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ENERGY SAVINGS THROUGH PHOSPHATE-BONDED REFRACTORY MATERIALS

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Abstract

In consideration of energy savings, the ideal refractory furnace lining should possess the following features:

- Lowest thermal conductivity possible in order to avoid heat loss.
- Single component lining in order to allow freeze plane changes caused by wear, infiltration and temperature changes of the furnace.
- Resistance against mechanical wear from cleaning tools and stirring in order to allow maximum output without equipment downtime due to maintenance.
- Resistance against thermo-chemical attack from aluminum and alloying elements.

Refractory materials with a low thermal conductivity typically possess a higher porosity, leading to lower strengths and resistance against chemical attack and wear. As a compromise, multi layer linings are required in order to meet energy saving requirements.

In this paper we present the features of chemically phosphate-bonded dense and light weight refractories and how such refractories can contribute to energy savings.

Introduction

In several reports, the U.S Department of Energy published theoretical energy requirement limits for aluminum production as a future target, with recommendations on how to reduce energy losses. The reports provide a basic description of the processes and equipment involved, their interrelationship, and their effects on energy consumed. The report uses onsite process measurements as benchmarks that industry uses to compare performance between facilities and companies [1]**.** The energy consumptions used in this paper are primarily based on numbers published by the Department of Energy. However, their reports do not consider the potentially significant energy losses from process interruptions due to a lack of preventive maintenance and material deterioration over time. Further, the Department of Energy reports do not consider equipment costs and availability. Energy input to metal output depends on factors beyond energy losses through the furnace wall. For instance, a focus on energy savings should consider fixed output costs due to depreciation of the equipment and the plant.

What is the Potential for Refractory Materials to Help Provide Energy Savings?

Refractory walls are engineered with consideration given to the freeze plane of molten aluminum and the thermal profile necessary to entrain the required heat in the furnace. The primary design objective is to keep furnace conditions stable over time in order to avoid interruptions of the production process. Interruptions such as additional door openings, furnace maintenance downtime, or changes in the thermal profile change the heat containment conditions and increase total energy consumption.

Heat loss in aluminum melting and holding furnaces through the refractory lining can be distinguished between wall losses at steady state operating conditions and heat storage losses during transient conditions.

Transient conditions occur during furnace cleaning, skimming, fluxing, charging and heat up / dry out procedures after a shut down. Almost 40% of the total heat input is flue gas losses and only an estimated 10% of the remaining available heat is heat losses through the refractory wall due to steady state operating conditions [2]. The Sankey diagram in Figure 1 shows that the majority of the heat loss of the remaining available heat is due to opening losses and heat storage loss of the refractory and is estimated to be 20%-30% depending on the furnace type and operating conditions. For instance, significant radiation losses through open doors or other openings in the furnace enclosure can add up to 49,000 BTU/hr/ft^2 based on a furnace with a production rate of 15,000 lbs/hour. Furnace shut downs can lead to process downtime and additional heat losses of other connected units like launders, holding or melting furnaces and filter/degassing systems. In this case, the production capacity loss far outweighs the energy losses.

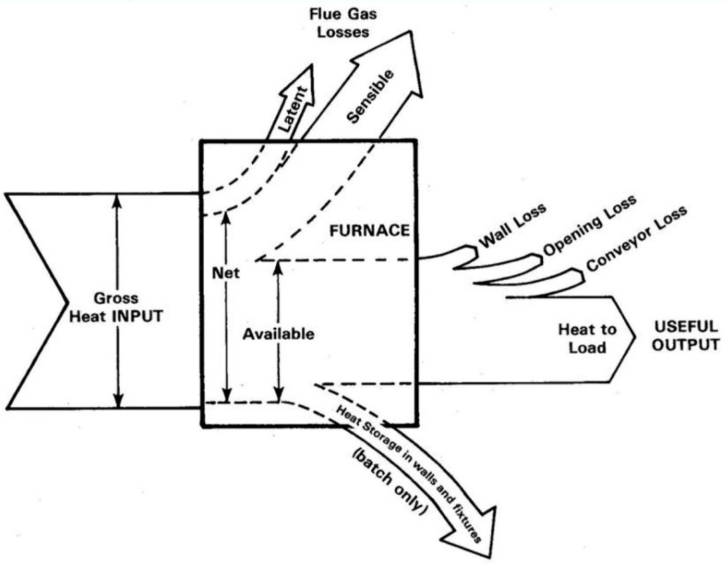

Figure 1. This Sankey Diagram depicts the magnitude and points of energy loss in an aluminum melting furnace. Only an estimated 10% of available heat is lost through the refractory wall during steady state operating conditions.

