DEVELOPMENT OF A COMPUTER PROGRAM TO MODEL DRYING OF CASTABLE BLOCKS AND LININGS

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ABSTRACT

A mathematical model has been developed to calculate temperatures, internal pressures and water movements inside a heated castable block. The program is also capable of calculating the optimum drying schedule for a given lining. Heating may be on one face or on all faces (e.g. a shape in a dryer). Extensive physical data are required to run the program, but all data can be measured using ASTM tests. The program has demonstrated many interesting features of castable dewatering, and has been used to develop dryout schedules for various metallurgical applications.

1. INTRODUCTION

Since the earliest days of refractory castables the safe and efficient removal of water has been a serious problem. When castables are heated, water vaporizes to form steam leading to high internal pressures and potentially if the strength of the castable is exceeded, an explosion. When castables are used to contain molten metal (e.g. in a ladle lining), even small amounts of water in the castable can cause metallurgical problems (mainly due to release of hydrogen into the melt).

Several researchers have studied steam spalling; the paper by Gitzen and Hart [1] is among the most memorable. Gitzen and Hart listed parameters which influence the likelihood of explosive spalling (permeability, bond strength, thermal conductivity, particle size distribution, concentration of casting water, placement method, ambient curing temperature) and they also used a spalling test involving the inserting of 2.5" castable cubes into a pre-heated furnace. Hipps and Brown [2] took this work further by embedding thermocouples and pressure gauges inside test blocks before inserting them into a preheated furnace and discovered that the pressure inside the test blocks was in excess of 145 psi. However, repeated surface spalling occurred before the pressure gauges had registered any pressure. Gong and Mujumdar [3] proposed a Finite Element model of the drying process. A program of research was carried out at the University of Missouri-Rolla [4, 5] during the late 1990’s examining in more detail the dryout parameters. UMR’s work led to a computer model which showed that during dryout of a castable heat transfer is mainly due to conduction, there is a sharp moving drying front, and that permeability of the castable has the greatest influence on the dryout process. Much work has also been done at the University of São Carlos (see for example, [6]). Most recently, Bogan [7] described in detail the various parameters that affect the dryout process.

Recent developments in castable technology have led to the use of castables with very low permeability and therefore a greater tendency for explosive spalling. The use of very large castable blocks and linings is now common, and these factors have combined to make it necessary to have a method for designing drying schedules that are safe and rapid. Therefore, the authors undertook a series of studies leading to the writing of a software program capable of calculating temperatures, water movements and internal pressures inside castable blocks and linings, heated from one side or on all faces.

2. THEORETICAL MODEL

2.1. Data

The data required by the model are:

- Permeability
- Apparent Porosity
- Water Loss
- Bulk Density
- Thermal Conductivity (including retained water)
- Flexural Strength at 400ºF

All of these variables are temperature sensitive. Permeability has the greatest effect on the amount of pressure generated in the castable. Flexural strength at 400º F is also used because the combination of permeability, vapor pressure and water content tend to cause a lower strength that is more indicative of conditions during dryout.

Since castable dryout may take up to many days, it is important to make measurements in appropriate ways. Thermal conductivity was measured by the ASTM calorimeter test (C 417-93). Bulk density, kerosene porosity and permeability values were measured at room temperature on samples heated at various test temperatures for 12 hours. Kerosene porosity was found to be important as water porosity measurement of the samples gave lower values caused by hydration. Water loss values were determined by heating samples at the test temperature for 12 hours and then weighing them when cooled. Using a rapid heating method such as TGA would generate incorrect answers. All the data used were determined by standard test methods, but it was found that the permeability test apparatus had to have state of the art instrumentation to give accurate measurements. It would perhaps have been helpful to make measurements of permeability at elevated temperature but this would have been complicated, and it is believed that room temperature measurements after a long heating at the test temperature would give similar results.

Data on the behavior of water at various temperatures are available in standard texts. Saturated vapor pressure values and values of viscosity of water vapor at high temperature were obtained from these references.

