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DRYING CERAMICS IN ULTRAHIGH-FREQUENCY
ELECTRICAL FIELDS

Technical Report No. WAL TR 671.1/1

By

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July 1961

made pp. (OMS Code 4230.1.6083.30.01
Ceramic Gages for Inspection)

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TITLE

DRYING CERAMICS IN ULTRAHIGH-FREQUENCY
ELECTRICAL FIELDS

ABSTRACT

The program undertaken was designed to determine the applicability of dielectric heating to the drying of ceramic components fabricated by wet processing techniques. The general characteristics of dielectric drying were studied along with the specific moisture removal characteristics for a typical wet-processed ceramic composition (50% clay, 25% flint, 25% feldspar). The results obtained in this investigation showed that rapid drying rates for ceramics are possible with the dielectric heating method. Wet ceramic components can be heated and dried uniformly in the electric field without the development of severe temperature and moisture gradients which might lead to cracking and/or warping of the components. Although drying rates were found to be extremely high, they are limited by the rupture strength of the material, i.e., its ability to withstand the stresses developed by the pressure of the escaping water vapor. Dielectric drying holds interesting possibilities for drying high-cost ceramic components or component systems which are difficult to process by other techniques.


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INTRODUCTION

The exploration of ceramic systems for Ordnance applications at Rodman Laboratory, Watertown Arsenal, requires detailed studies of all phases of product fabrication. One of the most common ceramic forming techniques, particularly for highly complex component systems, is wet processing; i.e., slip casting, plastic forming, etc. The subsequent drying operation is a critical one, and improper drying may result in either cracking or warping of the component. In many current ceramic programs, present conventional drying techniques have proved either unsuitable or infeasible for efficient production operation. Drying ceramics in ultrahigh-frequency electrical fields (dielectric drying), a relatively new concept, shows promise as a useful tool, not only in laboratory and pilot-plant drying operations, but in production as well.

When an electrically nonconducting material or insulator is subjected to the stresses of an electric field, the material will undergo a rise in temperature. This heating phenomena is known as dielectric heating. The magnitude of temperature rise will be dependent upon the electrical properties of the material and the strength of the field. Although dielectric heating experiments were conducted as far back as the mid-nineteenth century, the technique developed was not explored for practical industrial heating applications until just thirty years ago. Since then numerous applications have been discovered, and this heating method now plays an important role in the plastic, woodworking, and food processing industries. Because of its unusual electrical characteristics, water can be heated by the dielectric heating method at a greater rate than most other materials. It is understandable, therefore, why moisture removal has become an important and natural application for this unique method.

Conventional drying methods now used in the ceramic industry, other than air drying, require the application of heat external to the ware. The adjustment of temperature and humidity must be carefully controlled to prevent temperature and moisture gradients within the ware. If the surface temperature of the ware is allowed to rise at a greater rate than that of the interior, then the rate of evaporation of moisture from the surface will be greater than the rate of diffusion of water from the interior of the ware to the surface. This will result not only in a break in the capillary flow of water from interior regions to the surface, thereby slowing down the drying process, but will also cause the formation of moisture gradients which result in differential shrinkage. Where differential shrinkage occurs, stresses are set up in the ware and cracking or warping results. Since dielectric heating produces relatively uniform heating throughout a given mass of material regardless of size, it seems ideally suited as a method for the removal of moisture from wet-processed ceramic bodies.

Several investigators^{1, 2} have looked into the use of electronic drying as a means of removing water from ceramic bodies. Previous investigations

have shown the drying rates obtained by the dielectric heating method to be much greater than those found with more conventional methods now in use. Since there is uniform heating throughout a given cross section, the water can be heated as rapidly as possible. The only limiting factors controlling the rate of moisture removal from a material is the rupture strength of the material. If the rate of escape of the water vapor becomes too high, the structure can crack or disintegrate due to severe internal pressure buildup. This is particularly true of ceramic bodies of the clay type with relatively low permeability.

Because of the high initial equipment costs and high operating expenses, electronic drying has not been fully exploited for utilization in ceramic operations. While this heating method does not seem practical for low-cost production ceramic units, it might be found of great benefit, from both quality control and economic standpoints, for the drying of large ceramic sections presently requiring very long drying schedules, for high cost components, or in specialized work where present techniques are unsuitable.

The purpose of this investigation was to study the general characteristics of dielectric heating and the specific moisture removal characteristics of a typical wet-processed ceramic composition dried by this technique.

THEORETICAL CONSIDERATIONS

When a dielectric material is placed between electrodes to which an alternating potential has been applied, the usual spheroidal structure of the atom is distorted as the electrons within the material align themselves with the electric field.³ The negatively charged electrons will be attracted to the positive electrode, while being repelled from the negative. The positively charged nucleus will receive a force in the opposite direction. When conductor polarity is reversed, electron paths will be distorted in the opposite direction. In the course of one complete cycle, a lag in the electron displacement is encountered, relative to the change in conductor polarity, which results in an energy loss manifesting itself in the form of heat energy. The dipole displacement versus potential gradient relationship follows a characteristic hysteresis loop configuration with the energy loss being equal to the area within the curve. In electric fields where rapid reversal of polarity takes place, the molecules of the nonconductor are in a constant state of agitation, and distortion of the electron path and the rapid displacement of electrons results. While the total heating effect induced in a single molecule through one complete reversal in polarity (one cycle) is infinitely small, when an infinite number of molecules are stressed at ultrahigh frequencies (in the thousands of cycles per second range or higher), the total energy loss and resultant heating effect is considerable.

The heat energy developed in dielectric heating methods has been found to be dependent not only on the voltage applied across the dielectric material and the frequency of the electron displacement, but also upon the

electrical properties of the material or composite and the mass distribution between the electrodes.⁴ The power generated in a dielectric material and the resultant heating effect or energy loss can be expressed by the following relationship:

$$P = 2\pi f E^2 (k' \cos \theta) A/t \quad (1)$$

where

- f = frequency of electric field, cps
- E = voltage across dielectric material
- (k' cos θ) = loss factor (ϵ'') of dielectric material
- A = surface area of mass under electrodes, in²
- t = thickness of mass, in.

