

## CONTENTS

Table of Contents.....	1
Abstract.....	2
I MOTIVATION.....	2
II INTRODUCTION.....	3
III OVERVIEW OF A TYPICAL KILN FIRING.....	4
IV INTERPRETATION OF DATA FROM PREVIOUS KILNS.....	5
V CHRONOLOGY OF DATA COLLECTION.....	8
VI THE INFRARED CAMERA.....	11
VII KILN CONSTRUCTION.....	12
VIII THE KILN FIRING AND DATA COLLECTION.....	17
IX THE FINITE ELEMENT MODEL.....	18
A The Basics of Finite Element Modeling.....	19
B Dimensional and Structural Assumptions of the Model.....	20
C Property Assumptions of the Model.....	20
D Assumptions Concerning Conduction.....	21
E Assumptions Concerning Convection.....	23
F Assumptions Concerning Radiation.....	23
G Assumptions Concerning Heating.....	24
X ANALYSIS OF INFRARED DATA.....	31
XI CONCLUSIONS.....	33
XII SUGGESTIONS FOR THE FUTURE.....	33
APPENDIX A: BRIEF HISTORY OF BRICKMAKING.....	34
APPENDIX B: NARRATIVE CHRONOLOGY OF 1998 KILN FIRING.....	41
APPENDIX C: DATA FROM 1989 BURN.....	46
APPENDIX D: DATA FROM 1994 BURN.....	53
APPENDIX E: DATA FROM 1995 BURN.....	63
APPENDIX F: DATA FROM 1996 BURN.....	73
REFERENCES.....	83
WORKS CONSULTED.....	85

# **Non-invasive Evaluation and Modeling of a Colonial Brick Kiln**

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## **ABSTRACT**

The firing of bricks in a kiln built by colonial interpreters is examined through the use of infrared thermography. Data taken noninvasively with an infrared camera is compared to a computer model generated for this specific kiln structure in an attempt to determine if infrared thermography could be used as a control measure to ensure the quality of bricks in such a nonindustrial kiln. This model will augment the existing understanding of the brickmaking process as a way to increase the size of future colonial-style kilns without loss of quality.

## **I MOTIVATION:**

A model of a brick kiln, coupled with the ability to make relatively easy, noninvasive temperature measurements, would assist the Colonial Williamsburg Foundation not only in obtaining a better understanding of the process of firing, but also provide a measure of quality control that

would improve on the previously used method of using thermocouples.

An improved understanding of the heat flow through a typical kiln would also allow less experienced colonial interpreters to fire the kiln, and allow more bricks to be fired at once without loss of quality.

## **II INTRODUCTION :**

The idea for this project grew from a related problem posed to William & Mary's Applied Science Department in 1995: to determine whether or not colonial interpreters were being placed at increased risk of cataracts due to infrared radiation emanating from the open, blazing fires of the kiln. That fear was quickly shown to be unfounded by taking thermal readings of the kiln with an infrared camera, but that project led to the concept of using thermography as a quality control measure in place of the unsightly and distinctly non-colonial thermocouples and wires.



**Figure 1- A colonial interpreter installing a thermocouple into a kiln wall<sup>1</sup>**

In the seventeenth century, brickmaking was a business, and as such was done on a large scale. As a result of this large scale, colonial brickmakers would have been apprenticed and would have had the benefit of many years' experience to ensure brick quality. The colonial interpreter of today, however, in his attempts to relearn the art of brickmaking, is without such benefits of experience. To ensure that bricks will be of practical use in the Colonial Williamsburg Foundation's buildings, he is forced to monitor the temperature, to affirm that the bricks have achieved sufficient temperatures for the correct amount of time, with devices such as thermocouples. The desire for a technique to monitor kiln temperature without unsightly thermocouple wires while still maintaining quality control measures suggested a deeper examination into the validity and feasibility of using a thermographic model, coupled with infrared readings.

If a method could be devised which could monitor kiln temperatures using a device as simple and noninvasive as an infrared detector, it would be possible to make the firing of bricks much more foolproof. If bricks could be made safely by less experienced interpreters, they could be made and used more extensively, and perhaps even sold for profit, a concept of obvious interest to the Colonial Williamsburg Foundation



Figure 2- Panoramic view of the brick yard in October, 1998

### III OVERVIEW OF A TYPICAL KILN FIRING:

The brickmaking process begins in late fall by digging up a quantity of suitable clay. Good brickmaking clay typically consists of mild clay, meaning it contains 30 to 35 percent sand<sup>2</sup>. The actual quality of the clay can be determined by testing a few bricks in a potters' kiln. The clay is left exposed to allow the freeze and thaw cycle to break up chunks. After the last freeze, the clay is deposited in a pit and mixed with water by treading it barefoot. The clay is then molded into typical brick shapes with a mold and left to dry in the sun for several weeks. In mid October, the kiln is either built from the unfired bricks or, if a shell of fired bricks exists, it is

filled with unfired bricks and sealed up. Kiln size depends solely on the number of bricks molded during the summer, and can vary from around ten thousand bricks to well over ten times that.

Beneath the body of the kiln, tunnels, or "eyes" as they are called, were constructed and in those fires were built in order to fire the bricks. The firing takes approximately one week, the first two or three days of which is devoted to drying the bricks at low heat. After the bricks have thoroughly dried, the temperature of the kiln is increased slowly by building the fires. The temperature needs to reach between 1850F and 2000F to allow the bricks to harden enough for use in an outer wall of a structure<sup>3</sup>, and after those temperatures have been sustained for roughly six hours, the kiln is sealed up with mud and allowed to cool slowly.

#### **IV INTERPRETATION OF DATA FROM PREVIOUS KILNS:**

In studying the data taken from various kilns fired over the previous decade, a statistical picture of the evolution of a firing over a week was developed. For example, analysis of the kilns fired in 1989 and 1996 yielded the thermocouple data visible in Figures 3 and 4. Data from the thermocouple readings for 1989, 1994, 1995, and 1996 are reproduced in full in the appendices. Both are taken from thermocouple readings done by colonial interpreters over the course of a firing for the years indicated, and both correspond to a point roughly two feet below the surface of the

kiln in the central upper portion of the south side, above the eyes of one end.

It is important to note that since thermocouple readings were not taken until the kiln began to warm up significantly, a period of time corresponding to a typical drying period of two and a half days has been added to the graphs to make them more easily understood in terms of the 1998 firing. The drying times for the kilns of those years was in fact a bit shorter, on the order of one and a half days, but to keep the data comparable, it was assumed to be of the length now used.

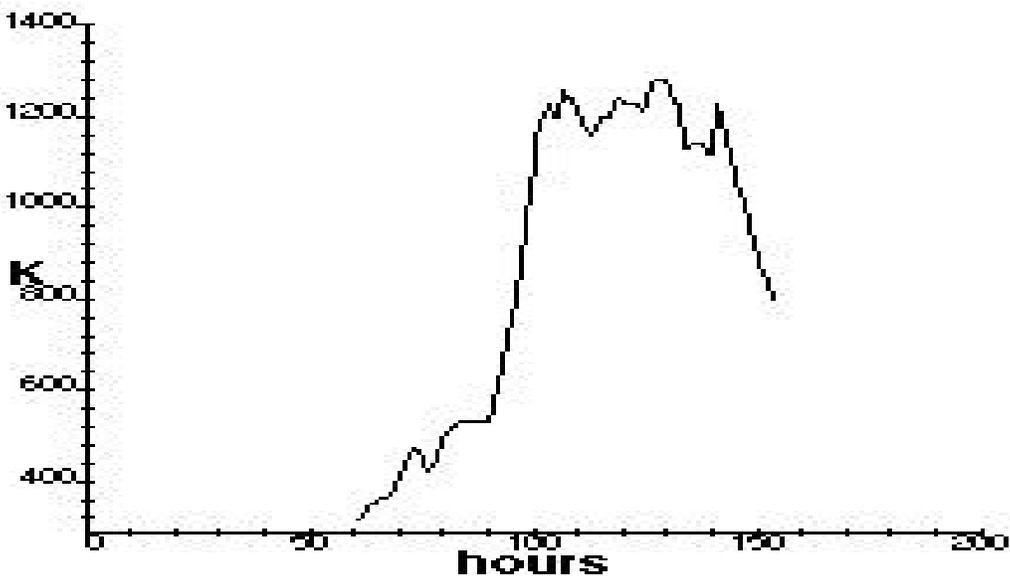


Figure 3- Plot of temperature vs. time for a given position in the 1989 kiln. Taken from readings done by interpreters in 1989.

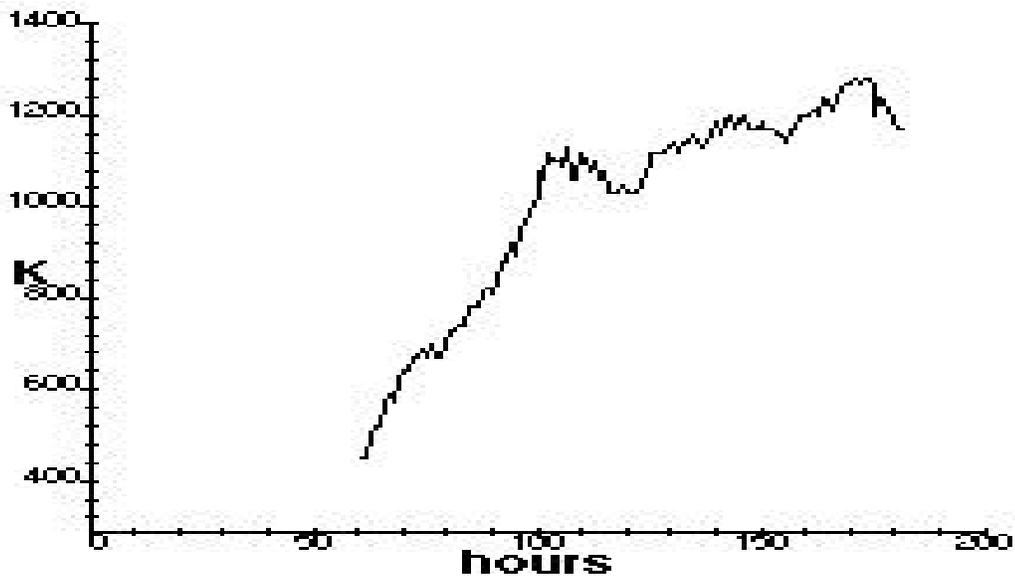


Figure 4-Plot of temperature vs. time for a given position in the 1996 kiln. Taken from readings done by interpreters in 1996.

Notice that although the 1996 kiln was fired over a longer period and reached higher temperatures for a differing length of time than that of the 1989 kiln, the same basic shape for the temperature curve is evident. This general shape was used as a benchmark for what was to happen during the 1998 firing and as a way to determine the portions of the week that would be most productive to record data. For example, by realizing that it would take roughly two and a half days to dry out the bricks, and that the kiln would be brought up to peak temperature within a few days after that, it was possible to plan trips to the kiln more effectively and motivate the timing of those visits to coincide with steeper portions of the temperature/time curve.

## **V CHRONOLOGY OF DATA COLLECTION:**

The months before October were spent becoming familiar with the use and limitations of the instrumentation, an Inframetrics 600 Infrared Camera System, and designing and constructing a mobile data collection cart (Figure 5).



**Figure 5- Custom data acquisition cart**

Designed to facilitate the movement of the camera and related equipment around the kiln, this cart enabled more data to be taken, simply because it shortened setup time (Figure 6). Without the cart, the image processor, monitor, camera, and all of the accompanying cables would have had to be unpacked and mounted on tripods every time a reading was to be

taken. When it was realized that data might be necessary nearly every hour, that became impossible.



**Figure 6- Data cart in use at the kiln**

The cart design, influenced by products available commercially, was built around an industrial style hand truck with inflatable balloon tires. The balloon tires were desirable because of the uneven terrain around the kiln and the hand truck was needed simply for strength. The body of the cart consisted of three shelves mounted to the hand truck and surrounded by a custom made sheet metal casing. Holes were drilled in each shelf to facilitate the passing of necessary cables from one shelf to another, and each component: monitor, image processor, and video camera, was held in place with custom fit webbing and buckles mounted to each shelf. The

extra space on each shelf was used to house other equipment, such as notebooks and a handheld thermocouple.

The system was powered by a 12VDC automobile battery connected to the camera through a cigarette lighter style connector. The battery supplied sufficient power to enable a whole week of operation without recharging. The setup, with a commercially available battery in place of the implemented automobile battery is shown in Figure 7.

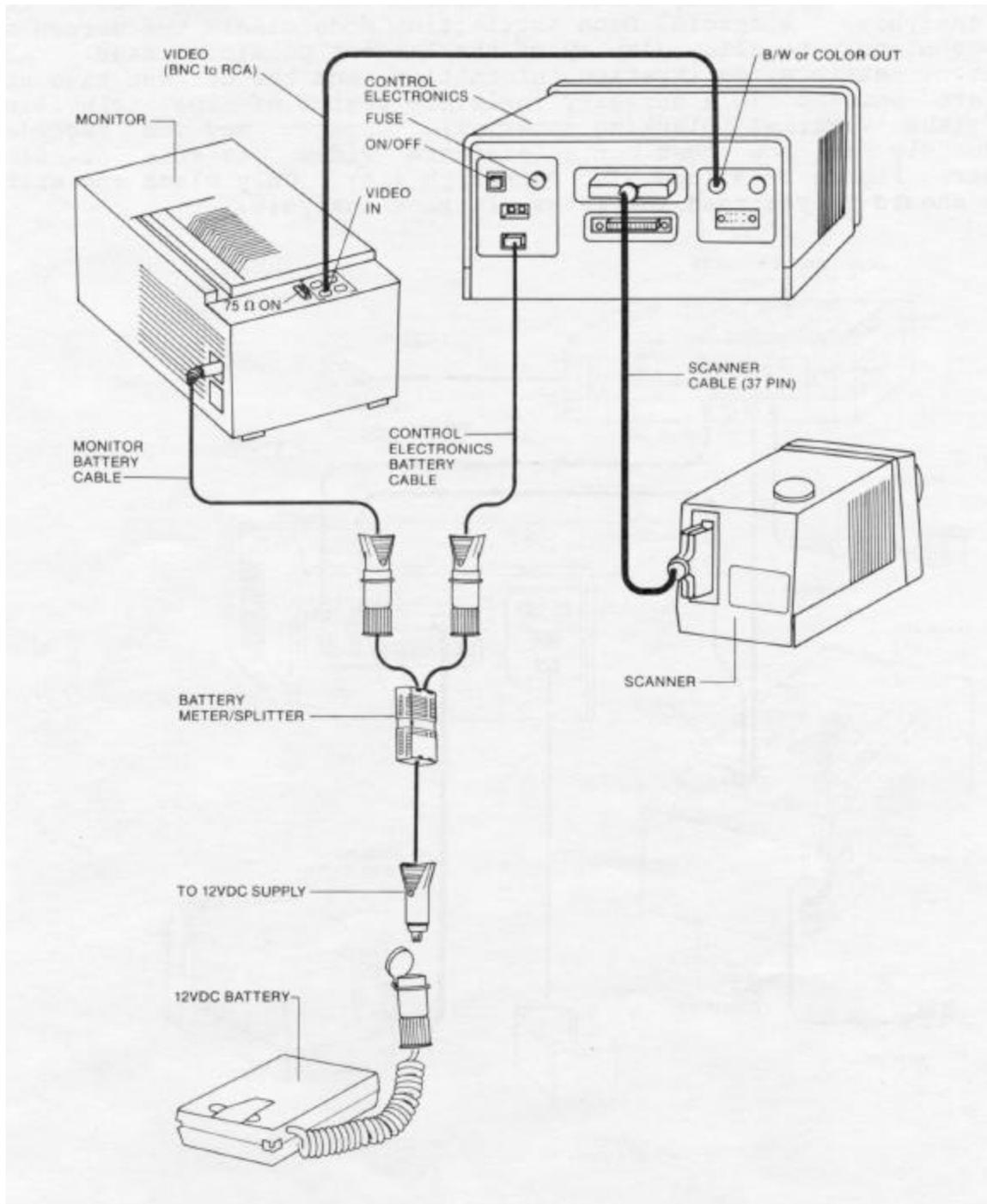


Figure 7- Diagram of Inframetrics 600 components as connected to a 12VDC source. <sup>4</sup>

The motivation for the selection of an automobile battery as a power source, as opposed to a rechargeable source available specifically for the camera, was twofold. Primarily, it was an inexpensive, replaceable and long lasting power source, but it also served as a weight to steady the cart while standing upright without support. The video camera was the only piece of equipment not operating on the automobile battery. The final requirement of the system was a supply of liquid nitrogen to cool the camera. This was provided by a 5 liter dewar which was left at the kiln site and refilled periodically with a smaller container. A funnel was employed as a means to fill the camera's reservoir from the dewar while minimizing spillage of LNO<sub>2</sub>.

Throughout the firing period, the camera equipment was left on the kiln site, covered in a tarp and kept in the tent used to store green bricks before firing.

## **VI THE INFRARED CAMERA**

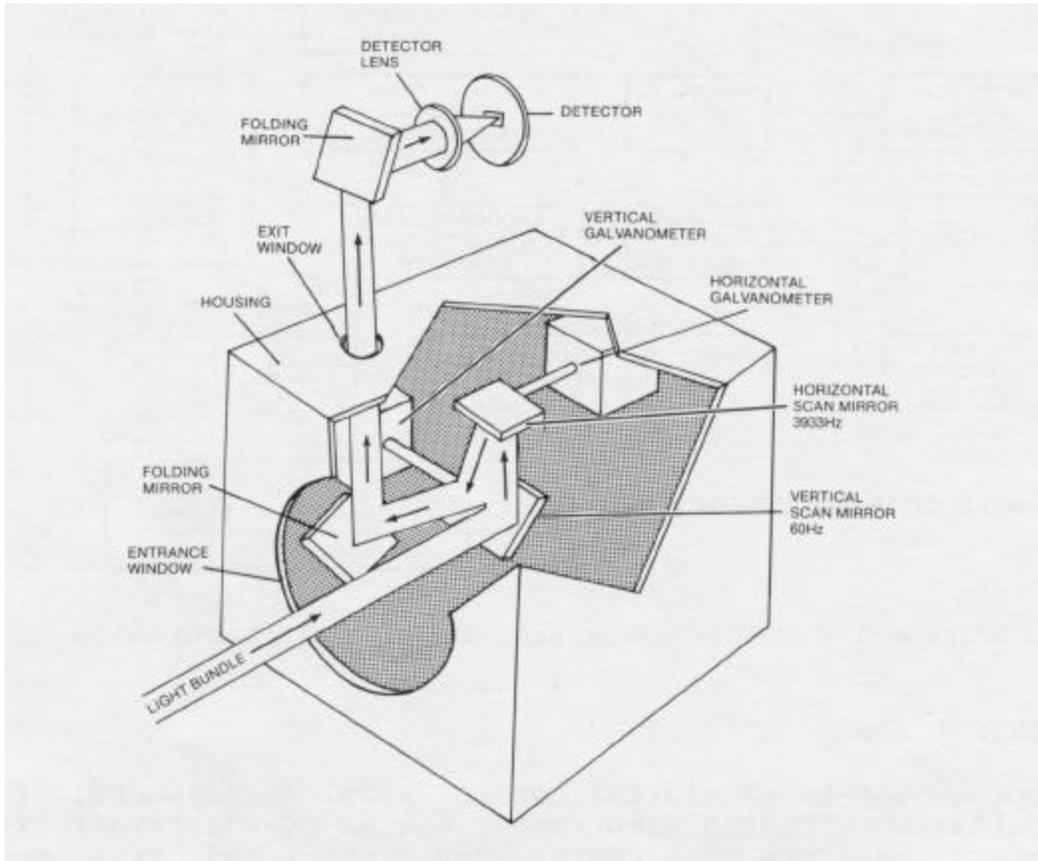
The Inframetrics 600 is a Liquid nitrogen cooled Mercury/Cadmium/Telluride (HgCdTe) detector, operating at 77 C. It has a typical minimum measurable temperature difference of .1C, a -20C to +400C range in the 8-12 micron range (up to +1500C in extended mode) and an ambient operating temperature of -15C to +45C.<sup>5</sup>

The detector itself incorporates electromechanical servos to perform both horizontal and vertical scanning. This means that during operation, a magnetic field oscillates a mirror against a torsional spring

shaft under closed-loop electrical current. Horizontal scanning is performed at 4KHz in a resonant mode (sinusoidal) and vertical scanning is done in a sawtooth pattern, similar to that of a television set, at 60Hz.<sup>6</sup> The scanning mirrors are responsible for the audible whine emanating from the camera while operational.

These mirrors are encased in a sealed, evacuated chamber to increase efficiency, and motorized focus and optional filter mechanisms are operated within the scanner case by the system through remote controls. The lens of the camera is Germanium, since normal glass does not transmit radiant energy with wavelengths longer than 4 microns.<sup>7</sup>

The radiant signal, whose path is visible in Figure 8,



**Figure 8 - Schematic of radiant signal path through Inframetrics 600. <sup>8</sup>**

is converted into an electric signal by the detector and amplified by the enclosed solid state electronics. The amplified signal then drives a digital readout, which in this case is displayed on a television style monitor in either false color or grayscale.

## **VII KILN CONSTRUCTION:**

The kiln itself was constructed entirely in the two weeks preceding the firing. Built in the field behind the cabinet makers' workshop in colonial

Williamsburg, the kiln was constructed on a base of previously fired bricks, stacked two thick to form a stable platform.

