Refractory Lining Configurations for Aluminum Process Vessels: The Keys to Long Thermal Effective Lifetime

Part 1 of 2

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Abstract

For primary aluminum producers the largest amount of energy used in the manufacturing process is consumed by the electrolytic process, 63%; an additional 23% is used in process heating. For the secondary aluminum producers 90+% of all energy used is for process heating.[1] This is energy consumed to re-melt metal or maintain metal at a desired process temperature. These energy requirements can be defined as the sum of energy absorbed by the metal and the amount of energy lost to the metal's surrounding environment. The design and performance of the refractory lining protecting aluminum process vessels has a very significant and direct impact on the energy lost to the surrounding environment. Therefore, it has very significant indirect impact on the amount of energy required to melt and hold metal at process temperature. The refractories' influence on overall process cost can exceed several hundred thousand dollars on an annual basis depending on the size of the processor. Yet, many processors and OEM's view refractory choice and lining design as nothing more than a default occurrence to purchasing a process vessel or hiring a contractor to do an installation or perform a repair. This paper describes some key concepts and performance considerations processors should thoughtfully consider with regards to refractory selection. It will also describe some consequences of failing to understand appropriate refractory specification in aluminum process vessel lining configurations.

Introduction/Background

Refractories are typically comprised of high melting, ceramic and/or oxide compositions which are utilized to protect the vessels used in high temperature manufacturing/processing from both chemical attack by the process stream and damage to structural components caused by excessive heat. Consequently, there is no 'standard' refractory composition that is uniformly appropriate for use in high temperature applications. Rather, appropriate refractory determination is based on the temperatures of the process stream, the physical and geometric constraints of the vessel structure, the chemical reactivity of the components of the process stream and the desired thermodynamic function of the refractory. In turn, these are dictated by the mineral and/or chemical composition of the refractory, its installation or placement method, its physical structure and properties, and the thermodynamic properties of the individual components as well as the final overall three-dimensional structure of the refractory.

A process vessel's refractory 'lining' may be comprised of a single refractory composition or more than likely a combination of several refractory compositions, layered in a 'configuration' which ideally provides the appropriate chemical, physical and thermodynamic characteristics necessary to allow the manufacturing process to occur in the most effective and efficient manner from both cost and operational perspectives. Therefore, the choice of individual refractory components, as well as the design of the overall refractory lining configuration, is critically important and directly impacts the competitiveness of a manufacturer or processor.

Secondary aluminum processing can be defined loosely as all the processing which occurs after aluminum metal leaves the primary electrolytic cells or pots for the first time. The secondary processes are divided into those that deal with the solid metal, such as machining, and those that deal with the liquid metal. Refractories are utilized in the latter of these two processes since creating and maintaining liquid aluminum metal requires heat. There is an interface in the processes between solid and liquid which requires an appropriate choice of refractory in order to accommodate the physical impact or abrasion that often accompanies introduction of solid materials into melting vessels.

From this point forward secondary aluminum processing will be referenced generally as aluminum processing. The described physical, chemical and thermodynamic properties, issues and consequences will be specific to secondary aluminum processing. We will consider the physical and chemical properties and interactions from the perspective of how these affect the thermodynamic performance of a refractory material and/or lining configuration over its lifetime.

Most common refractory materials are comprised of oxides which are primarily components of naturally occurring mineral products or refined, naturally occurring minerals. Common examples used in the aluminum industry are bauxite, mullite, andalusite, clay compositions, phosphates, aluminum oxide and silicon dioxide.[2] The non-refined materials also contain significant amounts of contaminant oxides such as titanium dioxide and iron oxide. It is perhaps not well known that a bag of refractory castable, a refractory brick or precast shape is actually a heterogeneous mixture of a variety of materials. For example, a bag of an 85% alumina castable may contain a percentage of pure alumina (Al_2O_3), bauxite, cement, silica (SiO_2), and perhaps some mullite, kyanite, or andalusite. Different suppliers will provide different blends of components in their products but they may all be referenced as an 85% alumina castable. Different amounts of these components can have a drastic effect on the performance of the refractory in service. The size of the different components will also affect the performance of the refractory since this plays a large role in defining the final porosity of the refractory structure being formed and/or chemical reactivity with the process stream. Many refractory producers attempt to utilize the highest amount of inexpensive materials possible in order to be competitive in the market place. More often than not, these inexpensive materials not only contain the desired mineral phase or oxide, such as Al_2O_3, but also amounts of accessory or contaminate oxides such as Fe_2O_3, MgO or TiO_2 which although present in rather small amounts relative to the desired Al_2O_3, in this example, are highly reactive with the process stream and/or drastically reduce melting points and hence service temperature. Assuming all refractories, which describe themselves by a particular alumina content for example, to be identical is a major mistake. Furthermore, much of the technical data found on standard refractory data sheets are irrelevant in determining the long term performance of a refractory as these describe the material entering into service, not what the material will be 6 months or more into a campaign.

