Improving Profitability by Analyzing Ferroalloy Furnace Lining Performance to Improve Lifetime

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ABSTRACT

Ferroalloy furnace life is often jeopardized because of refractory system inadequacies. Degradation of furnace linings is a result of many complex and interrelated variables, which often results in dangerous breakouts, lost production and unrecoverable profits.

Premature lining failure can be avoided by utilizing proper design, configuration and materials. However, certain investigative and performance determination techniques can be utilized to determine performance potential and provide clues to solving or preventing lining degradation. Often, the information can be utilized to stabilize deterioration, extend the periods between repairs and provide the operator with information that is useful for assessing required process changes such as lowering sidewall heat flux. In addition, this information can be utilized to provide the necessary design changes or improvements, not only to the refractory materials, but also to the lining configuration, composition and furnace shell.

The contributing effects of cooling inadequacies and/or inefficiencies, including improper or non-existent maintenance practices must also be included in the analyses.

Several ferroalloy furnaces have recently been investigated and analyzed with the intention of extending lifetime, postponing repairs, providing continued safe operation and providing adequate performance feedback for proactive operator response with required process changes. Analyses were utilized to determine repair possibilities, repair scope, identify responsible problems such as thermal shock, chemical attack, mechanical stresses, inadequate or improper refractory materials, improper or inadequate cooling and poor maintenance or operating practices contributing to the problems. Additionally, proper instrumentation was incorporated to provide the feedback required to monitor the actual situation instead of waiting for hot spots to appear.

Ferroalloy furnace refractory performance and lifetime improvement requires that the entire lining/cooling /shell "system" be properly analyzed to determine the responsible mechanisms of wear and failure. Expertise in refractory design, materials analyses, stress and failure mechanism analyses, cooling system performance and steel shell design and configuration is essential. However, the rewards of improved profitability due to uninterrupted production, postponement of repairs or reline shut-downs and improved reliability are too great to ignore. It becomes a question of "can you afford NOT to analyze?". Like trying to fly a jet airplane without instruments, running ferroalloy furnaces without feedback is a risky situation. Proper lining system performance analyses can provide the tools necessary to improve ferroalloy furnace lifetime and profitability.

1. INTRODUCTION

A Smelting Furnace is an asset which is capable of producing in excess of twenty million US$ of product per annum.

Many aspects of the furnace are key to the efficiency of the production, and the profitability of the furnace.

One of the most significant aspects of stable predictable furnace production is the refractory lining and cooling system.

However due to the fact that the lining is out of sight it is also often out of mind, until premature or unpredicted lining failure causes a break in production, and as a result could have serious financial consequences to the producer involved.

This paper addresses a process used in determining lining conditions in existing operating furnaces. It analyses the factors which cause premature lining wear, and suggests methods of building linings utilizing empirical formulae, operational experience, and an in depth knowledge of refractory behavior.

It goes further to suggest methods of measuring the Lining Cooling System operation in order to obtain the best achievable value out of the asset.

2. TRADITIONAL LINING PERFORMANCE

Upon evaluating a series of ferroalloy furnaces, it has been observed that typical lining campaign lifetimes vary significantly. This is amongst others determined by specific characteristics of the lining designs, installation & maintenance methods and procedures. The effect of operations and process conditions has also been observed to be of critical importance in determining the lining campaign life.

FeCr process conditions have been noticed to be more aggressive in comparison to FeMn whilst typical linings of the FeCr furnaces are of poorer quality resulting in high repair and reline frequencies.

Traditional ferroalloy lining designs comprise castable, electrode paste or carbon blocks whilst a series of different bottom designs has been installed utilizing paste, alumina ceramics and/or carbon blocks. Knowledge and understanding of failure mechanisms was limited and the traditional linings have mainly been selected, as capital costs are relatively low.

It should be acknowledged, however, that the traditional linings often show premature wear and require high repair and reline frequencies thereby negatively affecting production rates. The costs of lost production should be added to the capital cost of the linings. It should also be realized that unexpected break-outs could result in injuries where lining management systems are not installed.

Freeze-linings are becoming progressively more popular. The freeze-lining concept comprises high conductivity lining materials thereby minimizing lining hot face temperatures and exposure to lining attack mechanisms as discussed in subsequent section.

