Dryout of Refractory Castables

Jeffrey E. Bogan, ANH Refractories Company, West Mifflin, Pennsylvania, USA

517. ~~6~~ - 1545. JCC 4/11/03.

Introduction

The proper installation of refractory castables includes mixing, placing, curing and drying. Improper amounts of water used when mixing or poor densification during placement can lead to higher porosity, lower density and reduced strengths. Improper curing can result in the formation of undesirable hydrate phases of the cement. Each of these can contribute to inferior performance of the final castable lining.

The dryout process is usually the last step before a refractory castable lining is put in service. The dryout should not be compromised because, just as with the other installation parameters, problems will result if proper care is not taken to remove the water from the castable lining.

The recommended practices of the refractory castable supplier must be followed for each of the mixing, placing, curing and drying steps in order achieve the optimum lining. This paper will examine in more detail the factors related to dryout of or water removal from refractory castables. Water additions, cement hydrate phases, cement levels, curing conditions, permeability and dryout schedules will be considered.

Water Additions and Cement Hydrate Phases

Water is added to refractory castables to achieve the desired fluidity and to hydrate the cement. The water will fill gaps within a refractory castable and act as the vehicle to enable the material to move and flow so it can be installed properly. The water will also react with the cement to cause the cement to form interlocking crystals which bond the materials together.

There are two types of water remaining in the refractory castable after the castable has been installed and hardened:

1) Physical water
2) Chemical water

The physical water is the water remaining in the material that did not react with the cement but enabled the castable to flow. It is also referred to as the free water because it is in the pores of the castable not bound in any hydrate phases.

The chemical water is the chemically combined water tied up in the different cement hydrate phases and alumina or calcia hydrate phases.

According to Gitzen and Hart, approximately three quarters of the casting water remaining after hydration is free water in the pores. The remaining one quarter is primarily the chemically combined water.[1] However, with more recent castable technology developments of ultra-low cement refractory castables, the amount of chemically combined water can be closer to 10% of the total water added. The purity and amount of cement will all have a factor on the amount of free or chemically bound water in the refractory castable.

The free water and chemically combined water must be removed before the refractory castable can be used in high temperature applications. The water must be removed slowly because as it is heated it will expand and potentially yield internal pressures which could exceed the strength of the refractory castable and cause the lining to blow up or explosively spall. When water turns to steam there is a volume expansion of approximately 1600 times. This increase in volume is what causes the high pressures inside the lining. Therefore, the removal of the water must be done in a controlled manner so as to minimize the steam pressures that will be produced and dissipate the build up of the steam pressure.

When water reacts with calcium aluminate cement many different types of hydrates can be formed. The type of hydrates formed during curing will be determined predominantly by the curing temperature. A more detailed discussion on the affect of the curing conditions will be done later.

Hipps and Brown have identified several critical dehydration points based on the steam volume (water vapor) coming off from the free water in the pores and from the calcium aluminate cements in the early stages of heating[2]. These hydrates are associated with relatively high volumes of steam being released that can relate to high internal pressures within the lining. The major dehydration points they identified are:

212°F (100°C) – removal of free water in pores
440°F (227°C) – dehydration of $7C_3AH_6 \rightarrow C_{12}A_7 + 9CH + 33H$
530°F (277°C) – dehydration of $C_3AH_6 \rightarrow C_3AH_{1.5} + 4.5H$
1020°F (549°C) – dehydration of $7C_3AH_{1.5} \rightarrow 9C + C_{12}A_7 + 10.5H$

4 major
8 minor

where C = CaO; A = Al_2O_3; H = H_2O.

These dehydration points are shown in Figure 1 below as a function of the water vapor (steam volume). These hydrates will lose water over a temperature range and not at one specific temperature.

Hipps and Brown concluded that dryout schedules should be written to include holds just above these major dehydration points to allow steam pressure to dissipate. They suggest hold temperatures of 302°F (150°C), 572°F (300°C) and 1049°F (565°C)[2] during the dryout.

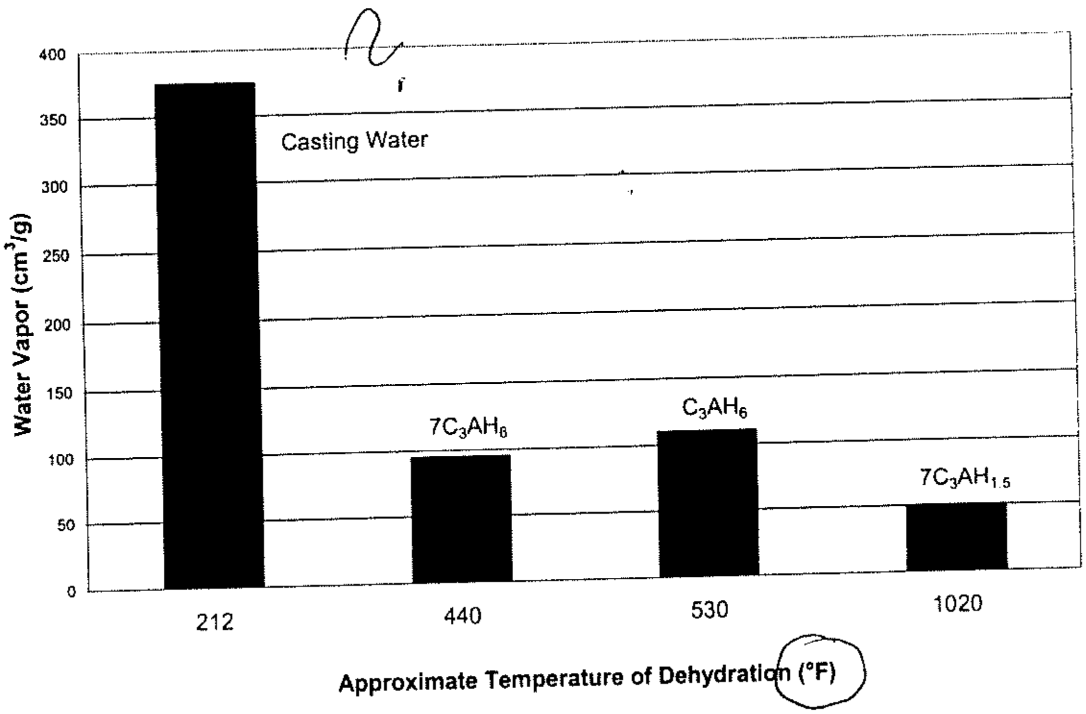

Figure 1: Major Dehydration Points of Water[2]

Less significant dehydration points, in terms of steam volumes, observed by Hipps and Brown were alumina and calcia hydrates. The dehydration temperatures and reactions of these phases are:

300°F (149°C) – dehydration of AH_3 (gibbsite) → AH + 2H
570°F (299°C) – dehydration of AH (boehmite) → A + H
750°F (399°C) – dehydration of CH → C+ H

where C = CaO; A = Al_2O_3; H = H_2O. These phases will dehydrate over a temperature range as well.