2.2. Mathematical Basis

The theoretical model incorporates a coupled thermal analysis and water movement model. Temperatures are calculated using a one-dimensional solution of the generalized heatflow equation

$$\frac{\partial^2\theta}{\partial x^2} = \frac{1}{\alpha}\frac{\partial\theta}{\partial t}$$

(where θ = temperature, α = thermal diffusivity, x = distance and t = time)

After each temperature calculation step the water pressure is calculated throughout the model and water movement is allowed. The location of the water is considered when calculating temperatures because evaporation of water requires significant amounts of heat.

Water movement is calculated by using the ASTM permeability test equation (C577-96). Water vapor is forced through the castable by differential pressure. Knowing the permeability of the castable at points along the gradient, it is possible to calculate the speed of water vapor movement. The effect of pressure on the speed of movement is not linear (i.e. doubling the pressure does not cause the water vapor velocity to double), and in the current model this fact is taken into account by varying the viscosity of the water vapor as the speed of movement increases.

The model calculates temperature and water movement at spatial intervals of 0.1 inch to 0.4 inch (depending on the thickness of the castable layers entered by the user), and at time intervals of 6 seconds. The spatial calculation interval is appropriate for castables since use of finer intervals would be meaningless. The result is a model that is stable for layer thicknesses and heating schedules typically used in the industry. Calculations can take several hours on a desktop PC. The model incorporates several features which are very important.

2.3. Pore Volume

From the apparent porosity and bulk density values, pore volumes are calculated and using these the relative filling of the pores with water is calculated. Self flowing castables tend to have pores virtually full of water whereas vibration-cast castables have pores which are less full. This turns out to be a very important feature of the model.

2.4. One-sided, Two-sided or Small Block Calculations

Although the model is a one-dimensional model, it is possible to do calculations for one-sided heating or two-sided heating. In this way, it is possible to simulate a lining of a ladle (one-sided) or the drying of a large block (e.g. arc furnace delta) inside a dryer. It is only necessary to consider the smallest dimension of the block. There is also a feature that allows steam to escape from the sides of a small block, which was particularly important during laboratory evaluations of the model, in which rectangular blocks with embedded pressure gauges and thermocouples were heated on one face in a furnace.

2.5. Self-Tuning

While it is very useful to have a model that can calculate pressures and water movements in a given example, it was recognized at a very early stage that the model should be capable of calculating the optimum dryout schedule by itself. The user enters details of the block, the maximum internal pressure deemed safe, and the program will do the rest. Three possible modes of dryout are permitted:

- Ramp and Hold (up to 10 temperature ramps, each with a hold period)
- Single linear temperature ramp (uniform heating rate)
- Series of linear ramps (up to 20 linear ramps with no hold periods)

3. OBSERVATIONS ARISING FROM THE MODEL

As soon as the model was working, some interesting conclusions emerged. These will be demonstrated using, in all cases, the same type of material, an ultra-low cement castable.

3.1 Pore-Blocking

The phenomenon which became known as "pore-blocking" is the cause of most explosions during drying. When pores in a section of the castable are full, it is not possible to force any more water through them. Under these conditions, water vapor cannot escape and pressure increases rapidly as temperature increases, leading to an explosion. As the pressure increases, the viscosity of the water vapor also increases and escape of water becomes essentially impossible. When pore-blocking occurs, it can take many hours without further increase in temperature before the pressure decreases.

In the first example, a twelve inch castable lining is heated from one side. Figure 1 shows the amount of free water present at different distances from the hot face. Initially, the pores are not entirely full of water, and as water is driven backwards from the hot face, and chemical water is liberated to become free water, the pores fill up. When the pores are full, no more water can move and pressure starts to increase.

Figure 2 shows pressures at the same distances from the hot face as in Figure 1. It can be seen that pressure starts to increase at 3.75 inches from the hot face at the time when pore-blocking begins. When the pores are blocked, the rate at which pressure increases is very high.

3.2. Ramp-and-Hold Schedules

It became clear that drying only occurs as internal pressure forces water to move. Without pressure, there is little movement of water. The most rapid dryout is achieved by raising the internal pressure and holding it close to the maximum allowable value. This value is generally considered to be a maximum of 150 psi or 1/4 of the room temperature MOR of the castable at 350ºF; whichever value is lower. The usual ramp-and-hold method turns out to be very unsuitable because it leads to pressure spikes and troughs. During the spikes, there is the risk of an explosion, and during the troughs, nothing is achieved.