With regards to thermal performance of a vessel, refractories impact how heat energy moves from the processing areas to the surrounding environment. Heat energy moves through space and matter by three methods. These are radiation, convection and conductivity. Thermal conductivity (Tc) is a thermodynamic parameter which is commonly used to indicate the relative ability of a solid material to allow heat energy to pass through it. It is a temperature dependent factor, meaning that it changes with temperature. It is somewhat analogous to the clarity or transparency of glass being a descriptor of the glass's ability to let visible light pass through it. It is uniformly used in the refractory industry to describe a product's relative insulating capability. Regardless of English or Metric units the lower the value of thermal conductivity the more thermally insulating the material tends to be. Although thermal conductivity can accurately describe the insulating character of a refractory material, it is a bit of a misnomer. Most ceramic materials have a thermal conductivity that is very similar relative to the range of all materials. Without getting into too much detail thermal conductivity is specific for heat transfer by conduction. It does not take into consideration heat transfer by convection or radiation. Refractory structures can be dense but they are typically not solid. The insulating capability of a refractory is more defined by what is not there rather than what is present. In other words, the porosity of the refractory can often determine its insulating capability to a much larger degree than the refractory material itself. Air gaps and pockets are great insulators as there is no conduction. As a refractory becomes denser and less porous, the 'thermal conductivity' becomes more dependent on actual conduction.

In addition to an air gap providing no thermal conduction it also does not provide for any strength. Hence, insulating materials tend to be weaker than non-insulating materials which are typically denser. A dense silicate such as Pyrex® Glass conducts heat very well and hence can be used as cooking ware. It is strong enough to stand on. Fiberglass bats are a silicate that has a significant amount of porosity; it is consequently less dense, very insulating but not very strong. Refractory strength characteristics are typically reported as an MOR (modulus of rupture) which is also known as flexural or bending strength. CCS (cold crushing strength) is the other commonly reported strength characteristic. MOR has both a compressive and tensile strength component while CCS is purely compressive. CCS is important in considering load bearing structures such as floors holding tons of molten aluminum and walls bearing superstructures. MOR is important in considering elements such as lintels, arches and other openings where failure due to the flexure or bending of the refractory is of concern. Shear stress occurs in a material when a force is applied parallel to its surface while an opposing force, such as friction, is being applied in a opposite face or plane. This would be the case when cleaning a wall with a scraping tool for example. This property is not measured or reported for refractory materials. The ability of a material to handle impact, such as dropping an ingot onto a refractory, is described by its impact strength. This property is also not commonly measured or reported. This characteristic is the ability of a material to withstand a suddenly applied load whereas properties such as MOR and CCS are determined by applying an ever increasing load slowly over a period of time. These can be proportional to impact strength but in and of themselves they do not indicate the ability of a material to withstand an impact, let alone a series of impacts over time. Using typical refractory strength data, which is relative to tensile or compressive forces, in order to specify refractory choice in wear areas resulting from impact, abrasion and shear stress is a misleading and often fruitless endeavor.

For many, properly designing an aluminum process vessel may require a paradigm shift regarding an understanding of what properties are important in a refractory and what are not. Refractory strength, of the type and magnitude being proposed by many refractory suppliers and installers, is not a priority for proper lining design. That does not mean that these are not important considerations in specific areas and for specific processes, only that these instances are exceptions, not the rule.

Discussion – Wear Mechanisms

When designing a refractory lining configuration to maximize energy efficiency it is important to consider the effect the manufacturing process will have on the lining configuration over an extended period of time. In order for a processor to gain a financial advantage from energy efficiency, the average energy efficiency over an extended period of time is the important evaluation criteria not the energy efficiency on the first day or even the first six months of operation. What is the value of a highly energy efficient furnace and combustion system if after six months the refractory lining fails? A failure in the refractories ability to properly insulate the furnace may not constitute a structural failure but it is a catastrophic event that negatively affects the processor's bottom line. Unfortunately, this may go un-noticed for long periods of time, wasting enormous amounts of energy. The effective energy efficient lining provides the appropriate amount of thermal insulation over many years of operation, not just the first 12 months, a typical warranty period. Understanding why and how refractories wear and fail is a critically important criterion in determining an appropriate lining configuration for a processors application. The next important criterion is to understand how refractory materials interact and work together to provide a proper overall lining configuration. This concept can be described as the Thermal Effective Lifetime (TEL) of the refractory lining configuration. The goal is to develop linings with very long TEL's.