Although the alumina hydrate phases have lower volumes of steam released compared to the phases in Figure 1; these hydrates can reduce the permeability and contribute to explosive spalling during dryout. The combination of the C_3AH_6 and AH phases dehydrating in similar temperature ranges may contribute to the tendency for explosive spalling at hot face temperatures around 600°F (316°C). However, the 600°F (316°C) is air temperature, so these phases would be dehydrating relatively close to the surface and not 3-4 inches into the lining – a common spall depth. Therefore, the explosive spalling that occurs around 600°F (316°C) is probably more related to vapor pressures from the free water in the lining than from the dehydration of these phases.

water (steam) expansion is 1600 fold

Cement Level

The cement level of refractory castables can vary significantly depending on the product and its intended use. ASTM C 401-91 has classified alumina and alumina-silica castable refractories based on lime (CaO) content as shown Table 1.

Table 1: ASTM C 401-91 Refractory Castable Classification based on Lime Content

Castable Classification	Total CaO Level*	Approximate Cement Level
Conventional (Regular)	> 2.5%	15 – 30%
Low-Cement	1.0 – 2.5%	4 – 8%
Ultra-Low Cement	0.2 – 1.0%	< 4%
Cement-Free	< 0.2%	No Cement

* Calcined basis

The cement level is important in regards to the dryout of refractory castables because it affects the rate of moisture loss, strength and permeability of the installed product.

The rate of moisture loss was measured on four different commercial castables with different calcium aluminate cement levels. The four castables are described in Table 2.

Table 2: Commercial Refractory Castables used in Moisture Loss Study

Castable Type	Cement Level (%)	Water to Cast (%)
Ultra-Low Cement (ULCC)	2.0	5.5
Low Cement (LCC)	4.0	5.6
Conventional (CC)	15.0	11.5
High Cement (HCC)	30.0	9.2

Two 9x4½x5-in samples were formed for each of these mixes. The samples were cured 20-24 hours before the molds were stripped. Then each sample was weighed and immediately placed in a dryer and dried according to the schedule in Table 3. The samples were removed from the dryer and weighed at various points throughout the schedule to measure the moisture loss. After the 800°F (427°C) hold the samples were put in a furnace and heated to 1000°F (538°C) and held for 5 hours. After cooling enough to handle, the samples were weighed for the last time.

Table 3: Dryout Schedule for Moisture Loss Study

	Ramp Rate (°F/hour)	Hold Time (hours)	Total Time (hours)	Weigh Samples
Start @ 70°F			0	After curing
Ramp to 150°F	50		1	
Hold @ 150°F		8	9	After hold
Ramp to 200°F	50		10	
Hold @ 200°F		8	18	After hold
Ramp to 250°F	50		19	
Hold @ 250°F		8	27	After hold
Ramp to 300°F	50		28	
Hold @ 300°F		21	49	After 6 and 14 hours into hold and at end of hold
Ramp to 800°F	30		~66	After 8.5 hours into ramp and at end of ramp
Hold @ 800°F		10	76	After hold
Heat to 1000°F		5	--	After hold

Figure 2 shows the moisture loss as a function of the temperature for these four different castables. More moisture is removed during the lower temperature stages (steeper slope of the lines) than in the higher temperature regions. The reason more water is removed during the lower temperature range is because the casting (free) water is removed in this range. As noted earlier, approximately 75% of the casting water remains in the pores as the free water and is not bound up in the hydrates. The maximum amount of free water will come off at or near the boiling point of water – 212°F (100°C). This indicates that controlling the dryout at the lower temperatures is very critical because this is where the bulk of the water is removed.

The relationship between the rate at which the moisture was removed and the cement level was evaluated for these commercial castables at three different segments of the dryout schedule in Table 3. Figure 3 shows the moisture loss rate as a function of the cement level between room temperature and 250°F (121°C). In this temperature range, the moisture loss rate tended to decrease with increasing cement level.

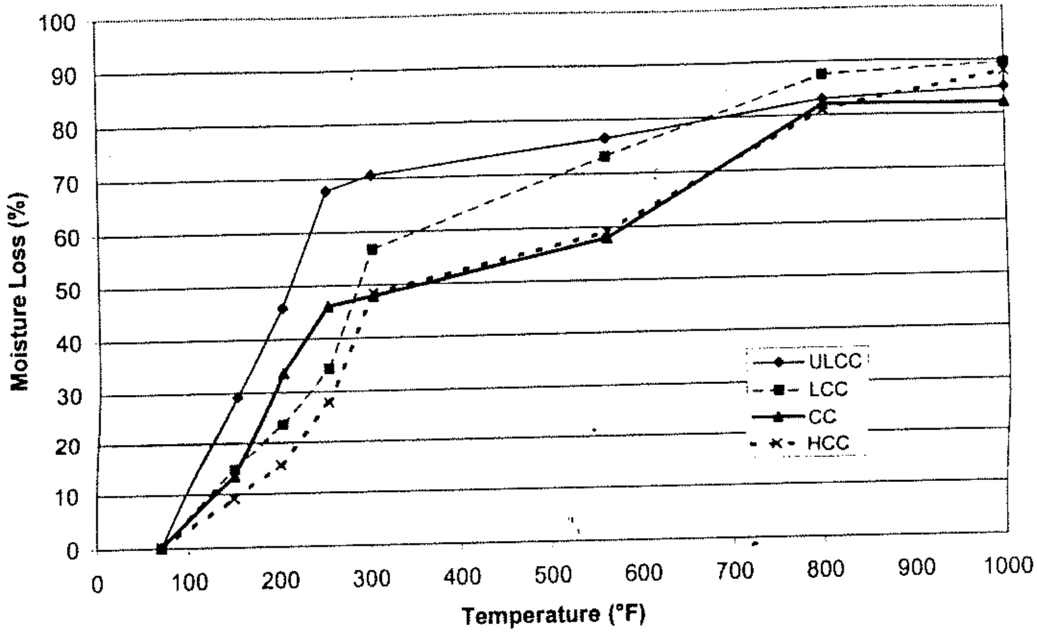

Figure 2: Moisture Loss of Different Refractory Castables as a Function of Temperature

The reason for this is because there was more water in the higher cement containing mixes that was still tied up in the hydrate phases. The correlation between the moisture loss rate and the cement content is low because there are other fine additives (such as fume silica) in the lower cement products that affect the moisture loss rate. These fine additives are a factor because they can contribute to the bond phase of low-cement castables. The fine additives will also decrease the permeability of the castable.

