–Moderate	High	Moderate–High	Low–Moderate	Low
Abrasion	Low–Moderate	Low–Moderate	Moderate–High	Very High	Very High	Extreme

and distribution and furnace operation. The lower zones of the blast furnace, from the bosh to the mid stack are most affected by thermal shock, high heat load and chemical attack. These zones are the real trouble areas on virtually all blast furnaces and are most responsible for termination of furnace campaigns or lengthy repair downtime.

From the upper middle stack to the stockline, mechanical wear and impact from charging, become the main contributors of wear, along with chemical attack.

Thermal attack includes exposure to high temperatures over time, severe temperature fluctuations and fatigue. Chemical attack includes attack by alkali vapor and condensate, carbon monoxide degradation, carbon deposition, oxidation and attack by slag or molten metal. Mechanical wear includes erosion from ascending dust laden gases, abrasive wear of descending burden materials and impact loads from falling burden materials.

A summary of these wear mechanisms, by severity and by furnace zone, is listed in Table 4.7.

It is universally agreed that the predominantly pellet charged, typical North American blast furnace, will be subject to more intense, high temperature fluctuations at the wall, than experienced by predominantly sinter charged European and Japanese blast furnaces.

It has been demonstrated by European ironmakers, that these temperature fluctuations increase dramatically as the pellet charge exceeds approximately 15 to 20% of the total metallics charged. Actual temperature peaks experienced by a 50% pellet / 50% sinter charged furnace, have been shown to be typically up to 1000°C (1850°F) over a 6–7 minute period, or approximately 150°C (300°F) per minute temperature change. However, the predominately sinter charged furnaces consistently experience wall temperature fluctuations of only approximately 40°C (100°F) over the same 6–7 minute period, or approximately 7°C (20°F) per minute temperature change.

This means that whatever refractory is chosen, it can experience exposure to temperature changes of up to 150°C (300°F) per minute, if pellets are charged and approximately 7°C (20°F) per minute

Table 4.8 Critical Spalling Rates for Various Materials

Material	°C/min.	°F/min.
High Duty	4	7
High Alumina	5	9
Chrome Corundum	5	9
Cast Iron	50	90
Silicon Carbide	50	90
Carbon	200	400
Semi-graphite	250	450
Graphite	500	900

if predominantly sinter is charged. Typical North American operation, utilizing predominantly pellet burdens, thus exposes wall refractories to the more severe temperature fluctuations, due to gas flow changes in the pellet burdens.

It has been demonstrated that all ceramic refractories, including silicon carbide materials, will spall and thermally crack if they experience temperature fluctuations of this severe magnitude. Critical spalling rates have been discussed in several technical papers and a list of typical critical spalling rates for a variety of materials is shown in Table 4.8.

These critical spalling rates define the maximum temperature variations that the hot face of the refractory materials can survive without cracking. Beyond these rates, spalling and cracking will occur. As can be seen from the table, the only materials which can withstand the normally occurring 150°C (300°F) per minute temperature excursions of a typical pellet charged furnace, are carbonaceous materials, the so-called *conductive* refractories.

The thermal shock failure effect is most severe when refractories are cooled from one side, like with staves or externally cooled jackets. This is because the thermal shock cracks occur parallel to the refractory hot face, which results in three problems. First, these cracks permit the alkali vapors and condensate to be exposed to a greater refractory surface area, including the interior of the refractories, hastening chemical attack. Second, because these cracks occur parallel to the hot face, air gaps form, which interrupt heat transfer to the cooling system, thus increasing refractory hot face temperature. Consequently, since chemical attack is temperature dependent, this increase in refractory temperature at the hot face will assure that the hot face is chemically attacked as temperatures exceed approximately 600°C (1100°F) for high aluminas and fireclays and 800°C (1500°F) for silicon carbides.

Third, as accretions (scabs) form and fall off as wall temperatures change, the falling scabs pull away this cracked layer of refractory which adheres to the scab, thus again exposing a new hot face to be thermally shocked, repeating the cycle.

As the thermal shock/chemical attack/scab pull-out of material cycle repeats itself over time, refractory lining thickness is reduced continuously until the stave or furnace jacket is completely exposed to the furnace environment. In the case of the stave cooled wall, exposing the staves to the same temperature fluctuations as the refractory before it, will cause cracking and spalling of the cast iron surface, shortening stave life dramatically. Wall temperatures can sometimes be controlled by burden distribution and charging techniques. However, these measures usually result in production and fuel rate penalties, which may prove unacceptable to plant goals.

In the mid-1970s, virtually all refractory/cooling system design improvements centered on finding refractories which were resistant to chemical attack. The effects of thermal shock were either unknown or ignored, until failures or minimal lifetime improvements were experienced, even with efficiently cooled silicon carbon linings. The Japanese and Europeans in particular began to study the thermal shock phenomenon in detail and many technical papers have been published on the subject. What was learned is that it was not enough to have a chemically resistant lining if thermal shock will be experienced.

In stave cooled or other externally cooled boshes, this is especially important because the continuous, vast expanse of hot face refractory surface, is exposed to many temperature differentials over this surface. This can result in severe localized spalling and subsequent loss of refractory support. Once support is lost, entire *panels* of refractory can fall out in *sheets*. This destroys the integrity of the wall unit and is the reason many stave designers now include refractory support *shelves*, integral to the stave, to support the refractories at various levels.