The important properties required of insulating materials to be heated by this method are good dielectric strength and high loss factor. The dielectric strength is the ability of the material to withstand electrical breakdown, and is expressed in volts/mil. The loss factor (ϵ'') is a product of the dielectric constant (k') of the material and its power factor ($\cos \theta$). The relative dielectric constant k' is a measure of the ability of a material to store a charge and can be expressed as follows:⁵

$$k' = \frac{C}{C_0} = \frac{\epsilon'}{\epsilon_0} \quad (2)$$

where C is the capacitance of the dielectric material between the plates of a condenser, C_0 is the capacitance of the system when a vacuum of a similar geometry to the dielectric exists between the plates, and ϵ' and ϵ_0 represent the real permittivities or dielectric constants of the dielectric and vacuum respectively. The power factor represents the amount of leakage current (I_C) which will flow through an insulator to produce a heat loss. Both dielectric constant and power factor depend upon the nature of the material, temperature, moisture exposure, voltage and frequency, and other factors. As can be observed in Equation 1, an increase in the loss factor (ϵ''), with other variables constant, would result in an increased heating effect. Table I gives the dielectric characteristics for some typical nonconducting materials. While it is not feasible or desirable in most cases to vary the electrical properties of a material to be heated or its mass distribution, the intensity of the electric field can be varied to yield maximum heating rates. The most important single factor is the voltage applied across the material, since the heating effect is a function of the square of the voltage as seen in Equation 1. The maximum allowable voltage is determined by the dielectric strength of the material to be heated. When moisture is present in the material, the dielectric strength is greatly reduced and with it the maximum allowable voltage.

TABLE I

ELECTRICAL PROPERTIES OF SOME TYPICAL DIELECTRIC MATERIALS⁶

	Dielectric Strength* volts/mil @ 25 C	Dielectric Constant (k') (10 ⁶ cycles) @ 25 C	Power Factor cos. θ (10 ⁶ cycles) @ 25 C
Fused Silica	500	3.75 - 4.1	0.0002
Cordierite	40 - 250	4.5 - 5.4	0.004 - 0.012
Steatite	200 - 400	5.5 - 7.5	0.0002 - 0.004
Alumina	40 - 160	4.5 - 8.4	0.0002 - 0.01
Porcelain, Wet Process	90 - 400	6.0 - 7.0	0.006 - 0.01
Porcelain, Dry Process	40 - 240	6.0 - 8.0	0.003 - 0.02
Titanium Dioxide	100 - 210	14 - 110	0.0002 - 0.005
Titanates (Ba, Sr, Ca, Mg and Pb)	50 - 300	15 - 12,000	0.0001 - 0.02
Water	- -	78	0.04

*Decreases with increased frequency

Another factor, frequency (f), can also be varied to yield greater heating rates, though its effect is not as great as that resulting from voltage variations. There are limitations, however, on the use of extremely high frequencies. One reason is that the impedance of the interelectrode capacitance varies with frequency. To obtain voltages at a given frequency, therefore, the impedance of the electrode system must be matched to the output impedance of the high-frequency energy source. When these impedances match exactly, a maximum heating effect is obtained. If the impedances vary slightly, heating is still noted, though the effect is not as great. When the variation between impedance is too large, no heating effect results.

Another important consideration which might restrict the choice of frequency utilized in the dielectric heating apparatus is the harmful effect which results from the formation of standing waves. When standing waves are formed in the electric field, the voltage along the electrodes becomes maximum at some points (the antinodes), and absent from others (the nodes), rather than uniform over the electrodes. This phenomena would lead to non-uniform heating. When an electrode is designed so that its length equals any integral number of half wavelengths for a given frequency, standing waves will develop. To prevent the formation of standing waves and the non-uniform heating which would result, the proper relationship between frequency and electrode dimension has to be chosen.

In dielectric heating applications, voltages developed are usually in the range of 1,000 to 5,000 volts, with frequencies ranging between 1 and 50 million cycles per second, sometimes higher.

In many applications it is advantageous to study the geometry of the component to be dried. It can be seen from Equation 1 that an increase in the area-thickness ratio will result in an increased heating effect. A component could, therefore, be dried more efficiently with the largest possible total surface area exposed to the field with a corresponding thickness to give the maximum A/t value possible.

While voltage across the electrodes can be adjusted to vary the intensity of the electric field and obtain maximum heating, another control factor built into most industrial dielectric heating equipment allows for a modification of the voltage across the material. This is accomplished by control of the interelectrode capacitance. By utilizing a motor-controlled upper electrode, the air gap between the electrode and material can be varied. Since the air gap represents a capacitance in series with the material, and the voltage drop across capacitances in series is additive, the voltage drop across the air gap reduces the voltage impressed across the material. For maximum heating, the air gap should be as small as possible. If the electrode approaches too close to the material, however, the danger of arcing is present due to ionization of the air in the remaining gap. The variation of air gap between the electrode and material represents another method to match the interelectrode impedance. In some commercial equipment this is the only method used for matching impedances.

In order to obtain uniform heating, both the electrical characteristics and mass distribution of a component and/or the entire workload should be uniform. When material composites or structures contain constituents of varying electrical properties, selective heating will result. This is the case, for example, with many laminate-type structures where layers of material with different electrical properties are present. To counteract selective heating effects, special techniques, depending on the type and severity of nonuniformity encountered, are required. When components with irregular geometries or uneven mass distribution are encountered, special techniques are also required to get uniform heating throughout the configuration. In some cases the electrodes may be designed to conform to component configuration, while in others, uniform heating can be had by balancing the workload. By balancing the load, through the use of either similar components or dummy loads properly positioned around the regular workload, compensation for nonuniform mass can be obtained. Components of similar heights should be grouped together to obtain uniform heating. As a general rule, the greater the load between the electrodes, the greater the heating rate because the ability to load the high-frequency energy source is better.

As mentioned previously, the heating rate of water in high-frequency electrical fields is higher than for most other materials. When materials containing moisture, for example, wet-processed ceramics, are placed within a high-frequency electrical field and stressed by alternating current voltage, the water with its unusual electrical characteristics heats up rapidly, and the complete mass is brought up to temperature uniformly. For this case the electrical properties of importance for dielectric heating are

determined by the water phase. While conventional heating methods cause the formation of temperature gradients within the ware, with the surface temperature higher than interior regions, the dielectric heating method gives uniform heating until moisture starts evaporating from the surface. The vaporization of the moisture at the surface has a tendency to cool the surface. When moisture has been completely eliminated, the energy input to the material will decrease as the loss factor of the mass decreases.

It takes approximately 1,100 Btu of heat energy to evaporate one pound of water. To evaporate one pound of water electrically, 19.6 kw of high-frequency energy is required.⁴ An electrical unit with this power output could evaporate 60 pounds of water an hour and would have a thermal efficiency of 50% and require 40 kw input electrical energy to operate. It has been calculated² that with a 20 kw high-frequency unit, the cost to evaporate a pound of water will be approximately 65 cents. In previous experiments comparing electronic drying with electrical infrared heat sources, gas infrared heat sources, and conventional electric oven drying, it was found that to remove between 450-490 grams of water from a standard brick shape, 60 to 70 minutes were required by the electronic system and 14 to 18 hours by the other methods.