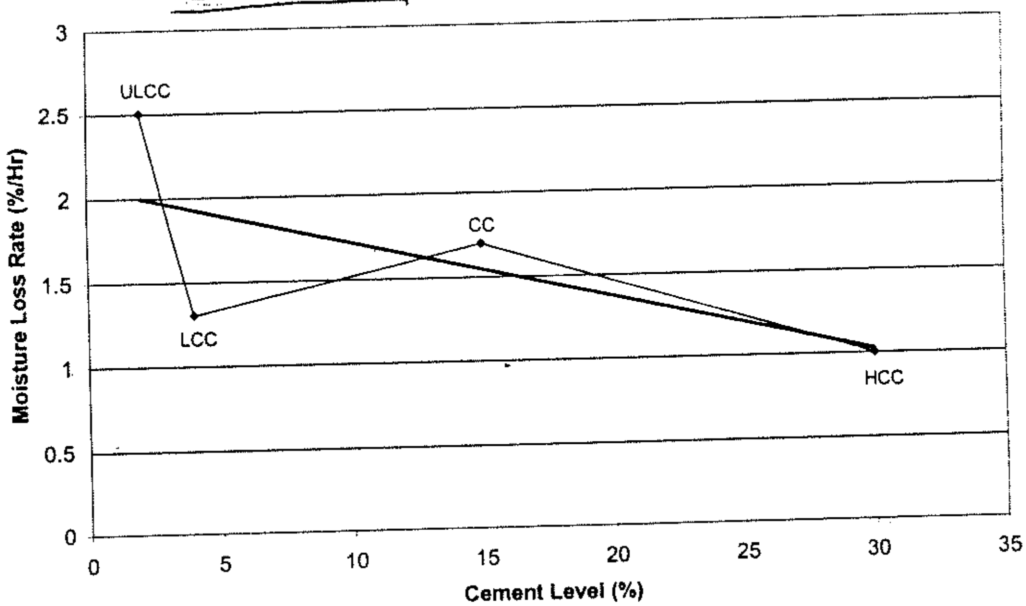

Figure 3: Moisture Loss Rate as a Function of Cement Level between Room Temperature and 250°F

Figure 4 shows the moisture loss rate as a function of the cement content during the 300°F (149°C) hold. There is no correlation between these two variables because of the different mix compositions. However, the low-cement and high cement castables lost about 20% of their total moisture during this hold. This shows that the cement level is not the ruling factor in when and how water is removed, but it is dependent on other characteristics of the refractory castable.

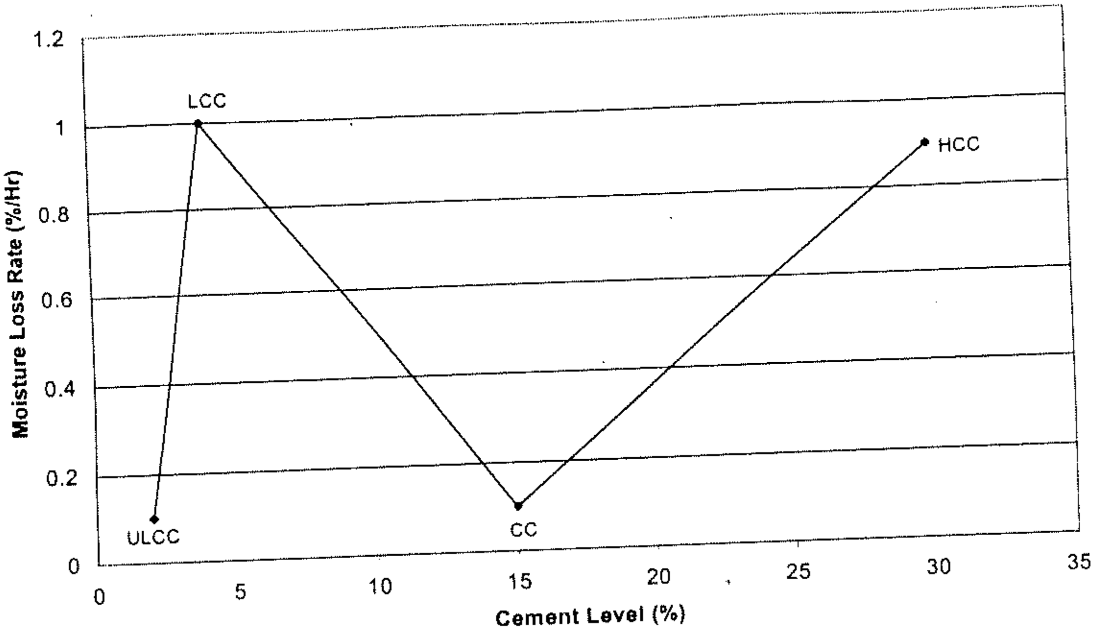

Figure 4: Moisture Loss Rate as a Function of Cement Level during 300°F Hold

Figure 5 shows the moisture loss rate as a function of the cement level when drying between 300°F (149°C) and 800°F (427°C). The trend line shown on the curve suggests that increasing the cement content yields a higher moisture loss rate in this portion of the dryout curve. A logical conclusion would be that the higher