The chemical attack mechanisms in the bosh and stack are identified as oxidation, carbon deposition, alkali, slag and hot metal attack. Oxidation can occur by steam formed from burden moisture, hot blast moisture or leaking coolers. Oxidation can also occur from carbon dioxide formation, leaking coolers, leaking outside air during backdrafting or from a *lazy* raceway which is too close to the refractory hot face.

Carbon deposition can occur especially when iron is present in the refractories, which breaks down the CO to CO_2 and C. The carbon builds up within the refractory, spalling it.

Alkali, most notably potassium and sodium, attack the refractory by destroying the bonding mechanisms which hold the refractories together. This attack causes refractory swelling and cracking.

All of these chemical reactions are temperature dependent reactions. This means if the refractory can be maintained at a temperature which is below the *critical reaction temperature* for chemical attack of that refractory, the chemical reactions cannot occur. One of the difficulties of trying to maintain a low hot face temperature of a stave or other outside cooled refractory wall, is that all heat must travel through the wall, to the cooling medium. Any interruption to the heat transfer such as an air gap between the stave or brick due to differential growth or a stress crack parallel to the refractory hot face, assures that the hot face refractory will be chemically attacked, because it cannot be cooled below its critical reaction temperature.

Additionally, in the event the refractory is effectively cooled, the formation of accretions is accelerated. However, as furnace temperatures fluctuate, these scabs fall off, exposing cool refractory to the hot gases, thermally shocking them, cracking the refractory as previously described.

Mechanical abrasion and erosion also contribute to bosh and stack wear, but on a much smaller magnitude than thermal shock and chemical attack, unless wall working is prevalent. If the tuyere velocity is too low or the furnace is *fanned* for extended periods or wind is drastically reduced many times or the bosh is allowed to *flood* due to improper casting periods, severe wall working can contribute to erosive wear by ascending dust laden gases. However, most modern high capacity furnaces are blown hard, cast virtually continuously and thus are generally not prone to bosh wall working. Thus, abrasion resistance of the bosh and lower stack refractory, although desirable, is not as important as thermal shock resistance and resistance to chemical attack.

4.4.4 Design Considerations

Bosh and lower stack wear is a combination of factors, primarily of thermal shock induced cracking, which accelerates chemical attack by exposing more refractory surface area to alkali and by increasing refractory hot face temperature by interrupting heat transfer.

Upper stack wear is a combination of different factors, primarily chemical attack and abrasion, especially at the stockline working zone. Thus, when analyzing the zones to determine suitable refractory materials, often the best potential for success will be to combine several grades or types of refractories in each system. Thus, the best properties or characteristics from each type used, will contribute to the overall success of the system.

For example, in a stave cooled system, the refractory *inserts* in the stave face can utilize highly conductive semi-graphite or graphite to optimize cooling efficiency. This permits 100% of the stave face to efficiently cool the refractories, thus lowering their temperature and consequently lowering the rate of chemical attack. Insulating types of refractory stave inserts reduce the stave's ability to remove heat by limiting the heat pick-up area to the exposed cast iron rib surfaces only. This results in higher refractory temperatures and increased chemical attack.

Another case would be the use of a refractory *sandwich* consisting of three different grades of refractory in the same wall thickness. For example, a silicon carbide layer of refractories could be *sandwiched* between a cold face lining of lower cost high alumina or highly conductive semi-graphite and an economical fireclay on the hot face to absorb the rigors of blow-in and initial thermal shock damage.

Another example would be to utilize lintel blocks of highly conductive graphite or semi-graphite to form the bridged opening for copper cooling plates or to form *passive* cooling bands or rings to enhance the cooling effect of widely spaced cooling plates.

The possibilities are endless but the important point is to remember to consider all of the important internal and external factors that will affect the *system* performance such as expansion provisions, differential movement, mechanical stresses, integration with the cooling elements and analysis of the wear mechanisms to be encountered.

There are many armor/refractory designs used in the furnace stockline area. The refractory in this area must withstand severe abrasion and thermal cycling resulting from contact with cold/wet burden materials. Various burden distribution systems such as the bell-less top and adjustable throat armor, can be utilized to divert materials away from refractory walls, increasing lifetime.

4.5 Gunning Materials

A variety of materials have been used for blast-furnace gunning repairs or in some cases for initial installations. These materials are generally mixtures of refractory aggregates and calcium-alumina cements and have been installed both from inside the furnace off suitable platforms or from outside the furnace through ports cut in the furnace shell or using automatic equipment lowered from the top of the furnace. As a result, the conditions under which gunning installations have occurred have varied from cold-weather ambient conditions where the gunning materials had to be warmed and hot-water used to provide set of the cement, to hot furnace conditions where cement set had to be retarded so that suitable strength could be developed. Despite the range of application conditions, however, the gunning materials have certain common requirements.

The gunning material particle size distribution and cement characteristics must be selected to minimize the amount of rebound experienced. Excessive rebound can significantly alter the designed refractory properties.

Careful consideration must be also given to prevent segregation or flow problems (blockages) during material transport. In many cases, materials may require special equipment for handling and pre-wetting.

All refractory materials for blast-furnace gunning must be selected to contain minimum levels of uncombined iron or iron oxide. Also, pickup of tramp iron during any manufacturing step (grinding, mixing) must be avoided. Uncombined or tramp iron in minute amounts will cause the material to experience failure due to carbon monoxide disintegration as was described in Chapter 3.

The refractory gun mix should always be designed for the specific method of installation and location in the furnace. Special aggregates and additives are commonly used to enhance the behavior in many areas. (For example, additives such as gypsum to accelerate or retard cement set, sulfur additions to improve resistance to carbon monoxide, metal fibers to enhance abrasion resistance, and/or organic fibers to allow rapid moisture escape during drying.)