In previous years, the kiln has been built entirely of unfired bricks, but in 1998, the kiln was constructed as three mortared walls, about two feet thick, built with previously fired bricks. This method not only provided a sort of insulation to keep heat in the kiln, but also allowed for a "kiln-like structure" to be standing year-round to aid in the explanation of brickmaking to tourists. The beginning of these walls are shown for the 1998 kiln in Figure 9 along with a view through an unfinished kiln eye from a previous kiln in Figure 10.



**Figure 9- The construction of the outer walls of the October 1998 kiln**



**Figure 10- construction of one of the kiln eyes. <sup>9</sup>**

Later, the kiln would be packed with unfired bricks (the tunnels are continued with unfired brick) and the fourth wall would be assembled, although not mortared. The fourth wall, however, was made a little thicker and daubed with mud more heavily to compensate for its lack of mortar. The process of filling the kiln is shown for a previously fired kiln in Figure 11.



**Figure 11- Unfired bricks are stacked within the kiln with about a thumbs space between to facilitate heat flow. <sup>10</sup>**

The kiln is then covered in mud, or "daub," as it is called, and covered with a canvas tarp until it is time to light the fires (See Figure 12).



**Figure 12- Finishing the construction and daubing of the kiln**

The kiln was constructed of about 10,000 bricks, stood 8'6" tall, was 16'6" wide on the sides with the eyes, and 15'2" deep (along the ends). Each eye was 1'6" wide, and 3'1" tall and extended completely through the kiln.

#### **VIII THE KILN FIRING AND DATA COLLECTION:**

On Wednesday, October 21, at about 4:00 PM a fire was lit with a flint and steel in each of the four kiln eyes. In order to complete the drying portion of the firing, they were maintained at relatively low heat (below 900F) until Saturday morning, October 24. It is important to note that this kiln was built without thermocouples, so the only check and estimation of temperature was the experience of the kilnmaster, Andrew Barry. On Saturday, the eyes of the kiln were fitted with iron "doors," to help keep heat in, and the protective canvas rain cover was removed from the top of

the kiln. The temperature of the fires was brought up slowly by adding an increasing number of logs per hour, reaching a peak temperature about Tuesday night and maintaining that until about 6:00AM Wednesday morning when the kiln eyes were sealed up with daub. At this point the kiln was allowed to sit with the canvas rain cover on until spring when the bricks would be needed for construction projects.

Throughout this whole process, the kiln was attended around the clock. The fires were stoked each hour and since the general trend of the kiln temperatures had been established from previous burns, data was taken in a manner commensurate with kiln activity. This resulted in a total of 44 trips to the kiln in one week (an average of every two and a half hours between Friday, October 23 and Wednesday, October 28), with data being collected in the form of a video (VCR) recording of the output of the Inframetrics camera.

Figures 13, 14, 15 and 16 are representative examples of thermograms of the kiln. Each is labeled according to date and time, and designated as one of four sides (1 through 4). These are labels constructed to keep track of the data during analysis. Side 1 is the side with eyes closest to the drying tent, side 2 is the side without eyes furthest from the tent, side 3 is the side with eyes closest to the footpath and side 4 is the side closest to the tent.

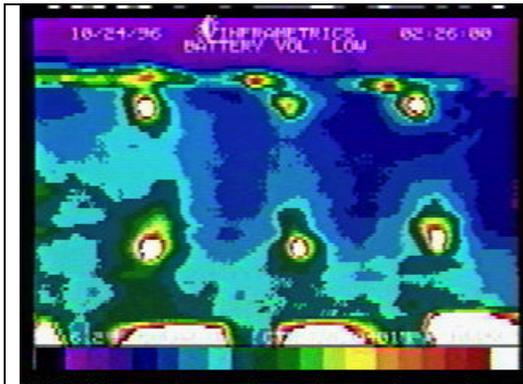


Figure 13- Saturday, 3:50AM, side 3

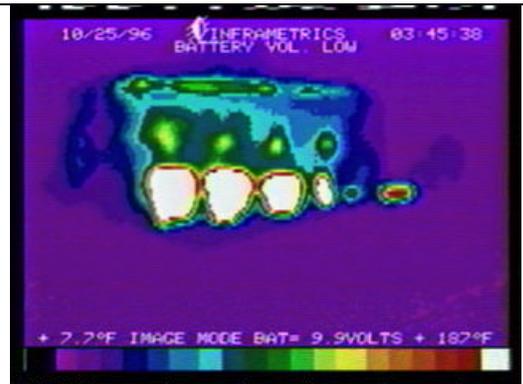


Figure 14- Monday 4:30AM, side 3

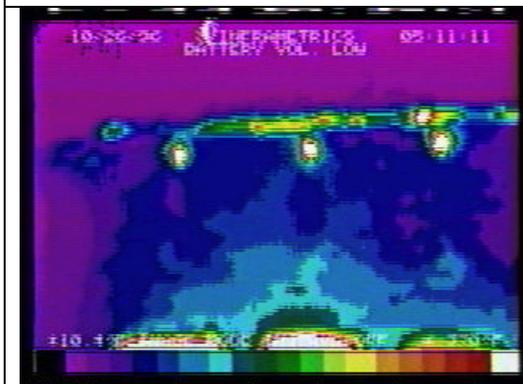


Figure 15- Tuesday, 5:45AM, side 3

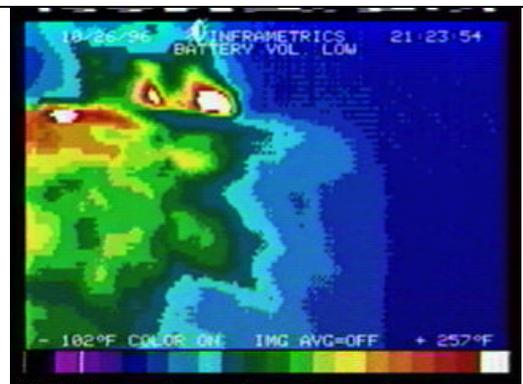


Figure 16- Tuesday, 10:00 PM, side 4

## IX THE FINITE ELEMENT MODEL:

The first step in understanding the kiln was to assemble a finite element model that could match the kiln's behavior. Finite element models allow the calculation of quantities such as heat flow through complicated geometries using initial boundary conditions.

## A.THE BASICS OF FINITE ELEMENT MODELING

Finite element modeling, or FEM, is a computer driven technique to aid in the analysis of structures and continua. Although the use of classical methods is probably the best way to analyze simple structures, when the geometry of a solid becomes complex, the complexity of classical methods quickly becomes prohibitively difficult. In such cases, a FEM is usually used to obtain a numerical solution.

The most important distinction between a classical solution and a finite element solution is in the way each "looks" at the solid. Classical approaches treat solids as continua whose behavior is governed by partial or ordinary differential equations, while FEM solutions view the solid as an assembly of finite sized particles. These particles are referred to as *finite elements* and the points at which one element touches another is called a *node*. The behavior of the particles (elements) and thus the overall geometry, is obtained by formulating a system of algebraic equations that can be solved by a computer.<sup>11</sup>

The use of classical methods is probably the best way to analyze simple structures, but when the geometry becomes complicated, finite element models become much more practical, if not necessary. A typical finite element solution to a structural problem will consist of several steps. The first step is to model, or *discretize* the structure. This consists of drawing the geometry of the structure into the program and dividing it into appropriately sized elements, or *meshing* the solid, as it is referred to. Next, the elements are assigned appropriate properties, such as density,

specific heat capacity, or thermal conductivity. Loads, such as heat flux or forces, are then applied and boundary conditions are assigned. A typical boundary condition might be ambient temperature, or an immovable side of a plate under stress. The last step is to solve the linear system of algebraic equations generated by the aforementioned steps, and to display the results in a meaningful way using images, plots, or data tables, for example.<sup>12</sup>

A program called COSMOS/M was used to create just such a model of the brick kiln. As might be expected, however, this model was based on myriad assumptions. The following is an account of each and how it contributed to the model. It is important to note here that only the final geometries and values used are chronicled here. In fact, the model described below is roughly the tenth consecutive model built in an attempt to describe the kiln accurately.

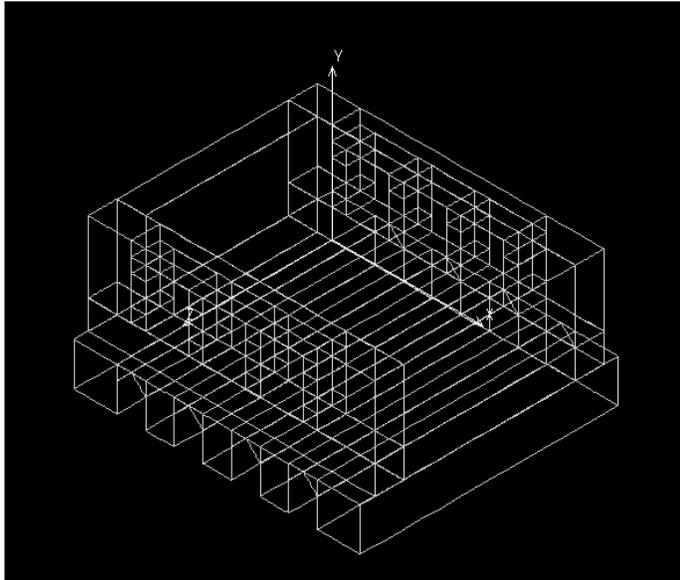
## **B. DIMENSIONAL AND STRUCTURAL ASSUMPTIONS OF THE MODEL**

The model was made to scale in SI units from measurements taken of the kiln and minor geometrical simplifications were made. The most significant of these was the assumption that the tunnels were pointed at the top and ended below the body of the kiln when in fact the tops were corbeled and reached into the body nearly six inches. Another simplification was to slightly enlarge the

the small vent holes intended to see pottery cones during the early stages of the firing, and later sealed. This assumption was made because mesh density of the model was too coarse (.25m x .25m x .25m) to allow smaller holes to be constructed.

### **C. PROPERTY ASSUMPTIONS OF THE MODEL**

The first, and perhaps most important, assumption made was to consider the kiln as two separate but connected solid masses. The first of these was the permanent, mortared kiln shell, while the other was the mass of unfired bricks in the center of the kiln. Each of these had different property values. For example, the loosely packed bricks in the center transmitted heat much more readily than the mortared outer walls. The assumption of solid volume was made to enable the COSMOS/M HSTAR module to handle the necessary computations in a feasible amount of time. In reality, the kiln is comprised of evenly spaced bricks in orderly rows. This simplification from a solid with regular gaps to a complete solid is similar to the assumption that the woven fabric of a shirt can be assumed to be one type of material rather than an assemblage of tiny strings.



**Figure 17- Skeleton of FEM showing geometric assumptions**

Following the geometrical assembly of the kiln in the modeling program, it was necessary to determine which factors accounted for heat transfer and heat loss.

#### **D. ASSUMPTIONS CONCERNING CONDUCTION**

Conduction is simply the transfer of energy from the more energetic particles of a substance to those particles of the substance with less energy. In solids, as is the case here, this transfer is due to vibrations and free electron transport. The rate of conduction through a layer of material is proportional to the temperature difference across the layer, but inversely proportional to the thickness of the layer. This relation can be described by:

$$Q_{\text{conduction}} = -kA \frac{dT}{dx}$$

an equation known as Fourier's law of heat conduction. Q is defined as a heat flux, through an area A, with a rate given by  $T/x$ . The constant of proportionality, k, is known as thermal conductivity, and was one of the parameters required by COSMOS/M in the design of the model. The value for "common brick" was obtained from a table as .72 W/(m K).<sup>13</sup> This value was scaled down to 80 per cent of its original value (.576) for the mortared elements of the kiln to account for the fact that heat doesn't propagate through the mortared walls as fast as through the main body. This is due to the fact that the major mode of heat transfer was hot air rising through the kiln, and there were no gaps for this current in the mortared sections. The value for thermal conductivity of the central mass of spaced bricks was .72 W/(m K) in both the x and z directions, but increased to 7.2 in the y direction. This huge increase was to account for the speed at which the heat propagated up through the kiln. This value needed to be determined by experiment with the finite element model because a value for thermal conductivity through unmortared bricks taken as a solid obviously hasn't been determined experimentally. The conductivity of the mortared bricks was assumed to be uniform in all directions.

Since the kiln structure was simplified to a solid, by definition the only way heat could transfer throughout the body of the kiln, at least as far

as the model was concerned, was conduction. This is also a simplification because in the actual kiln, air could circulate between the bricks and there would be convective heat exchange as well.

### **E. ASSUMPTION CONCERNING CONVECTION**

Convection is the transfer of energy between a solid surface and an adjacent liquid or gas that is in motion. The faster the motion, the greater the energy transfer. For this model, natural convection is assumed, as opposed to forced convection, which involves increasing the motion of the surrounding gas artificially, and can be expressed by Newton's law of cooling:

$$Q_{convection} = hA(T_{surface} - T_{\infty})$$

where  $h$  is the convection heat transfer coefficient,  $A$  is the surface area,  $T_{surface}$  is the surface temperature and  $T_{\infty}$  is the ambient atmosphere (fluid) temperature. For the kiln model,  $h$  was assumed to be  $.1 \text{ W}/(\text{m}^2 \text{ K})$  across the top of the kiln. Since the value of the heat transfer coefficient is determined by the air around it and the orientation of the surface (horizontal, vertical) and the shape of the surface (cylinder, plane), this value was also chosen according to the behavior of the finite element model. Convection was only considered on the top of the kiln, because the top of the kiln was the only side on which the main body of the bricks was open to the air. Radiation was the dominant heat transfer mode

elsewhere.  $T_s$  was calculated continuously by COSMOS/M and  $T$  was assumed to be 285K (55 F).

## F. ASSUMPTIONS CONCERNING RADIATION

Radiation is energy emitted by matter in the form of electromagnetic waves (photons) as a result of changes in the electronic configurations of the atoms or molecules. Unlike conduction and convection, radiation does not require a medium for transfer and can be described by The Stefan-Boltzmann law

$$Q_{radiation} = \epsilon \sigma A (T_s^4 - T_{surrounding}^4).$$

$\epsilon$  in this case is defined as emissivity, which, ranging between 0 and 1, measures how closely a surface resembles a blackbody (1 being a perfect emitter/absorber, 0 being a perfect reflector). The emissivity in this case was taken to be .93, a value in keeping with information available for both dried mud and brick faces.<sup>14</sup> The Stefan-Boltzmann constant,  $\sigma$ , was defined as  $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \text{ K}^2)$ . The surrounding temperature was again assumed to be a constant of 285K (55 F), and the surface temperature was modeled roughly and estimated using a time curve generated from data taken during the firing with a hand-held thermocouple. Thus, the surfaces were not all considered to be radiating at the same rate and as a result, as one would expect, the roof and portions of the kiln above the eyes radiated much more heat than the sides of the kiln without eyes.

The density of all portions of the kiln was taken to be  $1920\text{kg/m}^3$ ,<sup>15</sup> and the specific heat capacity of the bricks was taken to be  $835\text{J/kg K}$ .<sup>16</sup> These values were obtained from tables.

## **G. ASSUMPTIONS CONCERNING HEATING**

Perhaps the most complicated part of the model was the determination of how best to model the actual fires and the amount of heat they expel. Because a fairly accurate account of the number of logs thrown into each eye at a given phase of the firing was recorded, they were the backbone of the fire model.

Given that birch has a density of  $44\text{ lbs/ft}^3$  and maple has a density of  $38\text{ lbs/ft}^3$ ,<sup>17</sup> it was assumed that the kiln was fired with typical hardwood of density  $40\text{ lbs/ft}^3$ ,  $640\text{ kg/m}^3$ . A cord of wood (nearly nine cords were consumed throughout the burning) is 8 feet by 8 feet by 4 feet, but the solid content of a stacked cord is only about 70% so it was assumed that a cord of wood contains  $2.5375\text{ m}^3$ .<sup>18</sup> Given that an average log thrown into the kiln is roughly 16 inches long and 5 inches in diameter, the volume of one average log was assumed to be  $.005\text{ m}^3$  and given the aforementioned density of wood, the average log weighs 3.2 kg or roughly 3 kg (6.6lbs). Similarly, there are 1624 kg in a cord of wood. Now, it has been assumed that the summits of the kiln tunnels would absorb about 80 percent of the heat from each log as it is burned and the remaining 20 percent would either be lost when the doors are opened or enter the side walls of the tunnels. Given the dimensions of the kiln and the fact that

wood yields roughly 19,900 kJ/kg,<sup>19</sup> a conservative estimate, it was assumed that for each log burned, the top of the tunnels would experience a heat flux of 467.0 W/m<sup>2</sup> and the sides would experience a flux of 81.7W/m<sup>2</sup>. That correlates to 1842 Watts per log and assumes that each log is burned completely in one hour.

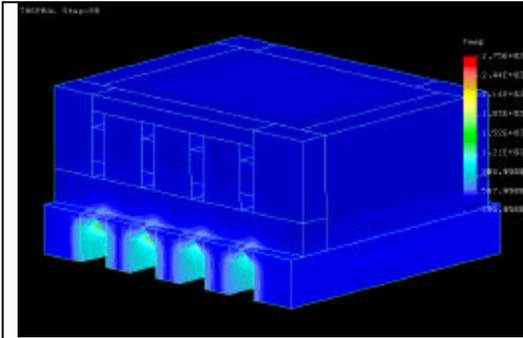
These assumptions were then used in conjunction with a time curve based on the number of logs burned per hour at the different eyes. A fairly accurate picture was recorded of the heat flux in the kiln eyes during the week of firing. Table 1 is a summary of the assumptions made for the model.

		Value for kiln shell	Value for kiln body
DENSITY	kg/m <sup>3</sup>	1920	1920
THERMAL CONDUCTIVITY	W/(m K)		
	in x direction	0.576	0.72
	in y direction	0.576	7.2
	in z direction	0.576	0.72
SPECIFIC HEAT	J/(kg K)	835	835
General value			
DENSITY OF WOOD	kg/m <sup>3</sup>	640	
MASS OF AVERAGE LOG	kg	3	
ENERGY PER LOG	Watts	1842	

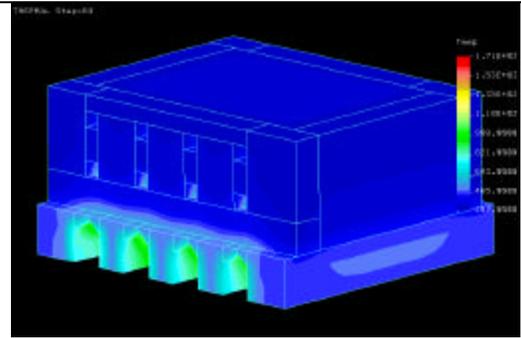
**Table 1- A summary of assumptions made about the kiln for the purposes of the finite element model.**

The model was then executed for the entire week, producing the following images. In looking at the images produced by the FEM, it is important to remember the scales can differ from day to day, and that the

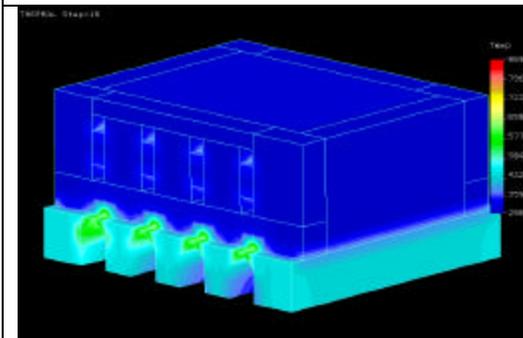
temperatures are given in Kelvin. The thermograms, however, were recorded in Fahrenheit.