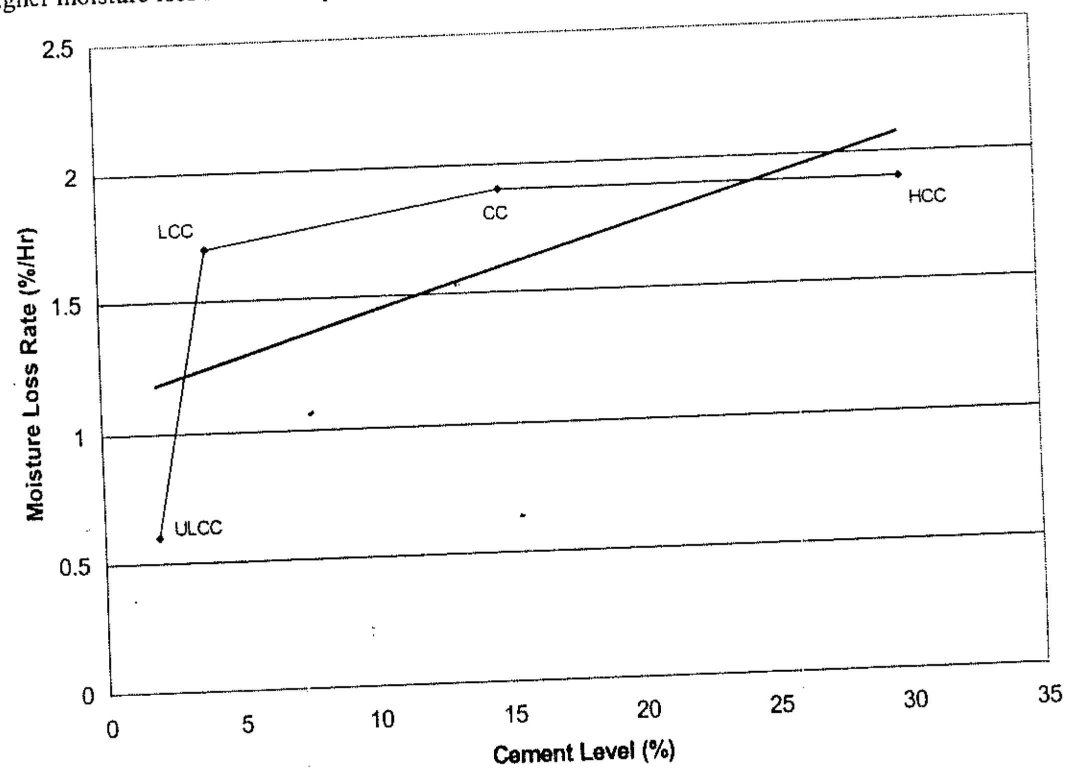

Figure 5: Moisture Loss Rate as a Function of Cement Level between 300°F and 800°F

cement mixes have more water still bound up in the cement hydrates that must be removed at the higher temperatures. However, the loss rates for the low-cement castable (4% cement) and high cement castable

(30% cement) were very similar. This shows that low-cement castables are not "automatically" easier to dryout just because they contain less cement. The fine additives made to ultra-low and low-cement refractory castables can have a dramatic affect of holding on to the moisture or preventing its escape. Anytime the moisture is inhibited from being removed, internal steam pressures can build and potentially result in explosive spalling.

Curing Conditions

The curing conditions of the installed refractory castable will have an influence on the type of cement hydrates formed. Curing at temperatures below 70°F (21°C) will yield CAH_{10} as the primary cement hydrate phase. This phase is a gel-structure that is relatively weak and has lower permeability. In addition, this phase requires more water to form and thus leaves less free water in the castable to help create pore channels that can aid in the moisture removal. Conversely, the CAH_{10} phase will have more chemical water in it to remove during the dryout.

An additional problem that occurs with the CAH_{10} phase is that when it is heated there is a volume shrinkage of approximately 50%[3]. The shrinkage results in some loss in the strength because the cement bonds "pull away" from each other and from the other particles within the castable. The higher the cement content in a castable the greater the affect this shrinkage will have on the final strength of the lining. The reduced strength in combination with the reduced permeability and higher amount of chemically combined water can make the installed castable lining more susceptible to explosive spalling because it may not be able to resist the internal pressures caused by steam generation while drying.

Curing above 70°F (21°C) should be done as much as possible to minimize the negative affects of the CAH_{10} hydrate. The hydrates formed above 70°F (21°C) will yield higher strength and permeability. These two properties will help make the refractory castable more conducive to a successful dryout.

Gitzen and Hart[1] have investigated the affects of the curing temperature on the different properties of a tabular alumina castable with 15% cement. Figures 6-8 show the relationship between curing temperature and transverse strength, permeability and explosion temperature, respectively. The strength and permeability testing were done on samples dried for 24 hours at 220°F (104°C). The explosion testing was measured by placing cured (not dried) 2½-inch cubes directly into a pre-heated furnace at various test temperatures. If the cubes did not blow up within 20 minutes, the material passed the explosion test at the specific test temperature.

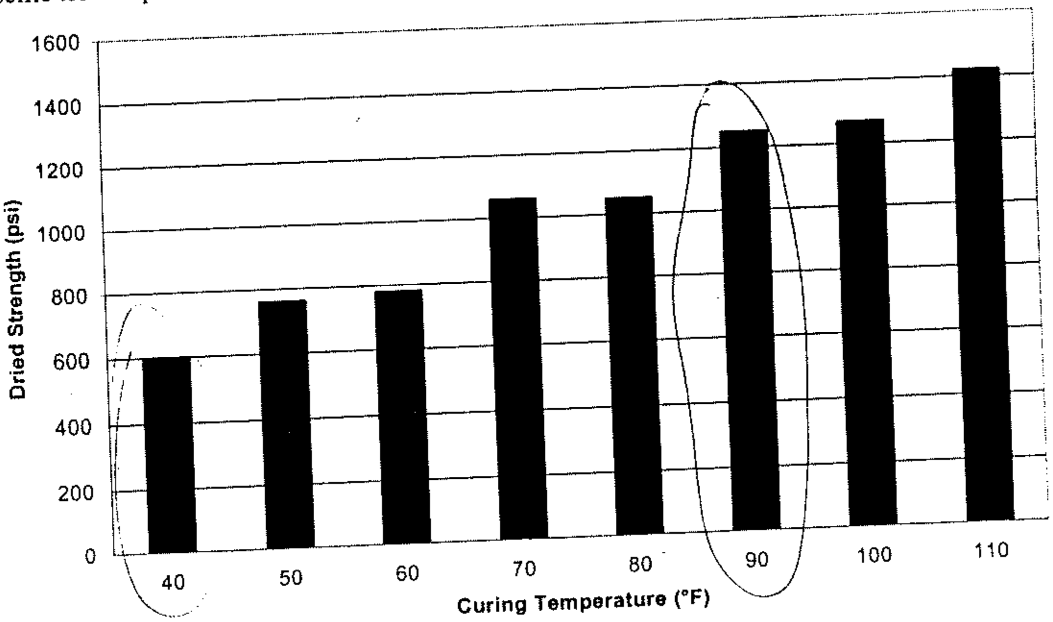

Figure 6: Dried Strength as a function of Curing Temperature[1]

Figure 6 shows the relationship between the strength and curing temperature. The chart demonstrates that the dried strength increased as the curing temperature is increased. The dried strength can be doubled if the material is cured at 90°F (32°C) compared to 40°F (4°C). As previously pointed out, the strength of the castable is important to be able to withstand the stresses from the pressure of the water being removed. Curing at 90°F (32°C) would provide more insurance of a safe dryout compared to curing at 40°F (4°C).