There are two general mechanisms by which a refractory wears and fails. The first is due to physical interactions and the second is due to chemical interactions. Each mechanism can increase the rate or severity of the other. For example, an expansive chemical reaction can induce physical stresses in a refractory causing it to physically fail via a fracture event.

For aluminum processes vessels, the common physical failure mechanisms are impact, erosion/abrasion, shear, compression, and thermally induced stresses such as expansion and shock. Some of these will be mentioned but only as they relate to their effect on the TEL of a refractory lining composition. Note then that in order to properly design a configuration it is important to understand the physical limitations of various refractory materials in specific locations within process vessels.

Chemical interactions detrimental to the refractory also severely limit the TEL of refractory lining configurations. In the case of aluminum process vessels this is primarily the result of oxidation/reduction reactions which occur between aluminum metal in a molten state and the refractory materials in contact with the molten aluminum. The causes and results of this are explained elsewhere[3] but suffice it to say that unless the refractory in contact with the metal is inert to reaction with the aluminum, detrimental reactions resulting in corundum formation will occur on the surface of the refractory and inside the refractory matrix itself.

There is a group of refractory products that are inert to these reactions and therefore they will provide maximum TEL in lining configurations.[4] A distinction needs to be made between refractories that are 'resistant' to aluminum penetration and reaction and those that are 'inert'. All typical, non-inert refractories will react in time with the aluminum metal. Examples of this reaction can be seen in this cup test picture and pictures of vessels which have been in operation for extended time frames (Fig. 1, 2). In order to forestall these reactions refractory suppliers will add certain types of materials to refractory compositions which either close off porosity through which molten metal can penetrate and/or keep the metal from obtaining a high degree of direct contact with the refractory components. These are termed penetration "inhibitors" and "non-wetting additives", respectively. These additives work very well for a period of time and these refractories are termed 'aluminum or penetration resistant'. Unfortunately after a few months these additives thermally decompose at aluminum processing temperatures and typically by six months the detrimental reactions begin to convert the lining and processors will see the telltale signs of corundum formation. Refractories which contain silica, silicates, phosphates, oxides of iron, titanium and other accessory oxides common in bauxite ores are not inert. These will react in time.

Figure 1 *- Cross section of a penetrated and converted Cup Test wall.*

Figure 2 *- Massive corundum formation near door area of melter. This cannot be removed at this point without significantly damaging the remaining lining.*

There are two negative consequences of this reaction which directly affect the TEL of a refractory lining configuration. The first is metal penetration and conversion (Fig. 3). In this case, although the overall refractory lining thickness remains the same, a portion of the lining is now a new, converted material which has a thermal conductivity that is much higher than the unreacted refractory. This is primarily due to the fact that the density of the new material is very high and that a significant portion of the affected area is filled with unreacted aluminum metal which has a very high thermal conductivity relative to ceramics. Therefore, the thermal effectiveness (ability to insulate) of this refractory component is reduced significantly. This particular issue is very apparent in over the road crucibles or transfer ladles where maximizing the amount of aluminum being transferred is a priority. In these cases, refractory lining thickness is often sacrificed for aluminum metal volume. In order to retain insulating capability, the refractories utilized tend to be more porous, insulating materials. Consequently, the porosity allows for more efficient metal penetration and conversion. Lifetimes of these types of linings are often only a few months before a reline is required due to excessive heat loss or physical damage caused by attempting to remove the formed corundum.

This physical damage is the second consequence of conversion and corundum formation. Most processors are familiar with the bane of corundum formation. It is pervasive, strong and hard, and adversely affects the mechanical operation of equipment, equipment lifetime, production

***Figure 3** - Cross section showing unreacted refractory with a characteristic Tc. The reacted portion has a new higher Tc affecting about 25% of the total thickness. The net effect is a loss of thermal efficiency.*

