BLAST FURNACE HEARTH RELINES: FROM CONCEPT TO CONSTRUCTION

Jesse Carreau – Allied Mineral Technical Services, LLC, Canada
Floris van Laar – Allied Mineral Technical Services, LLC, Netherlands
Max Iwamura – Allied Mineral Technical Services, LLC, Brazil
Matt Wieneke – Allied Mineral Technical Services, LLC, USA
Tim Ritter – Allied Mineral Technical Services, LLC, USA
Rudy Tolkamp – CIM-Tech, Inc., USA

This paper will discuss a systematic approach for the design and construction of a new hearth, employing an "inside-out" approach. A comprehensive diagnostic is first performed by reviewing thermocouple and operational data from the current campaign to determine expected process loads in the new campaign. Three-dimensional thermal models of the new hearth design are analyzed using boundary conditions developed from the diagnostic. The thermal models evaluate the performance of the hearth under normal and high process loads. The model also analyzes a "worst-case" wear situation, which evaluates the hearth refractory's ability to deal with additional wear during Blast Furnace unstable operation, high productivity operations, steam attack, and heavy leakage of gas or water. An expansion model is then developed to ensure the expansion design functions as intended. Finally, recognizing that construction is a pivotal phase of the hearth reline process, this paper will examine installation methodology and other considerations to ensure a successful hearth reline.

KEYWORDS: BLAST FURNACE – HEARTH RELINE – ATTACK MECHANISMS – ENGINEERING – MODELLING – DIAGNOSTICS – REFRACTORY DESIGN

INTRODUCTION

The steel industry undoubtedly faces mounting pressure to reduce its carbon footprint. While technological advancements and policy shifts will continue to make green steelmaking more viable, the industry's transition has been slow due to economic, infrastructural, and technical challenges. In the wake of these challenges, Blast Furnaces around the world require investment to continue operations. Companies are relying on fewer Blast Furnaces in North America, South America, and Europe than they did in the past, which makes the reliability of Blast Furnace refractory and cooling systems critical for success. This paper will discuss hearth relines, from concept to construction, by utilizing hearth design fundamentals, advanced modelling techniques, detailed engineering considerations, and construction guidelines for a successful installation. The hearth reline process described herein outlines an approach for designing and implementing a reliable refractory and cooling system tailor-made to the customer's conditions.

DIAGNOSTIC

A proper assessment requires the involvement of different disciplines in the blast furnace; from upper management to maintenance and operations. All disciplines can contribute useful knowledge of the blast furnace history, operation, and maintenance activities. A complete assessment is composed of three major parts: information gathering, data evaluation, and reporting of findings with conclusions and recommendations. For more detailed information on the assessment, please refer to the previously published paper "Hearth Campaign Extension Strategies Using Partial Repairs" [1].

HEARTH DESIGN FUNDAMENTALS

Many modern blast furnaces across the world are designed using similar fundamentals. For the sake of brevity, this section will focus on three fundamentals: hearth volume, sump depth, and "Critical Sump Depth Ratio".

The hearth volume of a blast furnace is defined as the volume between the centerline of the tuyeres and the centerline of the taphole. The hearth volume is the volume available for liquid accumulation and needs to be a minimum of 10% of the furnace inner volume to prevent high liquid velocities at high productivity. The recommended hearth volume to inner volume ratio is 14% or more. Ideally, the hearth volume would be maximized, but some factors limit the ability to increase hearth volume. Typically, the tuyere elevation and taphole centerline are fixed; the cost and complexity of modifying auxiliary equipment are not feasible in most cases. In addition, a large hearth volume makes it difficult to recover a furnace with a chilled hearth because of the large mass of iron that needs to be melted to restore normal operation.

The sump depth of a blast furnace is defined as the distance between the centerline of the taphole and the top of the hearth bottom and is the area available for liquid flow. A larger sump depth decreases liquid velocities in the lower hearth, which aids in reducing hearth refractory wear. Critical Sump Depth Ratio (CSDR) is the ratio between sump depth and hearth diameter. Blast Furnaces with CSDRs less than 20% experience excessive wear on the lower hearth sidewalls, causing an “elephant’s foot” wear pattern at high iron production levels.