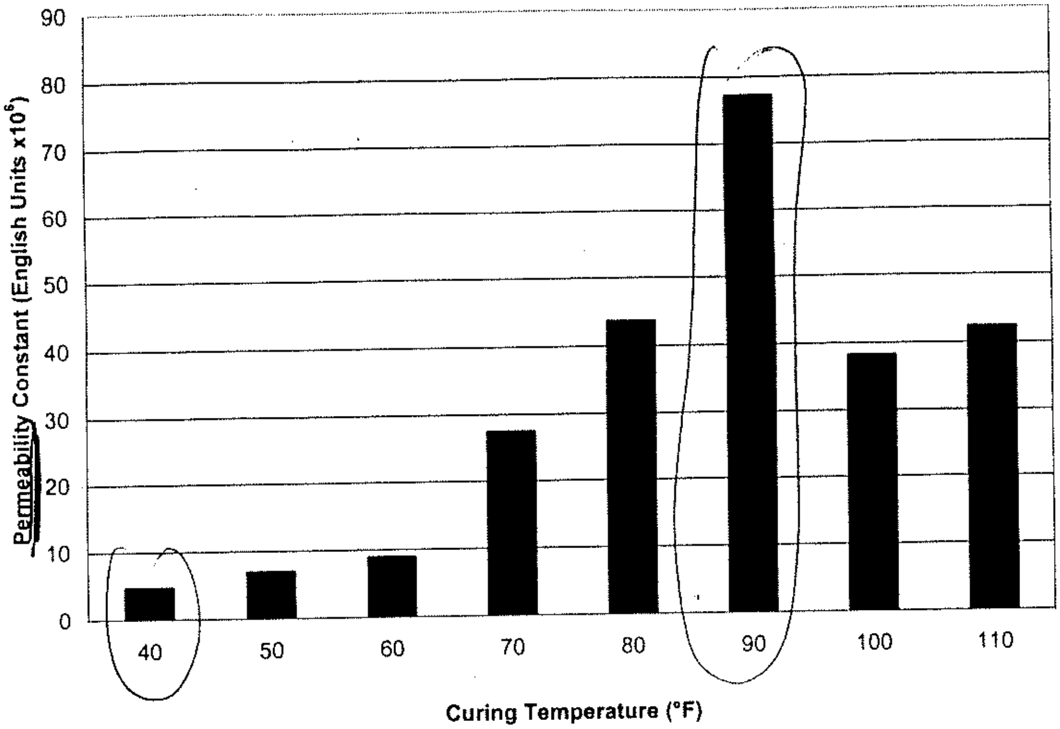

Figure 7: Permeability as a function of Curing Temperature[1]

The affect of permeability on the curing temperature is shown in Figure 7. Generally, the permeability increased with increasing curing temperature. There was a pronounced peak for the material cured at 90°F (32°C). This spike could be attributed to different phase structures or the degree of crystallinity of the hydrated cement.[1] Since the permeability of the refractory castable is important in enabling steam to escape, curing at higher temperatures is beneficial because the potential for explosive spalling would be reduced.

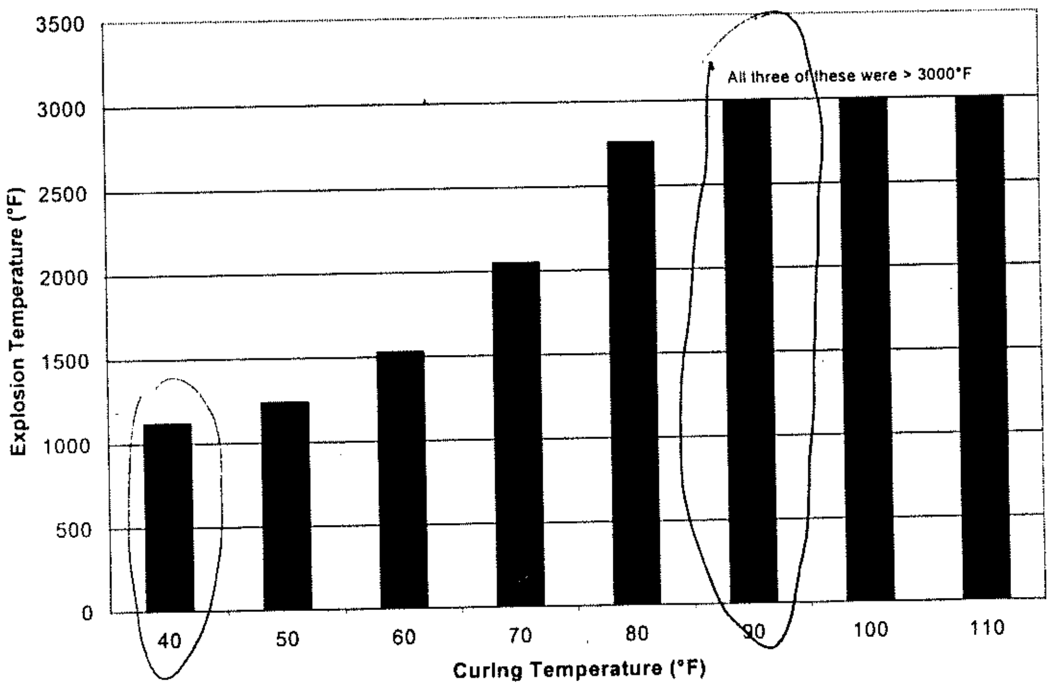

Figure 8: Explosion Temperature as a function of Curing Temperature[1]

The relationship of the explosion temperature and the curing temperature is exhibited in Figure 8. As the curing temperature was raised, the temperature at which the cubes blew up in the furnace increased. The increase in the explosion resistance is related to 1) the higher strength to resist the internal steam pressure and 2) the increased permeability to allow the steam to more quickly escape so the pressure is minimized.