Figures 3 to 5 illustrate clearly the disadvantages of the usual ramp-and-hold method. Note that pressure is low for most of the ramp-and-hold schedule, but high pressure is seen at the end of the schedule. Using the optimized schedule (which lasts only 41 hours instead of the 48 hour ramp-and-hold schedule), pressure is steadier and the

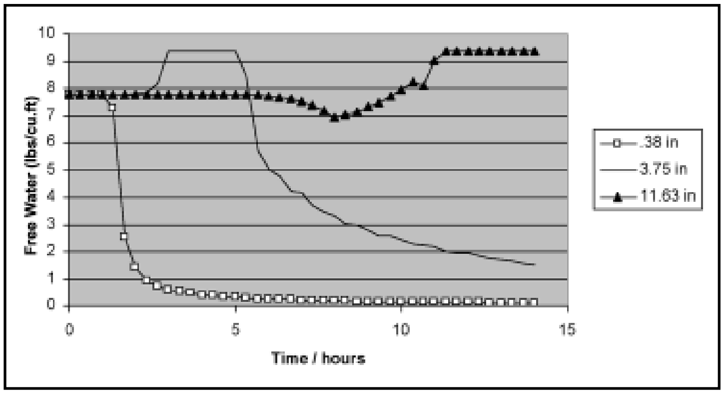

Figure 1. Pore-blocking example of 12" lining heated rapidly.

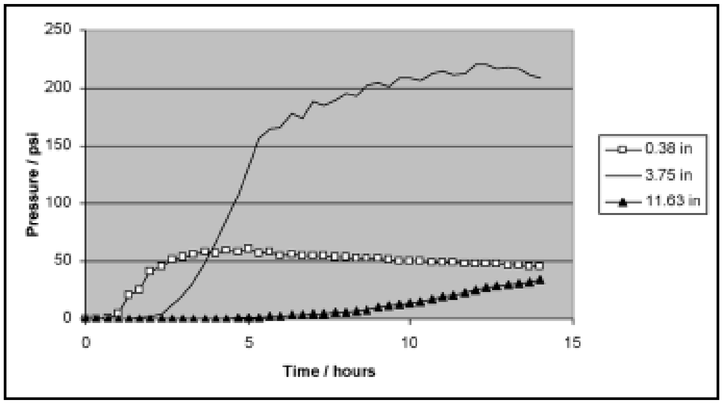

Figure 2. Pore-blocking example - pressures.

maximum pressure developed is lower. The optimized schedule also removes more water from the lining.

3.3. Effects of Adding Insulation

The DRYOUT program permits the user to model up to six layers of material, which can be castables or any other refractory material. When modelling brick, fiber blanket etc. it is necessary to provide the same details as for castables (thermal conductivity, bulk density, apparent porosity and permeability) but, of course, there will be no water present in these materials at the start of the dryout. Generally, therefore, addition of brickwork does not impede water movement. However, there is an important effect observed when external insulation is added to a castable lining. This is a practice undertaken deliberately during many dryouts, so that the cold face of the castable reaches a temperature above 212ºF.

The most rapid dryout of a lining is generally achieved by imposing a thermal gradient from hot face to cold face, so that water is removed from successive layers of the lining. When external insulation is applied, the thermal gradient inside the castable is less steep, so that water vapor is evolved simultaneously from a greater depth into the castable. The consequence of this is that there is a larger quantity of water trying to escape through the limited cross-sectional area of the hot face, and therefore internal pressure is higher and there is a greater risk of explosion. This is a point which should be given greater consideration during dryouts than is currently the case.

Figure 6 shows the maximum pressure developed in an 8" thick castable lining and the effect of adding external insulation. The furnace was heated to 1000ºF in 20 hours, followed by a 12 hour hold, but the hot face is only expected to reach 770ºF in this period because heat transfer from a gas flame is poor (this is a factor the model considers). Without external insulation the peak pressure reached is 121 psi but if 2" of external fiber insulation is added the peak pressure rises quickly to 253 psi. When external insulation is added, the back face of the lining reaches a much higher temperature so that more free water is evolved in a shorter time.