throughput and metal quality (Fig. 4). It also negatively affects TEL. As was earlier referenced, using MOR or CCS values to describe the relative ability of a refractory material to survive the removal of formed corundum on and in the refractory or to describe its ability to handle an impact is very misleading. As a result of the conversion process, formed corundum is chemically and physically bonded to the refractory. The physical act of removing the corundum is not accurately described by MOR but by the shear modulus. MOR may be proportional to shear strength for some materials but it is not an indicator of a refractory materials ability to be separated from process formed corundum. Rather, the refractory MOR will better indicate how difficult it will be to clean the refractory lining. The greater the MOR the greater the difficulty since the formed corundum has strengths 3-5 times that compared to any known refractory.[5] The cleaning effort is what is required to break the weaker non-reacted portion of refractory, not the stronger converted refractory or formed corundum. Thus, the act of cleaning removes a portion of the initial refractory lining (Fig. 5). Successive cleanings result in the original lining becoming thinner and thinner. As are result, TEL is reduced since a thinner refractory lining is less efficient as an insulator. Figure 6 depicts the thermal consequences of penetration, conversion and removal of the refractory material over time. As important, the physical stresses of cleaning the converted refractory and corundum exert physical forces and stresses which often succeed in cracking the remaining lining. This subsequently allows liquid metal to reach the backup linings which are more reactive with aluminum due to the combination of their chemical makeup and porosity. Reaction and conversion in these areas of a lining configuration result in the often seen heaving of hearths and collapsing of sidewalls due to the expansive nature of the conversion process and corundum formation in the backup materials. At this point a lining can be considered completely failed.

***Figure 4** - Small holding furnace with significant penetration, conversion and corundum buildup.*

***Figure 5** - Section of a used refractory removed from a dosing furnace. The refractory has been damaged and eroded from the cleaning process. The backside is also shown to demonstrate penetration and reaction through cracks and fissures. The freeze plane was in the backup which was penetrated and converted.*

Discussion – Maximizing TEL

In order to maximize Thermal Effective Lifetime (TEL) an aluminum processor must specify inert refractory compositions where refractory is in contact with molten aluminum. Other refractories will react and significantly reduce TEL. TEL in these cases can only be extended by routinely removing the reacted refractory and formed corundum and replacing it with unreacted new material. The cost of this process far outweighs the initial cost of inert refractory.[6] Therefore, when developing a refractory

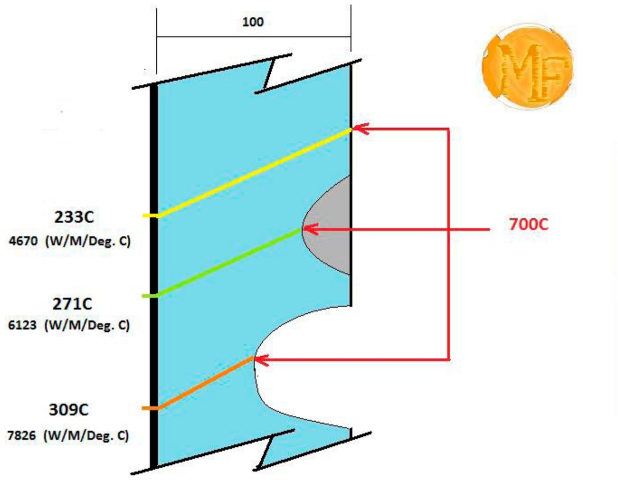

Figure 6 *– Sketch showing the impact on heat loss of conversion and loss in 100mm of an 85% alumina castable lining exposed to a hot face temperature of 700°C.*

lining configuration for an aluminum process vessel there are two distinct areas of consideration. Those areas in contact with molten aluminum metal and/or splash and those areas that are not in contact with molten aluminum metal and/or splash. Specification criteria in these areas are consequently different.

It was briefly mentioned that allowing aluminum metal to penetrate to the backup lining materials is very detrimental. Since these materials tend to be the highly insulating portions of a refractory lining configuration they are much more porous. The size of the porosity of these materials easily allows molten metal to move throughout their physical structure. This increases surface area and hence the rate and amount of reaction that occurs. Since these are expansive reactions, the process results in the often seen heaving and bowing in floors and walls (Fig. 7). It is very important to design a lining configuration that eliminates or greatly reduces the chances of this from occurring. Therefore, where a refractory lining is in contact with molten metal, in addition to inert refractory, it is always recommended to design a configuration which provides for the freeze plane of the metal to be located within the working or hot face lining of the configuration. Those who consider proper freeze plane placement as unimportant are not concerned with the long term performance of the vessel lining.