HEARTH HEAT FLUX CAPABILITY

Heat flux capability is a measure of the total heat the refractory and cooling system can sustain before experiencing wear. A high heat flux capability will ensure a refractory design can withstand extreme temperatures, chemical attack from molten iron and slag, and thermal stress, all while maintaining structural integrity and ensuring efficient drainage of molten iron and slag. Temperature data can be used in combination with the actual process conditions, thermal loads, and high-sigma event data that the refractory was exposed to during the current and historical campaigns. Using this data, a hearth can be designed for the actual encountered conditions and the expected maximum productivity for the next campaign.

Cooling system designs have different heat removal capabilities. See Tab. 1. The refractory design must coincide with the target productivity (heat flux) and cooling system capability. A refractory lining that is too conductive, paired with water spray cooling, may lead to higher refractory temperatures than desired and expose the lining to chemical attack mechanisms. A hearth cooled by copper staves and a graphite safety lining will be able to keep lining temperatures low, avoiding chemical attack and reducing stresses due to thermal expansion well into the campaign.

Tab. 1: Hearth cooling types and capabilities [2].

HEARTH COOLING TYPES & CAPABILITIES		
TYPE	**MAX. HEAT FLUX (W/M^2)**	**REMARK**
Water spray cooling	30,000	Lowest investment
Double shell cooling (cassette cooling, jacket)	70,000	Tolerable investment
Cast iron stave cooling	70,000	Higher investment
Copper stave cooling	320,000	Highest investment

ATTACK MECHANISMS

Alkali Attack

The hearth of a blast furnace is primarily composed of carbonaceous materials, which leads to a host of alkali attack mechanisms such as:

- Condensation of potassium in the pores of the refractory, which can react with CO and CO_2 to form K_2CO_3, causing expansion of the material [3].
- Potassium vapour penetrates the lattice of carbon, causing expansion of the material [3][4].
- Oxidation by K_2CO_3, causing carbon to disappear [3][4].
- Potassium reacts with the additives in the micropore carbon, such as SiO_2 or Al_2O_3 [3][4].

In most cases, alkali attack causes an expansion, which destroys refractories from the inside out. Post-mortems of refractory linings have shown this phenomenon, as seen in Figure 1. In this case, alkali penetrated deep into the refractory lining and caused an internal expansion. The lower block cracked and lifted the block above by approximately 120mm.

Fig. 1: Expansion due to alkali penetration.

Keeping the hot face temperature below approximately 800°C prevents alkali attack of carbon refractory; however, alkali attack of ceramic refractory and ceramic additives can occur above 560°C. Thus, refractories selected should contain minimal impurities such as SiO_2 and Al_2O_3.

CO Disintegration

CO disintegration, or the reversed Boudouard reaction ($2CO_{(g)} \rightarrow CO_{2(g)} + C_{(s)}$) occurs when CO gas diffuses into carbon-containing refractory. Iron or iron oxides in the refractory material react with the CO to create carbon deposits in the lining, which generates internal stresses within the refractory lining. Eventually, these stresses can build and lead to cracks within the refractory materials [5]. Figure 2 illustrates the mechanism of CO disintegration.