EQUIPMENT AND PROCEDURE

Electronic Dryer

The dielectric heating facility used in this investigation was a commercial unit and is shown in Figure 1. This unit requires electrical energy from a 3-phase, 60-cycle, 410-to-490-volt alternating-current source which is converted to radio-frequency energy at approximately 15 mcps. The power available for heating is 16 kw; however, only 83% of the rated capacity is utilized to provide a safety margin. The circuit diagram for the electrode circuit is shown in Figure 2. The flat-plate rectangular electrodes, as shown in Figure 3, are aluminum, and the height of the upper electrode can be automatically adjusted by motor control. The maximum workload height which can fit between the electrodes is 14 inches. The unit, which was designed for production-type operations, is equipped with a metal mesh conveyor belt operated by a variable speed motor. A blower is provided in the heating chamber for the rapid removal of water vapor formed during the drying cycle.

The oscillator is of the direct-tank loaded type, that is, the work placed between the electrodes which form the tank condenser becomes part of the tank condenser of the oscillator. There is no separation either electrically or physically between the high-frequency generator and the load. In this type circuit there is no need for matching impedances even under varying workloads because the oscillator is constantly in resonance.

While no controls were provided for varying either the voltage or frequency in this particular dielectric heating facility, these values had been

preadjusted to yield a field strength capable of evaporating 25 pounds of water per hour. Compared to a 20-kw unit mentioned previously which could evaporate 60 pounds of water per hour, the cost of evaporating a pound of water would be a little over 1.3 cents. Preliminary work with the dielectric unit showed that the intensity of the electric field was great enough to yield a maximum heating rate for drying wet-processed ceramics. With any ceramic, either clay or nonplastic oxide type, at any moisture content, the maximum safe rate of drying (as determined by rupture strength of material stressed internally by escaping water vapor) could be exceeded. Since the maximum safe heating rate for ceramics was available, a variation in air gap through the use of a mobile electrode could be utilized to great advantage to modify the voltage drop across the material and thus reduce the rate of heating and allow a study of the rate of drying up to the maximum safe rate.

Experimental Procedure

Since the voltage drop across a workload is variable during the drying cycle and extremely difficult to measure, it was decided to correlate the strength of the electric field in the dielectric unit under varying air gaps with the time required to evaporate a given quantity of water with a fixed initial A/t ratio. This was accomplished using a cylindrical nonporous ceramic crucible containing a given quantity of water. The exposed surface area and original height of the water column in the crucible were determined and the rate of water loss measured for varying air gaps.

A typical ceramic composition was used to study the drying characteristics of ceramic-type bodies in ultrahigh-frequency electrical fields. The body, composed of equal parts Georgia kaolin, Tennessee ball clay, flint, and feldspar, was ball-mill blended for 8 hours. The moisture content of the blended body was brought to 20% by weight. Specimens were hydraulically pressed in a steel die at 750 psi to 3 inches square by 3/8 inch thick. The hydraulic press and die assembly used are shown in Figure 4 along with some pressed test specimens. The specimens had good handling strength, suffered little loss in moisture, and when dry, had a specific gravity of 1.72. Pressed specimens were dried in the dielectric oven immediately after fabrication to prevent losses in moisture to the atmosphere.

Composite specimens of two different heights were built up from the individual pressed compacts, one containing two compacts (0.75 inch), the other, four (1.5 inches). The composite specimens were formed by stacking one compact on another and were designed to allow a study of moisture gradients through the cross section of a drying specimen. The compacts had good flatness, and water movement through the entire composite was not retarded at compact interfaces. Good contact (between compacts) was also desired for prevention of air spaces between the layers which would alter the electrical properties of the mass and therefore cause changes in its heating and drying characteristics.

The following part of the experimental program was designed to determine the rates of moisture removal from a typical ceramic body dried in a high-frequency electrical field. In addition, a study was made of the temperature and moisture gradients developed in a specimen during various stages of the drying cycle. The composite specimens were dried in the dielectric oven separately, resting on an asbestos board and centered between the electrodes. Prior to testing, each compact comprising the composite was weighed. The whole composite was then brought into the field and left there for a period of either 5 or 10 minutes (depending on the rate of drying), then removed, and the individual sections weighed again. This operation was repeated until all the moisture had been removed. During each interval of the drying cycle the temperature of the specimen at its surface, interior, and at the ceramic-asbestos interface was measured using a Chromel-Alumel thermocouple and a direct-reading potentiometer. The whole procedure was repeated for varying air gaps and specimen sizes.

Inherent Variables

The final phase of this investigation was to study the effect of and make corrections for certain variables inherent in the method used for determining the drying rates. The first variable studied was the effect of the asbestos board on drying time and temperature. This was determined by drying a typical specimen at a convenient drying rate without the use of the asbestos board and resting directly on the conveyor belt. Drying rates, moisture and temperature gradients were again measured, and the difference between this cycle and the one using the asbestos noted.

As mentioned previously, the greater the load under the electrodes, the greater the resultant heating effect should be. Since only one sample was dried at a time during the previous tests, it was thought of interest to observe the change in drying rate when a full load was utilized. A test specimen with normal moisture content was sent through the dielectric on the asbestos plate with eight samples of the same height surrounding it. The temperature and water loss of the center sample was measured and compared with heating rates of specimens dried without extra loading of the high-frequency field.

Specimens were fabricated, one for each size group, in an integral unit rather than in sections, and the effect on moisture removal rate and temperature distribution of the single unit over the composite was studied.

The benefit of effectively utilizing the geometrical configuration of a component to obtain greater heating rates was studied using a rectangular block (3" x 3" x 4"). First the specimens were dried standing on end with a given air space between the top electrode and surface of the workload. A similar sample was then dried on its side with the largest surface area parallel to the electrode. The identical air space between the top electrode and the workload was maintained.

The final variable to be considered was the effect of removing specimens from the high-frequency field during the drying cycle for temperature and moisture loss measurements rather than allowing them to dry completely in an uninterrupted cycle. To study the effect of interrupting the drying cycle on rate of drying, a model system was utilized. A given volume of water contained in a ceramic crucible was evaporated: (1) in an interrupted cycle typical of that used in the previous tests, and (2) in a continuous cycle. In the continuous cycle, a specific time period was chosen and the water remaining after that drying period measured. This was repeated for several drying periods. The amount of water remaining after a given time with no interruption in cycle was compared with the quantity left at the same time in an interrupted cycle. From these results, a correction factor could be derived to allow for a deviation in rate of water loss from cooling and reheating of samples while taking measurements.

DISCUSSION OF RESULTS

The results of experimental work designed to correlate field strength with rate of moisture removal are shown in Figures 5 and 6. Figure 5 shows the dependence of drying rate on air gap between the upper electrode of the dielectric unit and the surface of the water. The strong dependence of drying rate on air gap can readily be seen. Figure 6 shows the drying rate curve for the water system at a specific air gap. The initial A/t ratio for the water sample was 1.64. As drying proceeds, the height of the water recedes; and reduced drying rates are encountered as the air gap increases and the A/t relationship decreases. Both drying and heating rates could be increased if larger initial A/t ratios are utilized. Table II shows the time required to evaporate the 50 cc samples at several air gaps. The field strength of a dielectric system required to evaporate a given volume of water with a specific A/t ratio can be adjusted by varying the air gap.