Fig. 4.2 shows the location of four areas where blast-furnace gunning repairs have been made, and Table 4.9 indicates properties of some typical materials which have been used. Materials for the stockline and offtake areas are generally selected for maximum abrasion resistance and strength using very hard aggregates (silicon-carbide or fused–Al_2O_3) and high cement content as indicated by a relatively high CaO content. Materials for the stack can vary widely using aggregates ranging from fireclay to tabular fireclay Al_2O_3 and cements varying in Al_2O_3 content from 60 to 80%. Materials for the lower stack

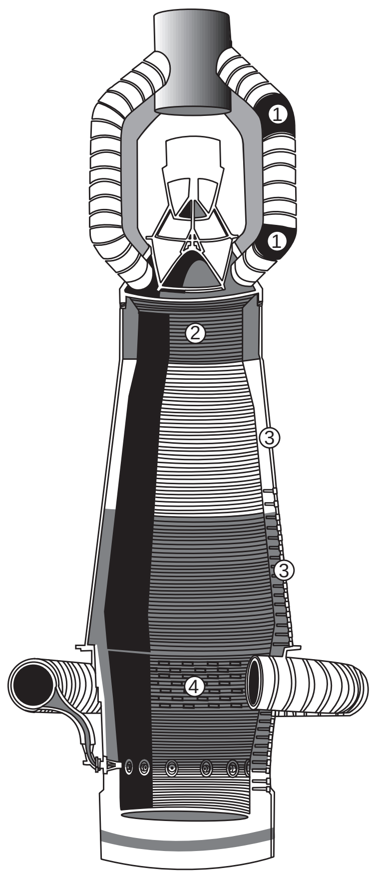

Fig. 4.2 Use of gunning mixes for blast furnace repair. Refer to Table 4.9.

Table 4.9 Properties of Blast Furnace Gunning Materials

Property	Stack			Stockline	
Composition (%)	$45Al_2O_3$	$60Al_2O_3$	$95Al_2O_3$	Regular	SiC
Al_2O_3	46	61	94	46	20
SiO_2	48	33	< 1	5	2
CaO	3	3	5	5	3
Fe_2O_3	<1.5	<1.0	<0.1	<1.5	<0.6
Other	2	2	<0.5	2	75 (SiC)
Density (lb/ft^3)	130–132	135–137	166–168	132–134	148–150
Modulus of Rupture (psi)					
at 1500°F	1000	1200	2300	2200	1500
at 2000°F	800	900	1800	1200	1200
at 2500°F	–	650	1000	–	1250
Linear Change After, %					
2000°F	–0.2	0.0	0.0	+0.2	0.0
2800°F	+0.3	+2.1	–0.5	+1.2	(0.5
Areas Used in Fig. 4.2	3	3,4	3,4	1,2	1,2

and bosh are generally selected from the group using the most slag, and/or alkali resistant aggregates and cements.

The success of gunning repairs in the blast-furnace vary widely. It should be realized that even the best gunning installation will not produce density and porosity equivalent for brick of similar composition, and that the operating condition(s) which affect the area under repair are likely to wear the gunned materials at a more rapid rate. Despite these factors, localized repair by gunning can extend campaign life and repairs can be rapidly accomplished with proper planning and preparation.

4.6 Taphole and Casthouse

4.6.1 Taphole Materials

Improvements in the properties of the taphole materials use to stop flow and maintain controlled metal and slag flow have allowed the modern blast furnace to lengthen the time of each cast, reduce the number of casts per day, and increased the percentage of time a furnace is casting to insure smooth furnace operations. The improvements in taphole material quality have also required improved taphole guns to allow proper extrusion of the more rigid materials and also improved equipment for opening taphole drills, including soaking bar practices.

Fig. 4.3 shows an idealized taphole where the extruded taphole materials have formed an extension of the taphole into the furnace. In this manner a taphole length significantly longer than the furnace wall length can be maintained for controlled casting and safety. This taphole length can be estimated each time the furnace cast is initiated and adjustments in taphole material quality or amount made to control hole length. Fig. 4.4 shows the taphole gun in position to extrude a column of taphole material into the furnace. Note the importance of a seal between the nose of the taphole and the furnace taphole extension. Fig. 4.4 also illustrates temperature increases in the gun proper that occur when the gun is held in position after extrusion to allow initial set of the taphole