Freeze-lining campaigns lasting over 15 years have been recorded in blast furnace hearth applications. Data from recent ferroalloy furnaces indicate excellent performance as well: lining temperatures are well below critical threshold values.

3. LINING ATTACK MECHANISMS

Lining detoriation occurs due to a series of principal attack mechanisms, which can be classified:

- Chemical
- Physical
- Mechanical

Examples of chemical attack mechanisms include:

- Redox reactions [slag/metal interface]
- Alkali attack [K, Na, Zn, etc.]
- Oxidation [H_2O, O_2, CO_2]
- C-deposition

C-deposition (CO-disintegration) is a direct consequence of non-equilibrium reaction mechanism:

$$2\ CO(g) <> CO_2(g) + C(s)$$

Fe-containing refractory impurities and the presence of catalysts e.g. H_2O and H_2 enhance the reaction. The effect is also determined by refractory properties. A typical example is illustrated in Figure 1. The effects of catalysts are clear.

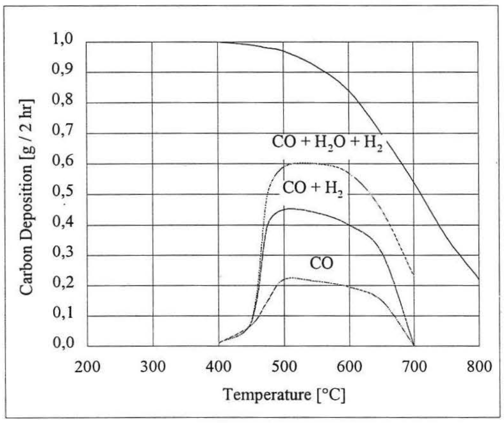

Figure 1: Carbon Deposition

Cyclic depositions of the C-particles in refractory pores finally result in disintegration of the refractory binder and/or main constituents as illustrated in Figure 2.

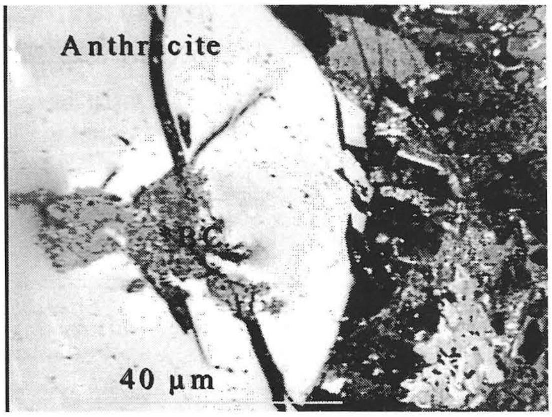

Figure 2: Boudouard Carbon Deposit

Physical attack mechanisms include a.o.:

- Melting of refractories
- Dissolution of C in unsaturated liquids
- Dissolution of 'white' ceramics

Arcing can also be classified in this group.

Melting of refractories will only occur above the liquidus temperature. Melting of 'black' carbonaceous refractories is therefore not a serious risk, but melting of 'white' ceramic refractories – for example bottom bricks – could result in severe wear.

Dissolution of C in unsaturated liquids is a well-known and serious wear mechanism when utilizing carbonaceous refractories. This aggressive mechanism can result in severe wear in few hours if the lining is in direct contact with the liquids and liquid C-levels are unsaturated.

The process is mainly diffusion driven, but convective movements will 'refresh' the boundary layer liquids continuously.
Liquid C-levels can be unsaturated when process conditions run 'under-coke'. As an additional effect, average process temperatures will increase since there is a shortage of reducing agents.

This attack mechanism has zero effects where a 'skull' of solidified metal/slag protects the lining. Hence, it is important to re-establish a protective skull in case the lining is exposed to liquids.

Critical mechanical attack mechanisms are:

- Stress cracking
- Spalling
- Abrasion, Erosion

Stress cracking is a result of specific refractory properties, lining temperatures and expansion design features. Considering full constraint conditions, refractories will be crushed when the expansion - caused by temperature increases – exceeds the compressibility. Examples are listed in Table 1.