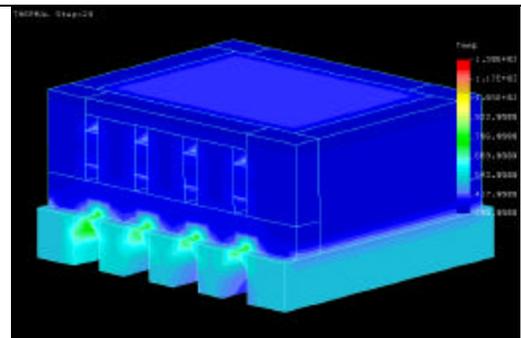
**Figure 18- FEM temperature distribution for Wednesday noon. Temperature ranges from 285K (dark blue) to 2750K (red).**



**Figure 9- FEM temperature distribution for Thursday noon. Temperature ranges from 285K (dark blue) to 1710K (red).**



**Figure 20- FEM temperature distribution for Friday noon. Temperatures range from 286K (dark blue) to 869K (red).**



**Figure 21- FEM temperature distribution for Saturday noon. Temperatures range from 285K (dark blue) to 1300K (red).**

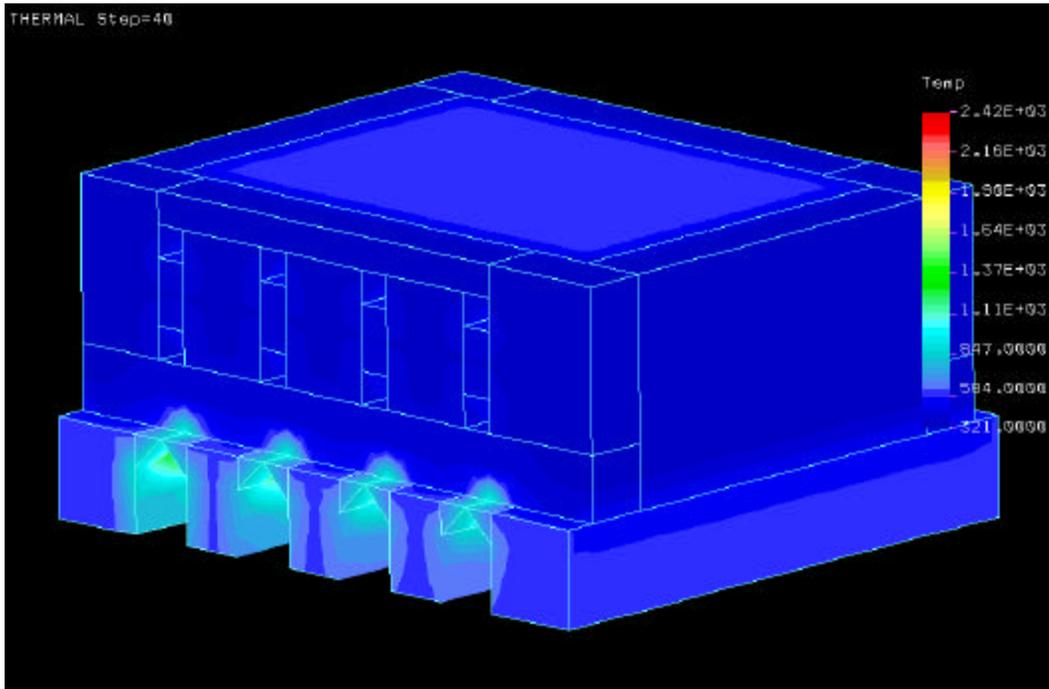
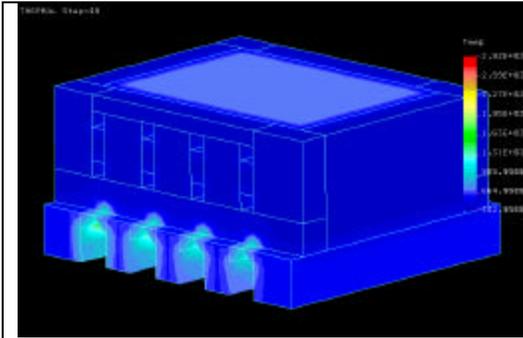
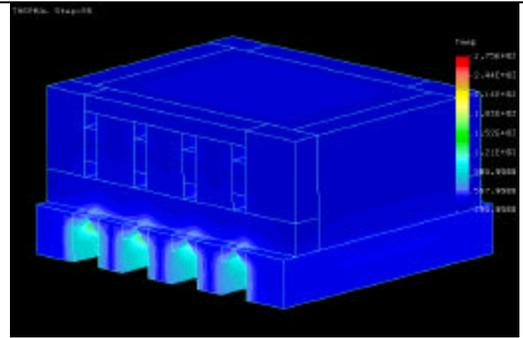


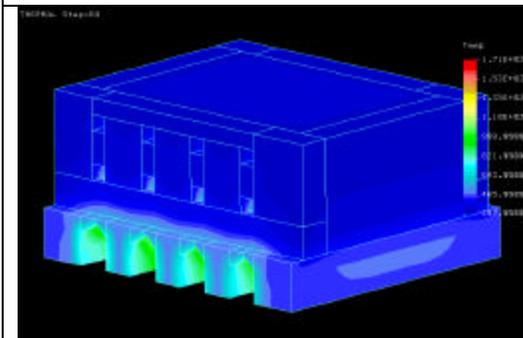
Figure 22- FEM temperature distributions for Monday noon.



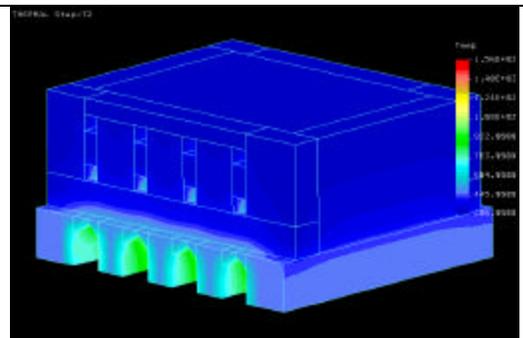
**Figure 23- FEM temperature distribution for Tuesday noon. Temperatures range from 342K to 2820K.**



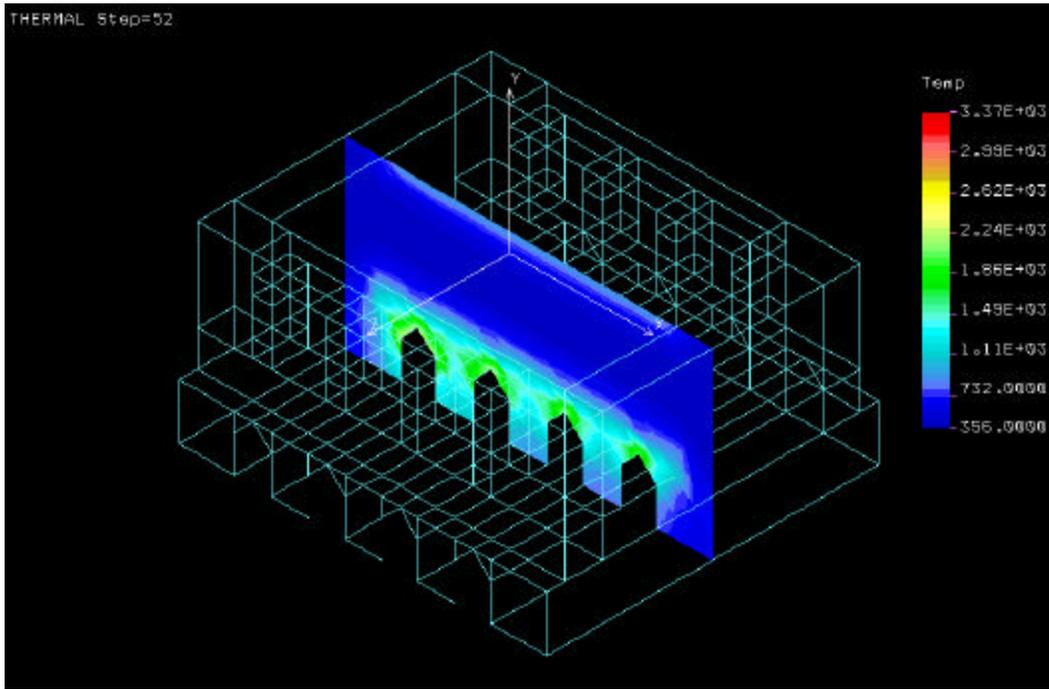
**Figure 24- FEM temperature distribution for noon on the second Wednesday. Temperatures range from 285K to 2750K.**



**Figure 25- FEM temperature distribution for noon on the second Thursday. Temperatures range from 286K to 1710K.**



**Figure 26- FEM temperature distribution for noon on the second Friday. Temperatures range from 286K to 1560K.**



**Figure 27- Cut away view of temperature distribution predictions of FE model, Tuesday midnight**

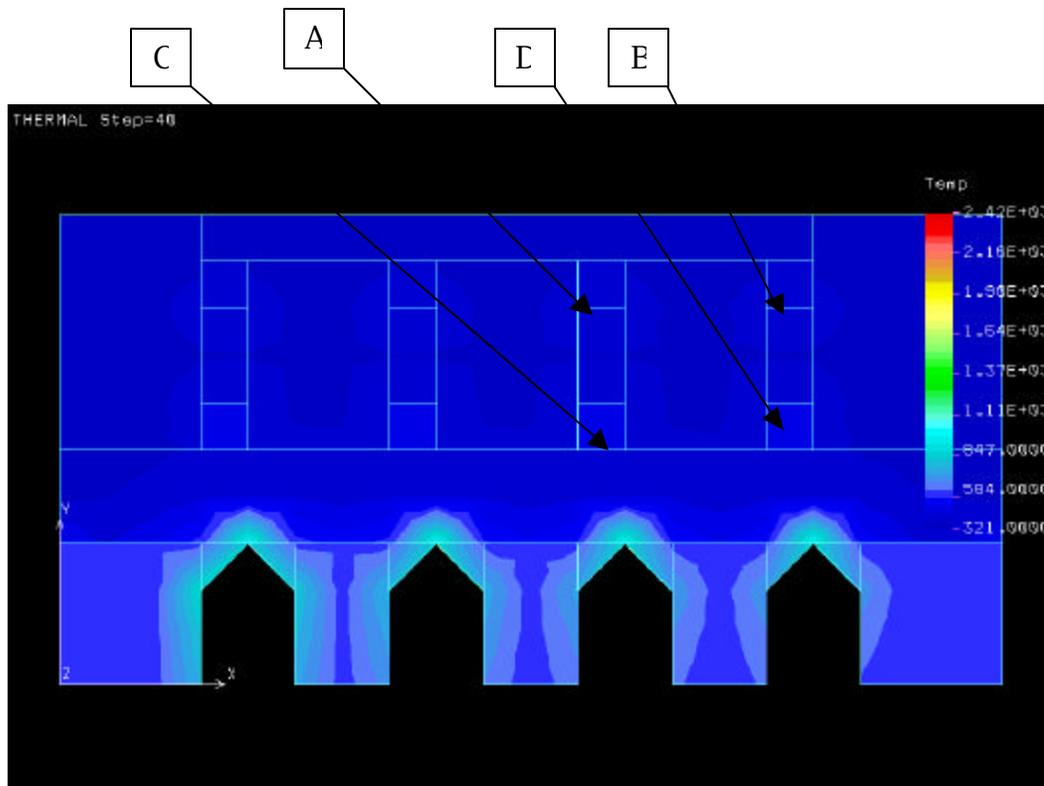


Figure 28- End view of FEM predicted temperature distribution for side 1, Monday Noon

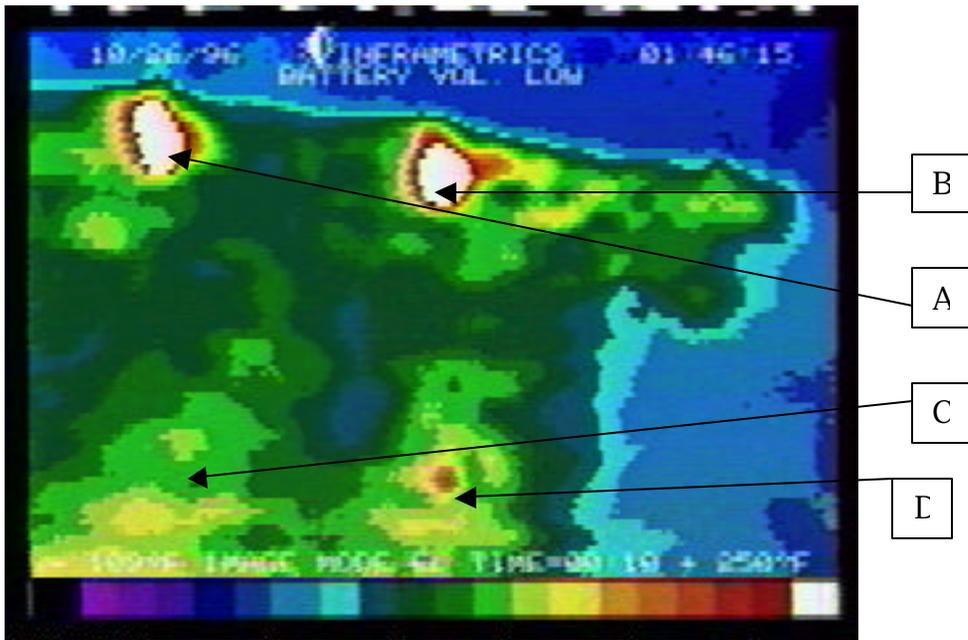


Figure 29- Thermogram of side 1 for 2:00AM, Tuesday

The comparison outlined above in Figures 28 and 29 is an example of the visual agreement between the model and what was observed. One will notice the general shapes of the warmer areas, specifically regions A, B, C, and D, corresponding to the holes in the shell of the kiln, intended to monitor the pottery cones during early stages of the firing.

#### **X ANALYSIS OF THE INFRARED DATA:**

Although qualitatively the model matches the actual kiln fairly well, quantitative measurements needed to be done as well.

By digitizing relevant images from the VHS recording of the thermal images, actual data was able to be extracted. This would normally have been accomplished with supplied software from Inframetrics, but due to

the age of the system and accompanying computer, and the computer's unreliability, the data was extracted by other means.

Using an image analysis program called IPLab,<sup>20</sup> chosen because of its availability and its ability to deal with color images, each thermogram was converted to its hues. After this conversion, the images were inverted and the scale across the bottom of each picture, unique to each, was used to manually recalibrate the values of the pixels.

For example, for a thermogram with temperature ranging from 102F to 257F, in inverted hue form, the color corresponding to 102F would show up on the image as a pixel value of 64 while that corresponding to 257F would be 246. The pixel values could then be averaged over a relevant area (a convenient feature of IPLab) and converted to their actual temperature value. This conversion was accomplished with a hand calculator, and the results were tallied by hand, and then entered into a program for graphing.

Figures 30 and 31 are plots of time vs. temperature for two specific positions on the kiln: the central region of side 1 and the upper right corner of side 4. The solid lines represent the model's prediction, while the points correspond to data taken from the thermograms at the same spots on the kiln.

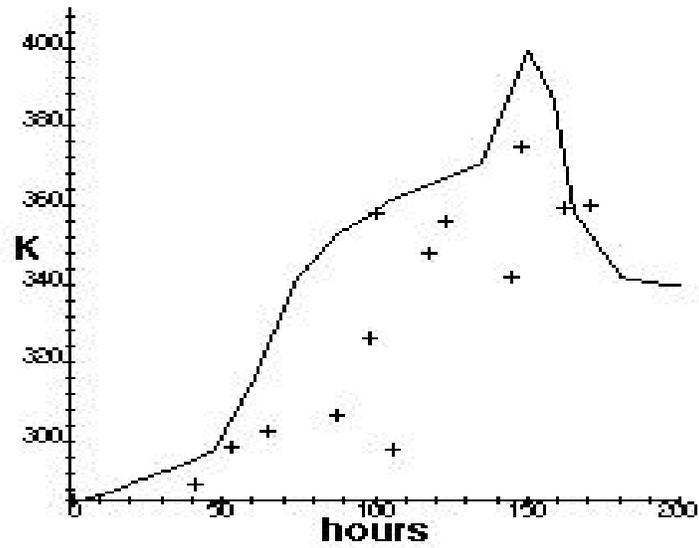


Figure 30- Temperature vs. time for both FEM predictions (solid line) and actual thermogram data (points) for the central region of side 1.

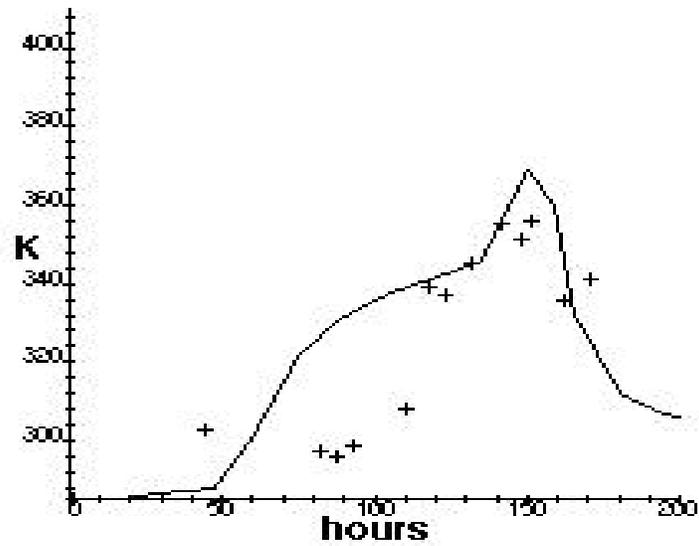


Figure 31- FEM predictions (solid) compared to actual data (points) for upper corner of side 4.

## **XI CONCLUSIONS:**

From the comparisons and observations outlined in this paper, it should be evident that a colonial style brick kiln can be modeled accurately enough to provide insight into its workings and achieve a better appreciation of heat flow through the body of a kiln. It is true that the 1998 burn was extremely successful, even without the help of technology, but it would be a mistake to assume that colonial-style brickmaking has no use for a nondestructive method for quality control based on that fact. The ideas in this paper should be viewed as a beginning and the techniques outlined in this paper are a positive first step towards the refinement of a finite element model and improved infrared imaging procedures. These improvements will lead to an even greater understanding of the brickmaking process, increasing yield and safely permitting successfully larger kilns to be constructed, without the necessity of experts to oversee the process.

## **XII SUGGESTIONS FOR THE FUTURE:**

If further steps are to be taken towards a standardized method of nondestructive kiln evaluation, two areas should be focused upon as areas in need of improvement: data acquisition and finite element model assumptions.

Although the readings taken of the 1998 kiln were highly accurate and detailed, it was challenging to extract relevant data due to the non-standard manner in which the data was acquired. For example, during the

1998 burn, due to the bulkiness of the camera and the location of obstacles like wood piles and uneven terrain, the kiln was often viewed from different angles. At times the camera was also panned from side to side and from top to bottom in order to cover the surface of the kiln. This could be improved upon by using a snapshot style infrared camera and taking data in a manner which would allow all of one side of the kiln to be visible at one time. Thus, four images could be taken for each hour and all of the images from each side could be easily compared. A method that would allow on site evaluation of the data, through a laptop computer would also be useful as a way to use the data being acquired to help the kiln as it is being burned, instead of analyzing the burn after the fact.

The finite element model is another area receptive to improvement. Making the geometry more realistic, improving the accuracy of the constants involved, and making those constants dependent on temperature would increase the effectiveness of the model. Specifically, a better understanding of how best to model the body of the kiln would be a great improvement. The 1998 kiln was modeled as a solid, transferring heat through conduction. If this could be changed to a patterned solid with gaps, convection could be considered inside the kiln.

With these suggestions and the material presented in this paper, it is evident that if desired, a completely nondestructive, noninvasive technique could be developed as a way to monitor the quality of bricks in a colonial-style kiln and to further the understanding of heat transfer through such a structure.

## **APPENDIX A: Brief History of Brickmaking**

Before attempting to analyze a material such as brick, a process like brickmaking, or a structure such as a kiln, it is important to understand its history, especially given the fact that the kiln was built to be historically accurate.

As the principal building material in the world today, bricks are defined as a rectangular unit of clay and sand, either fired in a kiln or dried in the sun. Bricks are also limited in size. As a rule of thumb, if you can lift it with one hand, it is a brick. If it takes two hands to lift, it is a block, no matter what material it is made of.<sup>21</sup>

Brickmaking has its roots in the mud huts of Mesopotamia around 5000 BCE.<sup>22</sup> These mud huts dried slowly, shrank and cracked. To alleviate this problem, the Mesopotamians mixed the mud with straw, shaped this compound into manageable bricks, and left these primitive bricks to dry in the sun before building with them. Evidence of the use of these sun-dried bricks can be found in Europe, South America, India, Africa, and Asia, as well as the Middle East and is in fact still used in some areas where wood is unavailable as a fuel with which to fire the bricks.<sup>23</sup>

Sun-dried bricks, however useful, gave way to the stronger, more useful kiln fired variety between 2500 and 2000 BCE.<sup>24</sup> Brickmaking flourished under the Sumerians until the collapse of the culture in roughly 1700 BCE, giving rise to the massive ziggurat of Ur and the Tower of Babel. With the “loss” of brickmaking technology, it had to be relearned by

later civilizations, most notably the Romans. In fact, the Pantheon itself owes much of its success to bricks, as well as concrete.<sup>25</sup>

Credit for the use of modern bricks, as opposed to the more flat style favored by the Romans, however, should probably be given to the Germans. Buildings built with the more familiar rectangular style of bricks can be found in northern Germany as early as 1150. From Germany, brickmaking spread through the agency of the Cistercians and the Premonstratensians throughout Europe.<sup>26</sup> Of particular importance is the spread of brickmaking to Britain.

It is uncertain when or how brickmaking was introduced to England, but it seems probable that the spread was a result of Britain's trading links to the Hanseatic league. It appears that along with the technology, bricks mainly appeared in Britain as ballast on ships loaded with other goods. There is evidence that very soon after bricks started arriving in Britain, brickmakers from the continent, notably the Netherlands and Germany, began arriving as well. As can be expected, brickmaking in England gradually changed from a need-based operation to a speculative industry and it is around this point in history that the story of Colonial brickmaking begins.

It is often thought that the log cabin was the preferred form of early North American dwellings, but in fact that style arrived with Swedish settlers only as late as the end of the seventeenth century. Brick, however, was a major building material from the beginnings of colonization. Among the early Dutch and British settlers in the new world

brick construction was well known.<sup>27</sup> Because of resistance to fire, brick construction became more common as manufacturing became less expensive.

To make bricks in a manner employed by early resident Virginians is a long and at times delicate process. It is begun in the late fall, "before *Christmass*"<sup>28</sup> by digging up a quantity of suitable clay. Suitable clay is often characterized as a "mild clay," meaning that it contains between 30 and 35 percent sand. The clay to sand ratio affects bricks in a multitude of ways. For example, the higher the clay content, the lower the firing temperature. However, this benefit is offset by large amounts shrinkage and the increased cracking encountered with such "fat clays." Conversely, a "thin clay," or one that contains more than 35 percent sand, requires temperatures well over 2000F, which is difficult to reach with a wood fired kiln.<sup>29</sup> Thus, a suitable clay is comprised of a middle ground between high and low sand content. Once dug, the clay is left exposed and allowed to "weather" or go through many freeze-thaw cycles in order to break up large chunks and make it more workable. The clay is then, after the last freeze, or around Easter, put in large pits dug for the purpose and there mixed with sand and perhaps other types of clay. The pit is then treaded barefoot until the clay has roughly the texture of dough or peanut butter. This is done to remove any chunks of mud that may remain and thus keep bricks from exploding during firing.

At this point the clay is molded into the typical brick shape by a molder and moved to a sand bed to dry for several weeks in the sun.



**Figure 32- "Bearing Off" the wet, or "green" bricks.<sup>30</sup>**

After the clay bricks have dried sufficiently to make them somewhat hard, they are stacked loosely in a covered tent built for the purpose and allowed to sit until October, when the actual kiln structure is built.