A refractory lining configuration is typically made of two or more types of refractories working in conjunction with each other. The hot/working face or lining is that refractory which is in direct contact with the process side of the configuration. The cold face/end is that part of the refractory furthest away from the process side and is often in contact with a shell or other supporting structure. If a cross section of the refractory configuration was made from the hot face to the cold end and a temperature profile was overlaid on this cutaway; one could observe a temperature decreasing from the hot face to the cold end. The rate of temperature decrease would change in different layers and that rate would be a function of that materials thermal conductivity. Somewhere in that temperature profile would be the temperature at which aluminum metal will change from a liquid to a solid or 'freeze'. The two dimensional plane where this occurs in the lining is called the 'freeze plane' (Fig. 8). Designing a lining configuration to make sure this plane occurs in the hot face refractory layer greatly reduces the chances that liquid aluminum will reach the insulating backup layers since the liquid metal will freeze or solidify before that happens. Of course if the opening is very large in size the freeze plane location will not matter. However, in most cases the initial penetration occurs through small cracks and fissures which often are the result of the physical stresses of removing reacted refractory and formed corundum. In this case the use of inert refractory components and proper placement of the freeze plane greatly reduce the chances of a hot face breach and therefore dramatically increase TEL. In figure 5, penetration through cracks can be seen on the backside of the removed refractory. These reached the backup due to improper freeze plane location. This leads to hot spots on a vessel shell (Fig. 9) or more catastrophic situations such as metal penetration into the hearth (Fig. 10).

Figure 7 *– Penetration and Conversion of a large portion of the upper and lower sidewalls of a melting furnace. The lower sidewall is heaved out significantly.*

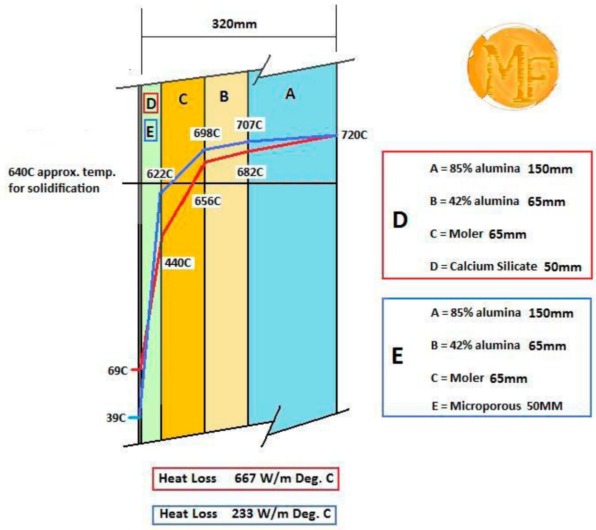

Figure 8 *– Sketch depicting freeze plane location of two different linings. Note how the location, in the Y-Z plane, changes as a result of changing the material in level D/E. Ideally the freeze plane would be located in level A or the working lining.*

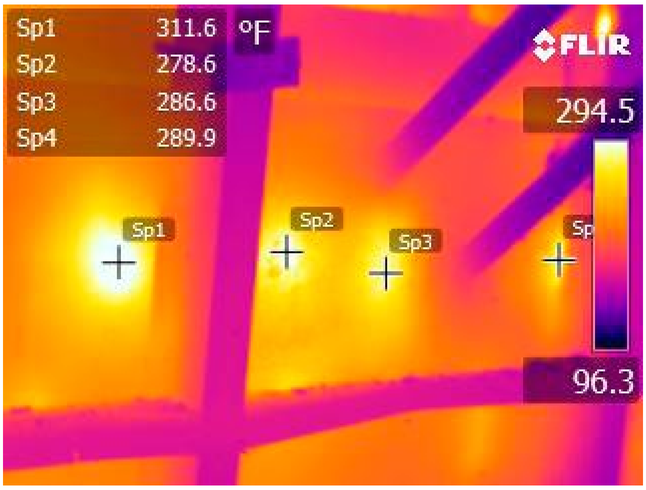

***Figure 9** – Hot spots shown in a FLIR image taken of a melter. The penetrated metal or 'fins' act as heat sinks moving heat out of the vessel and into the environment.*

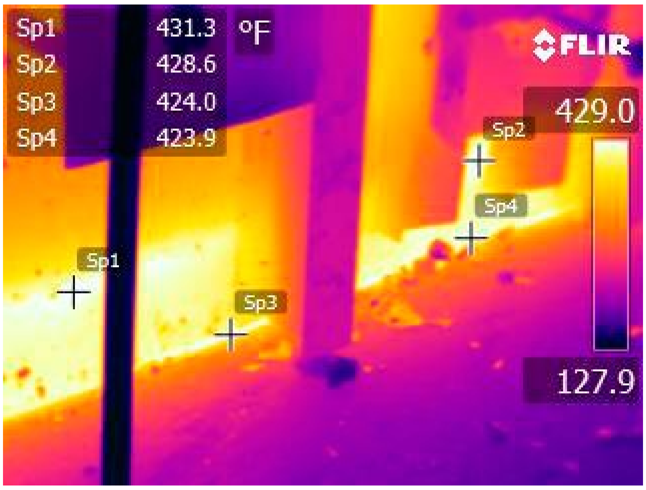

***Figure 10** – Metal present in the hearth of this furnace is resulting in significant heat loss through the shell and likely into the floor. It is likely a significant amount of the original refractory is converted and thus a tear out and rebuild will be mechanically difficult and expensive.*