	Compressibility [%]	Expansion @ 1000°C [%]	Crushing Temperature [°C]
Silicon Carbide	0.05	0.3	160
High Alumina	0.10	0.4	200
Amorphous Carbon	0.40	0.5	800
Semi-Graphite	1.00	0.4	2500
Hot Pressed Carbon	1.00	0.4	2500
Graphite	1.00	0.3	3300

Table 1: Crushing Temperatures

It is clear that sufficient expansion need to be provided in order to prevent stress cracking failures. The inherent 'strength' (flexibility) of semi-graphite, hot pressed carbon and graphite is also clearly recognized.

Cyclic expansion of e.g. sidewall linings can occur by repetitive contamination of joints as a consequence of dynamic furnace operations causing temperature fluctuations in the lining as schematically illustrated in Figure 3.

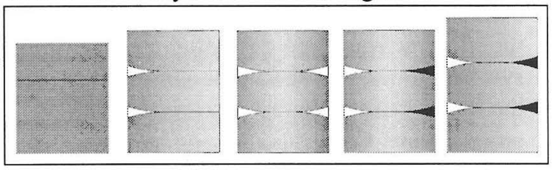

Figure 3: Cyclic Expansion

The effects of most attack mechanisms are insignificant below certain specific 'threshold' temperature levels. These levels are determined by e.g. reaction kinetics. Typical threshold temperatures are listed below:

- C-deposition 450°C
- Oxidation 650°C
- C-dissolution 1500°C

Consequently, lining performance can be improved by minimizing temperature levels. The application of high conductive refractories is required, but the external shell cooling system also needs attention. Besides, adequate and accurate lining management systems are required in order to monitor temperature developments and optimize maintenance strategies.

Each attack mechanism can affect the lining condition on its own, but typically combinations occur resulting in more severe damage. For example, penetration of refractories by e.g. Fe or alkalis will negatively affect the expansion coefficient and enhance stress cracking. Typical graphs are illustrated in Figure 4.

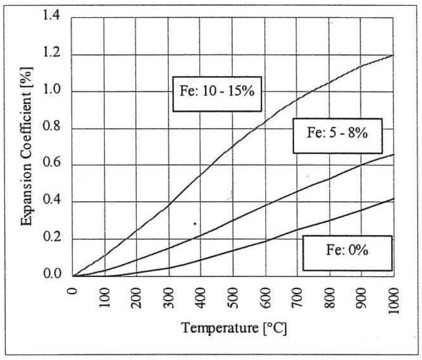

Figure 4: Expansion Coefficients

4. CRITICAL ISSUES

The fundamental lining attack mechanisms as discussed in section 3 are a general consequence of exposing refractories to high temperatures and liquid metal/slag.

Standard and customized experimental and numerical computer modeling techniques under laboratory conditions can quantify the effects of these attack mechanisms.

The real effects depend on the specific application and design features of the lining system. The lining system does not merely refer to refractory system properties, but also includes the shell configuration and cooling system characteristics. Even the best refractory systems can fail once the lining system shows deficiencies e.g. with regard to cooling and/or mechanical defects.

Ferroalloy furnace refractory systems basically comprise four zones:

- Bottom
- Wet Zone
- Dry Zone
- Taphole

Each zone is exposed to specific attack mechanisms. The lining design should be optimized to meet the resulting specific requirements thereof. For example, the wet zone lining design should be able to resist exposure to liquids and high heat loads. The taphole design should be able to meet a series of dynamic operating conditions and exposure to liquids whilst also be resistant against lancing.

The individual zones are inter-connected. Consequential results of severe wear in any zone can thereby immediately affect the other zones as well and result in premature wear and failure of the complete system.

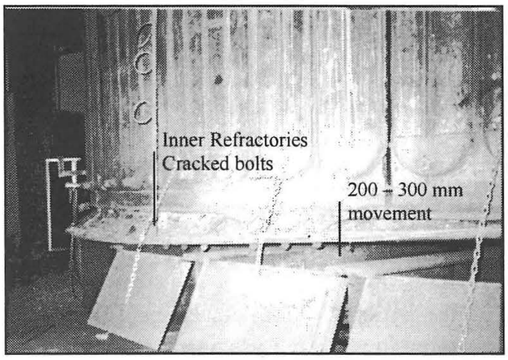

Figure 5: Lining Failure

Many ferroalloy furnaces suffer from lifting of the shell as illustrated in Figure 5. The bottom, wet & dry zone refractory structures are disrupted as well. As a consequence, thermal barriers are introduced resulting in higher refractory temperatures and premature failure as the shell and cooling are separated from the refractory system.

