CHEN 3600 Computer Aided Chemical Engineering
Department of Chemical Engineering

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**MEMORANDUM**

**Date:** February 13, 2012

**To:** Dr. Timothy D. Placek, Undergraduate Program Committee Chair

**Subject:** Course Project Analysis of Kiln Firing: Interim Report I

**Executive Summary** – This is an examination and analysis of data from an L&L Kiln. The data represents temperature readings from seven (7) different thermocouples relaying values to a computer for recording. Examining temperature versus time for thermocouple sampling data sets allows for certain conclusions to be drawn about the firing of such a kiln. The data was collected for a Slow Bisque Cone 05 Firing and a Fast Glaze Cone 6 Firing. The data were used to analyze the different stages in the firing process for a kiln and compare data from a Cone 5 and a Cone 6 firing.The findings for the difference in maximum temperature and the existence of a holding period between a fast glaze and slow bisque firing were consistent with what was expected. The rates of change for temperature with respect to time for slow bisque firing were also consistent with what was expected. One unexpected phenomenon was noticed in the analysis of the data, the existence of a constant oscillation in the temperature and in the difference between temperature values of the upper and lower interiors of the kiln. The holding time for the slow bisque firing was the most significant point of analysis due to the variations of the interior temperature of the kiln and the interior and exterior thermocouple temperatures of the kiln during this time. The cause in variation for the temperatures during the holding period was attributed to the shutting on and off of the heating coils and the downdraft ventilation set up of the kiln.

**Theory and Analysis** – Time and temperature data were gathered from thermocouples in an L&L kiln. The data sets were for two different firings, a Slow Bisque Cone 5 Firing and a Fast Glaze Cone 6 Firing. The data were obtained from Type S and K thermocouples. Two (2) Type S thermocouples measured the temperature of the top zone and bottom zone interior of the kiln. Five (5) Type K thermocouples measured the top section exterior temperature, the bottom section exterior temperature, the lid temperature, the temperature of the floor directly underneath the kiln, and room temperature.

Thermocouples are used to measure temperature differences. Thermocouples are made of two different metals joined together at one end. The non-adjoining side is held at an ambient temperature, while the junction end is submerged in the fluid for which the temperature is being measured. When the joined is heated or cooled a voltage is produced that can be correlated back to the temperature.

There are different calibrations of thermocouples. The calibrations used in an L&L Kiln are S and K. Each calibration has a different temperature range and appropriate environment. Omega Engineering reports that type K thermocouples are the most popular calibration. Type K thermocouples are made of a Nickel-Chromium alloy and a Nickel Aluminum alloy. The maximum temperature condition for this calibration is 2282°F. An advantage of a type K thermocouple is its low cost. Type S calibration is made up of Platinum and Platinum-Rhodium. This calibration is suited for higher temperatures than type K; the maximum temperature condition for S calibration is 3214°F. Type S thermocouples are more expensive than type K, but can withstand much higher temperatures. The high cost makes the S calibration not a popular choice for general use.

Another distinguishing feature of the L&L kiln is that it uses a Downdraft ventilation system that is designed to force the flame and heated air to circulate throughout the kiln. This system draws unwanted fumes by the carbonaceous materials in clay, smoke, and vapor out through the bottom of the kiln. Heat is introduced at the bottom of the kiln and naturally flows upward. The construction forces the heat back downward, to exhaust at thebottom of the kiln. In an electric kiln, holes are drilled at the top of the kiln and along the bottom as a mode to let in ambient air when the fan draws heated air, along with fumes and vapors, from within the kiln.

One of the types of data analyzed was that from a Slow Bisque firing. During bisquing, the clay is changed into ceramic material without fully fusing it. Most pottery is put through a bisque firing before it is glazed and then fired again to melt the glaze and fuse it to the clay body. Bisque firing allows the potter to create decorative works with stains, undergalzes, and glazes with a significantly reduced risk of the piece being damaged. Because the bisque firing is brought to temperature much more slowly than other firings, bisquing reduces the chances of pots cracking or exploding in the glaze firing.Electric kilns are preferred for bisque firings because they can be more easily controlled at very low, pre heating settings. The other type of firing, from which data were analyzed, is a Glaze firing. A Glaze firing is much faster, which is possible because most of the water has already been driven out of the clay.