The kiln itself can vary tremendously in size, from a small number of bricks (about 5000) up to nearly 100,000 bricks. The kiln built in October 1998 was roughly 16 feet square, nearly 9 feet tall, and consisted of roughly 10,000 bricks (roughly enough for a large chimney). The bricks are stacked carefully with about a finger spacing between each one so as

to allow heat to circulate more efficiently and tunnels, or eyes as they are called, that run completely through the kiln are left at the base. The kiln is then covered in mud, or daub, to help keep heat in, and keep smoke from coming out the sides of the kiln.

At this point the kiln is ready to be fired. There are two important components of firing, namely drying and the actual firing. The first of these consists of the first couple of days of the firing process, and is intended to simply finish "cooking out" the water from the bricks. Although they may have been drying for a considerable amount of time in the sun, water still remains and excessively high temperatures could crack the bricks. The general signal that the drying is done comes in the form of clear smoke. As the bricks dry, the smoke rising from the kiln is fairly thick and is described as being "white and puffy." When the bricks have lost most of their water, the smoke tends to run clear, signaling the next phase of the burn. The next step is the actual firing, during which, depending on the type of clay, the temperatures must reach at least 1650 F, ideally around 1850 F but below 2000 F, for between eight and twelve hours. This is the delicate part of the firing process because not enough heat will result in poor bricks but too much will cause cracked and destroyed bricks. The other challenge of this phase of firing is to allow the higher temperatures to reach as many bricks as possible and thus increase the percentage of bricks that are of better quality (naturally, the bricks closest to the fire are extremely hard, and those furthest away are more soft).

The kiln is then left to cool for a period of time, disassembled, sorted according to quality and then the bricks are ready for use.



**Figure 33- Sealed up kiln cooling off**



**Figure 34- Photo showing the kiln partially disassembled as the bricks are being removed and sorted for use in the spring. Note the differing colors of the bricks, denoting differences in hardness. The grayish bricks are much harder than the more salmon colored ones.**

## **APPENDIX B: NARRATIVE CHRONOLOGY OF 1998 KILN FIRING:**

This is a day by day account of the data taken. The times in bold listed without any narrative denote that data was taken, but nothing of particular note occurred.

### **Wednesday, Oct. 21, 1998-4:00PM**

At 4:00 in the afternoon I arrived at the kiln and took some measurements before the fires were lit. As could be expected, the data was fairly uninteresting, because the kiln was at about the same temperature as the surrounding environment.

**8:45 PM**

After the kiln was lit, I took some measurements of the eyes of the kiln. This portion of the firing was only meant to dry out the bricks, so the fires are kept intentionally low. These measurements are fairly close in and only show heat right around the eyes. The eyes are still uncovered at this point.

**Thursday, Oct. 22 - 1:50PM**

It had rained a little (maybe 1/4 inch) the night before and the fires are still very low at this point. There is still virtually no signature at the ends of the kiln without eyes. This marks the first time you can see the vent holes with the IR camera.

**10:50PM**

This reading only includes one perspective of the eyes. It is close up and the kiln is indeed warming up, but there still isn't much signature from the ends of the kiln without eyes.

**Friday, Oct. 23 - 9:50AM**

This marks the first day that a visible temperature increase is visible throughout the kiln. The kiln has warmed up thoroughly.

**3:30PM**

This is the first reading that I had the thermocouple for. This allowed me to get accurate ambient temperature readings and to read the temperature of the face of the kiln. The surface was about 96.8F and the reading inside the access hole is 280F (See figure).

**10:00PM**

The heat is really visible throughout the kiln now. This is shown both in the IR pictures and the thermocouple readings.

**Saturday, Oct. 24 -8:45AM**

No IR data was taken this time because the video camera died on me and I had to go get the charger, but I took several thermocouple reading in different spots of the kiln.

**10:00AM-10:30AM**

After sprinting to and from the lab to charge up the VCR battery at 10 AM the roof (logs and tarp) came off the kiln and at 10:30AM I took some more data, this time with commentary on position and variables after the data. This is a practice I keep up throughout the rest of the data. I take data and then, with the camera on video (visual) mode, I shoot video along with comments on variables or notes on things to notice.

**11:45AM**

At this point the goal is to bring the kiln up to temperature (about 1400F) slowly. The iron doors are added at this point and the fires are beginning to get much hotter.

**1:30PM**

This time I take a temperature reading on the far wall (without eyes) with the thermocouple.

**3:00-3:15PM**

This time I take a temperature reading on the close wall (without eyes) with the thermocouple. I take a reading on only dried mud and it is important to note that the dried mud is in the hot sun.

**4:20PM****5:45PM****8:40PM**

This marks one of the first times I pan from side to side in the video. The infrared video is followed by a dark narration (I hadn't hooked up the floodlight yet).

**9:35PM**

There is a dolphin sculpture in the near side of the kiln (as well as a ladder in the data). And on the side of the kiln with the eyes closest to the tent, a poker is visible in the video.

**10:30PM**

**Sunday 3:50AM** (not including daylight savings time)

According to the interpreters, despite a constant rate of adding wood (5 sticks each per hour for the outer eyes and 4 per hour for the inner two eyes) the coals aren't as good on the side closest to the public. The attempt is to spread the coals evenly throughout the length of the tunnels in the outer two eyes while piling the coals more to the middle of the two central tunnels.

**7:00AM** not including daylight savings time

The positions of the camera are identical to those at 3:50AM.

**10:00AM** Now using daylight savings time

A person daubing and a ladder are visible in the data.

**11:30AM-12:15PM**

This set includes one image of the fourth tunnel (farthest from the tent) without the doors on.

**3:00 - 3:30PM**

The hole in the wall above the eyes that I have been using to take temperature readings is now muddled up. There is also some new door art (Bobby painted a stick figure on the second door from the tent using a daubing brush). It is also convenient, because his drawing marks the iron door that is slightly thicker than the others.

**5:45-6:00PM**

The first time I use the halogen floodlight on the VCR camera while doing my narration.

**7:40PM**

**11:00 - 11:25PM**

One of the data sets is taken during a stoking.

**12:00 Midnight**

**Monday 1:00 - 1:20 AM**

A little fire glow is now visible through the top of the kiln (A ladder is used to climb up to see) immediately after the kiln is stoked.

**4:15 - 4:30 AM**

The fires are quite high now. The wood rate is up to 9 sticks per hour for each of the outer two tunnels and 7 sticks per hour for each of the inner two tunnels. It is also interesting to note that I Took some infrared images of the kiln from pretty far away (60 feet).

**9:15 - 9:45 AM**

There is some new daubed "art" on the door on the side of the kiln closest to the tent and the wood rate is still the same.

**12:00 Noon - 12:20 PM****4:00 PM****6:15-6:30PM**

I take one reading close to the eyes on the side of the kiln closest to the public.

**8:45 - 9:00PM**

An orangey glow is now visible through the cracks in the top of the kiln at all times (not just during the stoking). I measure the heat in one of these cracks with the thermocouple.

**Tuesday 2:00 - 2:20 AM**

I overslept a bit. The orange glow is becoming more pronounced in the cracks on the top of the kiln.

**5:40 -5:50AM**

It is EXTREMELY FOGGY. At this point, the interpreters say that the tunnel closest to the tent is hot enough that they are backing off to only 5 sticks per hour for it. They are also slacking off to 7 per hour on the other outer tunnel.

**8:50 AM**

It is less foggy, but still a bit damp. The lens of the IR camera may be a little fogged up. Some of the iron doors are rotated (their positions are switched).

**12:45AM- 1:10PM**

A small region (roughly ten bricks) in the top course was removed from the roof of the kiln to facilitate heat flow.

**4:00 - 4:20PM**

**6:25-7:00PM**

**9:45-10:00PM**

**Wednesday 1:00 AM-1:30AM**

The peak temperature is reached (in theory) at about 10PM and this data is being taken during full stoke.. The idea at this point in the firing is to maintain this high temperature until about 6:00AM It is also extremely foggy and there is some condensation on the lens of the camera.

**8:10AM**

No thermal data was taken due to the fact that I woke up asleep at my desk at 8:00AM, having missed the closing of the kiln, and was unable to take readings because I had a Chemistry Exam to attend. However, the last stoke was just after 5:30AM and then the doors were shut up by daubing over them and sealing the eyes shut. The kiln is now left to cool off on its own.

**12-1:00PM**

The kiln is cooling off now.

**9:00-9:45PM**

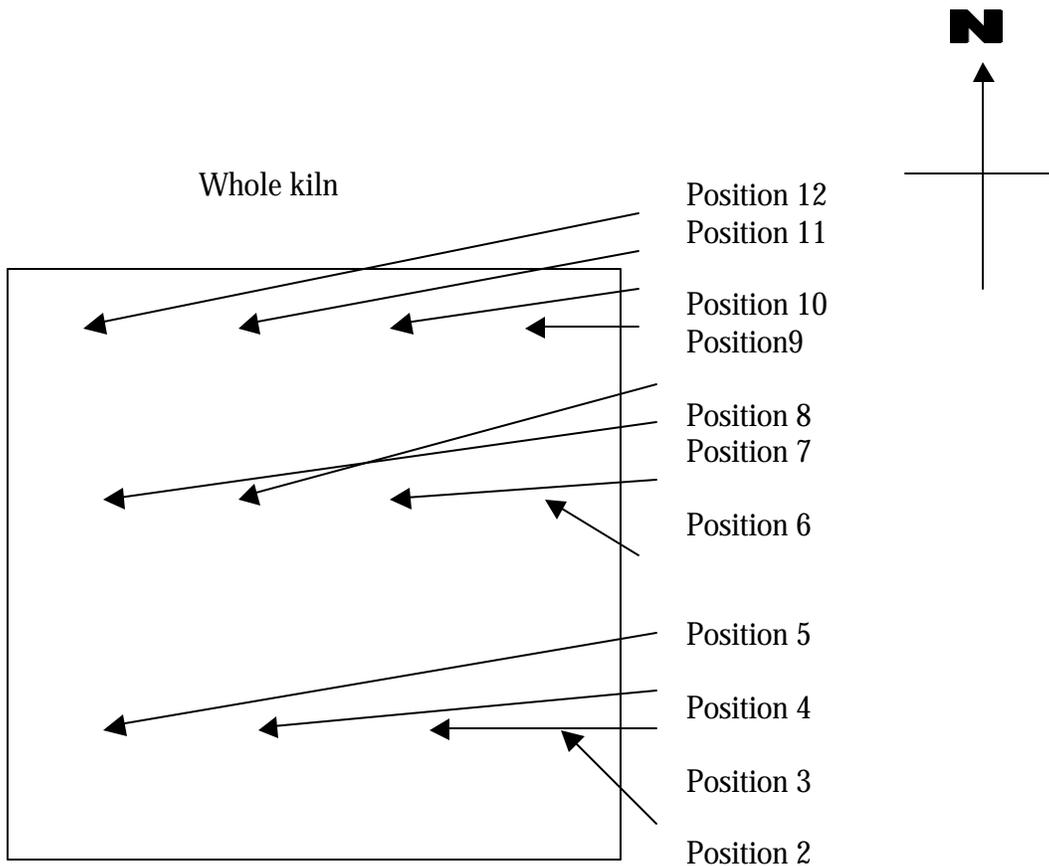
**Thursday 7:45PM**

The signature has dropped off significantly enough to make the kiln fairly uninteresting to look at.

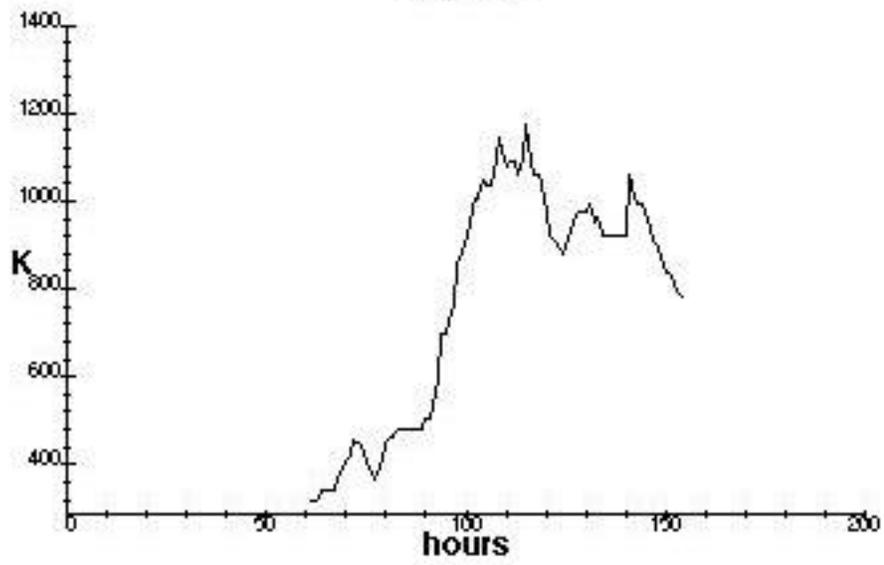
## APPENDIX C: DATA FROM 1989 BURN

The following is a compilation of plots of temperature (Kelvin) vs. time for given positions of the kiln fired in 1989. This data was compiled with the use of thermocouples by colonial interpreter in 1989 as the kiln was fired. It is important to note that since data was not taken in each case until the kiln had significantly heated up, a period of two and a half days, corresponding to a typical drying period, has been artificially added to the front of each plot to aid comparison with the 1998 kiln.

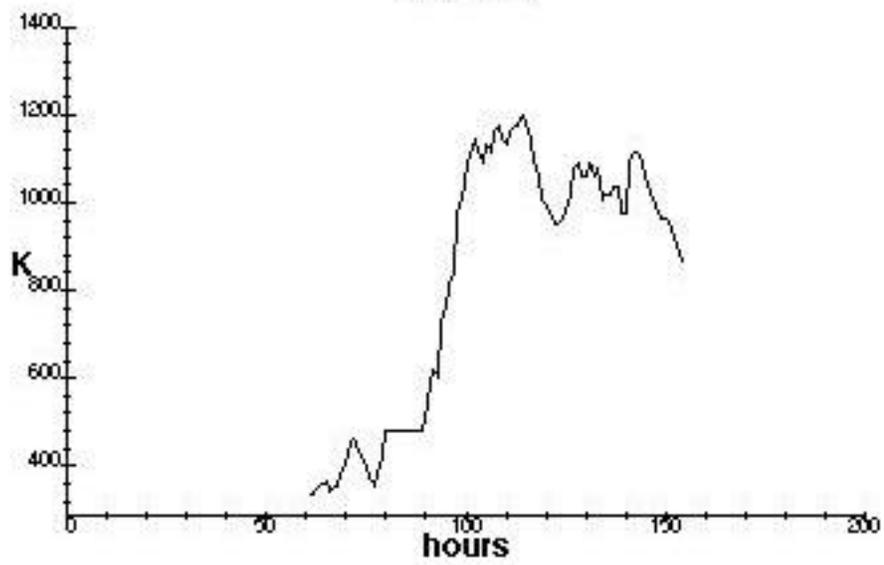
Below is a diagram of the position of each thermocouple's position in the 1989 kiln. Note that in this thermocouple configuration, as opposed to the configurations from 1994, 1995, and 1996, all of the thermocouples are in the same plane.