This effect is often caused by too high bottom plate temperatures and a rigid connection of the outer bottom plate segments to the vertical shell via a bolted and/or welded construction. The bottom plate temperatures could be too high due to insufficient (air) cooling and improper design and materials selection of the bottom refractories.

Radial expansion provisions of the outer bottom plate segments are immobilized by the rigid connection to the vertical shell. A jacket cooling system and/or stiffening beam structure enhances this effect.

Consequentially, radial movements are transposed into vertical movements. The vertical movements are significantly larger than the original radial movements would have been. It can be shown that for a typical furnace radius of 5 000 mm, each 1 mm radial movement could be transposed into a 100 mm vertical movement. The consequential vertical forces - exerted by the inner refractories - could result in consequential cracking of bolted/welded connections.

Clearly, the inner refractory system is also affected negatively: even the best refractory systems can not withstand any such movements.

These effects can only be counteracted by careful analyzing critical issues and having accurate and detailed knowledge of the behavior of refractories, cooling systems and their interaction when designing furnace lining systems. Operators should be familiarized with the lining system characteristics and requirements whilst also having an understanding of the effects of operations on the lining system condition.

A series of operating parameters have an effect on the lining temperatures and heat flux levels:

- Power Rate
- Tapping Practice
- Slag Basicity & Chemistry
- Superheating Temperatures
- Liquid Levels

Higher power rates generally result in higher temperature and heat flux levels. Arcing is also more likely to occur.

The effects of power rate levels also depend on specific furnace dimensions such as PCD, ELF, ELC, etc. These parameters should be optimized to maximize furnace operating efficiencies whilst minimizing negative effects on the lining system. Other critical design parameters include taphole elevation, electrode to bottom distance and the bottom (refractory) thickness.

The taphole system is exposed to fiercest process conditions. Premature failure is common. The taphole refractories selection and configuration need accurate analyses to meet all design and operational requirements. Optimized tapping practices should be developed minimizing the need for lancing.

The slag basicity can have a significant effect on the lining condition: typical FeCr acid slags are more aggressive than basic slags. This phenomenon provides a tool to protect the lining condition in latter stages of the campaign by producing more basic slags at the outer furnace zones close to the wall.

Superheating temperatures are determined by furnace operating and process characteristics as well as tapping strategies. Higher superheating temperatures facilitate tapping practices, but have a negative effect on the skull thickness.

5. FERROALLOY LINING STUDY

A furnace lining study was executed on a number of ferroalloy furnaces to develop a series of improved and 'ultimate' lining designs to achieve lifetimes > 15 years.

Plant surveys were executed to qualify and quantify critical issues and attack mechanisms in order to improve understanding of premature lining failure mechanisms. Forum discussions were organized with plant operators, maintenance personnel, technicians and management personnel in order to collect relevant data and information related to past and current lining performance and operating practices as well as general plant philosophies.

The lining conditions of critical zones of two furnaces were investigated in more detail by executing a series of core drillings. This method allows for collecting lining samples of 25 – 30 mm Ø and 100 – 500 mm length that can be visually inspected. A core drilling protocol was used to prevent creation of a new 'taphole' as some cores have been taken at wet zone lining levels. A more detailed analysis is possible by executing a series of physical and chemical tests as well as microscopic and mineralogical analyses. The latter services were provided by Corus Ceramic Research Center. The open holes were filled with refractory inserts afterwards in order to maintain lining integrity. The inserts are equipped with double TC's to monitor the local lining temperatures and heat flux levels.

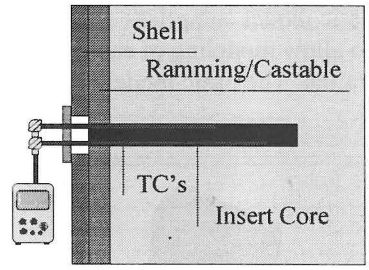

Figure 6: Core Insert Configuration

Examples of a schematic core insert configuration and core samples are illustrated in Figure 6 and Figure 7.