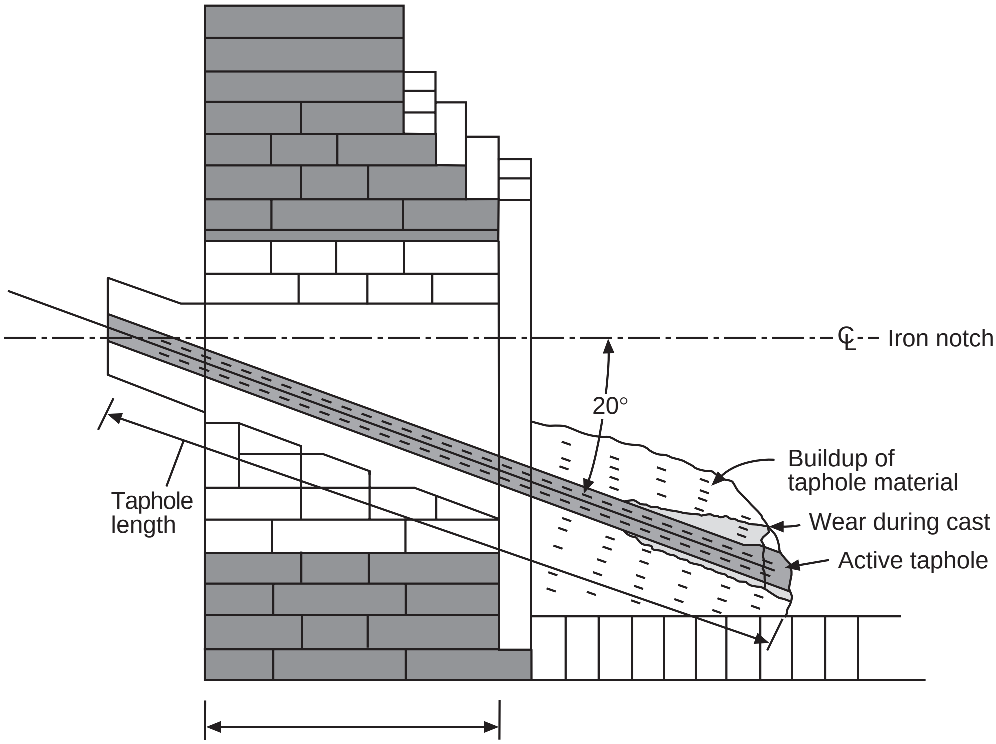

Fig. 4.3 Taphole construction and buildup inside furnace.

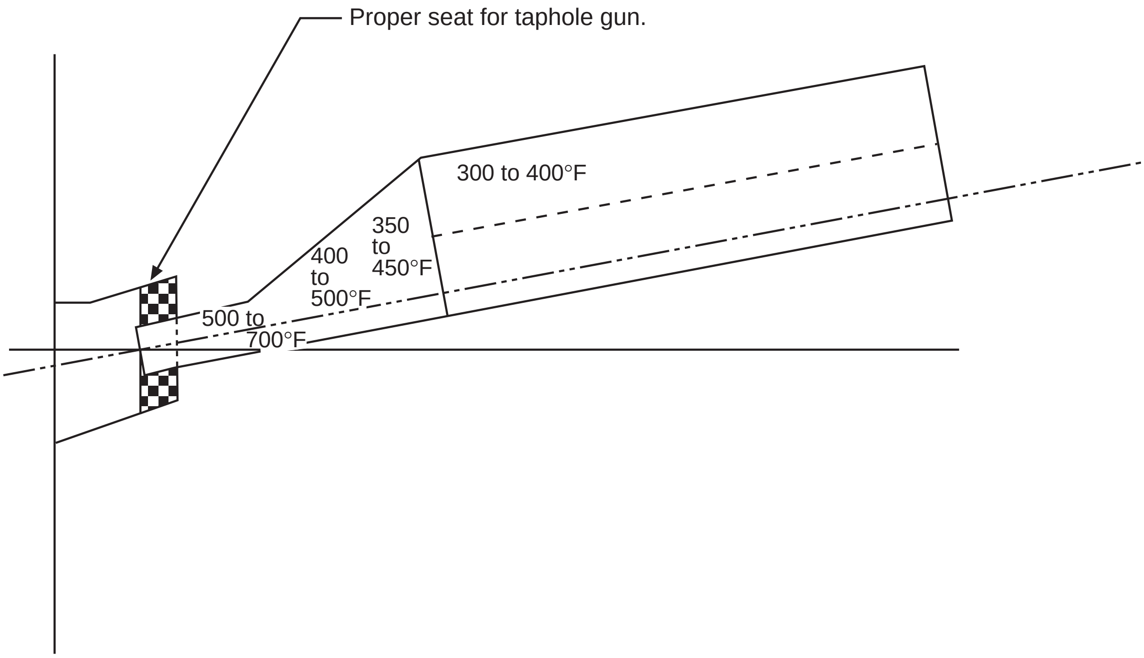

Fig. 4.4 Ideal position of taphole gun in iron notch for closing off a cast.

materials to prevent blowout by furnace pressure. As described in Section 9.2.3, practices may also be used in which the taphole is partially drilled shortly after removal of the taphole gun and a steel bar (soaking bar) inserted to facilitate rapid hole opening on the next cast.

The modern taphole materials are made from a variety of refractory aggregates mixed with one or more liquid carbonaceous materials to develop an extrudable mixture. These liquid materials include tar or resin type materials which will form strong carbon bonds when exposed to heat in the taphole. The refractory aggregate system is selected to provide the proper level of controlled taphole erosion and will vary widely with furnace size and the casting practice (number of tapholes, casting rates, metal composition, etc.). For example, high alumina or silicon carbide aggregates may be used on multiple taphole furnaces for minimum erosion rates.

In any case, any specific furnace requires a material designed for its particular conditions and the characteristics of the material must be rigidly controlled on a daily basis. Shipments of taphole materials may be tested frequently to insure characteristics such as extrudablity and content of liquid component. These parameters are critical in controlling taphole length and the ability to maintain long tapholes. Variables such as the effect of ambient conditions must also be controlled by storing the taphole materials in a warm, dry location and using inventory techniques to avoid changes in materials due to aging. It is extremely important to maintain the condition of the taphole guns by cleaning out materials from prior hole stoppages and by proper gun shielding or cooling to prevent overheating.

4.7 Hot Blast Stoves

4.7.1 General

A standard internal combustion chamber refractory stove design had been utilized for decades throughout the world. However, as the cost of fuel, especially coke, rose higher in Europe and Japan it became imperative for them to develop hot blast stoves that could produce higher blast temperature. As hot blast temperatures were increased to 1093°C (2000°F) and higher, the refractory design of the stove experienced extensive refinement and modification.