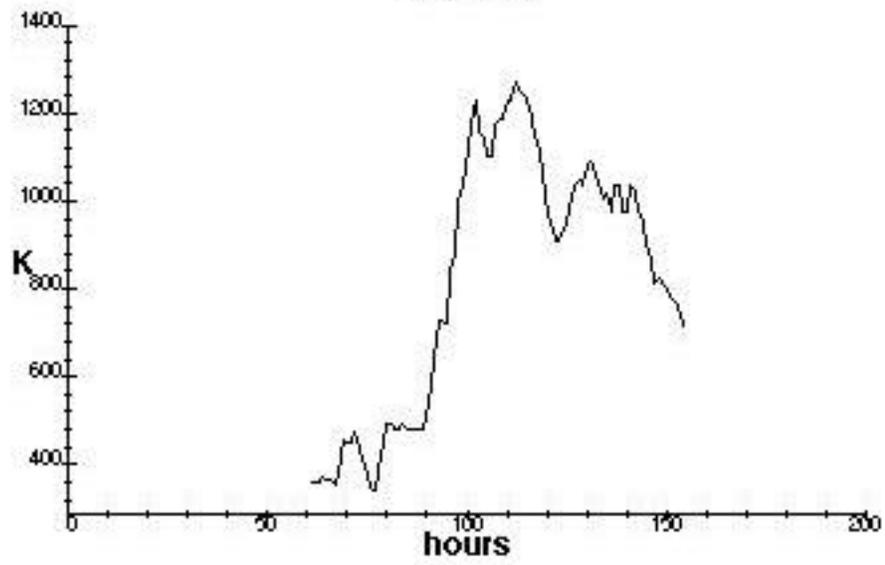
Position1



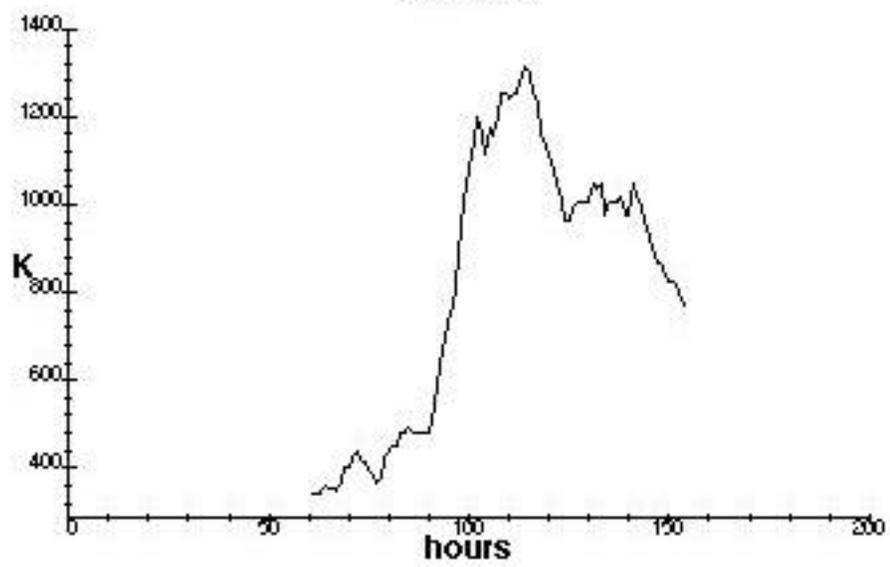
Position2



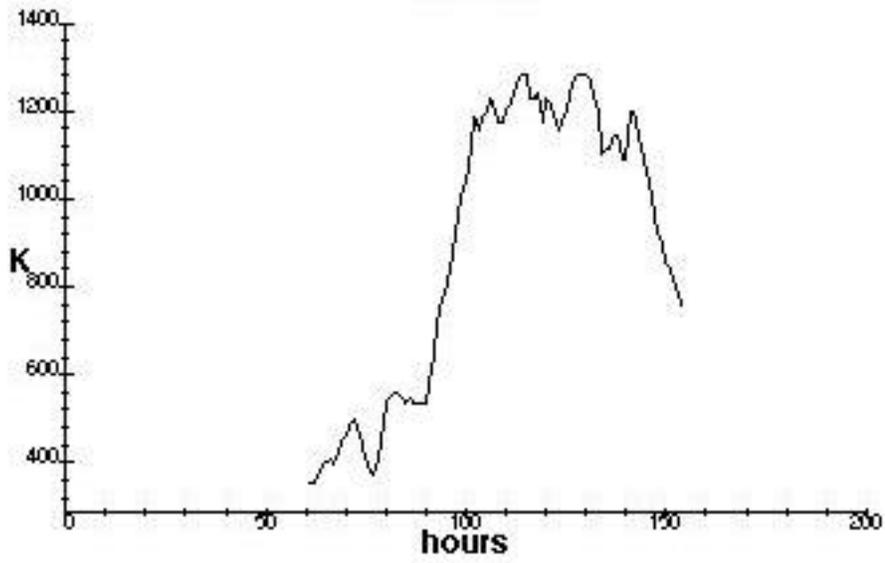
Position3



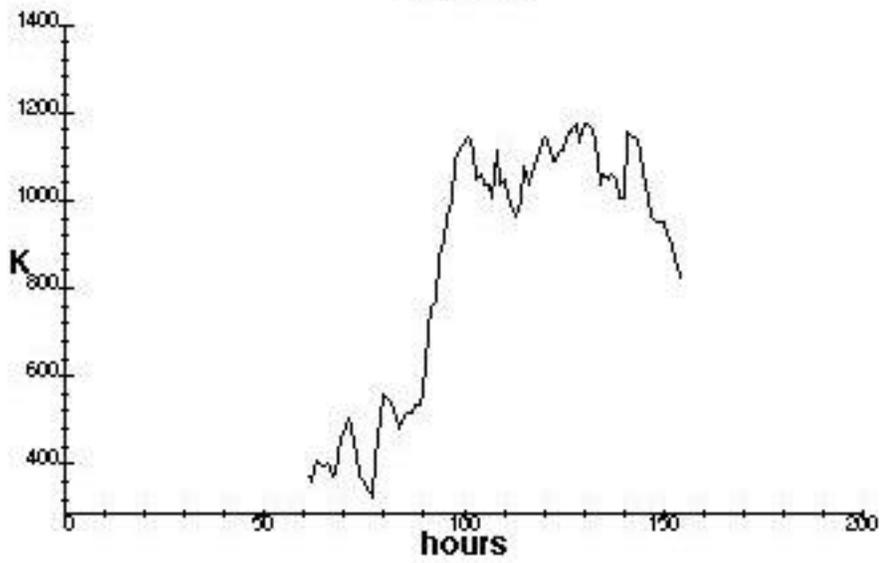
Position4



Position5



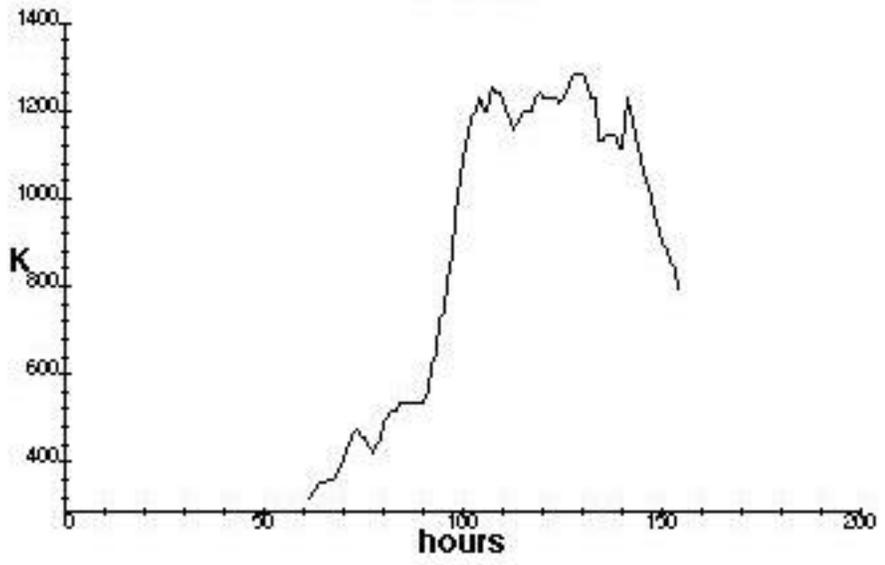
Position6



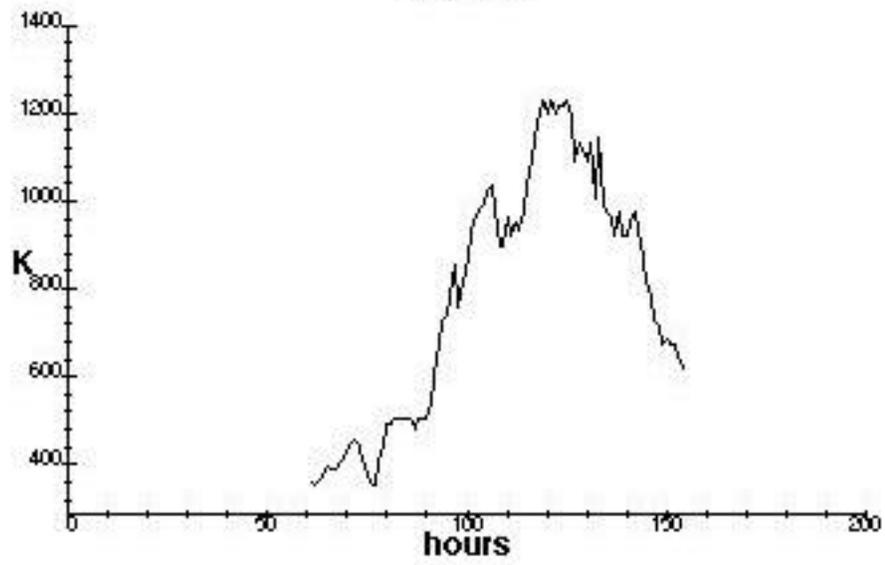
Position7



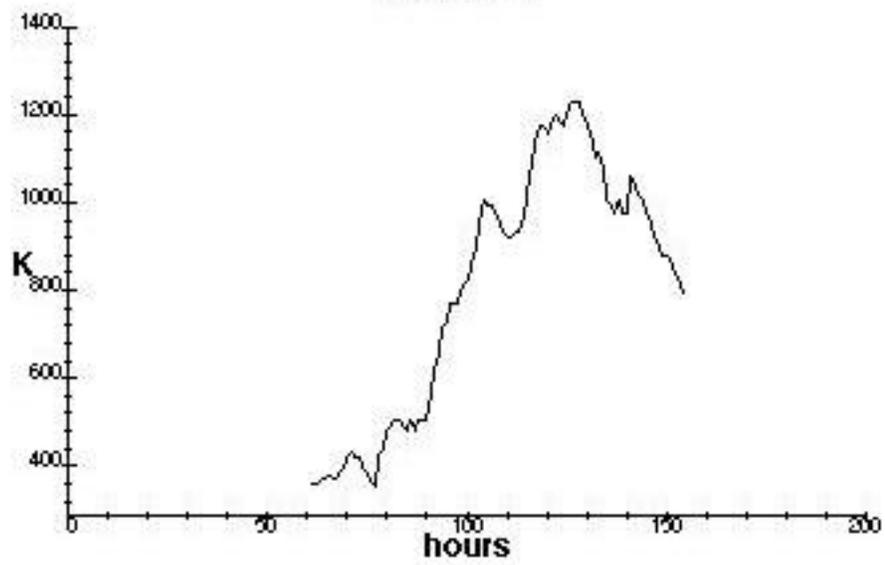
Position8



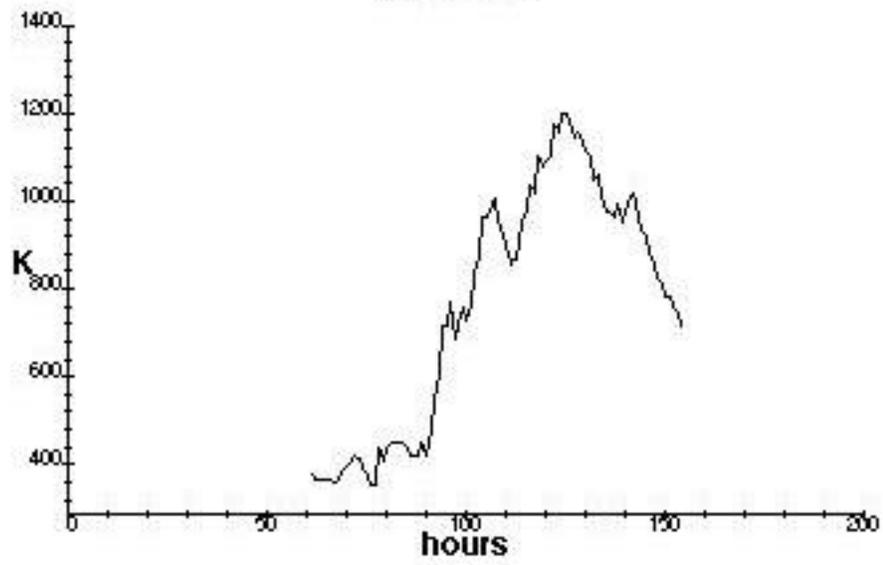
Position9



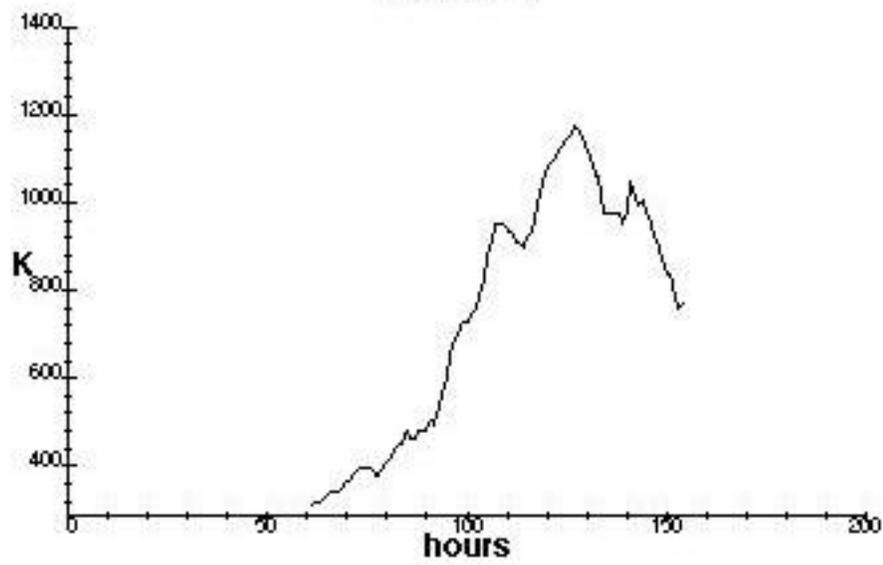
Position10



Position11



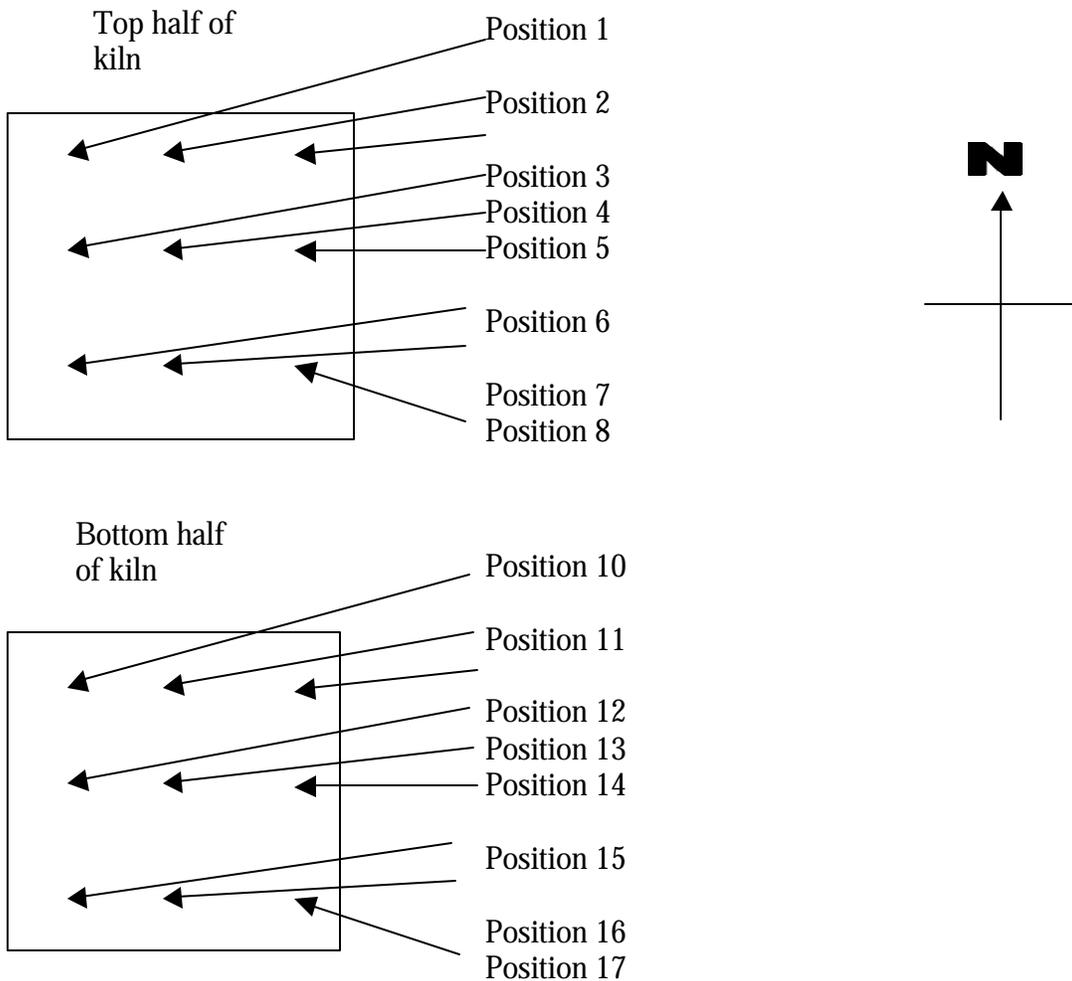
Position12

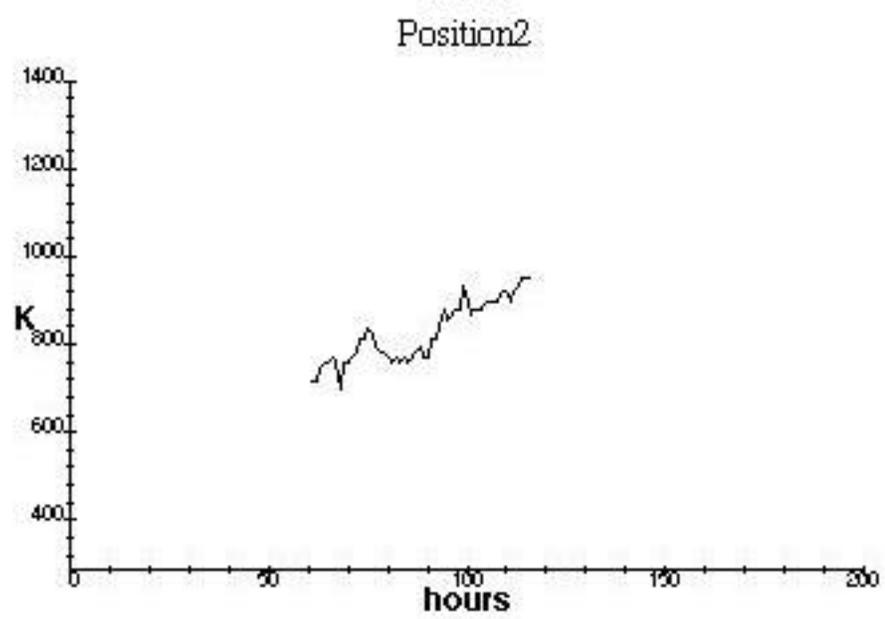
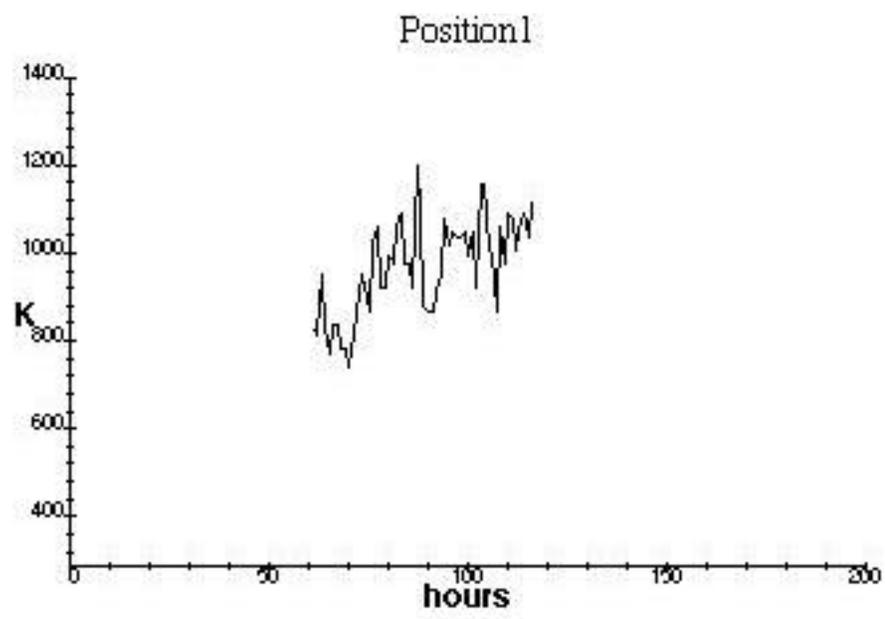


## APPENDIX D: DATA FROM 1994 BURN

The following is a compilation of plots of temperature (Kelvin) vs. time for given positions of the kiln fired in 1994. This data was compiled with the use of thermocouples by colonial interpreter in 1994 as the kiln was fired. It is important to note that since data was not taken in each case until the kiln had significantly heated up, a period of two and a half days corresponding to a typical drying period, has been artificially added to the front of each plot to aid comparison with the 1998 kiln.

Below is a diagram of the position of each thermocouple in the kiln in 1994.