Ultra-low and low-cement castables minimize the impact of the affect of the cement hydrates types formed at various curing temperatures because of the lower levels of cement used in these types of castables.

Permeability and Dryout Aids

The permeability of refractories, as defined by ASTM C 71, is the capacity of a refractory material to transmit fluids (liquids or gases). Permeability is an important characteristic relative to the dryout process because it relates to how quickly and easily the moisture is removed which can minimize the pressure build up within the installed castable.

There are many ways of increasing the permeability of refractory castables. Two specific ways include the use of organic fibers and powdered metals. Studies done with each type of dryout aid will be reviewed below.

Organic Fibers

Investigations of how permeability was affected by the cement content, fiber content and installation consistency were done. The permeability was measured on three 2-inch cubes for each prescribed temperature in each test performed. The samples were tested within 4 hours after being removed from the dryer to minimize any affect of moisture pickup.

Figure 9 demonstrates the affect of cement level on permeability in three commercial refractory castables. A conventional castable (CC) with 25% cement, a low-cement castable (LCC) with 5% cement and an ultra-low cement castable (ULCC) with 3% cement were tested. The low-cement and ultra-low cement castables contained relatively high percentages of –325M material compared to the conventional castable. Each product contained the same level of organic fibers.

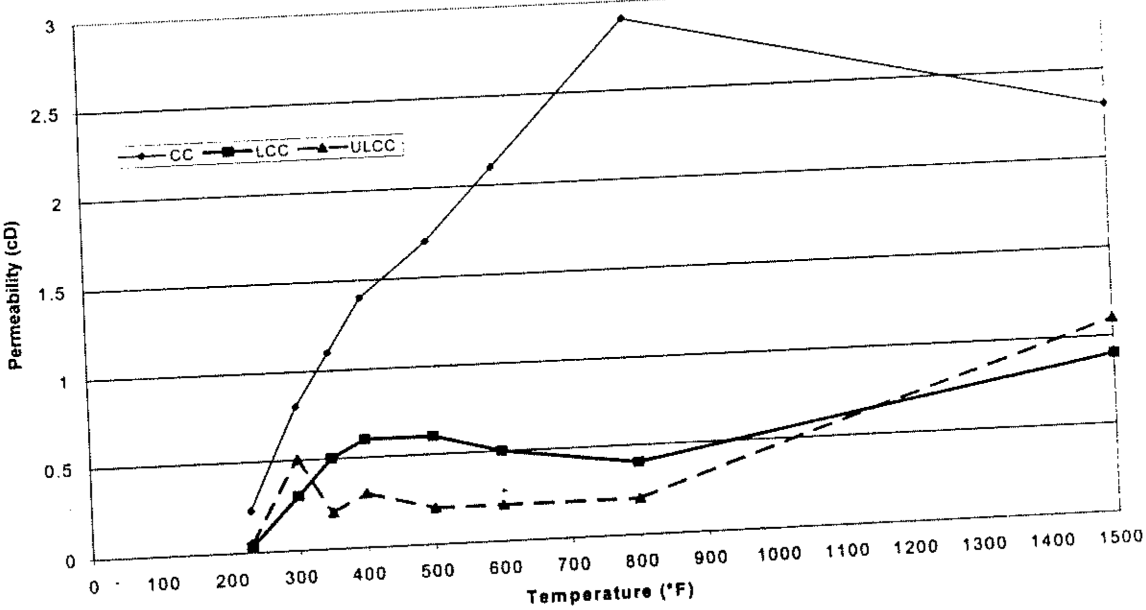

Figure 9: Permeability as a Function of Temperature for Different Classifications of Refractory Castables

The conventional castable in Figure 9 increased the most in permeability with increasing temperature and had by far the highest overall permeability. The increase in permeability with temperature is most likely related to the dehydration of the higher amounts of calcium aluminate phases. The low-cement and ultra-low cement castables increased in permeability initially, but then reached a plateau until firing. The high level of fine materials in the matrix kept the permeability relatively low. This shows that cement content is not the only factor in determining permeability of refractory castables.

The effect of installation consistency (pump cast and vibration cast) on permeability was evaluated using two commercially available refractory castables. The consistency or fluidity was changed by the addition of water. Castable A is a low-cement castable with organic fibers. Castable B is a low-cement castable containing no organic fibers for this study. These results are graphed in Figure 10. The pump cast consistencies had higher permeabilities because of the increased water. Castable B had essentially zero permeability up 800°F (426°C) at the vibration casting consistency. The reason for the very large increase in permeability of Castable B at the pump cast consistency was probably because an additional 2.25% water was added – a 50% increase in water compared to the vibration cast consistency.

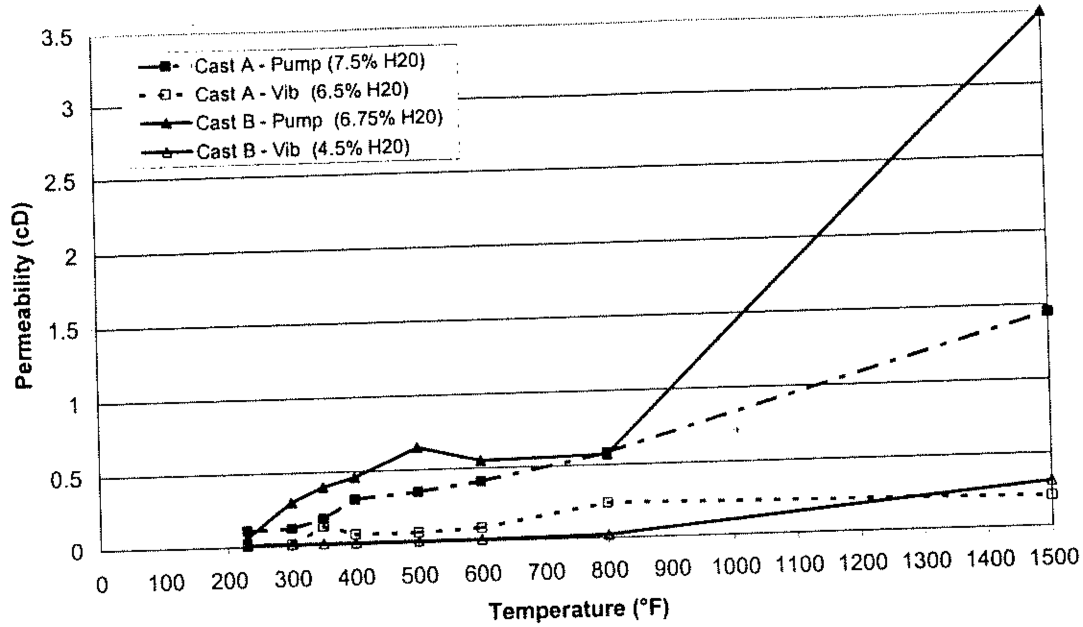

Figure 10: Comparison of Different Castables and Installation Consistency verses Permeability at Different Temperatures