In all but a very few exceptions, lining configurations utilizing typical non-inert refractories as the working lining do not have freeze planes that are located in the hot face refractory layer, see figure 8. Rather they are located improperly in the insulating backup layers or if these are insufficient in thickness, against the shell. This is a direct result of the thermal conductivity of typical non-inert refractory compositions. For these compositions to work as long as possible in service, it is necessary for them to have limited porosity and hence a relatively high density. This results in compositions which have relatively high thermal conductivities (table 1, available online; note that chemically and mineralogically the 45% brick and the IFB are nearly identical. The difference in Tc is a result of the porosity in the IFB. Some examples of other materials are given as a comparison.). This means the compositions are very adept at allowing heat energy to transfer from one side to the other. Consequently, the temperature drop from the hot face to the cold side is relatively small within a reasonable thickness. Figure 11 (available online) shows a thermal profile of a typical configuration which uses dense 70% alumina low cement castable as the hot face. It is backed up by a standard 1038°C (1900°F) insulating board product. Let's assume the optimum process lining configuration is 381mm (15 in) total thickness and the desired shell temperature is in the 60°C (140°F) range. In order to hit these target parameters the lining configuration is 254mm (10 in) of 70% alumina castable and 127mm (5 in) of board. For this exercise the freeze plane is defined to occur at a temperature of 582°C (1080°F) for a common 300 series alloy. In this configuration that occurs 272mm (10.7 in) from the hot face. Since the dense castable is only 254mm thick, it occurs in the backup lining. There are two means of getting the freeze plane in the working lining of this configuration. Figure 12 (available online) shows the option of increasing the hot face lining thickness. In order to achieve a freeze plane position just inside the hot face lining, the lining must be 635mm (25 in) thick. This has the effect of lowering the shell temperature from 60°C (140°F) to 56°C (132°F) but it is unreasonably thick. The other option is to let more heat escape and this is shown in Figure 13 (available online). In this case the backup lining thickness is reduced to 64mm (2.5 in) thick and the hot face increased to 318mm (12.5 in) thick. The result is a freeze plane position of 302mm (11.9 in) and a shell temperature of 78°C (174°F) which is much higher than the desired target temperature. The freeze plane is also very close to the interface.

Another major benefit of utilizing inert refractory compositions is that a significant amount of controlled porosity can be introduced into their structure. If the pore size is controlled appropriately; insulating and semi-insulating compositions can be created. Because some of these compositions have porosities >45%(v/v) they have less strength than their dense cousins. However, because they will not allow aluminum penetration, reaction or corundum formation, the strength requirement to survive a cleaning process is negated. Corundum which is formed on the surface of the metal and builds up on refractory surfaces can easily be removed by hand with very little effort and no resulting damage to the refractory. The consequence of this is that we can now have an insulating material in metal contact as a hot face refractory without concerns of conversion and reaction. This allows us to achieve the proper freeze plane placement in a lining configuration without sacrificing vessel volume or shell temperature. Figure 14 (available online) shows a lining configuration utilizing the inert semi-insulating refractory. In this case the freeze plane is located 251mm (9.9 in) into a 279mm (11 in) hot face lining. There is 102mm (4 in) of insulating board resulting in a shell temperature of 61°C (142°F). Figure 14 shows a comparison if the higher shell temperature of 78°C (174°F) from figure 13 was acceptable. In this case the total lining configuration would be 330mm thick (13 in) with a hot face thickness of 279mm (11 in) and a backup of only 51mm (2 in) board. This gave a shell temperature of 77°C (170°F) and a freeze plane location 162mm (6.4 in) inside the 279mm (11 in) backup. This configuration could provide the processor with a significant amount of increased production volume depending on the size of the vessel.