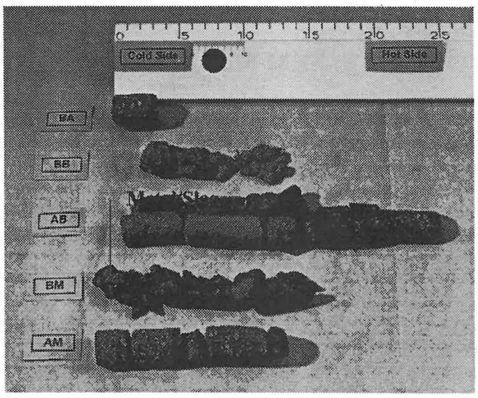

Figure 7: Core Samples

The text in Figure 7 refer to tests that have been executed e.g. X = XRD Analysis, M = Microscopic Analysis and C = Chemical Analysis.

As can be noted from the photograph, solid metal and slag was found at the cold face of this furnace lining indicating total loss of the local lining integrity. The original lining was only installed in 1998.

Steady-state 3D thermal FEM calculations were executed to determine the effect of operations and slag/metal thermal conductivities on bottom refractory and bottom plate temperatures and heat flux levels. A symmetrical section of the furnace was modeled. The heat input is represented by a fixed temperature half-sphere at the position of the tip of the electrode. The generic model accounts for progressive wear of the bottom refractories being exposed to too high temperatures until equilibrium is achieved.

The generic model comprises a set of building blocks to allow modeling of each bottom configuration. The basic model is illustrated in Figure 8.

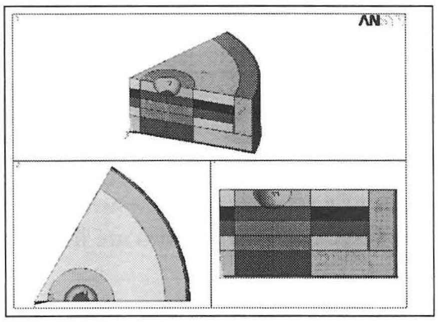

Figure 8: FEM Model Configuration

The model boundary conditions have been determined by comparing model predictions with site measurements and anticipated wear profiles. This resulted in two process condition simulation parameters representing normal and peak operations.

An example of typical results for peak operations and a typical ferroalloy bottom design is illustrated in Figure 9.

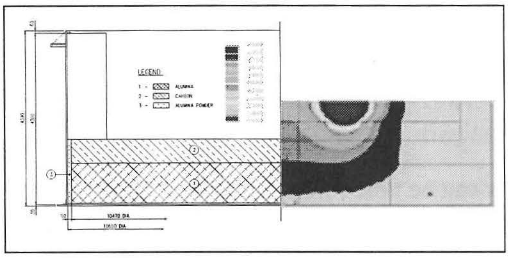

Figure 9: Existing Bottom Design

As can be noted, significant wear is anticipated as the insulating alumina courses and upper carbon course will be exposed to high temperatures. Output parameters also include maximum bottom plate and heat flux levels as well as average bottom heat loads. Isotherm profiles at all levels can also be generated.

The FEM model has been proven to be a useful tool in evaluating the performance of ferroalloy bottom designs.

The lining assessment and FEM models revealed a series of critical issues as addressed in Section 4 and allowed for defining critical design criteria for the bottom and wet zone lining components.

1D isotherm models were used to determine the thermal profile of existing and improved wet zone lining designs. A typical example of an existing ferroalloy wet zone lining design – comprising 230 mm ACS, 145 ramming and 600 mm Carbon - is illustrated in Figure 10.

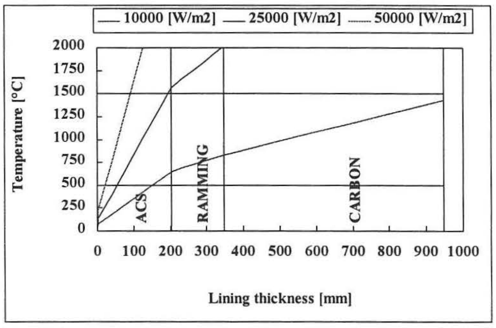

Figure 10: Existing Lining Design

As can be noted, temperature levels for moderate heat flux levels of 25 000 W/m³ already result in significant wear until 200 mm lining is left. The 500°C isotherm is located in the carbon component of this lining design thereby exposing the lining to CO-disintegration. The core samples illustrated in Figure 7 were taken from this lining design.