Aspects of the refractory lining in aluminum furnaces and the potential for energy savings will now be discussed, and in particular, how phosphate-bonded monolithic materials can contribute significantly to overall energy savings.

Steady State Conditions of the Refractory Lining

In consideration of energy savings, the ideal refractory furnace lining under steady state conditions should possess the following features:

- Lowest thermal conductivity possible in order to avoid heat loss.
- Single component lining in order to allow freeze plane changes caused by wear, infiltration and temperature changes of the furnace.
- Resistance against mechanical wear from cleaning tools and stirring in order to allow maximum output without equipment downtime due to maintenance.
- Resistance against thermo-chemical attack from aluminum and alloying elements.

One of the major problems in aluminum melting and holding furnaces is the corrosiveness of molten aluminum and its alloying elements. In addition, the refractory lining is exposed to low viscosity fluxes that penetrate the lining, and to mechanical wear from charging, cleaning and skimming. Often, these conditions do not allow the use of energy efficient insulating refractory materials as a hot face lining due to the lower chemical and mechanical resistance of high porosity light weight refractory products. Less energy efficient dense refractory materials must then be used.

The higher thermal conductivity of dense refractory materials, however, requires a multi layer furnace lining even though a single component lining is preferred to keep the aluminum freeze plane in the refractory hot face lining after the hot face has changed in operation. Changing of the refractory hot face lining during furnace operation commonly leads to the freeze plane moving into the insulating material, and that can lead to aluminum infiltrations deep into the porous insulating lining if the hot face layer shows cracking. Thus, it is essential to install hot face refractory materials that are resistant to interactions with the metal and atmosphere in order to maintain stable furnace conditions over a long period of time.

Figure 2 shows the thermal profile of a typical aluminum furnace side wall with a freeze plane (590°C to 660°C depending on alloy) inside a dense 88% alumina lining. An additional 75mm fireclay safety lining protects the insulating lining and steel shell from potential leakages. This type of lining can be considered “conservative” with regards to safety. The heat loss is 1100 W/ m^2 (350 BTU/sq.ft/h).

Figure 3 shows a lining that uses a microporous insulation board with only $0.03 W/m^2 °K$ thermal conductivity and a resulting 800 W/m^2 (254 BTU/sq.ft/h) heat loss. This would lead to more than 25% heat loss savings but the freeze plane of the aluminum can move into the microporous board leading to a higher risk of aluminum leakage.

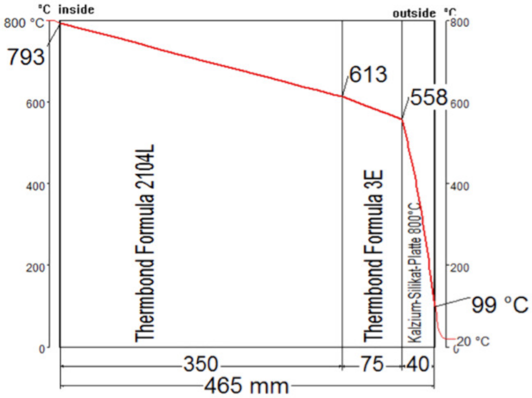

Figure 2. Thermal profile of a typical aluminum furnace side wall with a freeze plane

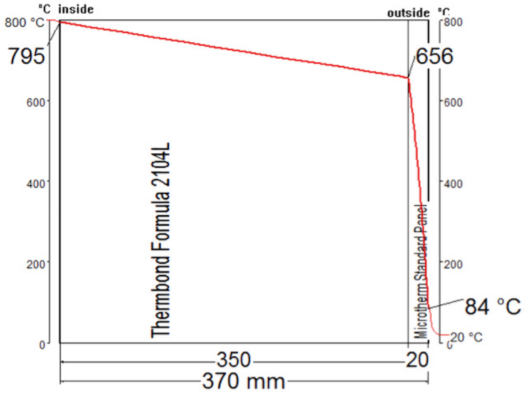

Figure 3. Thermal profile of a lining that uses a microporous insulation board.