Figure 11 shows the affects of organic fiber level and installation consistency on permeability. A commercial refractory castable different than the two mixes in Figure 10 was used in this part of the study. The addition of organic fibers had the biggest impact on increasing the permeability. The mixes with no organic fibers added had essentially zero permeability up to 800°F (426°C).

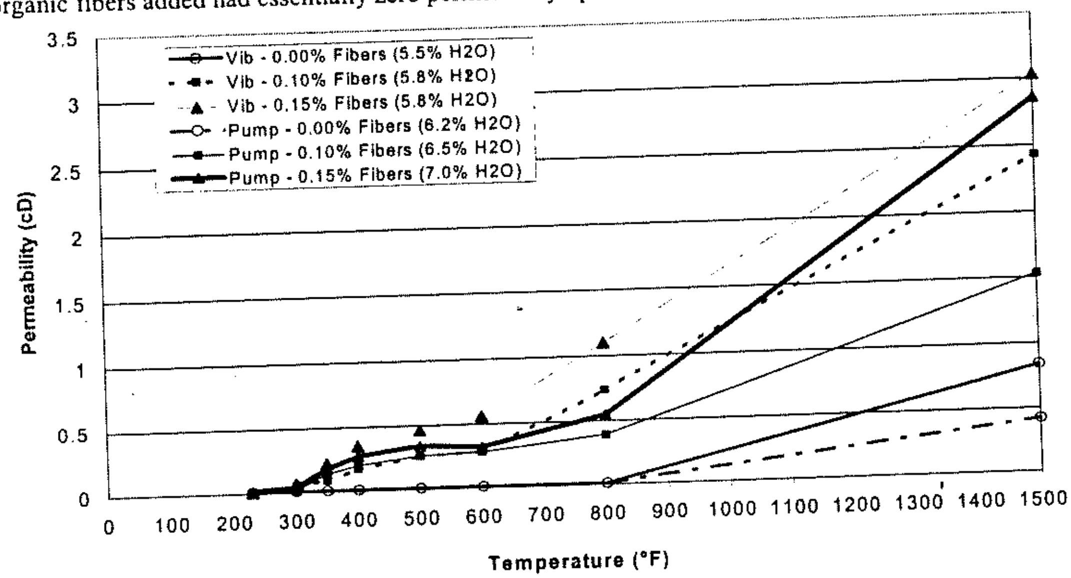

Figure 11: Affect Organic Fiber Content and Installation Consistency on Permeability at Different Temperatures

The relationship of increased permeability with increased water added was not observed with the product in Figure 11. The reason for this difference in behavior compared to the results in Figure 10 is unknown. It cannot be attributed to any specific characteristics of the mixes. A possible explanation may that the different samples were vibrated differently during the forming process. Other work has indicated that more intense vibration will reduce the permeability of a castable with little affect on the density or apparent porosity.

Powdered Metals

The metal powder in the refractory castable will react and give off hydrogen gas. The escaping gas creates channels within the castable matrix to allow moisture to escape as the material is being heated. These channels have proven to be very effective in enabling water vapor to escape. The dangers associated with the evolution of hydrogen gas often preclude the use of powdered metals. Also, the escaping gas can bring about some laminations and give unacceptable surface appearances. These imperfections are typically more of a problem from a cosmetic standpoint than a service perspective.

An explosion study was done comparing organic fibers and powdered metals in an alumina-silica-silicon carbide-carbon blast furnace trough castable. Samples were cast and cured at 75°F (24°C). Two 4½ x 2½ x 2½-inch cured (not dried) samples were put in a hot furnace at increasing temperatures until the samples exploded. The samples were considered to have passed the explosion test if they did not blow up after being in the furnace for 15 minutes.

Table 4: Explosion Testing of Blast Furnace Trough Castable

	Mix 1	Mix 2	Mix 3	Mix 4
Metal Powder (%)	5x	2.5x	x	None
Organic Fiber (%)	None	None	None	0.15
Water to Cast (%)	4.2	4.2	4.1	4.2
230°F (110°C) App Porosity (%)	9.7	10.1	11.2	11.7
Furnace Temperature				
1000°F (538°C)	Passed	Passed	Passed	Passed
1250°F (677°C)	Passed	Passed	Passed	Passed
1500°F (816°C)	Passed	Passed	Passed	Blew up
1750°F (954°C)	Passed	Passed	Passed	-
1970°F (1077°C)	Passed	Top blew off	Blew up	-

The results of the explosion study are shown in Table 4. The mixes containing the metal powder had a significantly higher explosion resistance than the mix with organic fibers. The higher the metal powder level, the better the explosion resistance as seen by the results at 1970°F (1077°C). The samples that did blow up, fully or partially, did so within 1 to 2.5 minutes after being placed in the furnace. Only one of the samples of Mix 2 had spalling damage, the top portion of the sample blew off. The samples from Mixes 3 and 4 that blew up were completely destroyed – no large pieces left.

Field experience confirms that powdered metals can be a much more effective means of promoting moisture removal compared to organic fibers. A blast furnace trough lining in Italy was installed two times with trough castable containing organic fibers and each time the lining explosively spalled during heat up. A switch was made to a castable containing powdered metal and the lining did not blow up.

The affect and benefit of dryout aids are clearly demonstrated above. It is recommended that a dryout aid, such as organic fibers or powdered metal, always be used when installing a refractory castable lining. The only time dryout aids could possibly be eliminated is during the manufacture of pre-cast shapes because the size of the shape maybe relatively small and the dryout very controlled. However, drying pre-cast shapes presents other problems which will be discussed later.

Summary of Different Factors Affecting Dryout

Table 5 shows the general summary of the factors affecting the dryout of refractory castables that can lead to explosive spalling. A plus sign in the column means that typically a higher value is beneficial in minimizing the potential for explosive spalling during dryout. A minus sign indicates the opposite.