The isotherm profiles of a 'normal' carbon block lining are illustrated in Figure 11.

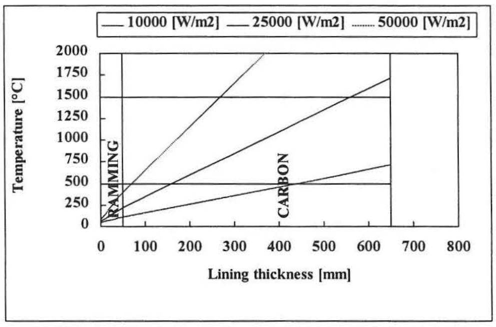

Figure 11: Carbon Lining Design

As can be noted, wet zone lining temperatures will be significantly lower in comparison to the lining discussed above. Hence, exposure to attack mechanisms will be reduced and performance improved.

The performance is even further improved by applying a graphite 'safety' layer to the shell in order to equalize local peak heat loads by radial and vertical heat transfer and to prevent penetration of liquids to the shell.

2D thermal FEM models were developed to determine wet zone isotherm profiles for complicated configurations e.g. when considering active copper coolers and/or bonded refractory constructions. These models account for radial and vertical heat flux components. The results are discussed in Section 6.

6. LINING DESIGN IMPROVEMENTS

Various critical issues and lining attack mechanisms have been discussed in the previous sections.

Main reason and catalyst for high wear rates is exposure to high temperature levels and sometimes even liquids. It should be realized that no refractories are capable of exposure to flowing liquids for long periods without showing signs of wear. Although the ceramic cup concept is also favored in blast furnace industries, it should be realized that the capital cost of these systems is significantly higher in comparison to the 'skull cup' philosophy of the 'thermal solution'. Technical defects of ceramic cups have also been reported in the past where the high strength cup crushes the outer lining components due to lack of expansion.

The best protection for both bottom and wet zone refractories will hence be provided by the solidified 'skull' at the hot face: the skull will also minimize heat losses due to its relative insulation. It should be acknowledged, however, that heat losses via the lining are relatively small in comparison to other heat sinks.

Skull integrity and build-up is enhanced by optimum cooling of the lining. This aspect is of special importance when considering the wet zone. Typical freeze-linings have already proven to function well in blast furnace systems for decades and multiple freeze-linings have already been installed and applied successfully in various ferroalloy smelter furnaces in South Africa and Europe. Typical isotherm profiles are illustrated in Figure 12.

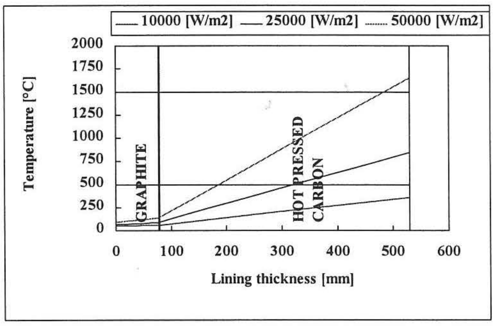

Figure 12: Freeze Lining Design

The shell cooling system need proper attention and maintenance for optimum performance of freeze-lining concepts as the systems can show premature wear upon loss of local cooling. Open spray (shower curtain) cooling or closed jacket cooling systems are preferred.

Typical freeze lining systems can also be damaged with the creation of open joints in the lining i.e. between graphite and shell and/or between hot face lining components and graphite.

Open joints – air gaps - induce a strong insulation effect thereby exposing hot face refractories to higher temperatures. A typical example of isotherm profiles is illustrated in Figure 13.

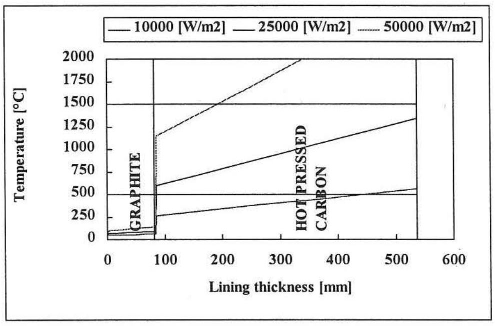

Figure 13: Air Gap Effects

Air gaps can be a result of shell expansion i.e. due to loss of cooling and/or contraction of inner components for example during stoppages.