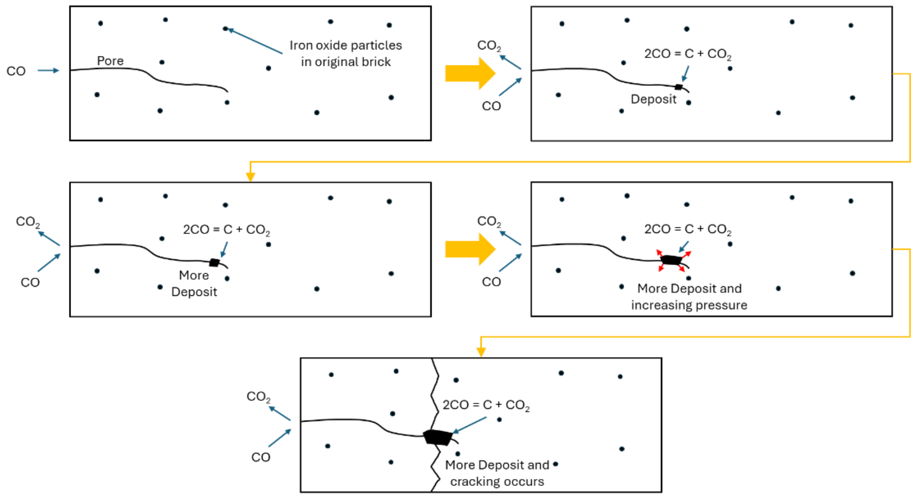

Fig. 2: CO disintegration mechanism

As soon as CO disintegration creates a crack in the refractory lining, the cooling efficiency of the refractory lining is significantly reduced and therefore refractory temperatures increase. CO disintegration can occur in temperature ranges of 450°C to 800°C. When purchasing refractory, it is critical that material specifications for all refractories stipulate an iron content of less than 1.0% to reduce the magnitude of these reactions.

Steam Attack

Although refractories in blast furnaces are mostly exposed to reducing conditions, there are instances where oxidation can occur, to which carbon materials are especially prone. Oxidation can occur from oxygen sources such as oxygen (O_2), water vapour (H_2O), and carbon dioxide (CO_2). The primary mechanism is water vapour, which can be introduced from the following sources:

- Raw materials
- Hot blast
- Reaction of FeO with H_2
- Leaking cooling members

The most common cause for steam attack is due to leaking cooling members and the reaction of FeO with H_2 to form H_2O. Moisture in the raw materials or hot blast typically does not affect the hearth lining, since any moisture is removed via the top gas before it reaches the hearth, and any entrained moisture with the hot blast decomposes almost immediately due to the high temperatures.

Iron Penetration

When the protective skull is worn away, liquid iron comes into contact with the refractory lining. Whether the iron penetrates a pore is a function of the surface tension of iron, the ferrostatic pressure, the contact angle (wettability), capillary pressure, the pore size distribution of the refractory, and the tension in the lining caused by differential expansion between the impregnated section and the unaffected section of the brick. Figure 3 shows an example of iron penetration observed during a post-mortem analysis. Severe attack of iron and slag was found inside the carbon blocks, despite the hot face appearing to be in good condition.

Fig. 3: Example of iron and slag penetration into a carbon refractory lining.

The percentage of pores larger than 1um indicates the susceptibility to iron penetration. Generally, this percentage should be less than 2% for large, high-pressure furnaces and less than 4% for smaller, low-pressure furnaces.

TAPHOLE DESIGN

Taphole Design Configurations

When designing a hearth, there are typically three concepts available to choose as the starting point: the small brick, large block, and double ring designs.

The jointed structure of the small brick lining provides better resistance to thermal cycling and allows the use of multiple grades of refractory in the taphole and/or sidewall such as a double densified graphite, semi-graphite, or carbon brick. This increases the ability of the refractory lining to freeze a process skull, which protects the hot face refractory and keeps lining temperatures below critical levels for chemical attack.

A large block design consists of blocks that can range from 1.5 meters to 2.5 meters in length. This design offers fewer joints for iron or slag penetration and logistical advantages, such as reduced manpower requirements and flexibility in installation across varying ambient temperatures due to the absence of mortar. However, large blocks are prone to large temperature gradients across the block's thickness, which can lead to cracking. A common design change to combat this effect is to "pre-crack" the large blocks to create a "double ring" hearth design, where two rings of medium blocks separated by a ram joint are installed. This is the medium block or double ring design. The double ring design enables the use of a high-conductivity (graphite or semi-graphite) safety lining similar to the small brick design.