Figure 7 shows the free water at 7" from the hot face in the two examples shown in Figure 6. This Figure shows that the uninsulated lining accumulates at 7" depth more water than the insulated lining. In the insulated lining at 23.3 hours, there is a spike (see arrow on graph) in the insulated case, caused by rapid movement of water towards the hot face. Although the amount of water is low, the temperature is quite high and a sharp pressure spike results. This water cannot move away from the hot face because the pores behind it are blocked.

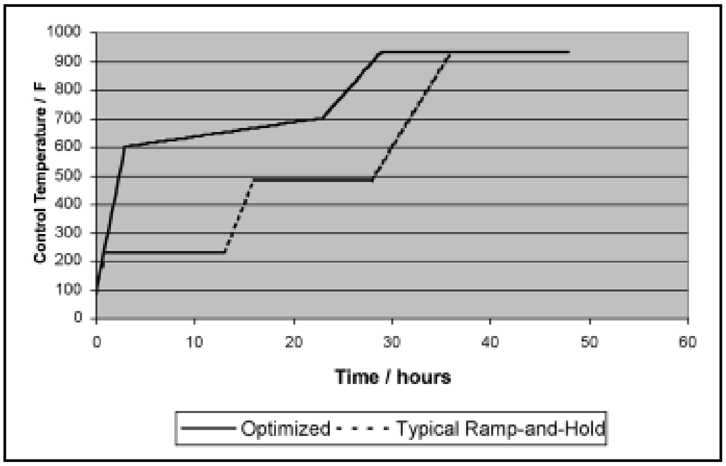

Figure 3. Comparison of dryout methods heating schedules.

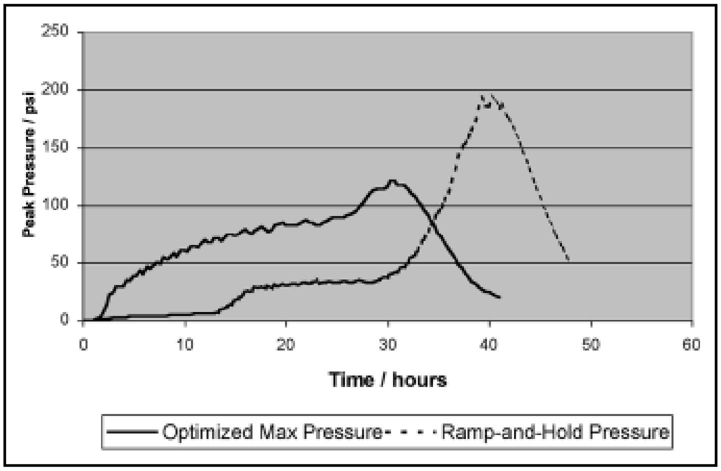

Figure 4. Comparison of dryout methods peak pressure values.

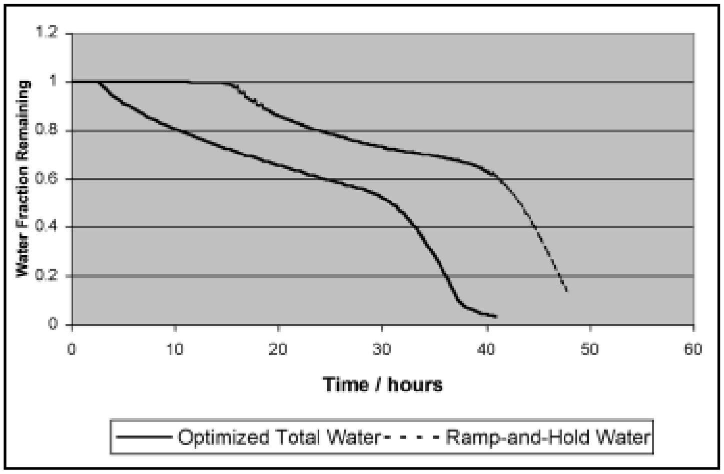

Figure 5. Comparison of dryout methods free water remaining in lining.