Remedial countermeasures to re-establish thermal contact comprise for example grouting and cleaning of shell.

Structural improvements can be achieved by utilizing (active) copper coolers or bonded refractory constructions. These systems 'bypass' open vertical joints by transferring the heat flux via the overlapping horizontal joints. This is schematically illustrated in Figure 14.

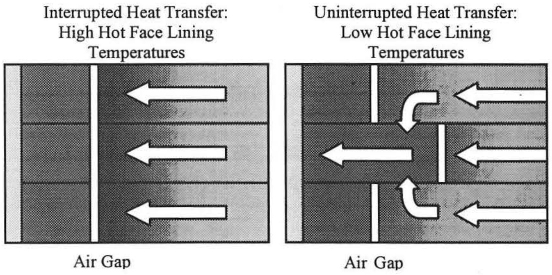

Figure 14: Lining Constructions

The application of active copper coolers has been halted during discussions with operators as the risk of steam explosions due to penetration of and contact to hot metal is considered too high.

The freeze-lining concept can not be copied directly to the bottom system as geometry considerations differ. Most critical in existing bottom designs to date are high bottom plate temperatures and high refractory wear rates.

Multiple bottom designs have been evaluated utilizing the FEM computer model. The thermal profiles depend largely on critical furnace dimensions e.g. distance taphole to top of bottom and bottom plate elevation. The optimum design can only be determined taking into consideration existing dimensions and requirements. Hence, no 'unique' bottom design can be developed and tailor-made systems are required.

A characteristic bottom design is illustrated in Figure 15 comprising two graphite layers on top of the bottom plate, one carbon layer on top thereof and a high alumina top course. As can be noted from the FEM results that are shown in the same figure, some high-alumina wear is anticipated, but carbon, graphite and bottom plate temperatures will be low.

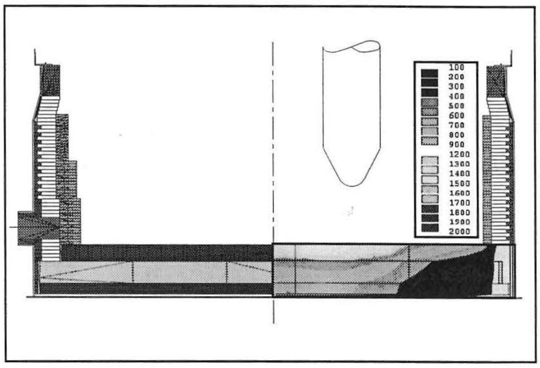

Figure 15: Improved Lining Design

The same figure illustrates the bonded refractory wet zone construction and a basic taphole design comprising a SiC-containing high-strength castable core to minimize effects of lancing and optimize clay curing & tapping practices.

The capital cost of improved lining designs can be higher in comparison to e.g. 'cheap' paste linings. More important, however, profitability can be improved when utilizing improved freeze-linings as large repairs are only required each 10 – 15 years whereas traditional linings are repaired each 2 – 5 years. Furthermore, power-rates can be maximized as the improved freeze-linings show superior performance in dealing with higher heat flux levels.

7. LINING MANAGEMENT SYSTEMS

No one will fly an airplane without instruments detecting weather, flight and airplane conditions. Similarly, no one should operate a furnace without instruments to control operations. To determine the lining condition continuously, lining management systems should be installed as it should be realized that even ultimate refractory and cooling materials and systems can be exposed to wear e.g. when operations are unstable.

Lining management systems allow the operator to monitor the lining performance during operations. The lining management system comprises temperature sensors – installed at critical positions – and a control room computer system that automatically processes relevant data.

Warning levels should be set and procedures should be developed in case critical levels are exceeded. A normal warning level system utilizes green, orange and red alert levels. Corresponding corrective actions include grouting, cleaning of shell, lower power rates, etc.

The system needs frequent generation, processing and storing of data to allow for future detailed analyses as well. Automatic calculation and visual representation of isotherm positions in the bottom and sidewall are a useful tool for operators.

A typical TC layout is illustrated in Figure 16. The application of double TC's and shell TC's allow for calculation of local heat flux levels and joint conditions.