Kilns are not just fired to a specific temperature; they are fired to a cone level, which accounts for time as well as temperature. Pyrometric cones are useful in determining when a firing is complete. Pyrometric cones are made from carefully controlled compositions and bend at a specific temperature range. These cones exist in different categories designated by numbers, each of which corresponds to a heating rate and temperature combination, which will make a specific cone bend. Cone 5 and Cone 6 cones are used in the two firings from which data were analyzed. The firing process of a kiln has different stages. For a Slow Bisque firing process there is a holding or candling period, a firing period, and a cooling period. For a glaze firing the process is the same but without a holding period. Figure 1 shows the basic temperature profile of a Slow Bisque Cone 5 firing.

Before the firing process is started, the clay must be almost completely dry. Any water trapped in the clay, when heated to temperatures reached during the firing process, will vaporize and could cause damage to the clay or the kiln. Prior to firing, candling ensures the clay is completely dry. During the candling period the heating element maintains close to a constant, uniform temperature throughout the kiln. Under close examination of the holding period in Fig. 1, one will notice that there is oscillation in the data. This variation from a constant temperature occurs because the heating element will shut on and off in order to maintain a constant temperature in the kiln. It is crucial for the clay particles to heat slowly. As the clay is slowly heated, the water evaporates from the clay. If the clay is heated too quickly, the water will turn to steam inside of the clay body and cause an explosive expansion of the clay.



**Figure 1** Time versus temperature plot of a Cone 5 Slow Bisque Firing.

During the firing period, the temperature rises until the target temperature is reached. The temperature increases semi-linearly during this phase. For a typical bisque firing, the general heating process is an overnight warm up at low heat, two hours of a low heat with an increase in temperature of no more than 200°F per hour**,** two hours of medium heat and an increase of temperature of no more than 300°F per hour, and then high heat at an increase in temperature of 300 to 400°F per hour until the required temperature has been reached.

During the firing period organic materials, sulfur, and carbon in the clay will burn off between the temperatures of 572⁰ and 1470⁰F. It is important for these materials to be burned off to prevent carbon coring form occurring, which would weaken the clay body. Even after the holding period, clay stills contains 14 percent of chemically bonded water. The chemically bonded water escapes from the clay body between 660⁰ and 1470⁰F. If the water heats too quickly, it again can cause the explosive production of steam inside the clay body. Because of these necessary changes in the clay the [firing process](http://pottery.about.com/od/potterygloassary/g/firesched.htm) must allow for a slow buildup of heat. Beginning at about 1650⁰F the clay particles start to fuse; this is called sintering. After the pottery has sintered, it is no longer truly clay but has become a ceramic material. Bisque firing usually is completed at about 1730⁰F, after which ware has sintered but is still porous and not yet vitrified. This allows for wet, raw glazes to adhere to the pottery without it disintegrating. Vitrification is the next physical change in the firing process. It is a gradual process during which the materials that melt most easily, do so. The clay dissolves and fills in the spaces between the more [refractory](http://pottery.about.com/od/potterygloassary/g/refract.htm) particles. The melted materials promote further melting, as well as compacting and strengthening the clay body. During this stage, aluminum silicate is formed; these long, needle-like crystals which act as binders, knit and strengthen the clay body even further.

During last period of the process, the kiln will shut off and cool naturally. The cooling is an exponential decline in temperature. During cooling, a sudden shrinkage of cristobalite, a crystalline form of silica, occurs at temperatures below 420⁰F. Cristobalite is found in all clay bodies, and care must be taken to cool the kiln slowly as it moves through this critical temperature otherwise, clay pieces will develop cracks.

**Results and Discussion** – The first point of analysis is with the holding/candling period of the slow bisque firing. During this stage of firing, the kiln must be kept at, or close to, constant temperature in order to slowly heat the clay and evaporate out all of the water in the clay. By looking at Fig. 2, which is a magnified segment of the hold time in Fig. 1, it is evident that the temperature exhibits an oscillation instead of a constant temperature. A variable heating rate is the cause of this oscillation. The controller senses when the kiln is getting too cool or too warm and either heats or vents, causing a fluctuation of temperature.



**Figure 2** Plot of a portion of the hold time in a Slow Bisque firing.

In addition to noticing a varying temperature during the candling process, it was evident that a temperature difference existed between the Top S thermocouple and the Bottom S thermocouple throughout the firing. A representation of this temperature difference is shown in Fig. 3 below.