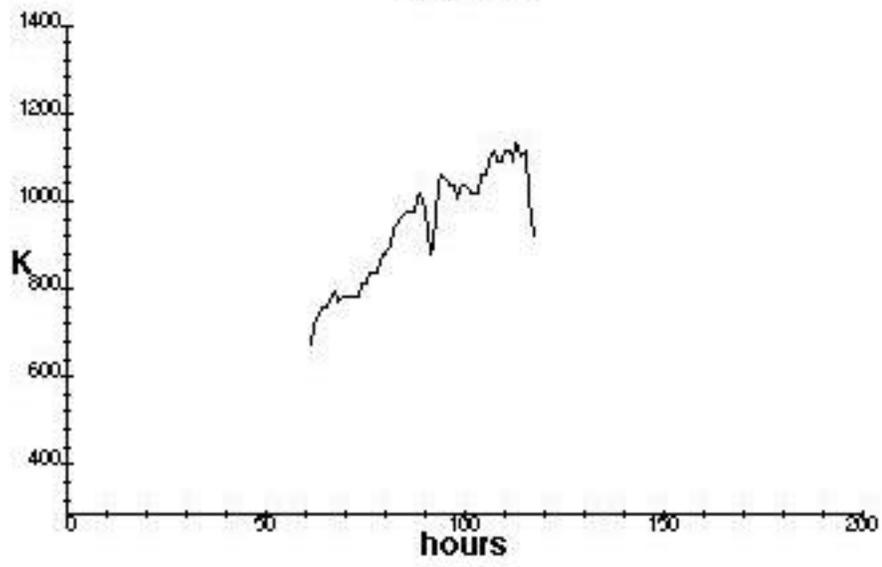
Position3



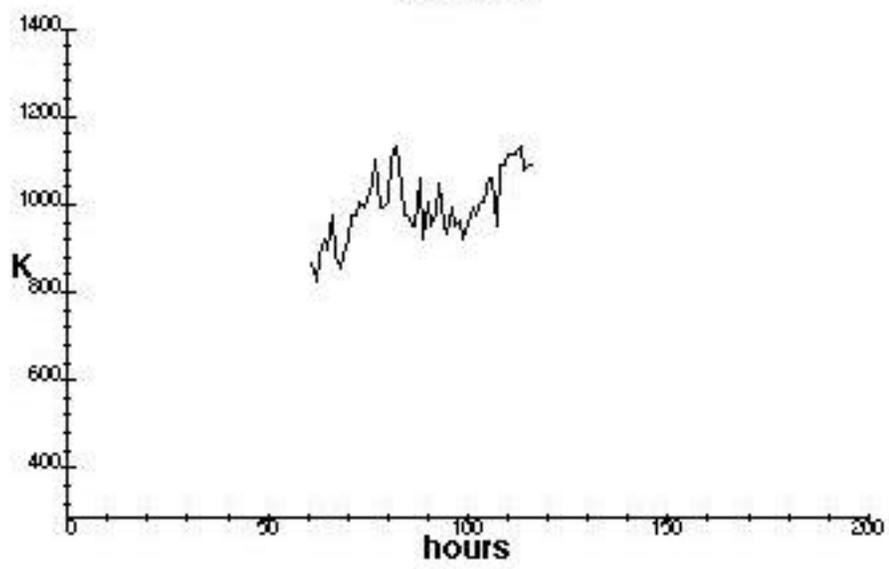
Position4



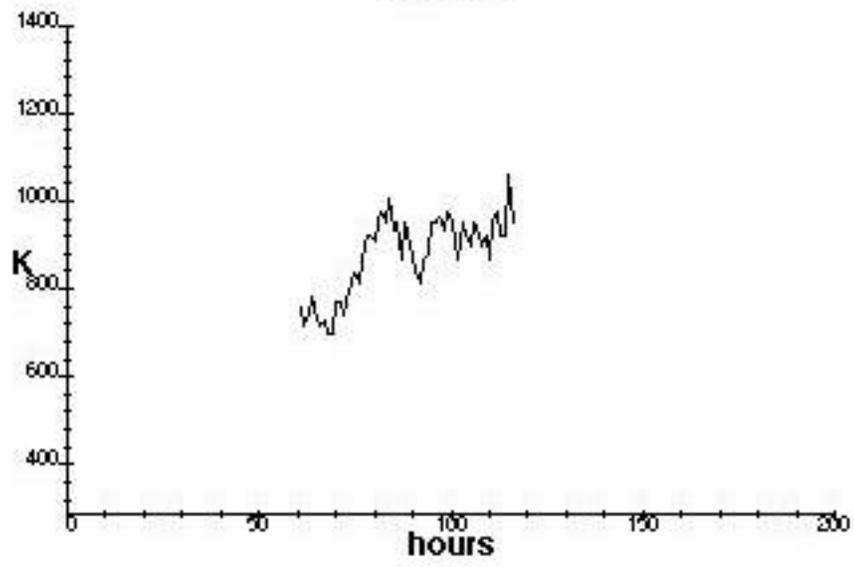
Position5



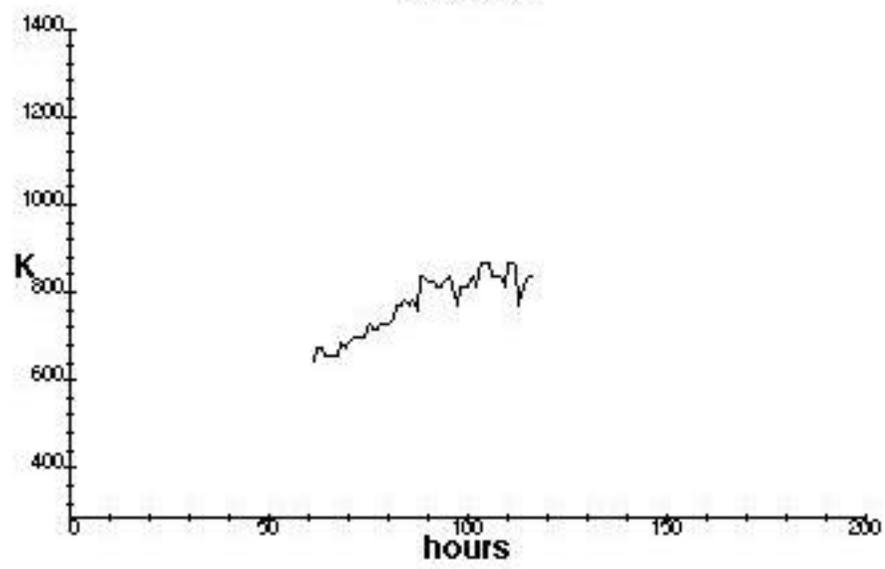
Position6



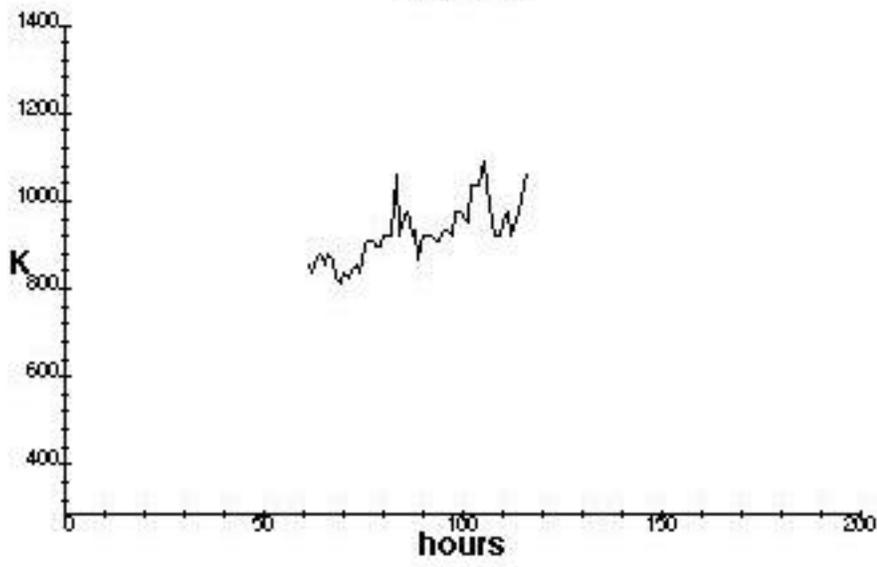
Position7



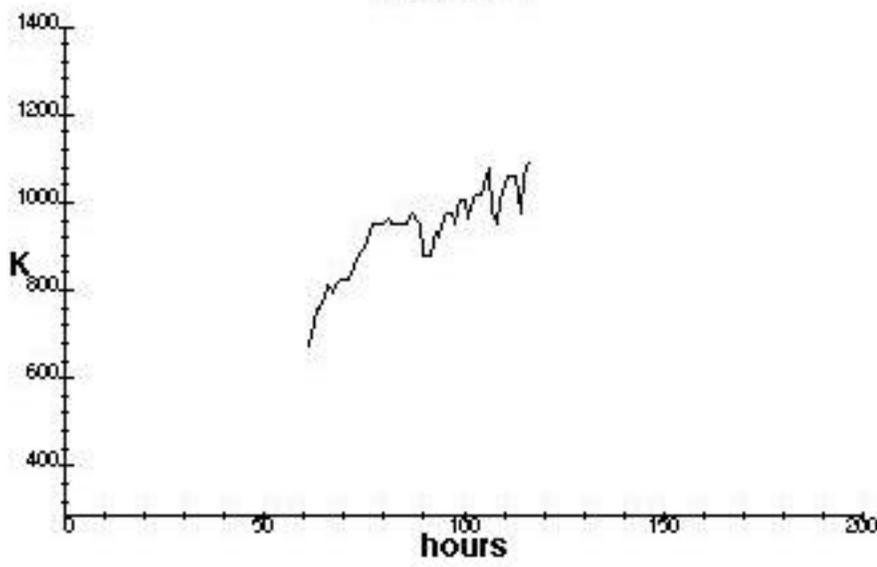
Position8



Position9



Position10



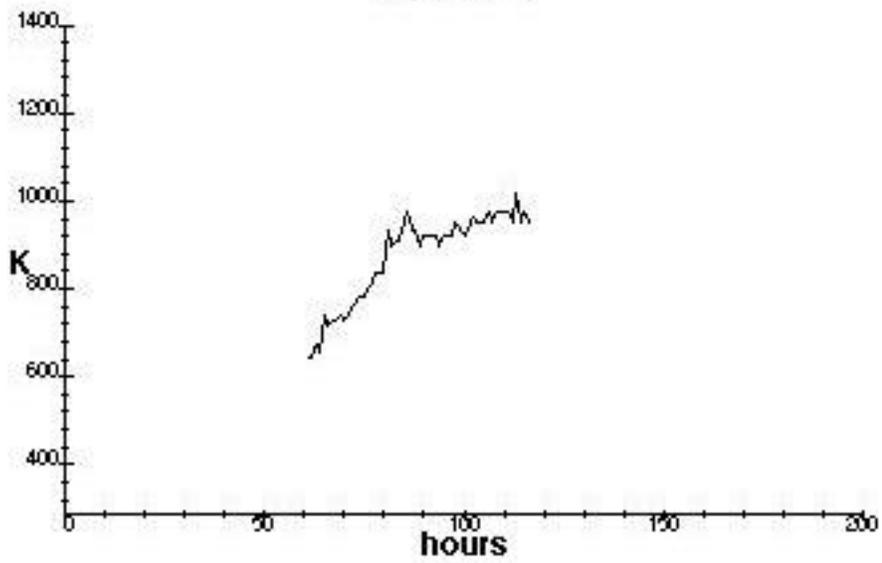
Position11



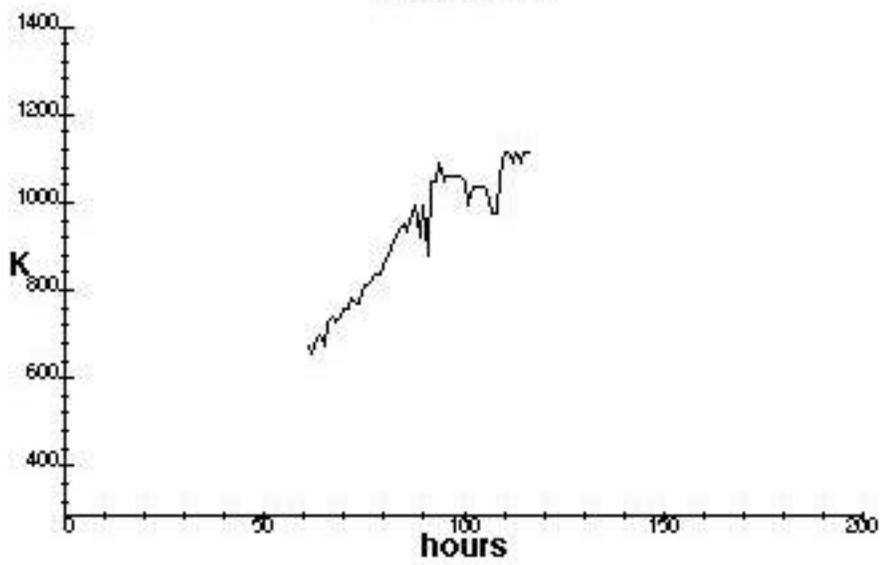
Position12



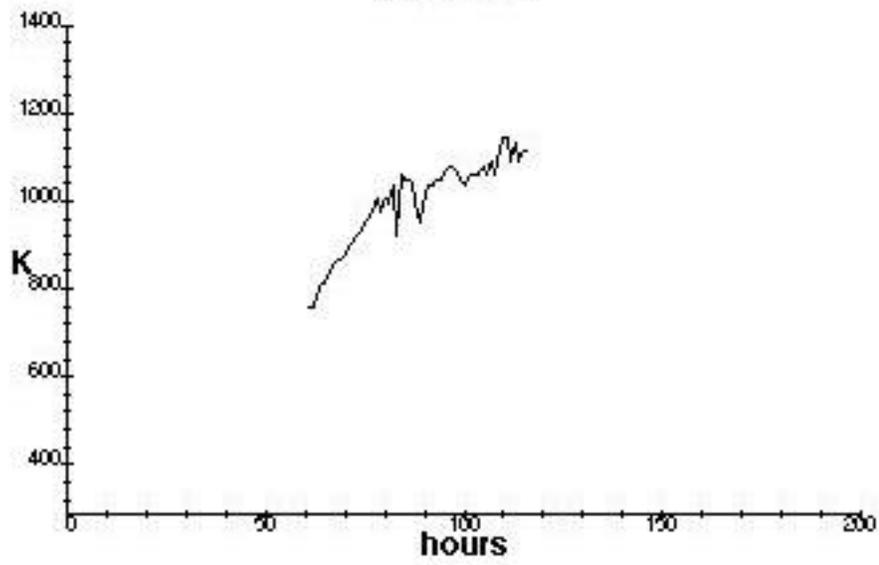
Position13



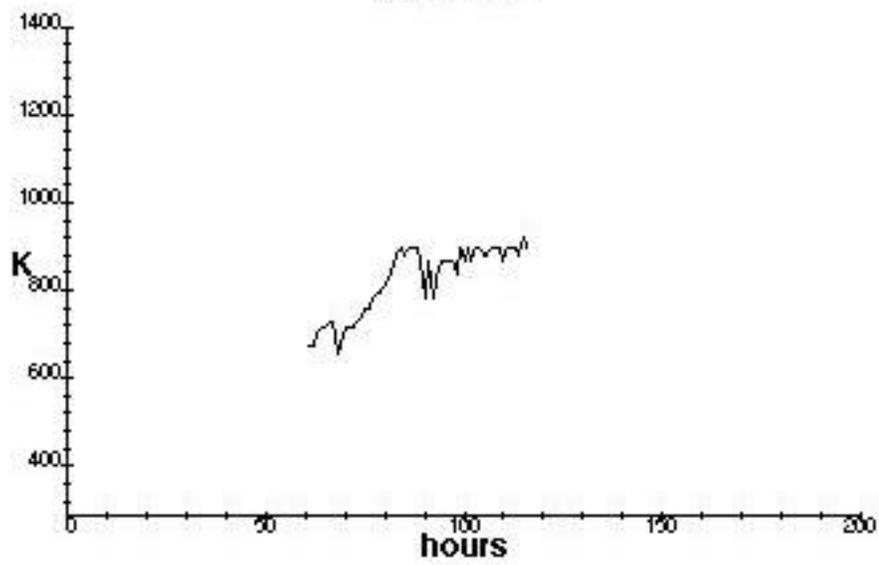
Position14



Position15



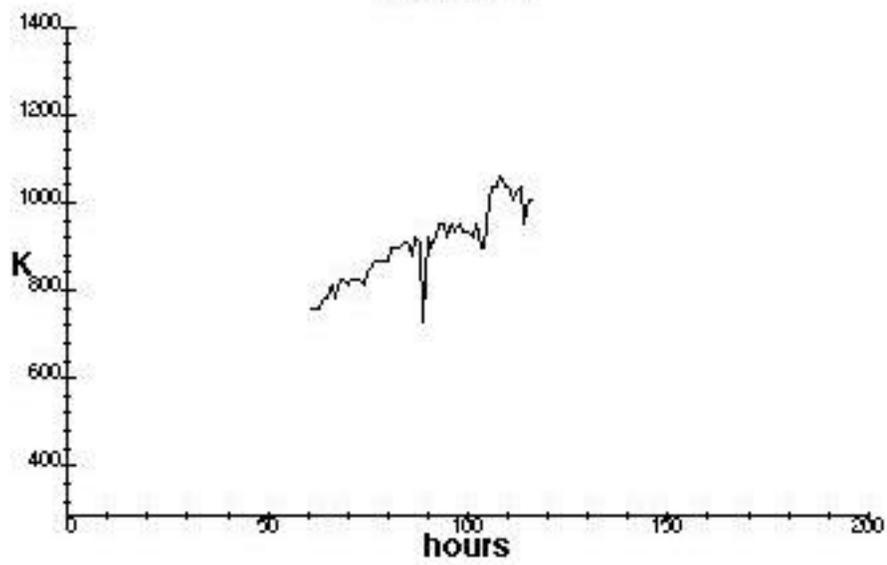
Position16



Position17



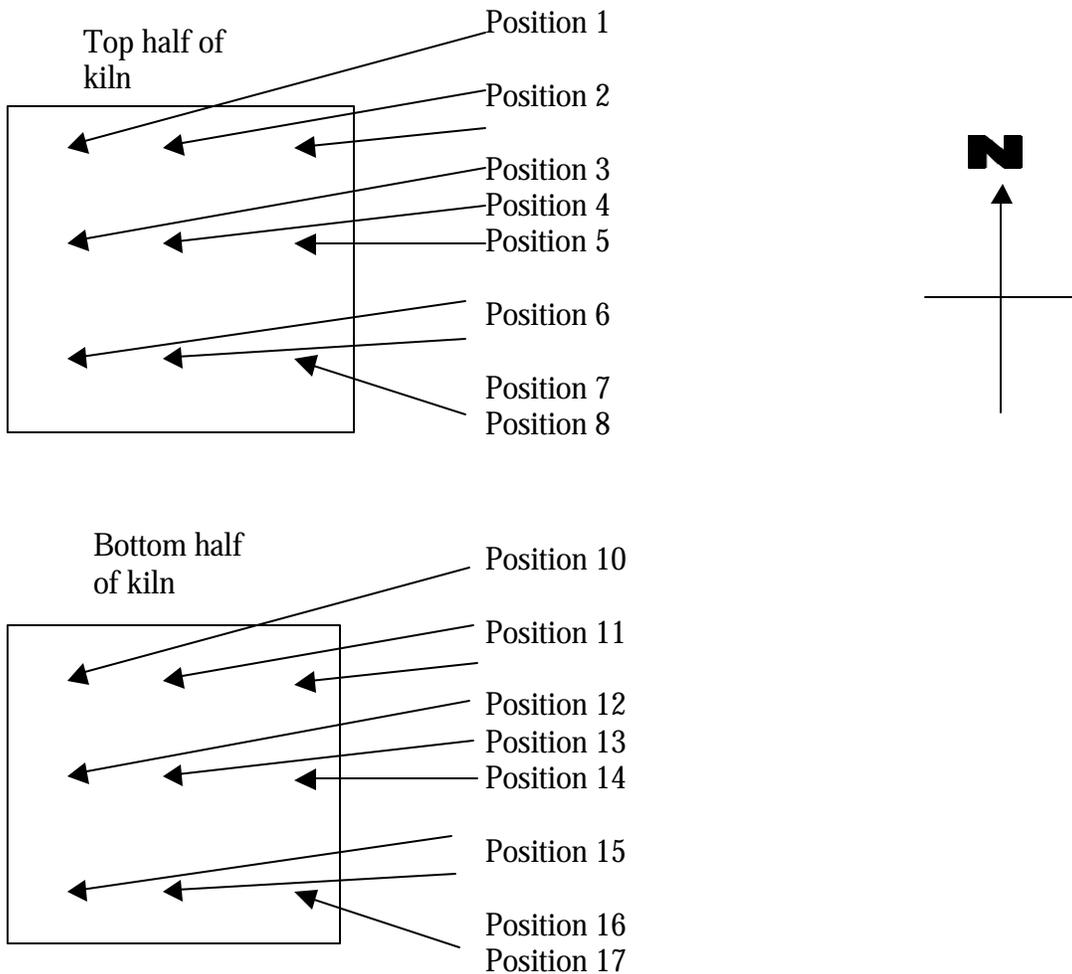
Position18



## APPENDIX E: DATA FROM 1995 BURN

The following is a compilation of plots of temperature (Kelvin) vs. time for given positions of the kiln fired in 1995. This data was compiled with the use of thermocouples by colonial interpreter in 1995 as the kiln was fired. It is important to note that since data was not taken in each case until the kiln had significantly heated up, a period of two and a half days corresponding to a typical drying period, has been artificially added to the front of each plot to aid comparison with the 1998 kiln.

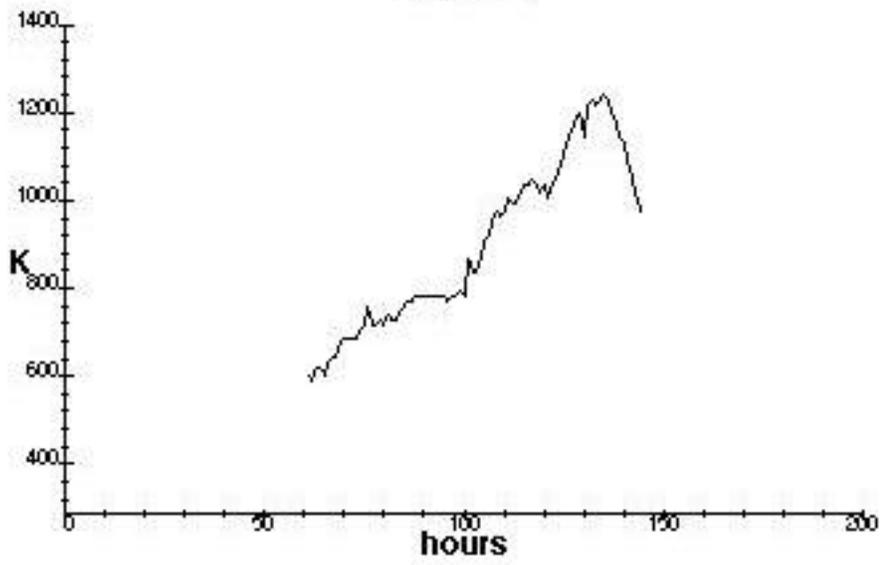
Below is a diagram of the position of each thermocouple in the kiln in 1995.