It is interesting to note that the new design features that were adapted by the major stove designers are remarkably similar in concept. The reasons for this similarity are that the major problems encountered in the standard internal combustion chamber stove, when operating at hot blast temperatures of 1093°C (2000°F) and above, are universally recognized. These are the major problems: shifting and movement of the metallic checker supports, differential thermal expansion of the combustion chamber skin and breast walls which causes the breast wall to tilt (commonly called the banana effect) and the differential growth of the ring wall, resulting in the tilting, cracking and failure of the stove dome. Additionally, higher efficiency interlocking checkers within a given stove volume were required to provide the higher hot blast temperatures.

The proper selection of stove refractories is essential to satisfactory operation and long life. Correctly chosen refractories become more critical as the required hot blast temperature increases. The refractories must be carefully selected for their expected load/temperature condition and zoned to provide for the desired temperature gradients and expansion characteristics.

Both 57 and 63% alumina refractories are suitable for high temperature stove application. They are used for top checkers in many cases because high alumina has a greater heat capacity than silica. In addition, high alumina refractories have good spall resistance at all temperatures. However, silica has certain technical advantages such as excellent spall resistance in combination with the lack of expansion for temperatures higher than 600°C (1112°F). This makes silica a desirable refractory material for those areas of the stove where the normal operating temperature is not lower than 600°C (1112°F). Therefore, silica is an excellent choice for the dome, the upper combustion chamber wall and the upper checker chamber wall. Silica also has the characteristic of glazing at high temperatures. This characteristic will result in less fouling or plugging of checker flues as it eliminates both the build up of dirt and the cauliflower effect that can be found around the flues of high alumina checkers. As a result, a top setting consisting of several courses of silica checkers is often installed above the high alumina checkers.

4.7.2 Basis for the Selection of Refractory and Insulating Materials

4.7.2.1 Dense Quality Brick

The most decisive criterion for the selection of stove refractory materials is their creep characteristic. Since creep is the ongoing deformation of a refractory due to temperature and pressure, each quality of refractory has a designated creep specification. The basis of this specification is that the refractory will have a maximum deformation of 0.2% at a load of 0.2 N/mm^2 (28 psi) at a specific temperature for a time duration of 20 to 50 hours, see Table 4.10. The maximum design temperature for a given quality of refractory material is based on this specific temperature. As a safety factor the maximum design temperature in many cases is set at 50°C (122°F) below the specific creep temperature, see Table 4.11.

4.7.2.2 Checker Brick

While the maximum design temperature shown in Table 4.11 is satisfactory for use in selecting the dense quality stove brick, a lower maximum design temperature is recommended when selecting checker brick made from the same quality refractory material. This difference in design temperature is due to the design of a checker brick. The design of a high efficiency checker incorporates an interlocking system: each checker is interlocked to the course below it by three depressions which match with projections in three different checkers. This interlocking design reduces locally the bearing surface of the checker which causes localized higher bearing pressure. As a compromise for the localized higher bearing pressure, an adjustment is made to the maximum design temperature. Based on the location of the checkers in the height of the checker column, the maximum design temperature is lowered compared to dense brick made of the same quality refractory material, see Table 4.12.

Table 4.10 Designated Creep Specifications for Dense Quality Brick

Quality	Alumina (%)	Specific Creep Temperature
High Duty	39	1200°C (2192°F)
Super Duty	42	1250°C (2282°F)
High Alumina	53	1350°C (2462°F)
High Alumina	57	1400°C (2552°F)
High Alumina	63	1500°C (2732°F)
Silica	1	1500°C (2732°F)

Table 4.11 Maximum Design Temperature for Dense Quality Brick

Quality	Alumina (%)	Maximum Design Temperature
High Duty	39	1150°C (2100°F)
Superduty	42	1200°C (2192°F)
High Alumina	53	1300°C (2332°F)
High Alumina	57	1350°C (2430°F)
High Alumina	63	1450°C (2642°F)
Silica	1	1450°C (2642°F)

Table 4.12 Maximum Design Temperatures for Checker Brick

Quality	Alumina (%)	Maximum Design Temperature
High Duty	39	900°C (1650°F)
Super Duty	42	1050°C (1922°F)
High Alumina	53	1250°C (2282°F)
High Alumina	57	1350°C (2462°F)
High Alumina	63	1450°C (2642°F)
Silica	1	1450°C (2642°F)

4.7.2.3 Insulating Materials

Insulating bricks will always have a dense quality brick in front to protect the insulating brick against wear. The insulating brick is selected based on the hot face temperature of the dense quality brick in front of it. No consideration is given to the temperature drop through the dense quality brick. The most important properties of insulating bricks are thermal conductivity and shrinkage at high temperature. Table 4.13 lists the maximum design temperatures for different density quality insulating materials.

Low shrinkage of the insulating bricks can be achieved if they are selected based on the maximum design temperatures shown in Table 4.13. This is a necessary characteristic in the selected density quality of the insulating brick to avoid open joints which might cause stove shell hot spots.

In order to achieve a maximum design stove steel shell temperature of 100°C (210°F), it is common to require a layer of insulating material that is 230 mm (9 in.) thick. This condition can exist at the top of the checker wall and at the top of the burner wall. Since the grade of insulating brick is chosen based on the hot face temperature of the dense brick that is in front of it, the most economical design would be to split the total required thickness into several thicknesses of different density qualities. The high density quality insulating brick would be used on the hot face with a lower density quality as a back up. In general, the backup insulating brick has a density quality of either 800 kg/m^3 or 650 kg/m^3.