TABLE II

TIME REQUIRED TO EVAPORATE A GIVEN VOLUME OF WATER AT VARYING FIELD INTENSITIES	
Initial Air Gap (Inches)	Time Required to Evaporate H ₂ O Samples with A/t = 1.64 (Minutes)
2.3	45 (50 cc)
2.8	70 (50 cc)
3.8	100 (46 cc)
4.8	120 (46 cc)
5.8	165 (35 cc)

The results obtained on drying a typical wet-processed ceramic body in a high-frequency field are shown in Figures 7 through 14. Figure 7 shows the variation of drying rate with air gap for two composites with different A/t values and containing 20% moisture. The drying rate for the composite with the largest A/t ratio (2.05 for the 1.5-inch-thick composite, 1.50 for the 0.75-inch-thick composite) is markedly higher than for the smaller specimens. At the faster drying rates the difference is considerable. The graph in Figure 8 shows the variation of drying rate for these same composites as a function of the residual moisture content at intervals during the drying cycle. The air gaps shown gave the maximum safe drying rate for their respective composites. The drying rates determined with the water and clay systems under maximum conditions are in good agreement with the results reported by Kohler.¹

Figures 9 and 10 show the variation of percent moisture loss versus time for varying air gaps. The time required to dry the ceramic composite was shorter as the air gap between the electrode and mass was reduced. For the 1.5 and 0.75-inch-thick composites the maximum safe rates of drying occurred at air gaps of 5.9 inches and 4.75 inches respectively. At smaller air gaps, specimens failed when the high stresses, developed from water vapor pressure buildup, exceeded rupture strength of the material. While a complete curve was obtained for an air gap of 3.9 inches and the 1.5-inch-thick composite, it was obtainable only after the measurement intervals in the drying cycle were reduced from 10 to 5 minutes. Specimens left in the field for 10 minutes exploded. It can be assumed, therefore, that the drying rate at the 3.9-inch air gap would be greater than shown in Figure 9.

Figures 11 and 13 show the moisture distribution in various sections of the composite at the maximum safe drying rate. The bottom of the compact had a greater drying rate than the interior or the upper sections. This probably was because the asbestos board insulated the bottom area and restricted heat dissipation. The top compact dries slower than the rest because of the surface cooling effect. The curves in Figures 12 and 14 show the temperature distribution throughout the composites during the drying cycle. After 90 to 100% of the moisture has been removed, the temperature rises to a maximum value and then drops off. This sharp reduction in temperature and heating effect results when the water is close to or completely eliminated, since the loss factor of the mass is reduced. During the very fast drying cycles the temperature may reach as high as 400 F. The moisture vaporized at these temperatures cannot escape fast enough through the pores, and the specimen is mechanically ruptured.

Inherent Variables

Figure 15 shows the effect of drying the specimens on solid asbestos board rather than directly on the conveyor. The drying rate is seen to be considerably greater for specimens dried on asbestos, probably because of the reduced heat dissipation. The bottom compact still has a greater drying rate but not as great as in the case when asbestos is used. It is suggested that the bottom compact loses water at faster rate under these circumstances

because there is still little evaporation from the lower surfaces, and water flow is up toward the evaporating surfaces. The temperature distribution of the composite dried on the conveyor itself is shown in Figure 16. The temperature at the ceramic-conveyor interface is lower than in the interior sections.

In Figure 17 the effect of loading the high-frequency field with a group of specimens in contrast to one specimen alone is illustrated. Contrary to the general rule outlined previously, the experimental results indicate that the rate of drying for the sample composite dried alone was somewhat greater than those dried in the presence of other composites. It is possible that the dry compacts making up the additional load led to an unfavorable change in the electrical characteristics of the total load, i.e., the total loss factor was reduced and thereby the field intensity in the area of the wet compact was reduced.

The effect of the geometry of components to be dried in an effort to gain greater A/t ratios and resultant heating rates is illustrated in Figure 18. The identical specimen standing on its end had a faster drying rate than when it lay flat.

Figure 19 shows the drying rate curves for the composite specimens and an integral unit of the same dimensions. The rate of drying for the integral unit is very close to, though slightly below, that of the composite.

Figure 20 shows the temperature distribution in the integral unit. This temperature distribution was found to be similar to that for the typical composite shown in Figure 14.

The final phase of this investigation was undertaken to study the effect of removing specimens from the high-frequency field for temperature and moisture gradient determinations. Table III shows the effect of interrupting the drying cycle on the rate of moisture removal.

TABLE III
EFFECT OF INTERRUPTING DRYING CYCLE ON DRYING RATE

Volume H₂O Sample 70 cc
Air Gap 2.35 Inches

<u>Cycle</u>	<u>Time (Minutes)</u>							
	<u>10</u>	<u>20</u>	<u>30</u>	<u>40</u>	<u>50</u>	<u>60</u>	<u>70</u>	<u>80</u>
Interrupted Cycle								
H ₂ O Left in								
Crucible, cc	52	31.4	22.8	17.2	11.4	5.7	2.9	0
Continuous Cycle								
H ₂ O Left in								
Crucible, cc	-	-	20	14.3	8.6	-	-	-

The results indicate that the removal of specimens from the field during the drying cycle had only a small effect on the drying rate. The difference between the rates of drying will increase with time and the length of the drying cycle. In a drying cycle of the duration studied above, the maximum difference in drying rate is about 4%.