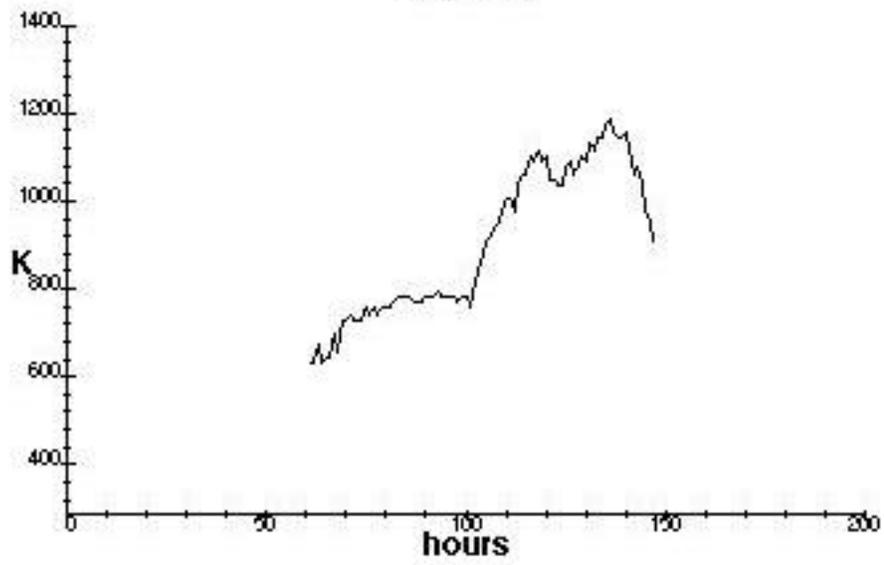
Position1



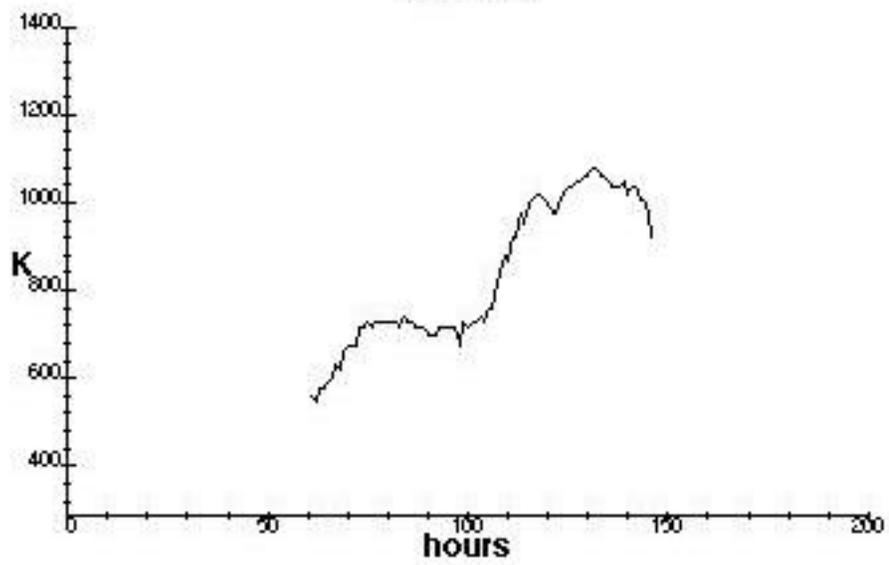
Position2



Position3



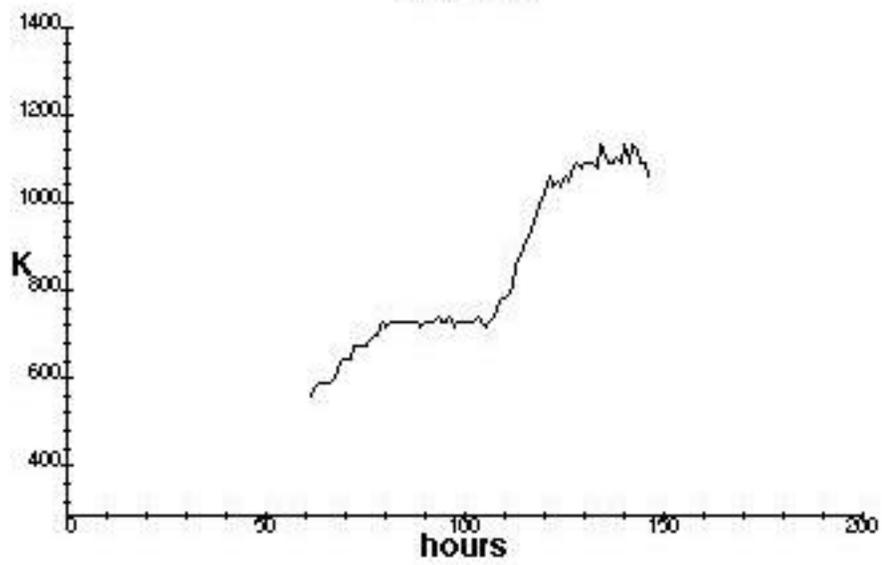
Position4



Position5



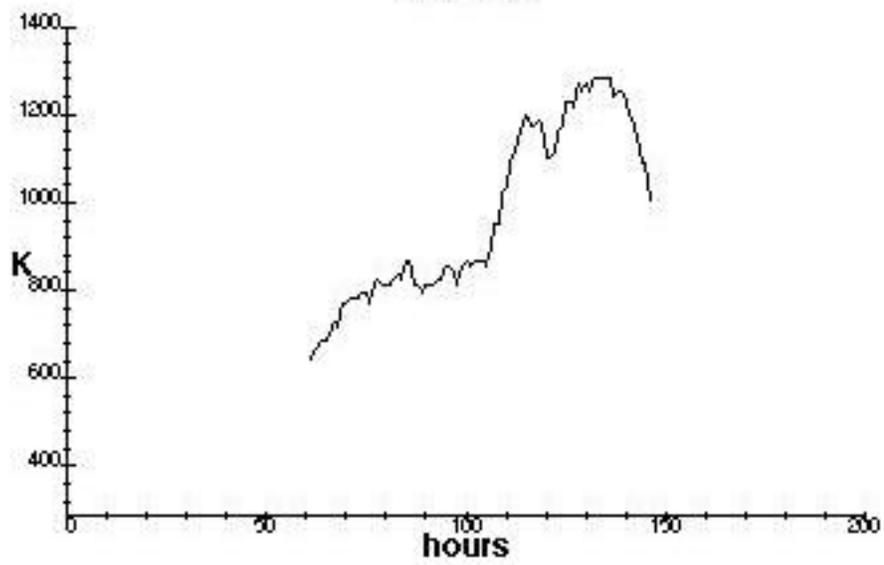
Position6



Position7



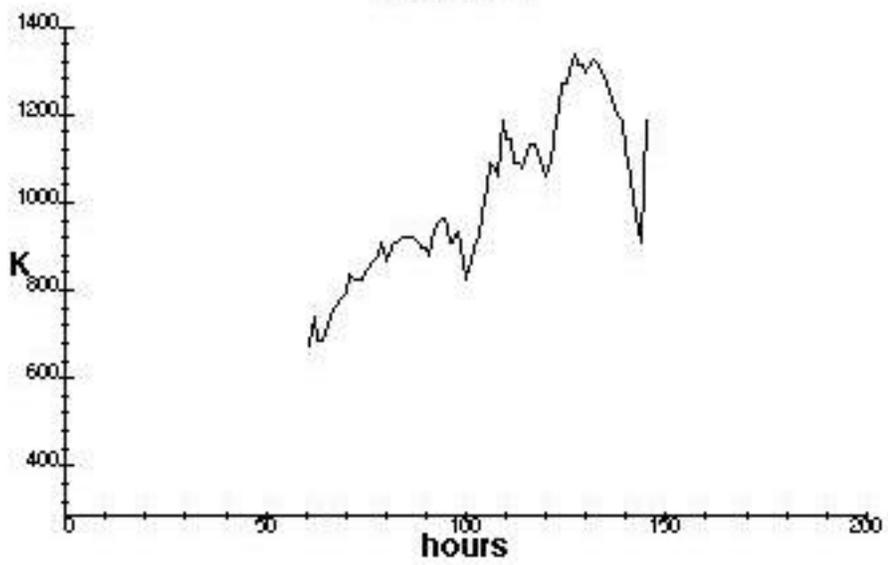
Position8



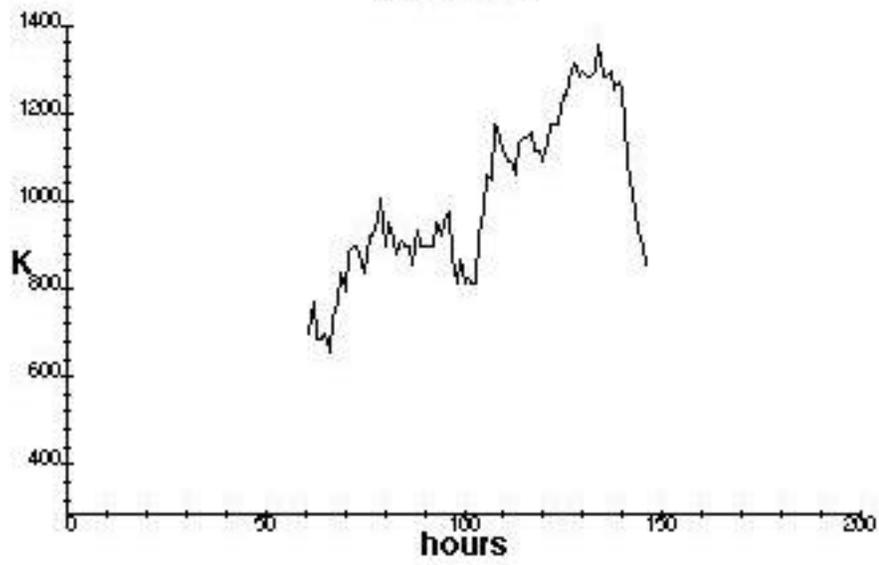
Position9



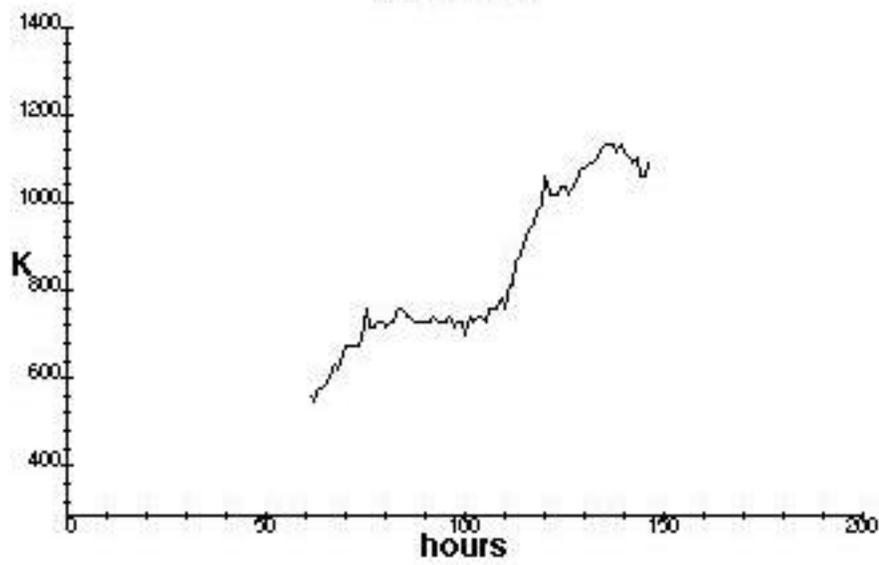
Position10



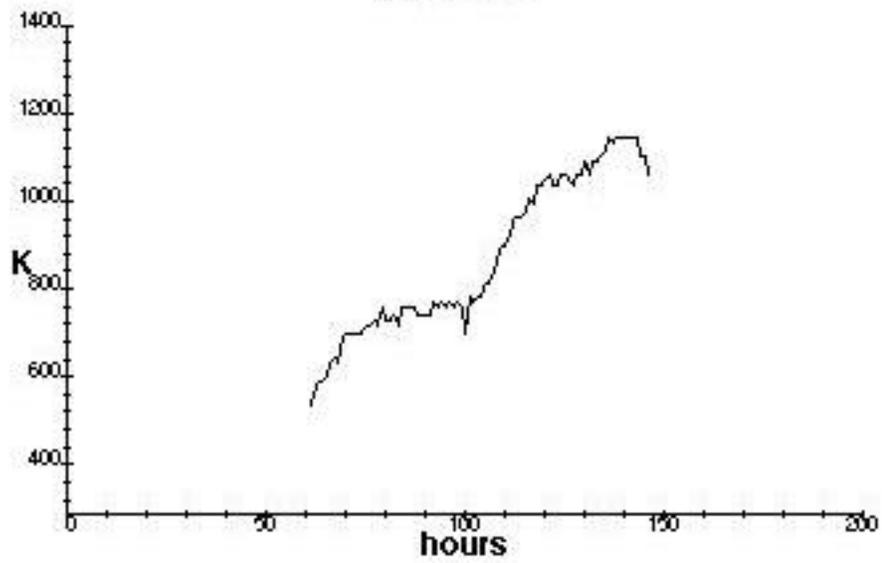
Position11



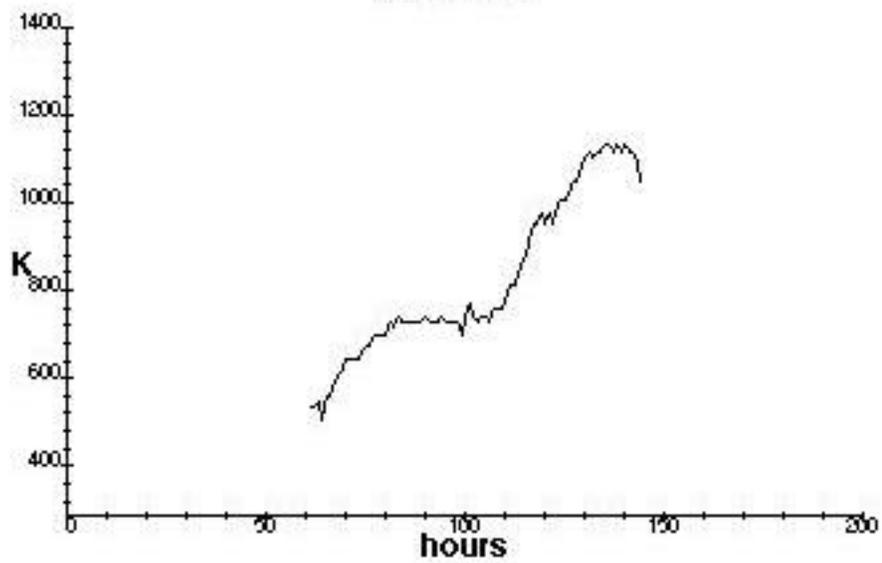
Position12



Position13



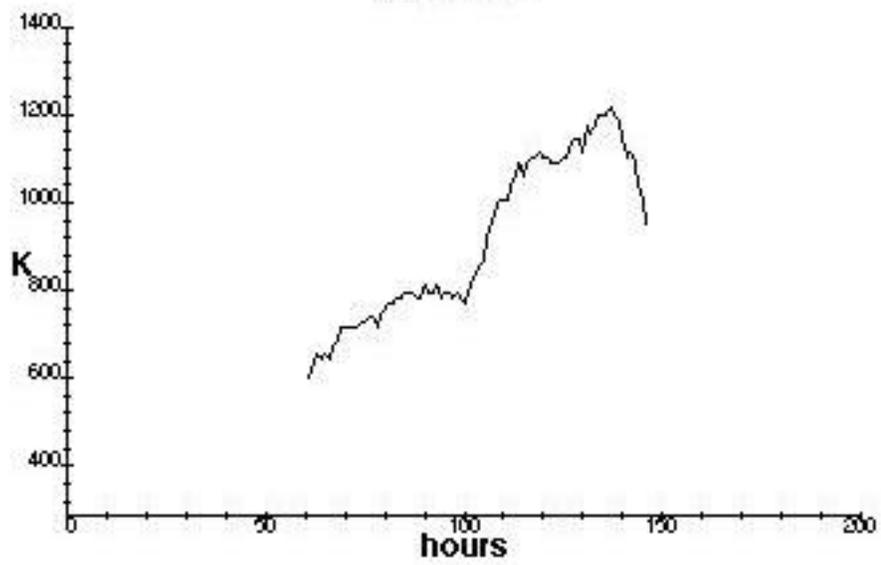
Position14



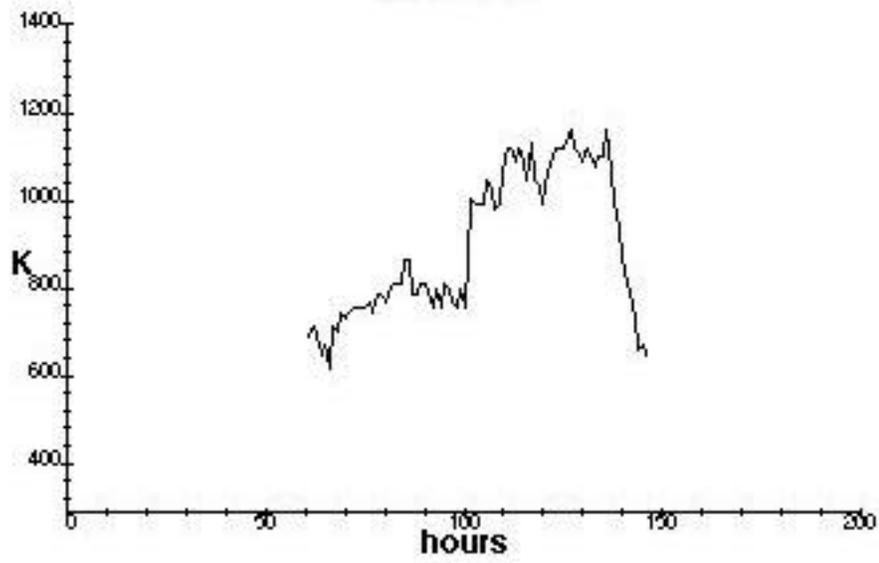
Position15



Position16



Position17



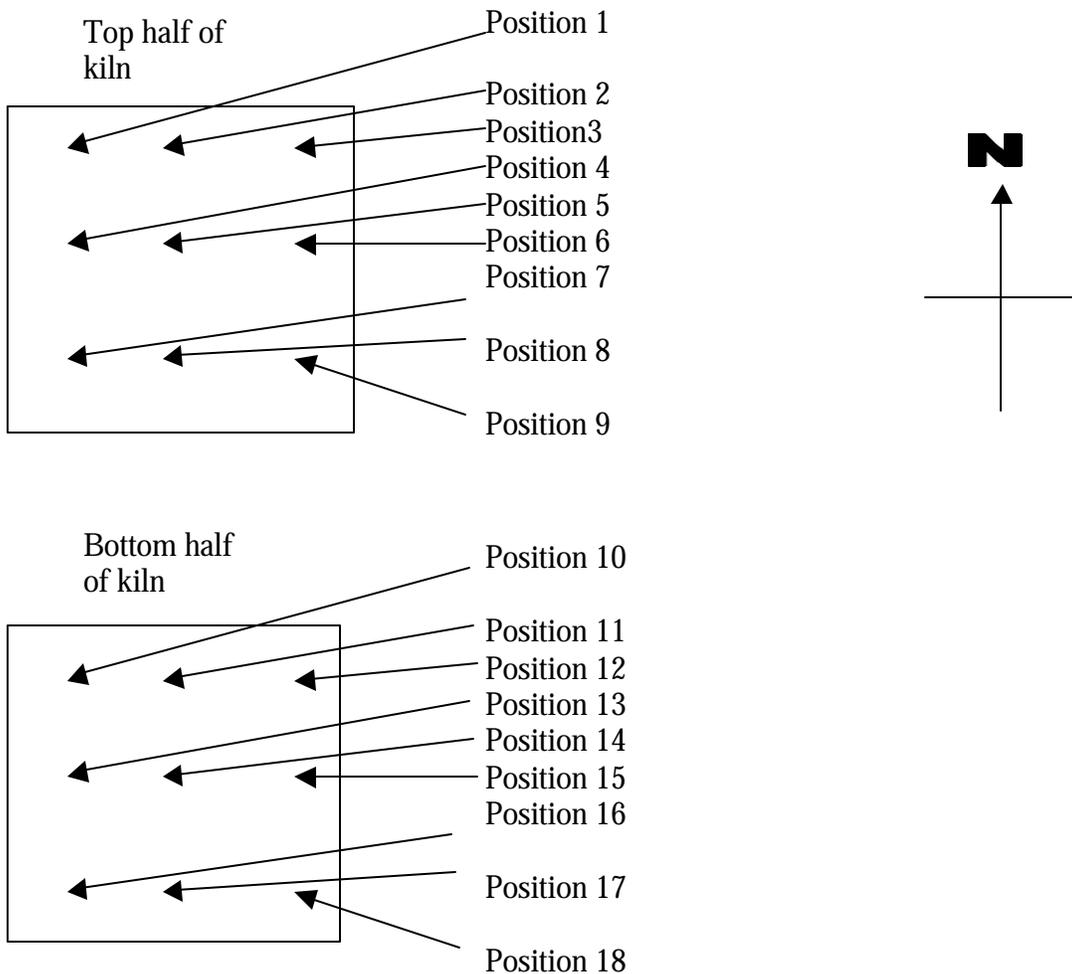
Position18

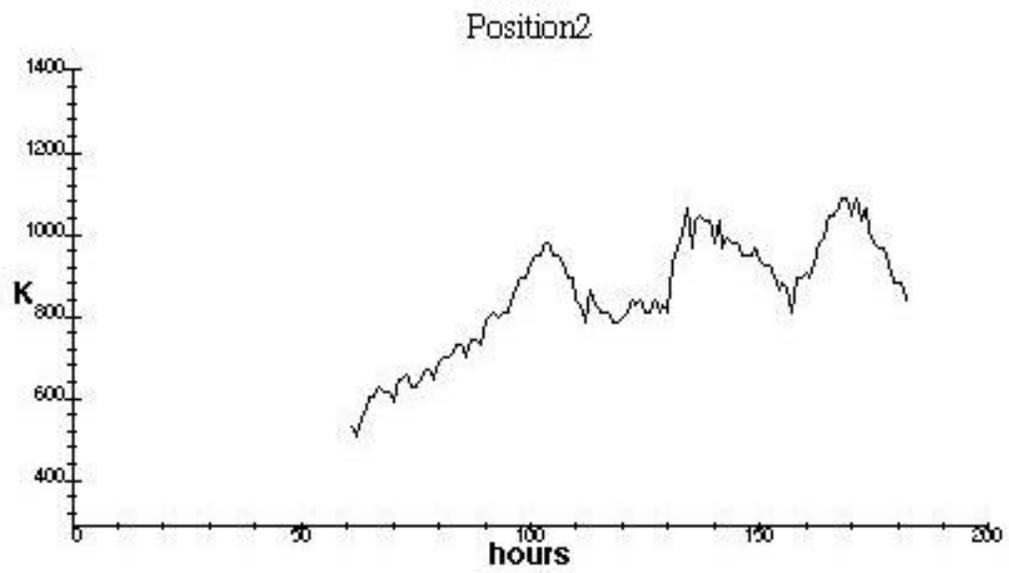
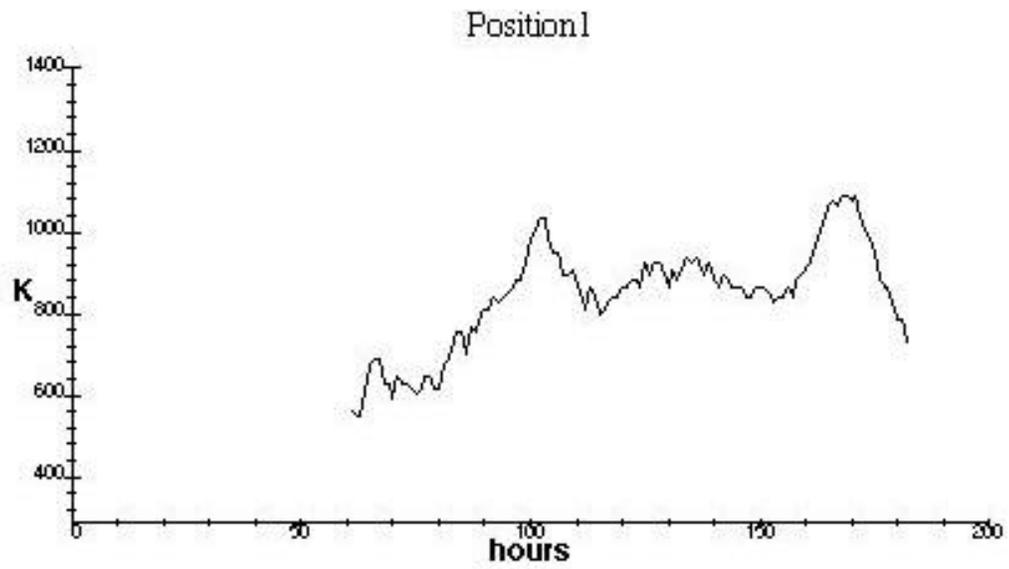


## APPENDIX F: DATA FROM 1996 BURN

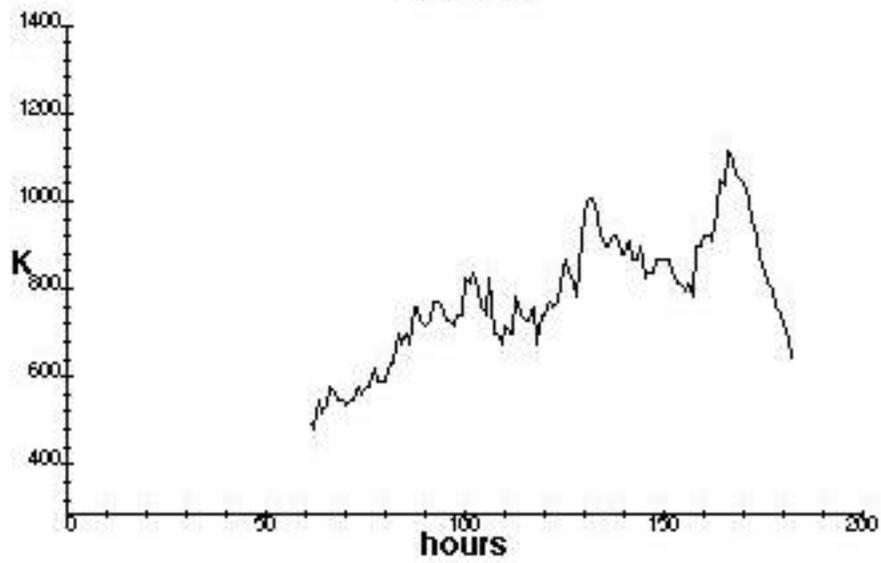
The following is a compilation of plots of temperature (Kelvin) vs. time for given positions of the kiln fired in 1996. This data was compiled with the use of thermocouples by colonial interpreter in 1996 as the kiln was fired. It is important to note that since data was not taken in each case until the kiln had significantly heated up, a period of two and a half days corresponding to a typical drying period, has been artificially added to the front of each plot to aid comparison with the 1998 kiln.