Taphole Core

In the design of taphole linings, the choice of center materials plays a crucial role in balancing thermal performance, wear resistance, and operational reliability. Among the most used center materials are insulating white bricks, black carbon-based refractories, and castable formulations, each with its own set of trade-offs.

Center bricks made from lower conductivity white Al_2O_3 materials help retain heat for clay sintering and protect surrounding refractories, though they lack resistance to slag and thermal shock and are more vulnerable to gas leakage.

Black materials, including micropore carbon, semi-graphite, and graphite, are widely used for their excellent slag and thermal shock resistance, and compressibility. Black materials can be more susceptible to damage from oxygen lancing, and other operational activities.

Finally, a castable core provides a low conductivity solution for better clay sintering, enhanced chemical and iron/slag erosion resistance, reduced joints for gas transport, and ease of localized replacement. The castable core can be replaced during short, planned outages from the outside, which also provides an opportunity to inspect the adjacent brickwork to validate taphole thickness and/or calculations in the taphole area.

COMPUTER MODELLING

Three-dimensional computer modeling and analysis is a valuable tool for the design of blast furnace hearths since it provides a visual representation of temperatures throughout the hearth refractory, shell, and cooling system. The temperature results calculated in an analysis of the hearth can be used to help determine refractory temperatures, cooling water temperatures, shell temperatures, refractory selection, expansion, cooling water heat load, and wear profiles.

Boundary Conditions

Boundary conditions are the constraints applied to the model's computational domain, and they provide the 'driving force' for heat transfer. Factors that influence boundary conditions for a hearth thermal model include PCI and/or NG injections, coke CSR and CRI, productivity rate, tapping temperature, and cooling water flow rates, temperatures, and pressures.

These boundary conditions are commonly obtained from the process information of an existing installation or, if needed, a similar installation. Boundary conditions can be developed from thermocouples embedded in the existing hearth refractory and from cooling water instrumentation.

Model Results

A validation model is a crucial step in the basic engineering process. Utilizing actual customer process and temperature data, the model can be fine-tuned to achieve thermal results consistent with real-life conditions. It is possible to validate or tune the model to within 20°C of actual refractory temperatures, providing precise results. After the validation model is complete, the hearth can be modelled at various stages in the campaign.

Figure 4 represents the temperature profile in the hearth with a worn lining, approximately 15 to 20 years into the campaign. Since the hot face lining has been partially eroded, the temperatures in the cold face lining and the cooling system increase. It is critical that the worn lining at the end of the campaign is evaluated. Otherwise, the cold face lining may fail due to the higher temperatures, or the cooling system may be overloaded with the additional heat load, causing even higher temperatures and accelerating wear in the furnace lining.

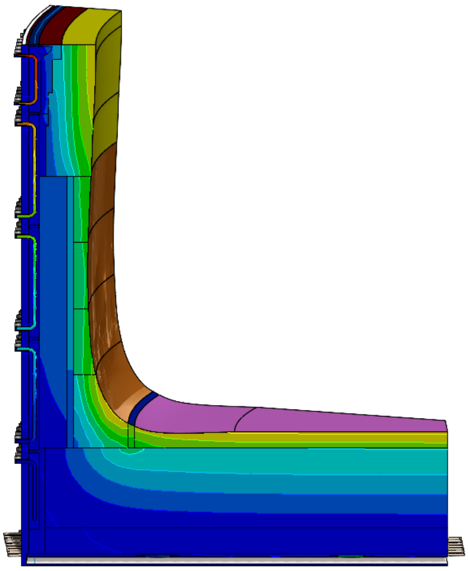

Fig. 4 - Worn Lining Temperature Profile

High process loads in the hearth area, typically local to the taphole, may require intensified cooling via a copper stave. Thermal analysis around a taphole, or the stave specifically, can indicate areas of concern. Common modifications to the cooling and refractory in the taphole include refractory selection, insulating the tap stream from the carbon materials using a Al_2O_3-SiC castable, stave material, cooling water flows, upgraded cooling system, addition of a water-cooled taphole nozzle, larger taphole nozzle(s), and longer taphole nozzle(s).