This example shows the limits between potential energy savings and safety risks. Refractory linings below the metal line should allow freeze plane changes without risking aluminum leakage.

How to Reduce Corrosion and Wear

Because of the dynamics of refractory corrosion and wear, the temperature profile of a furnace lining can change within a short period of time depending on the operating conditions and furnace design. As a consequence, the refractory lining needs to be monitored because the initial calculated thermal profile of the lining under ideal conditions is only temporary. For instance, the thermal profile of the lining changes with the following factors:

- Corundum build-up on the lining.
- Flux salt infiltration of the lining.
- Aluminum infiltration in pores and cracks.
- Reduction of the wall thickness due to mechanical wear.

Corundum Build-Up

There are two types of corundum build up, internal and external corundum growth.

External corundum growth is a function of oxygen partial pressure in the furnace in the presence of aluminum and alloying elements like silicon and magnesium. The corundum build-up occurs at the metal line, or belly band, of the furnace at the interface of the atmosphere, aluminum bath, and the refractory lining. The capillary system inside the corundum build-up sucks up metal which oxidizes on the surface and promotes further growth. As a consequence the effective furnace volume shrinks, reducing the energy input to metal output ratio.

In contrast, internal corundum formation is the result of a reduction process of refractory components by aluminum metal and alloying elements. This reaction takes place in the pore system of the refractory material and leads to a decomposition of the matrix. With an increase in temperature the reduction process develops faster [3]**.** Typical chemical reactions are:

$$3\ SiO2\ \text{(refractory)} + 4\ Al\ \text{(metal bath)} = 2\ Al2O3\ \text{(corundum)} + 3\ Si \qquad (1)$$

$$3\ Mg\ \text{(alloying metal)} + 4\ Al_2O_3\ \text{(refractory)} = 3\ MgAl_2O_4\ \text{(spinel)} + 2\ Al \qquad (2)$$

In order to diminish molten metal reactions, low silica content in the refractory is favorable.

However, low cement castable technology typically relies on ultra fine silica fume in order to obtain desired flow characteristics for placement and high strengths in operation. Since any reaction with silica can only take place if the metal is wetting the refractory lining, one approach to prevent reaction is to employ non-wetting additives. In conventional cement bonded monolithic materials, additives like $BaSO_4$, CaF_2 or AlF_2 can temporarily prevent the refractory lining from penetration by aluminum metal and alloying agents. However, these additives possess limited temperature stability and tend to react with certain fluxes even at low temperatures thereby losing their effectiveness [3,4].

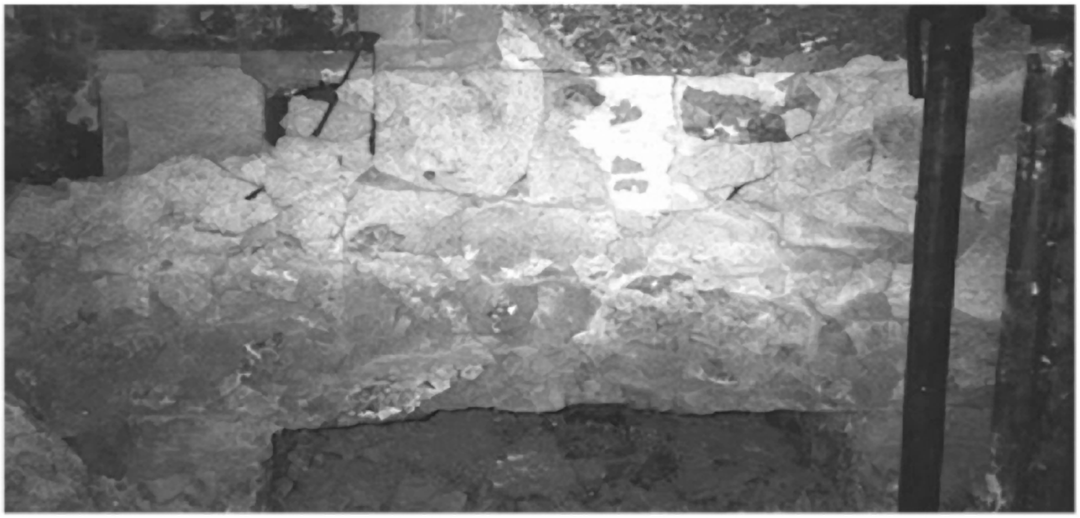

Figure 4. Corundum build-up on a hot wall of a side well furnace increases energy consumption.