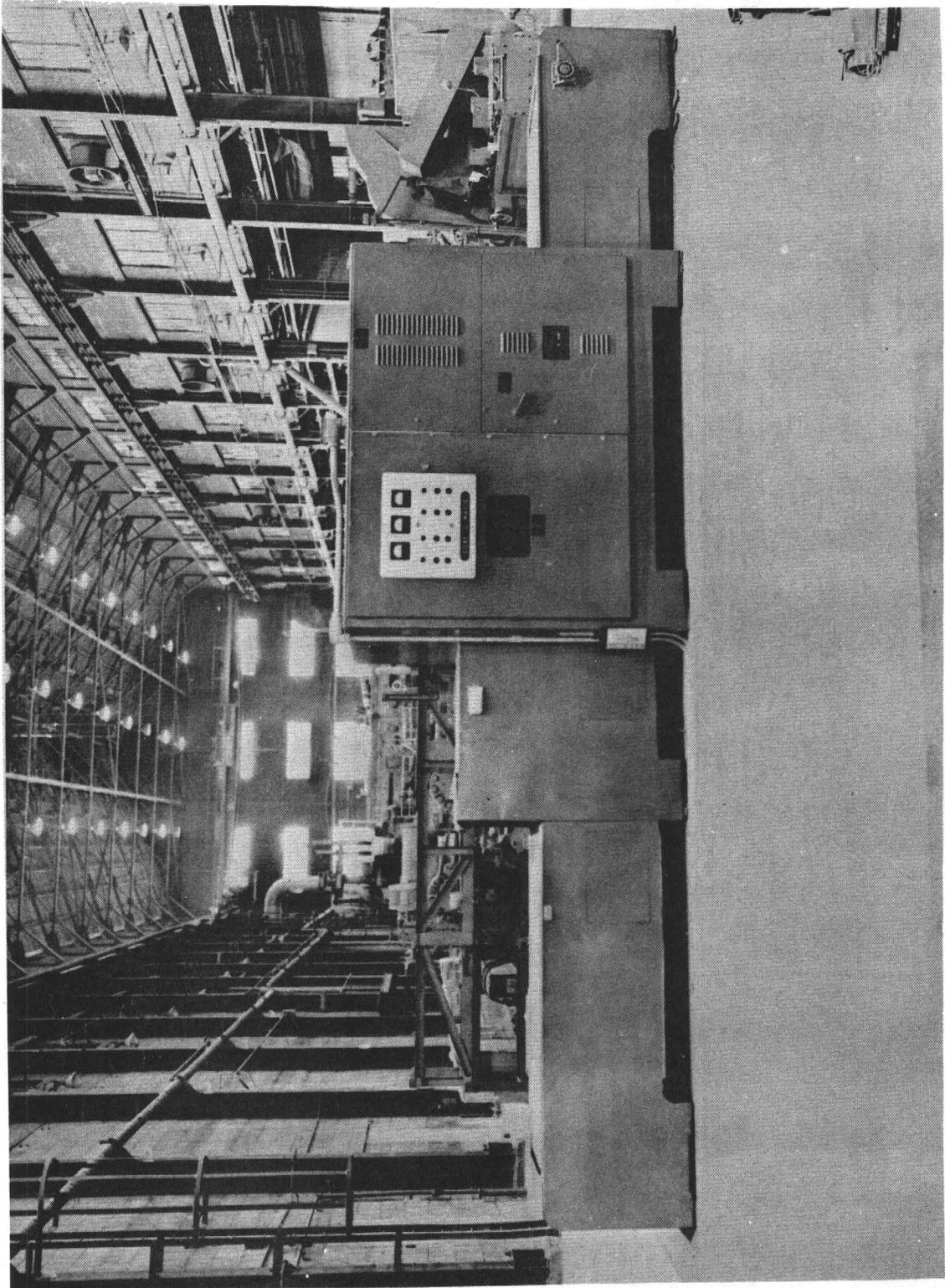
CONCLUSIONS

1. The results obtained in this investigation show that rapid drying rates for wet-processed ceramics are obtainable with the dielectric heating method.

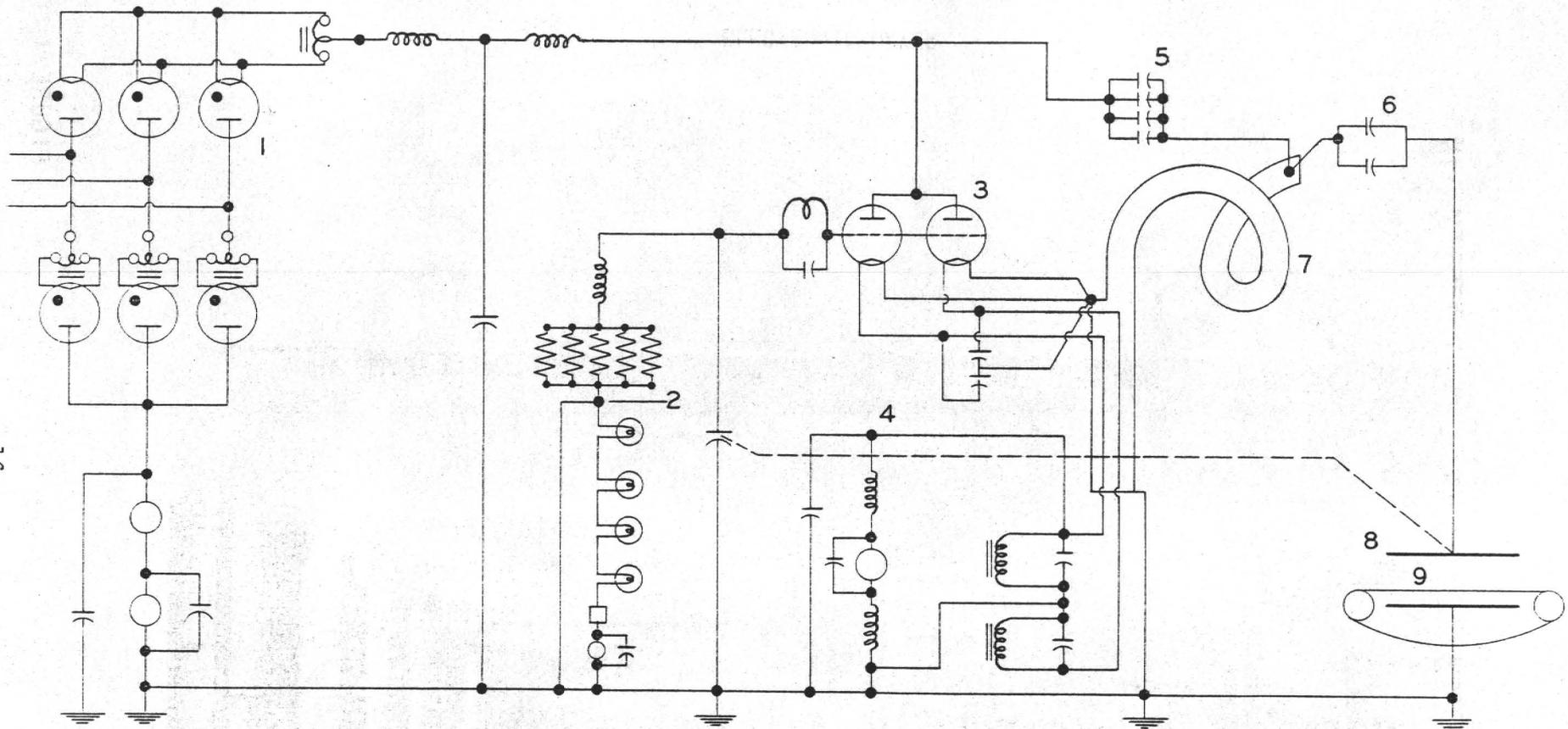
2. The drying rates, while determined primarily by the voltage drop across the workload (as evidenced by the variation of drying rate with air gap), are also affected by frequency, area-thickness ratio of the component, and electrical characteristics of the materials to be dried. The drying rate is seen to decrease in clay-water systems as the percent moisture decreases.