Table 5: Summary of Factors Affecting Dryout

Factor	Low	High
Water Content	-	+
Cement Level	+	-
Strength	-	+
Fine Additives	+	-
Curing Temperature	-	+
Permeability	-	+
Dryout Aids	-	+

These are not fixed rules because of varying conditions and interactions that can take place. For instance, an ultra-low cement castable could be more difficult to dryout because of the fine additives in the matrix sealing the structures compared to a high cement castable. Adding additional water may open the structure up more because of the additional free water in pores, but the strength of the installed lining would be negatively affected.

Types of Dryouts

There are essentially two approaches to drying refractory castables:
1) One-sided dryout
2) Two-sided dryout

One-Sided Dryout

A one-sided dryout can be defined as heating the lining from one direction with the intent of removing moisture from the castable. The water will be driven from the hot face to the cold face of the refractory lining. There will be some loss going to the hot face in the early stages of drying, but as the process continues all of the remaining moisture will be removed from the cold face because of the high temperature on the hot face.

The one-sided dryout is commonly used in the field to dry castable linings such as ladles, reheat furnaces, blast furnace troughs, tundishes, cement kilns pre-heaters, aluminum furnaces, incinerators, etc.

The dryout schedule recommended is based on experience. The length and ramp rates of the schedule will depend on the material type, lining thickness, number of components in the lining, tons of material installed and restrictions of the unit being dried out. If the lining thickness varies within a unit to be dried out, the thickest section should be used to establish the schedule. The schedule is always based on the material or section of the unit that is most susceptible to explosively spalling.

A typical dryout schedule will include both ramps and holds. A typical ramp rate for drying refractory castables is 50°F/hour (28°C/hour) if holds are used. In some cases a ramp rates of 75-100°F/hour (42-56°C/hour) may be used because of the type of castable (i.e. insulating), level of dryout aid used or later in the dryout schedule most of the water has been removed so the rate can be safely increased. If no holds are used, the ramp rate must be decreased to allow time for steam pressure to dissipate. Ramp rates of 15-25°F/hour (8-14°C/hour) should be used if no holds are included in the schedule. For thicker the linings, slower ramp rates are recommended.

Approximate temperature ranges where holds may be placed are 250-300°F (121-149°C), 600-700°F (316-371°C) and 1000-1200°F (538-649°C). A fourth hold can also be added in the 400-500°F (204-260°C) section of the dryout schedule. Typical hold times are 1 hour per inch of thickness of refractory castable being dried out. In the case of composite linings (dense hot face castable and backup insulating castable) the thickness of both materials must be taken into consideration when proposing a dryout schedule.

There are mixed opinions about the need for holds in a one-sided dryout. Temperature holds are beneficial because they allow for steam pressure to dissipate within a lining before increasing the temperature more and continuously generating steam pressure. Slow ramp rates can allow the water vapor to escape as it is formed so high pressures are not produced or at least minimized. When in doubt, it is better to be conservative and use a slower ramp rate.

A good rule of thumb is to target a cold face temperature of 230°F (110°C) on the cold face of the lining whenever possible. A temperature of 230°F (110°F) indicates that all of the free water has been removed from the lining because the shell temperature cannot go above 212°F (100°C) while free water is still in the lining. There are times when it is impractical to monitor the cold face temperature because of the lack of accessibility to the shell, time constraints or it may not even reach 230°F (110°C) until the vessel is in service. In these situations, there must be enough confidence in the dryout schedule that it will sufficiently dry the lining to a point that vessel can be put safely into service.

If at any point during the dryout high-pressure steam is observed, the temperature should be held or reduced. The schedule can be resumed after the high-pressure steaming stops. The high-pressure steam is an indication that the pressure within the lining is high and, therefore, the chance for explosive spalling is increased.

If the lining has to be cooled, it must be cooled in a controlled manner. Cooling the lining too quickly can result in thermal shock damage to the lining. The recommended cooling rate is 100°F/hour (56°C/hour).

Two-Sided Dryout

A two-sided dryout can be defined as heating the material from more than one direction (5 or 6 sides) with the intent of removing moisture. These types of schedules are used to dry pre-cast shapes.

While drying the shapes, the water will be driven from the hot face to the center of the piece. However, unlike a one-sided dryout, all of the moisture loss must be removed through the hot face. Therefore, the dryout schedules used must be much more conservative than one-sided dryout schedules.

The dryout schedule recommended will again be based on experience. The length and ramp rates of the schedule will depend primarily on the material type and size of the shape.

The two-sided dryout schedule will include both ramps and holds. A typical ramp rate for drying cast shapes is 25°F/hour (14°C). Hold temperatures may be every 50-100°F (28-56°C). The times of the hold must be sufficient to allow the heat to penetrate the cast shape and allow moisture to escape without building excess steam pressure.

The maximum dryout temperature will depend on the capabilities of the dryer being used, requirement of the customer and whether the cast shape contains metal inserts (not metal fibers). However, a dryout to at least 600°F (316°C) will cover 3 of the 4 major dehydration points discussed above.

Cast shapes must be cooled in a controlled manner from the maximum temperature to about 300°F (149°C) to prevent thermal shock damage. The recommended cooling rate is 100°F/hour (56°C/hour).

Conclusion

The dryout of refractory castables is one step in the installation process of a refractory lining. There are many variables that can affect the dryout. The type of refractory castable being installed, the curing conditions and the use of dryout aids are important because they will affect the strength and permeability of the final product. The permeability and strength are related to the ability of the castable to release the water vapor formed during dryout and to resist the pressures created by the steam. The dryout schedule selected is usually based on experience and will take into consideration the material type and lining configuration. A successful dryout does not happen by chance, it is planned.

References

1. W.H. Gitzen and L.D. Hart, "Explosive Spalling of Refractory Castables Bonded with Calcium Aluminate Cement", *American Ceramic Society Bulletin*, Vol. 40, No. 8, pp503-510 (1961).

2. D.L. Hipps and J.J. Brown, "Internal Pressure Measurements for Control of Explosive Spalling in Refractory Castables", American Ceramic Society Bulletin, Vol. 63, No. 7, pp 905-910 (1984).

3. G. MacZura, L.D. Hart, R.P. Heilich and J.E. Kopanda, "Refractory Cements", *Ceramic Proceedings*, Columbus, Ohio, 1983.