4. OTHER FEATURES OF THE MODEL

4.1. Cube Model

Work on explosive spalling began with researchers inserting 2.5" castable cubes into a preheated furnace to find out at what temperature they exploded. It is only fitting therefore that this phenomenon should be considered. As discussed previously, during development of the dryout program, verification work was done using rectangular castable blocks with embedded thermocouples and pressure gauges.

During these experiments, water escaped not only from the hot face and cold face, but also from the exposed sides of the blocks, a mechanism that reduces internal pressure greatly compared to an infinitely wide block.

The mathematical model is 1-dimensional but a method was introduced to model escape of water from the sides of a block, by considering the shortest distance to the outside of the block. This mathematical strategy was good enough to allow validation of calculations within experimental error. It also enables us to calculate the effects of inserting 3" cubes into a preheated furnace, and this will now be considered, using the same ultra-low cement castable used in calculations so far. Three furnace temperatures were chosen, 700ºF, 900ºF and 1000ºF. Figure 8 shows calculated maximum internal pressures for the three cases. Maximum pressure is expected approximately 40 minutes after insertion.

It is noteworthy that a 3" cube can safely be inserted into an oven at 700ºF (70 psi is quite a safe pressure) but a 12" lining of the same castable must be heated to 700ºF over a period of some hours to avoid an explosion.

4.2. Other Factors Considered in the Model

Steel anchors embedded in a lining are considered – these are thought to have little effect on water movement but they do affect heat transfer. The effects of steel shells have been included, but this is a complex matter. If the shell forms a hermetic seal against the castable, very high internal pressures result. It is much more likely, however, that water can escape from the lining into a narrow gap or crack between the shell and the castable. Either option can be modelled.

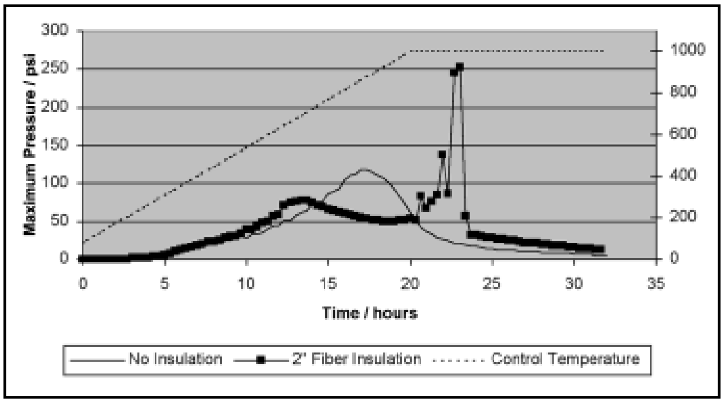

Figure 6. Effect of external insulation. 8" lining without and with insulation.

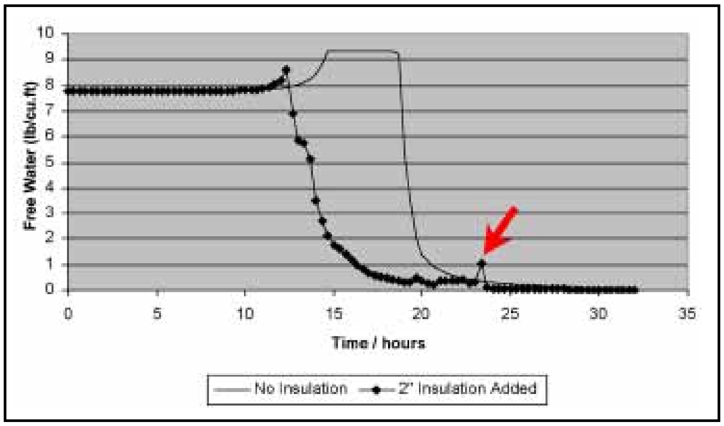

Figure 7. Water at 7" from hot face.