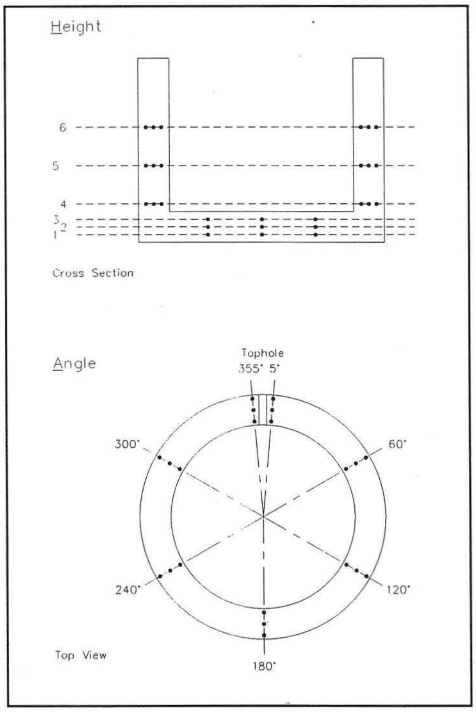

Figure 16: Typical TC LayOut

It is acknowledged that the lining management system requires an additional investment. However, capital costs are insignificant in comparison to consequential damages of unexpected lining failures. In this respect, the lining management system should be considered as a low-cost insurance.

8. MAINTENANCE STRATEGIES

All airplanes need regular maintenance. Similarly, ferroalloy furnace linings need regular maintenance.

Frequent inspections are required to determine the condition e.g. according to subsequent schedule:

Daily Actions

- Check Lining Temperatures

Weekly Actions

- Check shell condition (scaling/debris, deformation/cracks)
- Check spray cooling system

Monthly Actions

- Check water quality

Quarter Year Actions:

- Infrared Thermography
- Check jacket cooling system
- Grouting
- Check TC functioning

Maintenance actions include for example cleaning of shell, grouting, etc.

Preventive or remedial actions to protect the lining include operational procedures as well e.g. lower power rates, adjusted burden composition etc.

Clearly, optimum maintenance practices and a thorough understanding & full knowledge of the lining condition and attack mechanisms will minimize lining wear and outage frequencies & durations. The profitability will increase accordingly.

9. RELINE STRATEGIES

When relining a furnace, minimum down-time duration is often crucial as a consequence of production losses.

Optimum preparations will result in minimum down-time duration. An experienced team will also be required as well as good communications between various companies & contractors that are involved.

Partnering between customer and suppliers/contractors has proven to result in efficient procedures and relines. A main contractor can be appointed to organize a full program and minimize plant personnel involvement.

An example of a recent on-site program that has been developed and executed during the reline of a 15-m ferroalloy furnace is listed below.

On-Site Program	
Shut down Furnace	Day 1
Quench furnace	Day 1
Cut into furnace	Day 2
Demolish refractories	Day 2 - 9
Gritblast and paint inside	Day 10 - 11
Install refractories	Day 12 - 26
Close shell	Day 27
Complete refractories	Day 27 – 30
Start recomissioning	Day 31
Total Downtime Duration	**30 days**

As can be noted, total downtime duration for the repair is limited to 30 days only whereas earlier relines at the same plant lasted 50 – 60 days typically.

The increased profitability by the reduced downtime duration already paid for a large part of the reline contracting costs.

10. CONCLUSIONS

Company profitability can be improved by analyzing ferroalloy furnace lining performance in order to improve lifetime of the lining system.

A full understanding of critical wear mechanisms is required to allow for development of improved lining designs.

Repair frequencies and durations are minimized utilizing improved lining designs. Targeting campaign lifes of 10 – 15 years and eliminating large repairs will increase furnace production availability significantly. Consequential damages of unexpected premature lining failure will also be prevented.

Power rate and productivity levels can be maximized utilizing sound lining systems combining the most appropriate materials in a suitable configuration and being installed according proven procedures.

Lining management systems allow operators to monitor the lining condition during the campaign. This allows for proper control of the refractory, shell and cooling integrity. Remedial maintenance strategies can be optimized to eliminate unexpected premature failure of any lining system component.

11. ACKNOWLEDGMENTS

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