It is evident that corundum build up is one of the major factors impacting energy consumption because it:

- Changes the thermal conductivity of the wall.
- Reduces the furnace capacity due to corundum growth in the hearth area.
- Reduces the lifetime of the refractory lining and leads to downtime costs.
- Requires intense cleaning of the lining with cleaning fluxes and mechanical tools which relates to wear on the hot face lining, heat loss in the furnace and production downtime.

Flux Salt Infiltrations of the Lining

Flux salts penetrate refractory linings whenever the temperature of the furnace wall is above the melting point of the flux. Evaluations of refractory samples taken from a furnace lining have shown that the wall was deeply penetrated with flux salts after one year in operation. The wall was originally installed with an 85% alumina refractory castable with 18% porosity. After 1 year the wall showed infiltrations of 3% sodium and 3% potassium. The flux used in this furnace contained 47.5% KCl, 47.5% NaCl and 5% fluoride salt with a melting point of 1130 F. The flux infiltration not only causes a higher thermal conductivity of the wall but also a reduction in hot strengths due to glass phase penetration. The mechanical abuse due to cleaning and skimming typically causes wear on the interface metal, flux cover, and atmosphere of the so called belly band. Besides the use of cover fluxes, it is also a common practice to apply exothermic cleaning fluxes which can lead to serious damages of the furnace wall. The purpose of using cleaning fluxes is to loosen and disperse corundum build up on the wall in order to maintain the furnace capacity. However, components of the refractory lining can also get attacked by aggressive fluoride salts such as $Na2SiF6$. This practice requires process downtime because cleaning flux is applied on the hot walls of a drained furnace. After coating the walls with 3-6mm of flux, the reaction will be facilitated with burners turned on high for at least 10-15 minutes [5].

Aluminum Infiltration in Pores and Cracks

Refractory linings are prone to cracking due to shrinkage and chemical attack. In brick linings the weak link is the brick joint. In monolithic linings the cold joints between cast panels can be the weak link. Aluminum infiltration, and consequently corundum formation, leads to pressure build up from crystallization in the pores and cracks and eventually spalling of the refractory material [6].

Transient Conditions of the Refractory Lining

Transient conditions occur during the initial dry out of a cast refractory lining and the heat up after a shut down or during door openings. The lining is often exposed to thermal shock during skimming, cleaning, fluxing and charging. This all leads to energy losses and as a consequence to stresses in the lining that can cause damage and eventually a reduction of the furnace refractory lifetime. To maximize energy savings, the ideal refractory furnace lining under transient conditions should possess the following features:

- Excellent thermal shock properties.
- Low heat capacity in order to reduce storage heat loss.

Thermal Shock Properties

Thermal shock resistance of refractory materials in aluminum furnaces is required in the door area of the furnace due to door openings during charging, skimming and cleaning. In particular sills, jambs, and lintels and the floor of aluminum furnaces are prone to thermal shock.

An ideal thermal shock resistant material should possess the following thermo-mechanical properties:

- Low thermal expansion.
- High thermal conductivity.
- High strengths under consideration of the stress/strain relationship. (A high σ/E ratio leads to good thermal shock properties) [7].

In order to avoid thermal shock, mullite containing alumina silica refractories or silicon carbide materials are the preferred materials in aluminum melting furnaces. However, the silica content of these choices is a source for potential chemical attack and corundum growth which can lead to limited furnace lifetime.

The energy absorption rate of a refractory lining during heat up to operating temperature after a shut-down is not dependant on the heat up time. However, a 140 hour heat up process leads to a production loss of 2.1 million lbs of aluminum (15,000 lbs/h production rate). It is evident that a faster heat up would lead to large production and energy savings particularly if other process units connected with the repaired furnace are on hold under temperature waiting for the furnace to be put into operation and production to commence.