A very important matter is that furnaces are dried out by controlling the temperature of air (or gases) inside the furnace, and not by directly controlling the surface temperature of the castable. The thermal mass of a wet castable lining is huge, and there is a very considerable temperature lag between the control thermocouple and the castable. The DRYOUT software uses a dialog box labeled "thermocouple location" to deal with this problem. The control thermocouple may be considered to be inside the surface of the castable (i.e. hot face temperature equals control temperature), or to be suspended near the castable and not touching it. This makes a big difference in the calculated pressure. In all the foregoing examples, the control thermocouple was considered to be near the hot face but not touching it.

The DRYOUT program also takes into consideration surface condition variables, such as relative emissivity of the castable being dried and the convection coefficient along the castable-air interface. The convection coefficient is calculated knowing the airspeed, percent water in the atmosphere and orientation of the lining or in the case of a shape in a dryer if it is being heated on all exposed faces.

4.3. Reporting Tools

There are several reporting tools available. Graphs are generated of free water, temperature and pressure at every calculation interval, and graphs of total free water, total combined water and maximum pressure are also generated. These graphs are in twenty colors, so they cannot be easily displayed here. Data is also dumped to a proprietary file format or to an Excel spreadsheet for further graphing by the user.

5. EXAMPLE

The DRYOUT program was used to model large castable blocks that were 56 inches long. The blocks were made from high-cement, low-cement or ultra-low cement vibration-cast compositions and were heated in the same dryer. It was desired to use one schedule for all three production quantity blocks. The model indicated (Table 1) that a linear rate of 25ºF from ambient to 1200ºF was the only safe rate to use for all three compositions. This rate has been used for about 9 months without steam spalling of a shape. The new dryout time is 45.6 hrs - a significant improvement from the traditional ramp and hold schedule of 65.3 hrs.

Figure 9 shows the internal pressures expected in blocks made from the three castable types. Internal pressure is much higher in the LCC material than in the others, and the High-Cement and Ultra-Low Cement materials could be heated more quickly. This occurred probably because the LCC material had the lowest permeability. It was necessary, however, to dry all three materials in the same dryer, and therefore, only this drying schedule was possible.

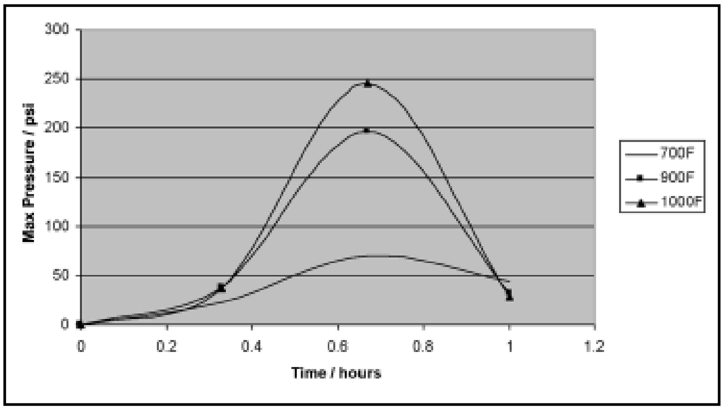

Figure 8. Rapid heating 3" cubes.

The DRYOUT program was also used to develop much more rapid drying schedules for all three materials involving a series of linear heating ramps. This is called the "self tune feature" of the program. These schedules can only be used when there is one castable type in the dryer. For the High-Cement material the optimized drying schedule lasted 15.8 hours, for the LCC material 32.0 hours, and for the Ultra-Low Cement material, 13.5 hours. These schedules are not shown here for reasons of client confidentiality.

The DRYOUT program is being used to calculate the optimum drying schedules for many different grades of castable, and it has been found that although there is a similarity between most of the schedules (typically, a fast initial heating rate, then a slow heating stage, and finally rapid heating after most of the chemically-bound water has already been removed), the optimum schedule for each castable is unique. It is for this reason that full details of each castable and lining have not been given, because it would be dangerous to attempt to follow schedules given in this article unless all the conditions are the same as in our calculations.

6. CONCLUSIONS

The DRYOUT program has been used to find efficient dryout schedules for precast shapes, tundish linings, steel ladles and aluminum furnace linings. It has been a valuable tool to show how close a shape or lining is to a dangerous internal pressure and allows one to change a design and remodel it before the design is implemented.