3. Components are heated uniformly in the ultrahigh-frequency electrical field, with the interior temperature of the ware slightly higher than its surfaces, which are cooled during moisture evaporation. Neither the slight moisture nor temperature gradients developed in the ware by this method was great enough to cause cracking and/or warping.

4. Drying wet-processed ceramics by the dielectric heating method, while not advantageous for low-cost production units because of high initial equipment costs and high operating expenses, seems to hold interesting possibilities for use in drying high-cost components or component systems which are difficult to dry by other techniques.



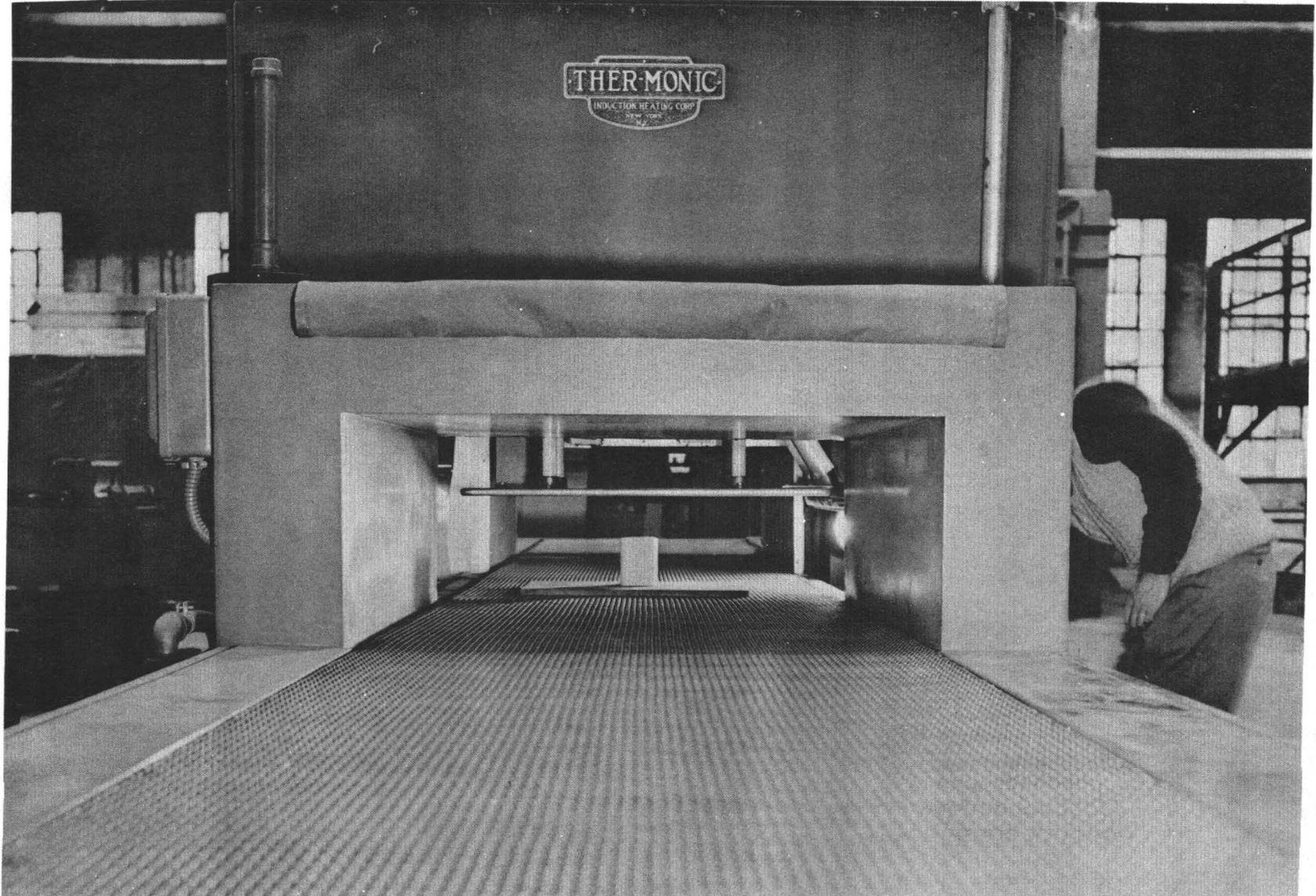
ELECTRONIC DRYER



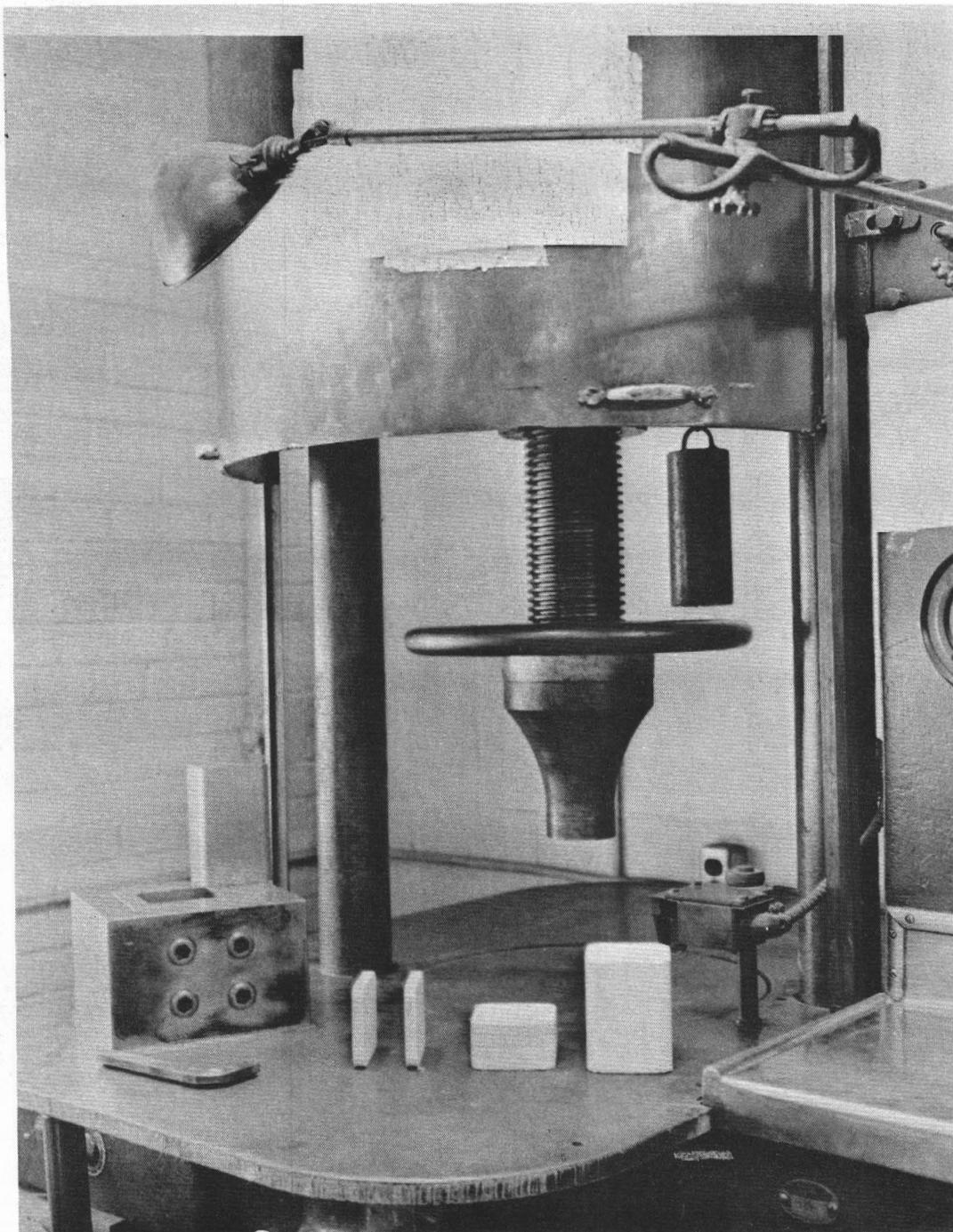
- 1. RECTIFIER TUBE
- 2. ELECTRODE BLOWER MOTOR
- 3. OSCILLATOR TUBES
- 4. CONVEYOR DRIVE MOTOR
- 5. PLATE BLOCKING CONDENSER