It should be pointed out that there are certain areas where proper placement of the freeze plane in the working lining is difficult or impossible to achieve. This first situation is when the available lining thickness is too small. This usually occurs within the range of less than 76mm (3 in) but it also depends on the metal temperature and melting point of the alloy. The second situation is when there is a need to use dense strong materials to deal with impacts and/or abrasion. Impacts are typically the result of flowing streams dropping from a distance, as would be the case of a ladle pouring metal into a holder from a height of a meter (39 in) or so. They are also the result of dropping or dumping solid metal into a vessel, as would be the case in the lower stack of stack melters and scrap wells in large melters. These could occur around lintels and jambs where solid ingot or sows are loaded. In dry hearth applications a significant portion of the lower sections of the hearth and lower side walls see impact during the loading process. Abrasion can be seen in solid loading processes that cause the scrap, ingot or sow to be pushed along the surface of a refractory. It also occurs where liquid metal is moving at relatively high velocities such as degassing stations containing stirrers and liquid metal pump inlets and outlets. In these areas, stronger, and hence dense refractory materials are required. Consequently, obtaining proper freeze plane placement can be a challenge. In cases where a multiple lining concept is achievable, a dense/strong inert hot face is backed up by an insulating inert refractory and then non-inert backup insulation. The freeze plane in these cases is located in the insulating, inert backup while the hot face provides the necessary strength and/or impact resistance. Pre-cast 'Big Blocks' used in dry hearth vessels are an example of a design using this approach.

Many installers, OEM's and refractory suppliers will sell the concept of thermal or energy efficiency based on the sole parameter of shell temperature. This is very misleading. Processors need to understand that the described shell temperature is usually only representative of the vessel in its first few weeks or months of service – before the lining begins to convert and react. Second, it is very easy to design lining configuration offering incredibly low shell temperatures. One simply needs to increase the amount of insulating backup or the insulating capability of the backups. There are some incredibly good insulating materials, such as micro-porous boards, that can dramatically decrease shell temperatures with a very thin cross-section. Processors must understand that 'over-insulating' a process vessel below the liquid metal line is a recipe for disaster. Doing so pushes the freeze plane well into the reactive insulating material and invites penetration and expansive reactions which can not only destroy the lining but the steel shell and support structures of the vessel (Fig. 15). It must be recognized that in order to obtain the longest TEL it is sometimes necessary to provide for a shell temperature that is higher than what is achievable so that the lining configuration remains intact and functional for the longest possible period of time.

The ideal design criterion for those areas in contact with molten aluminum metal and/or splash is to provide a design which puts the freeze plane in an inert hot face lining or an inert backup lining. If this is not possible, the use of an inert hot face lining provides a significant amount of long term protection so as to maximize the TEL of the configuration.

Figure 15 *- Torn steel shell caused by the expansive reactions between backup materials and penetrated aluminum metal. The force exerted by crystal growth/expansion is very significant.*

For those areas that are not in contact with molten aluminum metal and/or splash, the lining configuration can contain as much insulation as desired since there is no need to consider the freeze plane position. In these areas it is often desired to increase the insulating character of the hot face refractory and the amount of back up insulation. The limit to which this can occur is once again controlled by the wear mechanisms affecting the lining configuration in these areas. Therefore, maximizing TEL is predicated on determining a long lasting insulating configuration.

Above metal line the common physical wear mechanisms are impact and abrasion. The common chemical wear mechanisms are reactions which occur between the head space gases/combustion gasses (if present) and the refractory. There are also temperature induced reactions that are most commonly seen in refractory lightweight castables. Also included in this discussion will be the impact of chemical reactions resulting from the use of fluxes. Technically these react both above and below the liquid metal line. In all these cases TEL is reduced by loss of lining, chemical changes that result in loss of lining and/or chemical changes that compositionally change the lining causing an increase in thermal conductivity. If fluxing is done to clean corundum which is bonded to the refractory walls, the use of inert refractory linings will eliminate this need as well as the need to coat surfaces with non-wetting compounds such as boron nitride (BN). This can provide a significant economic advantage in its own right.

Physical stress induced wear of refractory above the metal line is usually the result of design specifications not taking into account process actions that occur as a result of operator – vessel interactions and not process stream interactions. These include events such as using the lip of a launder or furnace as a lever fulcrum point to perform a task, for example using the edge of a launder to rest a pry bar upon while moving or attempting to remove an object. Other actions may include opening and closing doors, lids and gates while having other items sandwiched between the moving parts. In these cases stresses are concentrated at these points and can cause the refractory to mechanically fail. Since it is most often desirable to have insulating and hence porous materials above the metal line in order to maximize thermal efficiency, these refractories tend to be relatively weak. If such occurrences are a possibility it is beneficial to cap troughs, launders, holders, etc. with 75mm (3 in) of denser, stronger refractory to avoid premature wear. In these cases the loss of thermal efficiency is offset by the loss that would occur in time due to loss of lining thickness and/or a good seal condition between vessel components.