How Can Phosphate-Bonded Refractory Materials Contribute to Energy Savings?

Based on the described factors which have an impact on refractory lifetime and the stability of the aluminum manufacturing process, it can be concluded that refractory materials which could eliminate or reduce the discussed problems could also contribute to energy savings.

Phosphate-bonded refractory castable materials have long been used in the aluminum industry because of favorable properties in contact with molten aluminum. Phosphate-bonded refractory materials support almost every installation method including casting, gunning, patching and ramming. The major characteristics of these materials are as follows:

Non-Wetting to Molten Aluminum and Aluminum Alloys

Due to the non wetting properties of liquid phosphate-bonded refractories, primary corundum build-up can be totally avoided**.** It also reduces the necessity and intensity of mechanical cleaning of the walls and the need for cleaning fluxes. The result is that phosphate-bonded materials do not show corundum build up and therefore eliminate related problems like production capacity losses and wall deterioration. Figure 5 shows the same furnace wall shown in Figure 4 after the reline with a liquid phosphate-bonded high alumina castable after one year. The wall stayed clean and the corundum build up problem was solved. Figure 6 shows a cup test conducted with an 85% alumina phosphate-bonded castable tested with 7075 alloy enriched with 5% Mg. The test temperature was 1800°F and the holding time 120 hours. The result shows that phosphate-bonded materials are resistant to high Mg-alloys which potentially cause spinel formation and consequently cracking of the refractory lining.

Figure 5. Same furnace wall shown in Figure 4 one year after reline with liquid phosphate-bonded refractory.

Figure 6. Castable refractory cup test shows phosphate-bonded materials are resistant to high Mg-alloys.

Moreover, light weight phosphate-bonded materials are also non-wetting, reducing the risk of deep penetration and leakage should the hot face lining be compromised.

Chemical Bond to Existing Refractory

Liquid phosphate-bonded materials allow veneer repairs that have monolithic properties. This reduces maintenance downtime and stops corundum build up on old conventional monolithic materials after the repair. The outcome is less refractory waste because up to 80% of existing linings can be maintained indefinitely rather than torn out and disposed of repeatedly. Due to the use of a two component phosphate-bonded material, phosphoric acid penetrates into the pores of the existing lining and forms, with the alkali and alumina in the existing refractory, a strong chemical bond with up to 2000 PSI tensile strengths.

Fast Firing Properties

During setting, liquid phosphate-bonded products develop a bonding system that contains meta- and polyphosphates. These are ring and chain structures with polymer like behavior that allow extremely fast heat up rates of the material because this flexible binder system compensates for occurring thermal stresses. Hence this property leads to faster maintenance turnaround with reduced downtime. Linear heat up rates of 200°F per hour or greater without holding time are possible. [8]. With the proper consideration of other variables, the same heat up rates for lower sidewalls, hearths, and ramps are also possible with liquid phosphate bonded products.

Extremely Thermal Shock Resistant

Due to the very flexible polymer-like bonding system, even high alumina materials can withstand direct flame impact without pre-drying. This means big block shapes can be installed without pre-dry-out. Burner throats can be rammed in place without heat up restrictions and furnace heat up can be conducted without costly external equipment and manpower.

High Strengths and Abrasion Resistance

Depending on the liquid content, phosphate-bonded materials show abrasion resistance of less than 3cc making them suitable for full thickness linings in high impact floor, sill and ramp applications. These materials contain little or no silica and are non-wetting against aluminum. It is also possible to install these high performance materials as a veneer over worn out refractory in impact areas.

Summary

The refractory lining of an aluminum furnace does more than determine the heat losses through the walls during steady state conditions and heat losses due to storage heat during transient conditions. To a greater extent, the refractory lining has an impact on energy losses from process interruptions due to interactions with the metal, mechanical wear, and equipment availability. Moreover regular downtime maintenance of a furnace can lead to additional energy losses in connected units like launders, degassing units, holding furnaces, and other heated equipment.

Liquid phosphate-bonded refractories can contribute to energy savings because production interruptions can be reduced due to cleaner furnace walls and a refractory lining that is easy to maintain.

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