Expansion Model

Engineering design of a blast furnace hearth includes incorporating expansion within the hearth refractory, cooling elements, and shell. Without proper expansion allowance, the refractory can crush, resulting in premature failure. The expansion model must be set up with proper boundary conditions. A fixed point in the model must be established that will allow realistic expansion without confining the expansion such that the stresses are artificially high. Typically, a location on the shell is used as the fixed point, with sliding supports to mimic contact with the surrounding refractory. Figure 5 shows the stress within the course due to the thermal expansion of the refractory and shell based on the temperature output of the thermal model.

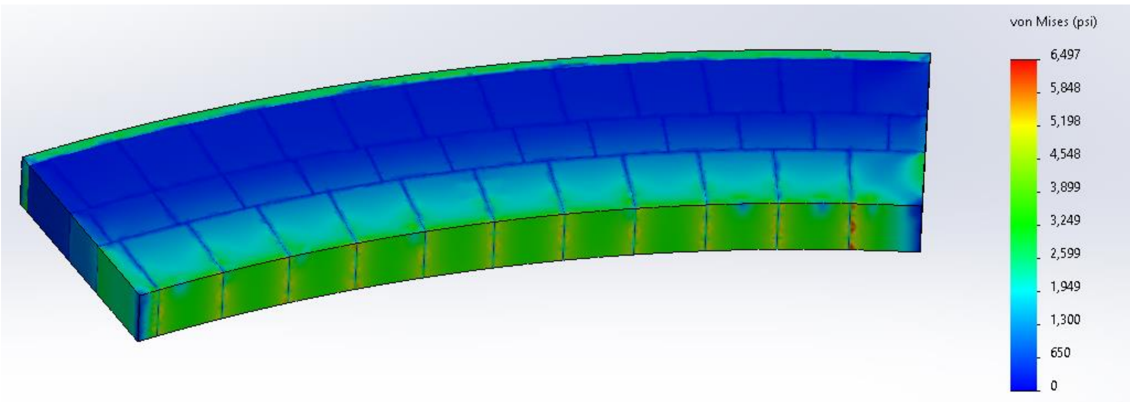

Fig. 5 - Stress Plot in Single Refractory Course with Mortar Joints

Figure 5 shows that the highest stresses in the blocks are in the vertical hot face joints. The success lies in a design where the materials do not exceed maximum material stresses caused by high-temperature events. For medium or large block designs, different materials are used to compensate for expansion, such as ceramic board and compressible alloys.

OVERVIEW OF MECHANICAL COMPONENTS

In addition to refractory, mechanical components can be implemented as part of a hearth design. Leaks, whether gas or water, can cause significant damage to the hearth refractory in the form of steam attack. Mechanical seal plates can help protect the refractory by baffling or directing leaks away from the steel shell or taphole spool. Gas or water channeling can deteriorate the interface between the refractory and the cooling system, leading to higher hearth temperatures, increased wear, and the potential for a furnace breakout. Figure 6 shows the horizontal water stop plate concept, while Figure 7 shows the taphole gas seal concept.

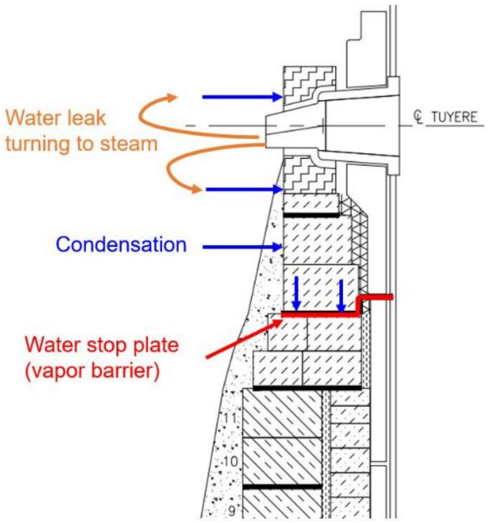

Fig. 6 - Water Seal Plate Concept.