Below is a diagram of the position of each thermocouple in the kiln in 1996.

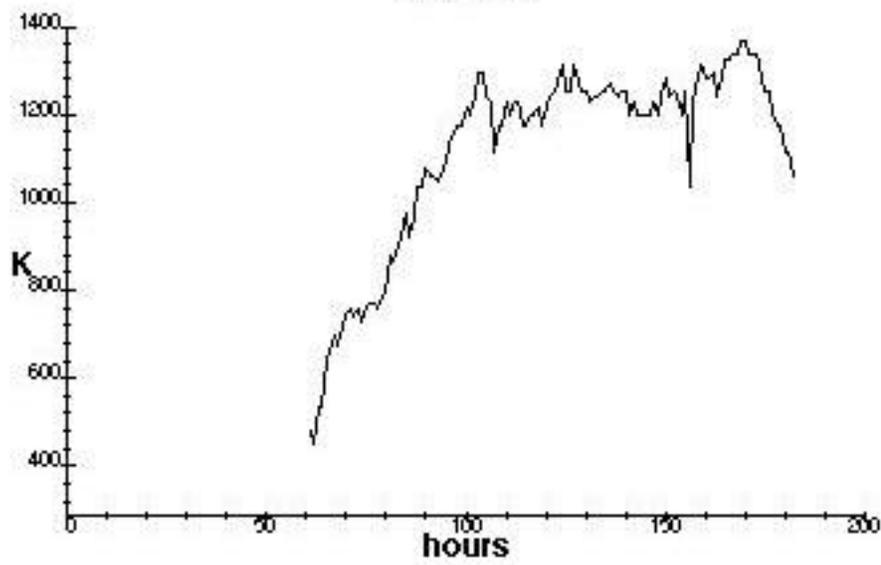




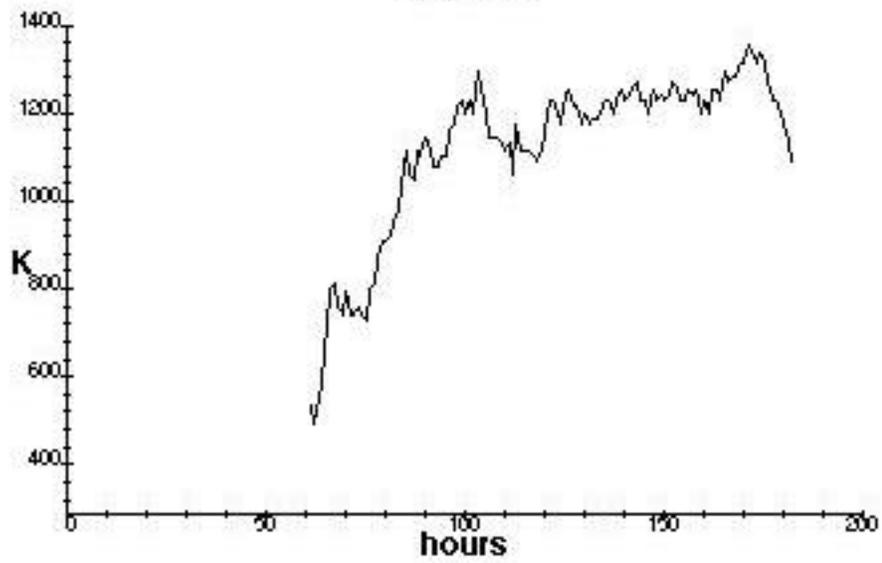
Position3



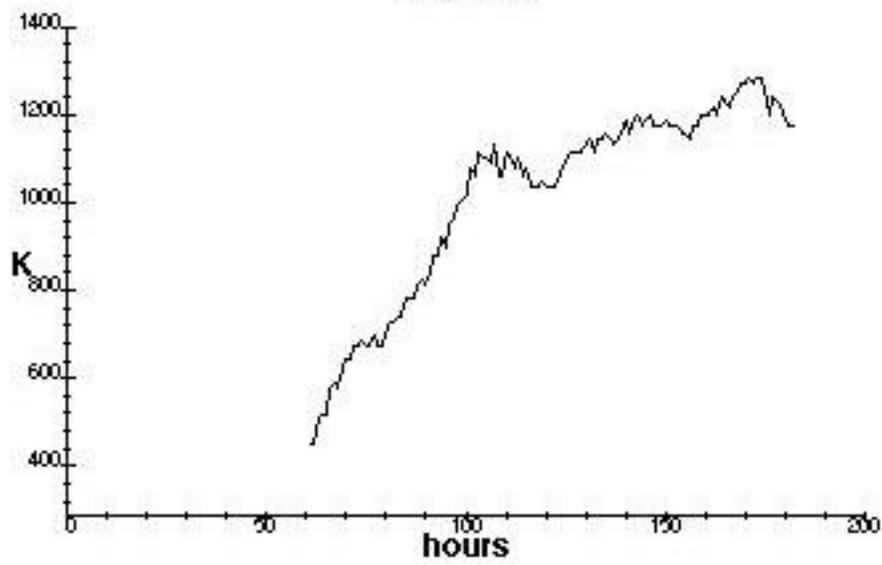
Position4



Position5



Position6



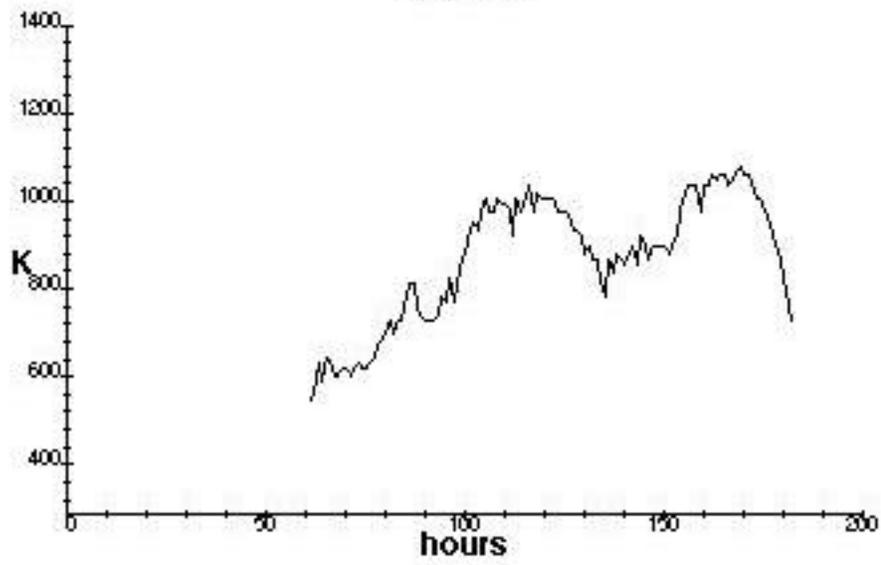
Position7



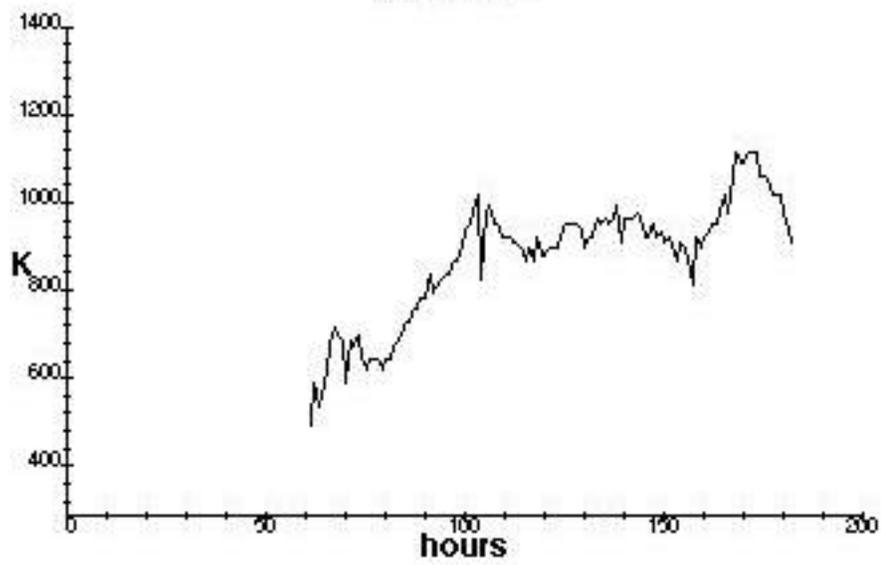
Position8



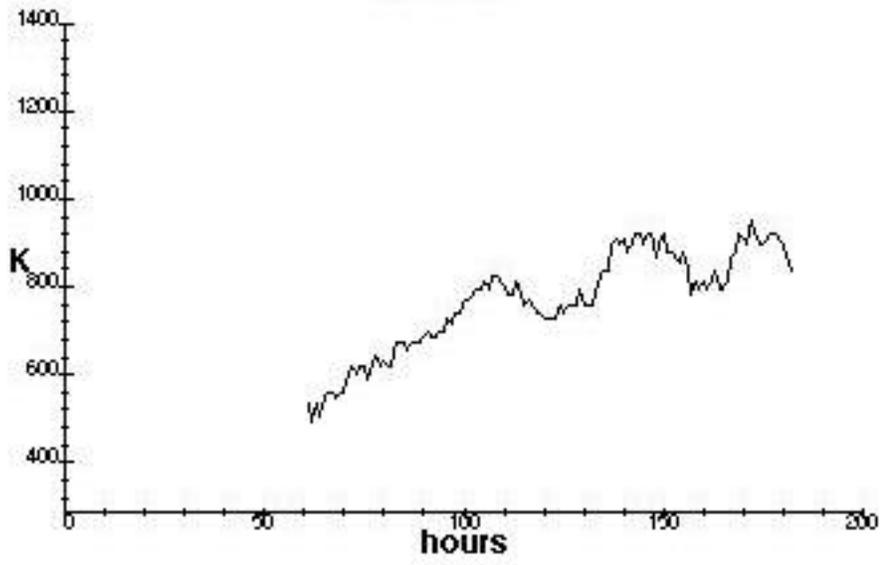
Position9



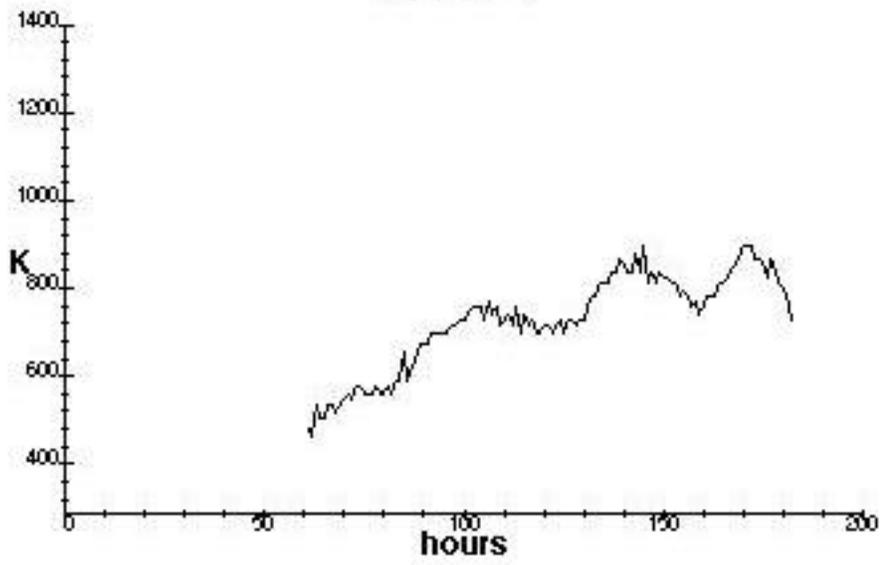
Position10



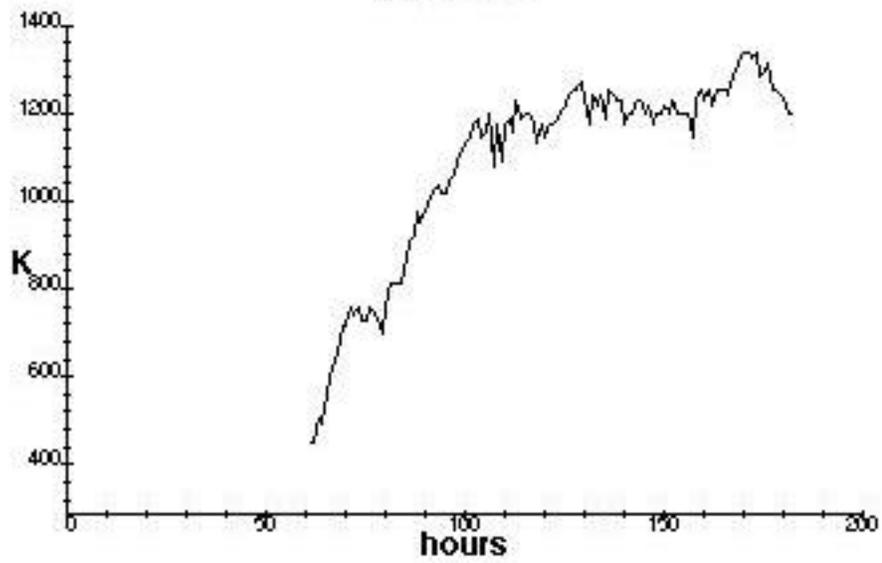
Position11



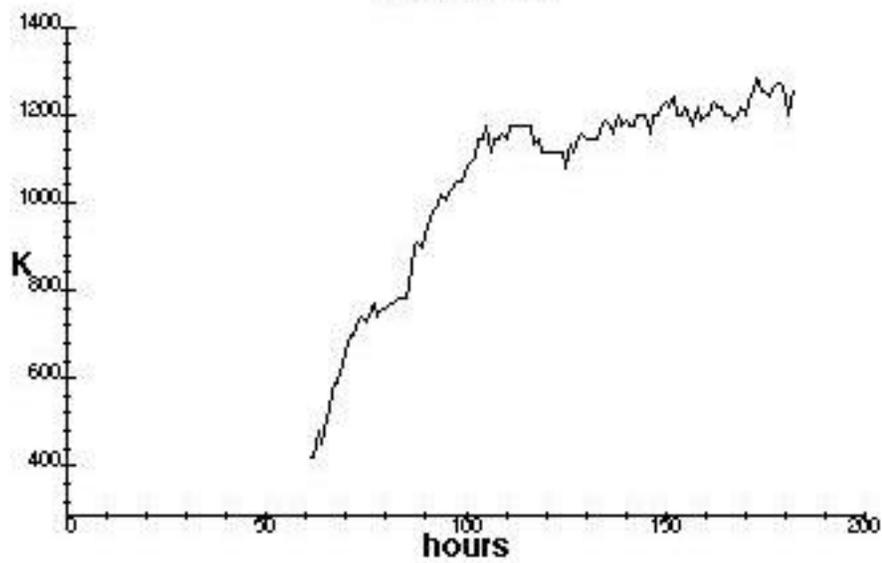
Position12



Position13



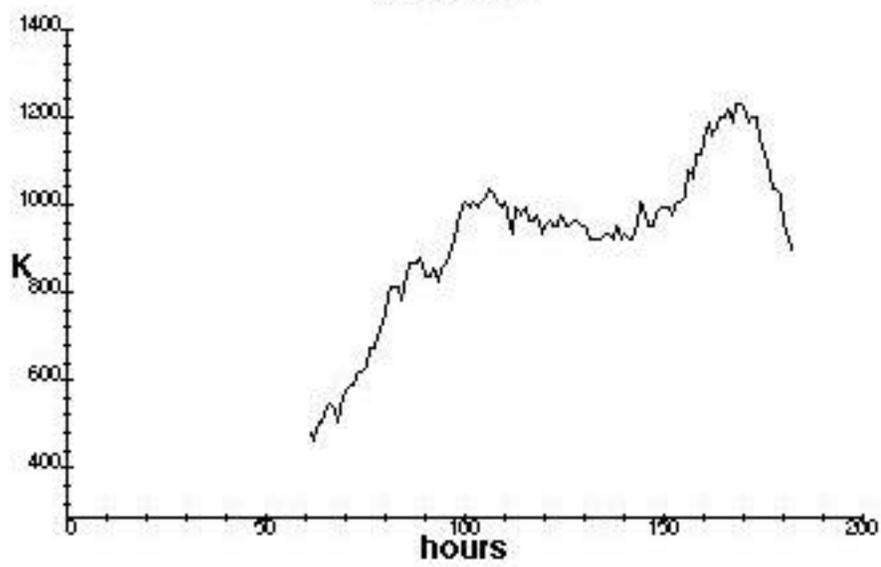
Position14



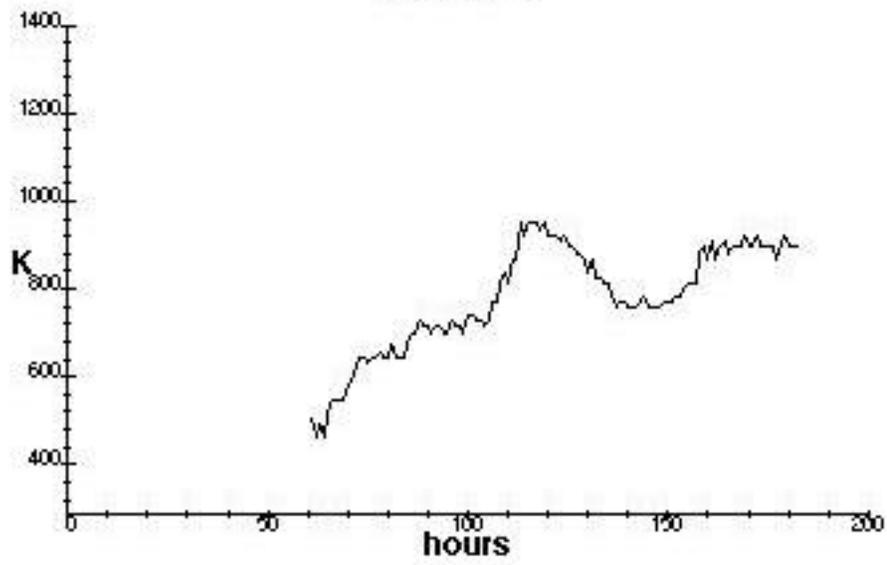
Position15



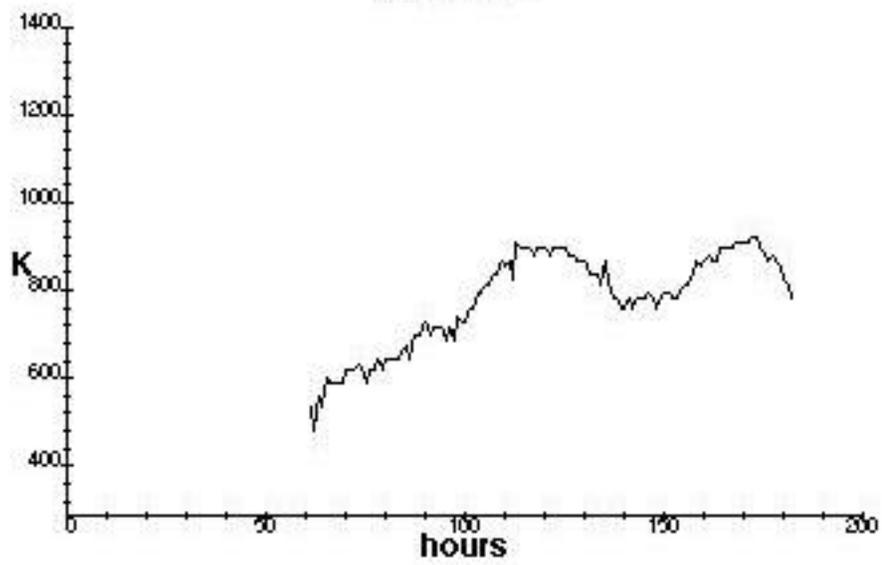
Position16



Position17



Position18



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