Table 4.13 Maximum Design Temperatures of Insulating Materials

Density at Maximum Design Temperature	Thermal Conductivity at 20°C (68°F)	Maximum Design Temperature Quality
Slab	0.1 W/m°K (0.69 BTU in/ft^{2}h°F)	800°C (1472°F)
800 kg/m^3	0.2 W/m°K (1.38 BTU in/ft^{2}h°F)	800°C (1472°F)
650 kg/m^3	0.2 W/m°K (1.38 BTU in/ft^{2}h°F)	1000°C (1832°F)
700 kg/m^3	0.25 W/m°K (1.39 BTU in/ft^{2}h°F)	1225°C (2237°F)
600 kg/m^3	0.3 W/m°K (2.08 BTU in/ft^{2}h°F)	1225°C (2237°F)
850 kg/m^3	0.35 W/m°K (2.43 BTU in/ft^{2}h°F)	1300°C (2372°F)
1100 kg/m^3	0.45 W/m°K (3.12 BTU in/ft^{2}h°F)	1450°C (2642°F)

In addition to the insulating brick, a 38mm (1.5 in.) layer of slab type insulation is mortared to the stove shell.

In order to make use of the creep characteristic to select the proper qualities of refractory and insulating layer thickness, it is necessary to perform a number of thermal gradient calculations. Many times as many as fifty separate calculations are required.

Although the creep characteristics of the dense quality brick and the checkers have a significant bearing on the refractory design of a hot blast stove, there are other physical characteristics of the refractory that have an important role in choosing the grade of refractory to be used. These other important values, depending on the area of the stove where the refractory is to be used are: volumetric weight, resistance to thermal shock, residual quartz content, thermal conductivity, and permanent linear change.

4.7.3 Selection of Hot Blast Stove Refractory and Insulating Material

4.7.3.1 Checkers

As shown in Table 4.12 the refractory material quality for checkers can range from high duty material to Silica. The different checker brick refractory qualities to be used in a stove are selected based on the temperature gradient through the checker work. The temperature gradient is determined by using the information from the stove capacity calculations. The upper limit of the temperature gradient is determined by adding 50°C (90°F) to the calculated maximum operating dome temperature and is termed the *design dome temperature*. The calculated maximum waste gas temperature is used as the lower limit of temperature gradient. When selecting the refractory quality to be used for the checkers, the temperature gradient through the checkers is assumed to be linear. The maximum design temperature for the different refractory qualities as discussed in Section 4.7.2.2 is based on the creep characteristics of the refractory material.

The height of a checker quality can be calculated using the following formula:

$$H = \frac{(Tmdt - Tldt)}{(Tdd - Twg)} \times \text{The Total Checker Height} \qquad (4.7.1)$$

where

H	=	Calculated Height
Tmdt	=	Maximum Design Temperature of Subject Quality
Tldt	=	Lower Design Temperature (This temperature is set by the maximum design temperature of the preceding refractory quality or in the case of the first checker setting, the waste gas temperature).
Tdd	=	Design Dome Temperature
Twg	=	Waste Gas Temperature

The installed height of the quality checker selected is then determined by converting the calculated height to an even number of checker courses based on the height of a checker.

An example follows.

Given:

Total checker height = 30.9 m
Tdd = 1450°C
Twg = 350°C
Super Duty Quality Checkers
Tmdt = 1050°C (See Table 4.12)
Tldt = 900°C (See Table 4.12)

Height of a checker = 150 mm

$$H = \frac{(1050°C - 900°C)}{(1450°C - 350°C)} \times 30.9 \text{ m}$$

$$H = 4.214 \text{ m or } 4214 \text{ mm}$$

$$\text{Number of checker courses} = \frac{4124 \text{ mm}}{150 \text{ mm}} = 28.09.$$

Use 28 courses of 150 mm brick.

4.7.3.2 Checker Chamber Wall Brick

In the refractory design of a modern stove, the checker chamber wall brick is terminated on each side by the combustion chamber. At each end of the checker wall, special corner shapes that have an increased thickness for better support of the breast wall and to avoid sharp corners in the checker work is provided. Normally, the lower 60% or more of the checker chamber wall is laid up using high duty brick.

The selection of both the dense quality brick and the insulating brick for the checker chamber wall must be done on the basis of the temperature gradient through the checker work. The same procedure as was described for determining the height of each checker quality (see Section 4.7.3.1) is to be used when calculating the height of the various qualities of dense brick and the first layer of insulating fire brick. However, in determining the course height, a mortar joint of 3 mm must be added to the brick height of both the dense quality brick and the insulating brick. The calculated height of each quality then must be rounded off to an even course height.

As stated in Section 4.7.2.3, the first layer of insulating brick behind the dense quality brick is selected based on the hot face temperature of the dense brick. The required thickness of insulation will increase with the height of the stove to achieve a stove shell temperature of 100°C (212°F). The selection of the insulation quality for this additional insulation should be done as described in Section 4.7.2.3. To ensure free vertical expansion of the dense quality lining, an offset in the dense quality lining must be provided at least one course below the elevation where the second layer of insulating brick will start.