Figure 3 shows the oscillation of temperature reading difference during a portion of the holding period of the slow bisque firing. The figure was generated by subtracting the temperature values of the top S thermocouple from those of the bottom S thermocouple. By studying this figure, it is evident that at all times the thermocouple positioned at the bottom of the kiln registered a higher value for temperature than the value registered at the top of the kiln. The average temperature difference between the two thermcouples was around 9⁰F. The bottom thermocouple was at least 7⁰F higher than the top thermcouple with the max being around 12⁰F. Once again, the variable temprature difference provides evidence of the control afftecting the kiln temperature.



**Figure 3** Plot of the difference in the temperatures of the interior thermocouples

Together, Figure 2 and 3 show the physical manifestation of the cycling nature of the ventilation system. When the control detects that the kiln is getting too hot or heating too fast, the vent is opened and a portion of the heated air is removed from the kiln. In order to avoid creating a vacuum inside the kiln, ambient air is pulled into the kiln. The hot air is removed through the bottom surface while ambient air is pulled in, causing a difference in temperature between the two S thermocouples as shown in Fig. 3. The ventilation system does not constantly run; instead, it allows the kiln to heat up to a point and then vents enough heated air to cool it down appropriately. This oscillating pattern persists throughout the entire process, but the portions shown were chosen because of their constant average temperatures.

Figure 4 shows the relation between the temperature values of the K thermocouple on the lid and the K thermocouple on the floor directly beneath the kiln. This demonstrates how the temperatures at the bottom of the kiln, where fumes are being vented out, are constantly changing, while the top thermocouple is more stable in temperature.



**Figure 4** Relation between the temperature values of the K thermocouple on the lid which is the top plot and the K thermocouple on the floor directly beneath the kiln, which is the bottom plot.

The next point of analysis was a comparison in the temperature profiles of the Fast Glaze Cone 6 firing and the Slow Bisque Cone 5 firing. Figure 5 represents the data comparison between the two firings.



**Figure 5** Plot of the Cone 5 Slow Bisque Firing versus the Cone 6 Fast Glaze firing.

Figure 5 shows the difference in data values between a Cone 5 Slow Bisque firing and a Cone 6 Fast Glaze firing. A Fast Glaze firing has no holding period. This is because a fast glaze firing is performed after most of the water has been driven out of the clay. Another obvious difference is in the maximum temperatures reached. The cone 6 firing had steeper rates of change during the firing period and reached a higher maximum temperature than the Slow Bisque firing. Glaze firing is expected to occur at a higher temperature than bisque firing because the glaze firing fuses the glaze together in combination with the surface of the clay body.

The final point of analysis of the firing data was evaluating rates of temperature change with respect to time for the different periods in the firing process for a Cone 5 Slow Bisque firing. Figure 6 shows the plot of the rates for each period during the firing.

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**Figure 6** Plot of the rate of change for the different firing stages in a Slow Bisque firing.

Figure 6 shows the instantaneous rate of change for temperature with respect to time, plotted against time. From this figure it can be noted that although there is an initial jump in the rate of temperature change at the beginning of the holding period, the average rate of change during this period is 0. This initial positive rate is the result of the kiln increasing the temperature in order to reach the desired holding temperature of around 180⁰F. The rate of temperature change increases greatly in the positive direction at the beginning of the firing period and remains positive for the duration of the firing period. This can be explained by the fact that the temperature continues to rise during the firing period. The few dips in rate of temperature change during this period can be explained by the kiln slowing the rate of change near the end of the firing period. The cooling period illustrates a negative rate of change supporting the fact that the temperature is decling towards zero during the cooling process.

**Conclusions and Recommendations** – The analysis results were consistent with what was expected in the firing process of the kiln. In the Slow Bisque firing’s holding period, the rate of change of temperature with respect to time averaged to be around zero, which was expected due to the nearly constant temperature maintained throughout this period. However, the kiln temperature during the holding does vary in somewhat due to the heating coils in the kiln and the ventilation system shutting on and off in order to maintain a constant temperature in the kiln. The figures representing the rates of change of temperature through the other periods in the Slow Bisque firing were consistent with expectations. Lastly, the temperature profile of the fast glaze versus the slow bisque firing showed expected differences of a higher maximum temperature and the lack of a candling process in a fast glaze firing. The previously discussed oscillations were not expected but were able to be explained by utilizing the data provided.

**References-**

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Attachments