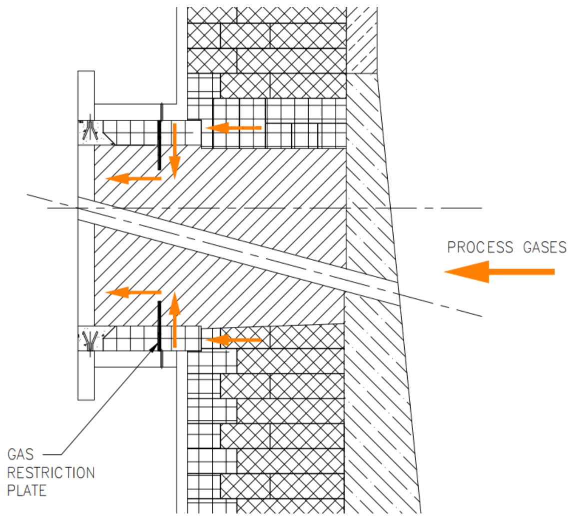

Fig. 7 - Taphole Gas Restriction Plate Concept

HEARTH CONSTRUCTION

Small Brick Design

In a small brick installation, each ring of brick is tightly packed using jacking methods, with a nominal 1.5 mm (1/16 in.) mortar joint per brick. After demolition of the repair area, the shell must be thoroughly cleaned, via grinding or sandblasting, to ensure optimal heat transfer to the cooling system. Elevation marks should be placed at the top of every three courses to guide installation, allowing for consistent elevation checks and adjustments.

A laser level should be used to establish an accurate starting point. During installation, all bricks must be “double-buttered” for a proper seal. Brickwork should begin at the taphole centerlines and proceed outward, with keys staggered between courses. Each course is laid dry first to identify and resolve shell discrepancies. Any brick being installed near areas of the shell that need welding must stop at a minimum of 1000 mm (3’) from the area intended for welding to prevent gaps from being formed between the shell and brick due to shell expansion during the welding process.

Each course must be level within 3 mm (1/8”) around the circumference. Two closures (partial cut brick) are allowed per full ring, while partial repairs permit only one closure per area. The minimum closure brick size must be 75 mm (3”) at the small end of the taper. In some cases, a double cut, using a half brick and a larger-than-half brick, may be necessary. Bonding must be maintained between the inner and outer rings and between the layers.

Medium Block / Double Ring Design

A dry-fit check should be conducted well in advance of installation to confirm proper alignment and interlocking of the blocks. Equally critical is the development of a detailed methodology plan; improper sequencing or block numbering can bring the entire process to a halt. Due to their size and weight, larger construction openings and heavy-duty hoisting equipment are essential for proper placement within the furnace.

Carbon blocks should be kept dry to prevent cracking during heating. Additionally, appropriate lifting equipment, such as slings, cranes, and vacuum lifters, must be used to avoid breakage. Impact jacks applying 15–25 tons of pressure, along with 5-8 mm (1/4") steel jack plates, are necessary for proper placement. Ramming joints must be compacted in five steps every 150 mm (6"), and a center pin beam stand or laser light should be used to maintain alignment. Contamination from moisture, oil, or dust must be avoided, and proper grinding tools and straight edges should be used for leveling.

CONCLUSIONS

A successful blast furnace hearth campaign starts with a systematic approach to the design, supply, and installation of the new lining. The design shall be informed by the process parameters of the current furnace operations, allowing computer modeling of the hearth to predict refractory, cooling water, and shell temperatures along with thermal expansion of the hearth components. Refractory materials shall be selected based on the computer modeling to minimize the effect of various attack mechanisms. The installation of the newly designed hearth must be supervised and installed with specific requirements to ensure a lengthy and successful campaign.

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