Means must be provided to allow the various layers of the checker chamber wall to expand freely both in the circumferential direction and in the vertical direction. To insure that each wall layer can independently expand in the vertical direction, during construction a small gap can be provided between each layer. One method of doing this is by installing 5 mm thick expanded polystyrene between the dense quality brick and the insulation brick and to install oil paper between the layers of insulation. Provision for the circumferential expansion of the dense wall brick can be accomplished by dividing the wall into a series of horizontal and vertical panels. An allowance for circumferential expansion should also be provided in the first layer of insulating brick behind the dense quality brick in the higher areas of the stove were two layers of insulating brick are installed. The width of the expansion opening at each end of the dense quality wall should be increased. This will ensure the unobstructed independent vertical movement of both the checker chamber wall and the breast wall. Ceramic felt can be installed in the expansion openings to block the flow of hot gases.

4.7.3.3 Combustion Chamber

The extreme flame temperatures produced in the combustion chamber of a modern stove has been the cause of many problems related to expansion and numerous designs have been created to minimize these problems. The large variations in the magnitude of expansion, both toward the shell and toward the checker chamber, are caused by the high thermal gradient through the walls. This thermal gradient results in the well known *banana* effect on the breast wall, due to the growth of the hot face being more than the growth of the cold face, causing the top of the wall to bend toward the checkers. Like wise, the skin walls want to bend outward, and cracks can open where movement is restricted. If both faces of a brick are kept nearly the same temperature, the growth will be vertical. This can be done by installing insulating brick between the skin wall and the breast wall. Installing continuous vertical slip joints between the walls will allow each wall to grow without damaging the adjacent wall.

There are three principal walls in a stove: the burner wall; the partition wall consisting of the skin wall, intermediate insulation, and the breast wall; and the checker chamber wall, each have different vertical expansion rates, because of different construction and different temperature levels. To prevent cracking that will be caused by this uneven thermal expansion, the partition wall system is kept separated from the burner wall and the checker chamber wall by means of an expansion joint.

If the stove has a hemispherical dome, the dome should only be supported by the burner wall and the checker chamber wall. When the partition wall is the same height as the burner and checker chamber walls, the dome can become cracked. During stove cool down, the partition wall cools much slower than the other two walls. As a result, the partition wall will act as a wedge which will cause the dome to crack just above the partition wall. To eliminate this problem, it is best to keep the top of the partition wall several courses below the start of the dome skew back brick. A flat arch can be constructed to bridge over the top of the partition wall. Ceramic felt can be used to fill the opening between the underside of the flat arch and the top of the partition wall.

4.7.3.3.1 Partition Wall The skin wall is normally constructed using either 57% high alumina or 63% high alumina brick for its entire height. The dome design temperature is used to determine which of the two qualities is best suited for a particular stove design application based on the data shown in Table 4.11. The density quality to be used for the insulation layer directly behind the skin wall is also selected base on the dome design temperature using the data from Table 4.13.

Similar to the checker chamber wall, a large portion of the height of the breast wall is laid up using high duty brick. However, the maximum elevation for the various qualities of breast wall brick is **not** based as may be thought on the temperature gradient through the checkers. Instead, it is first necessary to establish the temperature gradient over the height of the insulating layer between the skin wall and the breast wall. The limiting elevation for a specific quality of dense brick is established by locating the elevation where the breast wall face temperature of the insulating layer equals the maximum design temperature of that refractory quality.

Means must be provided to allow the various layers of the partition wall to expand freely both in the circumferential direction and in the vertical direction. To permit free vertical expansion during construction, a small gap can be established between each layer. One method of doing this is by installing 5mm thick expanded polystyrene between the back side of the dense quality brick layers and the insulation layer. The circumferential expansion of the various layers of the combustion chamber wall can be accomplished by dividing each wall into a number of panels. The panel construction of the skin wall should allow for both the horizontal and vertical movement of the individual panels. The panels of the insulating layer and the breast wall need only to allow for horizontal expansion. The width of the expansion openings at each end of the dense quality walls should be increased. This will ensure the unobstructed vertical movement of each wall. Ceramic felt can be installed in the expansion openings to block the flow of hot gases.

An alternate partition wall construction that can be employed is to use silica brick in the upper portion of the partition wall. This can be done at the elevation where both the skin wall and the breast wall have a consistent operating temperature above 600°C (1112°F). At that temperature, the expansion of the silica has stabilized and it has excellent spall resistance. Since the expansion of both the silica skin wall and breast wall is stabilized, there is no longer any need to be concerned about the temperature gradient between the two walls. Thus, the insulation layer between the skin wall and breast wall can be eliminated. This will simplify the construction of the partition wall and reduce its installation cost.

A number of design steps are used to minimize the short circuiting of gas through the partition wall. The expansion joints are made with special interlocking brick and the opening filled with ceramic felt. In addition the expansion joints in each layer of the partition wall should be set off from each other so that no through paths exists. As an additional precaution Hoogovens, one of the principal designers of hot blast stoves, installs alloy steel sheets on the inside radius of the breast wall. The sheets have a thickness of 0.5 mm (0.020 in.)and are triple overlapped. To aid in their installation, the top 50 mm (2 in.) is bent at a 90° angle to the vertical surface of the sheet so the sheets can be hung in the mortar of the breast wall.

4.7.3.3.2 Burner Wall The method used to determine the quality of dense refractory brick and insulation brick that is to be installed in the burner wall will depend on the design of the stove dome. In the case where a self-supporting dome is used, the method of selecting the quality of both the dense brick and the insulating fire brick is uncomplicated. The method to be used will in general be the same procedure, with some slight modification, as was used in determining the same materials for the skin wall. However if the dome is to be supported by the stoves refractory walls, the vertical expansion of the checker chamber wall and the burner wall must coincide as closely as possible.