In vessels that utilize combustion heating systems the gases above the metal can move at great speeds. Gases that impact the refractory in predictable patterns, such as walls opposite burners, can undergo abrasion by the gas molecules as well as particulates present in the head space area. Attention must be paid to the temperature limits of refractory materials in these locations, such as burner impact zones. These areas will often experience higher temperatures relative to the 'average' temperature a thermocouple may be indicating for a vessel, which in turn may be controlling burner output. Approaching or exceeding the refractories maximum operating temperature will cause the abrasion/erosion rate to increase significantly. In these areas it is advisable to utilize denser, abrasion resistant materials qualified for the appropriate temperature. The other option is to utilize a burner layout which reduces high speed, impacting flow patterns.

In some cases combustion systems utilize fuel sources that have a significant amount of impurities. These can be fuel oils, waste oils, and some types of gases.[7,8] These impurities are defined as 'ash content' and are not combustible. They typically contain compounds comprised of S, V, Na, K, Ca, Mg, Si and Al. In sufficient quantities these can affect the performance of refractory materials as well as metal quality. It is also worthwhile to note that although electrical resistant heaters do not affect head space gases; when they are energized for the first time in the presence of oxygen, many types undergo chemical changes that cause the heating elements to shed oxide components which can negatively affect refractory performance. The initial energizing of these elements should always occur in an oxygen containing environment away from the process vessel.

Thermally induced chemical changes are primarily seen with lightweight refractory materials; in particular, castable systems. Many lightweight castable systems utilized a significant amount of clay based materials as aggregates for the composite. When the castable is mixed with water to form or cast it into place many of the clay materials will hydrate. This hydration causes the clay to swell. In service the material is exposed to constant heat which causes the clays to dehydrate based on a time/temperature relationship. The result is that over time the clays shrink with dehydration. This results in the formation of cracks and gaps similar to what one sees in a dry lake bed. The formation of these reduce the TEL since it effectively reduces the average lining thickness and causes a densification of the remaining refractory mass thereby increasing its thermal conductivity.

The final type of chemical interaction to be discussed is a result of fluxing. Fluxing is used to clean metal that is in its liquid state. Scrap or recycled metals are typically the target of this process. They contain oils that also have ash content and hence impurities, paints which contain many types of transition element compounds and just plain dirt which is primarily comprised of silica and alumina. The flux works by reacting with these impurities forming compounds that are less dense than the metallic aluminum. As a result they float to the top of the bath and can be mechanically removed by skimming or filtration. It is important for processors to have a good understanding of the types and amounts of impurities present in their feedstock. In this way they can specify the appropriate type of flux and the appropriate amount of flux required to clean the metal. Therein lies the rub; processors will often add too much flux based on the logic that it is better to add too much than too little. Unfortunately the flux cannot make a determination as to what constitutes a contaminant and what does not if they are chemically similar, such as refractory. Unreacted flux will react and remove many refractory compositions in the same manner it works with actual impurities. Over-fluxing therefore increases the wear rate of refractory material in contact with the flux. This is typically seen in belly band areas where deep 'dishing' can occur over time. The result on TEL is twofold; first is a reduction due to loss of lining thickness and second is a reduction due to densification of the refractory due to specific types of chemical reactions between the flux and refractory. In order to maximize TEL, processors need specify refractory materials resistant to this type of chemical reaction and they need to minimize the amount of fluxing performed. It is appropriate to use more flux than necessary to react with impurities. But, this should be just slightly more. Of course reducing fluxing also will reduce process costs so the benefit is twofold as well.

Fluxing also can create a negative chemical effect above the metal line. At certain temperatures flux components and/or flux reaction products can volatilize. This means the change from a solid or liquid form into a gas form. In the gas form these materials will come in contact with the refractory materials above the metal line. The components of the gas phase are commonly compounds comprised of one or more of Na, K, S, and F. Because they are in a gaseous state they can easily penetrate refractory porosity. Once they reach a temperature which will allow them to return to a solid state (like the freeze plane of aluminum) they will crystallize out. This process can be expansive and will potentially fracture the refractory structure. Other reactions with the refractory will form very low melting phases which cause the refractory to densify and lose structure. The latter example is common when the refractories contain a significant amount of SiO_2. Fiber modules are particularly susceptible to this wear mechanism due to their high SiO_2 content and low densities. TEL is negatively affected due to loss of lining and/or densification/increase in thermal conductivity.

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About the Author

Ken McGowan is a founder and the President of Westmoreland Advanced Materials®, Inc. (WAM®). His background and experience encompass Chemistry in which he holds a doctorate, Material Science and Ceramic Science. He holds several patents on inert refractory compositions, refractory compositions for unique processing conditions as well as ceramic based tissue scaffolds for bone growth and regeneration. In addition to the aluminum industry, he and WAM® provide consulting services and products to many industrial technology sectors.

Article References and additional figures available online at ***www.diecasting.org/dce.***