Most traditional dryout schedules are very conservative. In today's economic climate there is an increasing need to quickly get shapes dried and linings back into operation. The self-tune feature of the DRYOUT program has allowed us to predict the safest, but yet fastest, dryout schedule.

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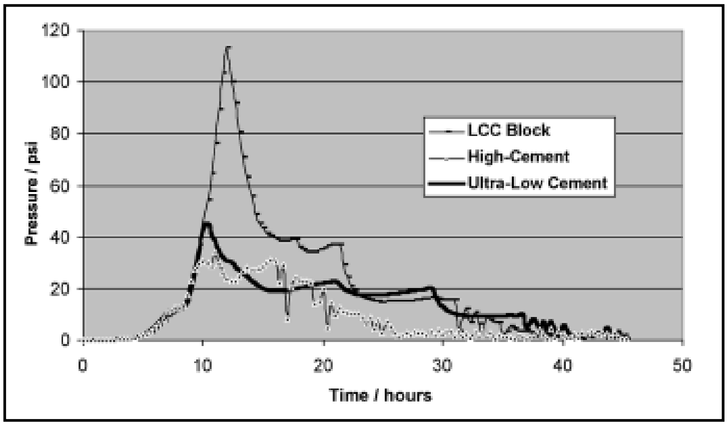
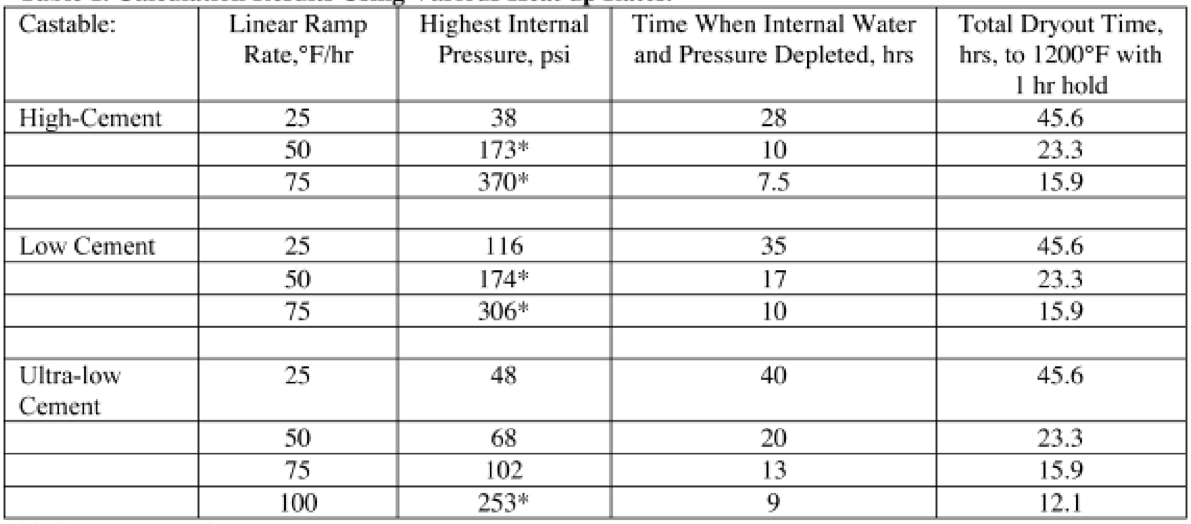


Figure 9. internal pressures at center of large castable blocks heated at 25°F/hr to 1200°F.

Table 1. Calculation Results Using Various Heat up Rates.



Castable:	Linear Ramp Rate,°F/hr	Highest Internal Pressure, psi	Time When Internal Water and Pressure Depleted, hrs	Total Dryout Time, hrs, to 1200°F with 1 hr hold
High-Cement	25	38	28	45.6
	50	173*	10	23.3
	75	370*	7.5	15.9
Low Cement	25	116	35	45.6
	50	174*	17	23.3
	75	306*	10	15.9
Ultra-low Cement	25	48	40	45.6
	50	68	20	23.3
	75	102	13	15.9
	100	253*	9	12.1

* indicates dangerous internal pressure.