- 6. ELECTRODE COUPLING CONDENSER
- 7. MAIN OSCILLATOR TANK COIL
- 8. ELECTRODES
- 9. TANK CONDENSER

CIRCUIT DIAGRAM FOR ELECTRONIC DRYER



ELECTRONIC DRYER - DETAIL ELECTRODES AND HEATING CHAMBER



DIE ASSEMBLY AND SAMPLE PRESSED SPECIMENS

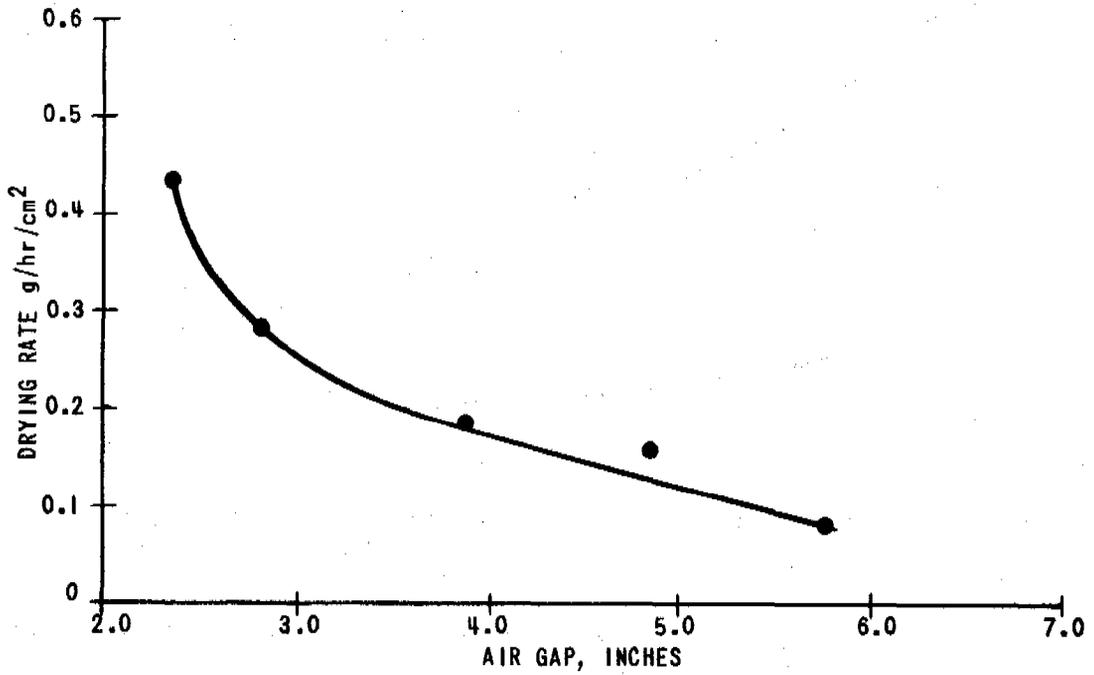


FIGURE 5: DEPENDENCE OF DRYING RATE ON AIR GAP FOR WATER SYSTEM (A/t 1.64)