In the case of a self-supporting dome, the height and quality of the hot face dense brick and the insulating brick to be installed behind the dense brick are determined in the same manner as the skin wall. The quality for both will be based on the dome design temperature. However, to insure that the stove shell temperature is not greater than 100°C (212°F), an additional layer of insulating brick must be added between the shell slab insulation and the insulating fire brick.

When the dome is to be supported by the stove wall refractories, it is necessary to equalize the vertical expansion of the checker chamber walls to the vertical expansion of the burner wall. If this is not accomplished, the dome will crack due to the different expansion rates of the two walls. To accomplish this equalization, a sandwich type construction is used for the burner wall. The sandwich construction consists of high alumina or silica hot face brick, a layer of insulating brick, a 229 mm (9 in.) wide dense quality layer which for a substantial portion of its height is high duty brick, a second layer of insulating brick, and the slab insulation against the shell. The 229 mm (9in.) wide layer is used in balancing the vertical expansion of the burner wall with the vertical expansion of the checker chamber wall.

To balance the vertical expansion of the two walls, it is first necessary to determine the vertical expansion of the checker chamber wall. Next the vertical expansion of the 229 mm (9 in.) wide high duty brick wall is determined. The height of high duty brick layer is then adjusted by selecting a height of either high alumina or silica brick to bring the vertical expansion of the wall equal to the vertical expansion of the checker chamber wall.

All layers of the burner wall must be able to freely expand in the vertical direction. During construction a small gap can be provided between each layer. On method of doing this is to install 5 mm (0.2 in.) of expanded polystyrene on the backside of the dense brick layers and oil paper on the backside of the insulating fire brick.

The layers of dense brick and insulating fire brick that form the burner walls are each divided into panels similar to that which was done for the partition wall in order to allow for circumferential expansion. Ceramic felt can be installed in the openings that have been provided for expansion to block the flow of hot gases. The width of the expansion opening at the end of the dense quality wall should be increased. This will ensure the unobstructed independent vertical movement of both the burner wall and the skin wall of the partition wall.

4.7.3.3.3 Protection Walls Protection walls are installed in the combustion chamber to protect the inner wall of both the burner and partition wall from thermal shock. The incidence of thermal shock is most prevalent in the lower section of the combustion chamber during stove change over.

Due to its good thermal shock resistance a Mullite based 57% alumina brick is used to construct the protection wall. The creep properties of the selected quality of refractory have less significance since the only load on the wall is its own weight. Therefore, the maximum design temperature listed in Table 4.11 can be increased allowing this quality of dense brick to be used in an area where the operating temperature will be in excess of 1350°C (2430°F).

The protection wall normally is started at the top of the internal burner or from the bottom of the combustion chamber well of a stove with an external burner. It extends to an elevation which is two times the diameter of the hot blast outlet above the centerline of the hot blast outlet.

4.7.3.3.4 Hot Blast Outlet Rings The dense quality layers of the burner wall and the protection wall have different average temperatures. Therefore each layer moves upward relative to the stove shell and relative to each other. A refractory arch ring extending from the hot face of the protection wall and the subsequent layer of dense refractory of the burner wall into the nozzle beyond the stove shell would be sheared and broken at the lines between these different walls. The resulting gaps and possible collapse of the refractory would result in damage to the insulation and overheating of the stove shell. To allow for the differential vertical expansion of the dense refractory layers of both the protection wall and the burner wall, the hot blast outlet is designed as separate rings. Each ring is part of one dense quality layer being made from the same quality refractory material as that layer and can expand with that layer.

4.7.3.4 Stove Dome

The shape of the stove dome can be either hemispherical or parabolic. Both dome designs can be supported either by the burner wall and checker chamber wall or they can be self-supporting. The hemispherical dome is normally used for stove having a diameter less than 9 m (29.5 ft). The parabolic dome which has better stability than the hemispherical dome and can be used equally well for stoves of any diameter.

Both types of domes are constructed having one dense quality layer and two insulating layers. The choice of refractory material for the density quality is based on the design dome temperature. Based on Table 4.11, the dome brick can be made from 57% high alumina, 63% high alumina or silica refractory materials. The layer of insulation at the back of the dense refractory can be one quality less than the highest quality stove insulating material used up to this point. The reduction of one quality grade is made on the basis of a compromise between load bearing characteristics and shrinkage characteristics of the insulating material selected. Since the insulating layer will only support is its own weight, this compromise can be considered as acceptable. All bricks in the dense quality layer and in the first insulation layer are tongue and grove type. The second insulation layer, a 600 kg/m^3 dense quality insulating brick, is glued against the steel dome. Tongue and groove type brick are not used for this layer.

The dome design should provide for expansion. The dense quality layer should be designed with provision for both vertical and radial expansion. In between the dense quality layer and the first layer of insulating brick a gap should be provided to allow for the vertical expansion of the dense quality layer. No provision for expansion is built into the first layer of insulating brick. When the refractory dome is supported by the burner wall and checker chamber wall, a suitable clearance must be maintained between the top of the first layer of insulating brick and the inner surface of insulation attached to the steel dome. This provision is not required if the dome is supported by the steel shell.

When the dome is supported by both the burner wall and the checker chamber wall, a refractory skewback is provided. The skewback is made of special shapes that are keyed together in both the horizontal and vertical direction. This construction minimizes the radial forces and most of the dome's weight is transmitted to the stove wall in the vertical direction. The skewback is constructed using the same dense quality refractory as was used for the dome. This same dense quality brick is also used in the top courses of both the burner wall and the checker brick wall on which support the skewback.