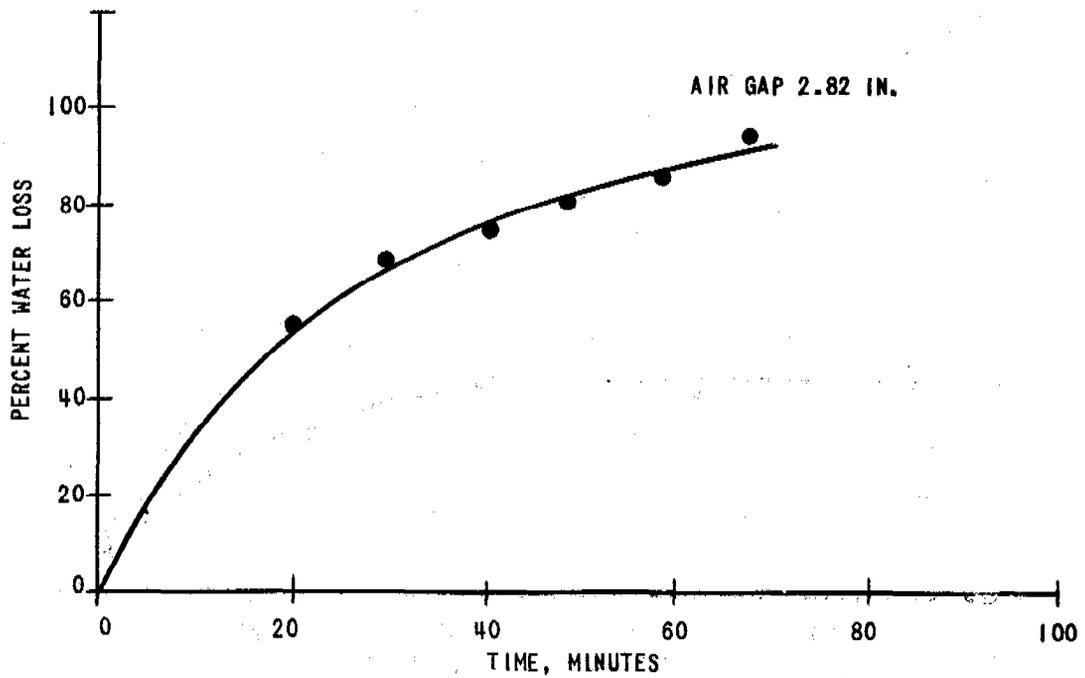


FIGURE 6: VARIATION OF PERCENT WATER LOSS WITH TIME

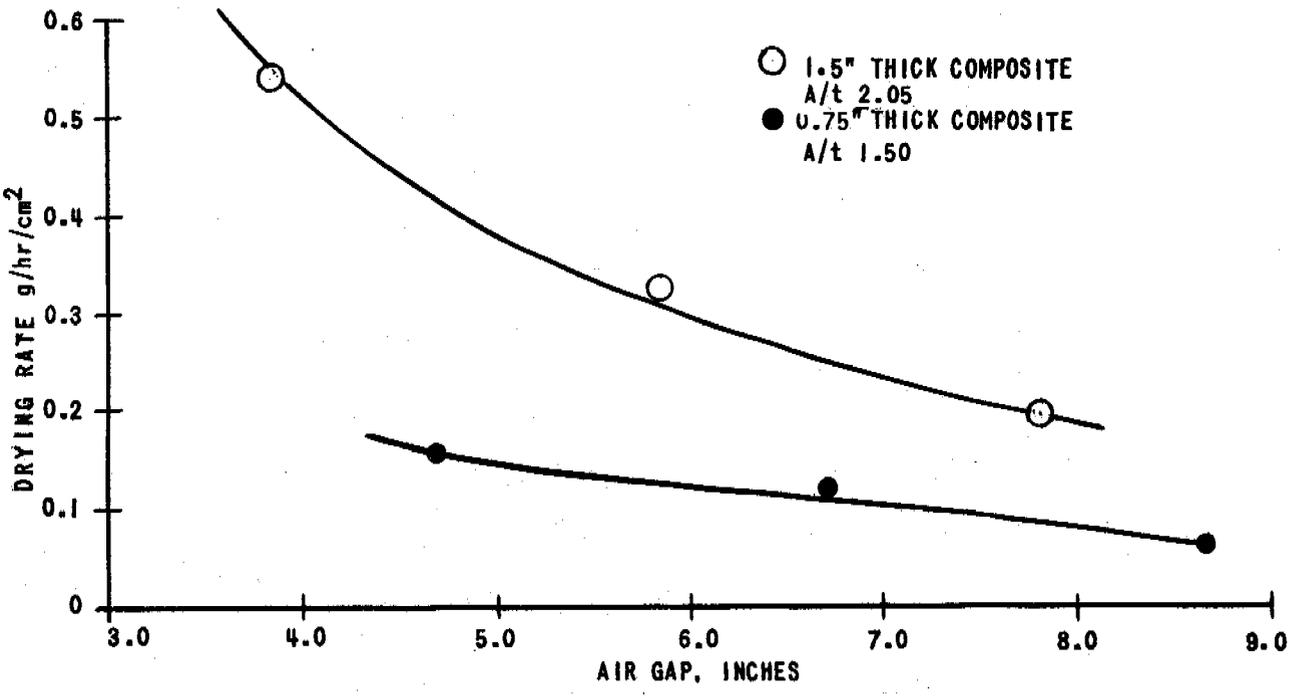


FIGURE 7: EFFECT OF AIR GAP ON DRYING RATE FOR CERAMIC SPECIMENS OF DIFFERENT A/t RATIO

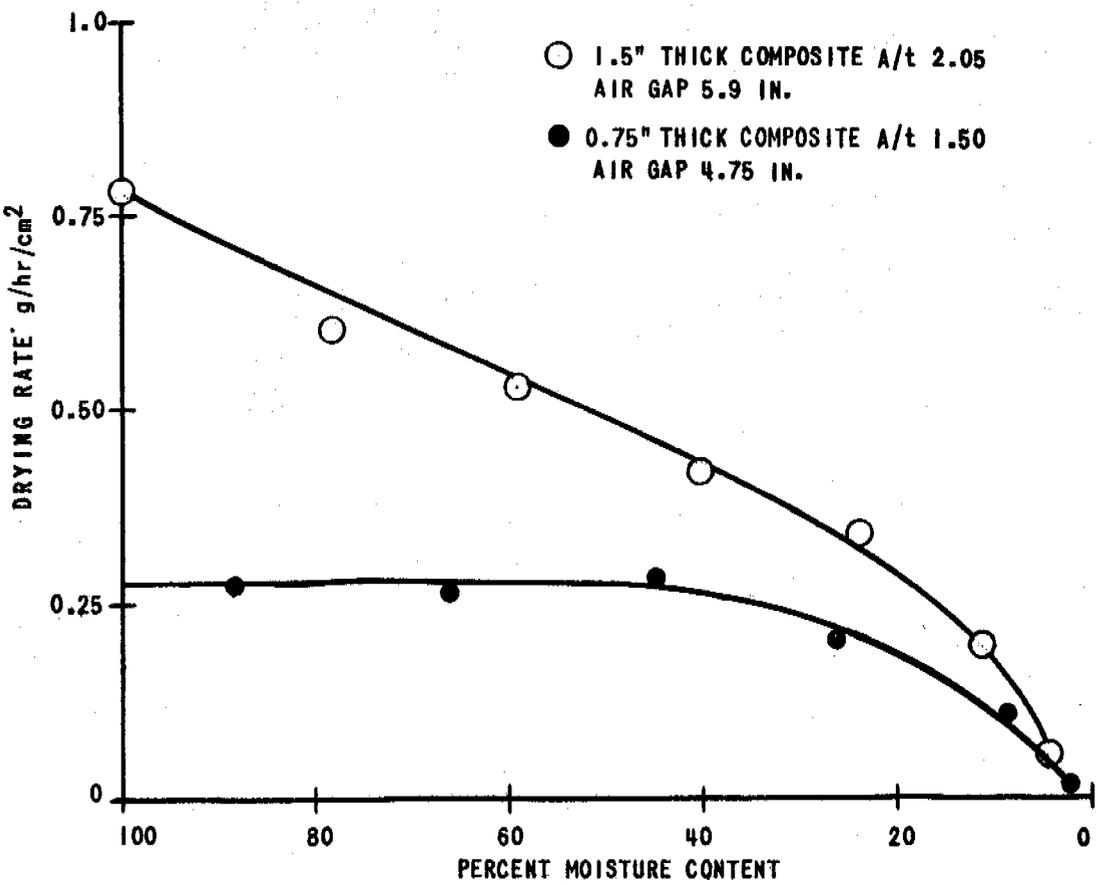


FIGURE 8: DRYING RATE VERSUS PERCENT MOISTURE CONTENT FOR CERAMIC SPECIMENS CONTAINING 20 PERCENT MOISTURE

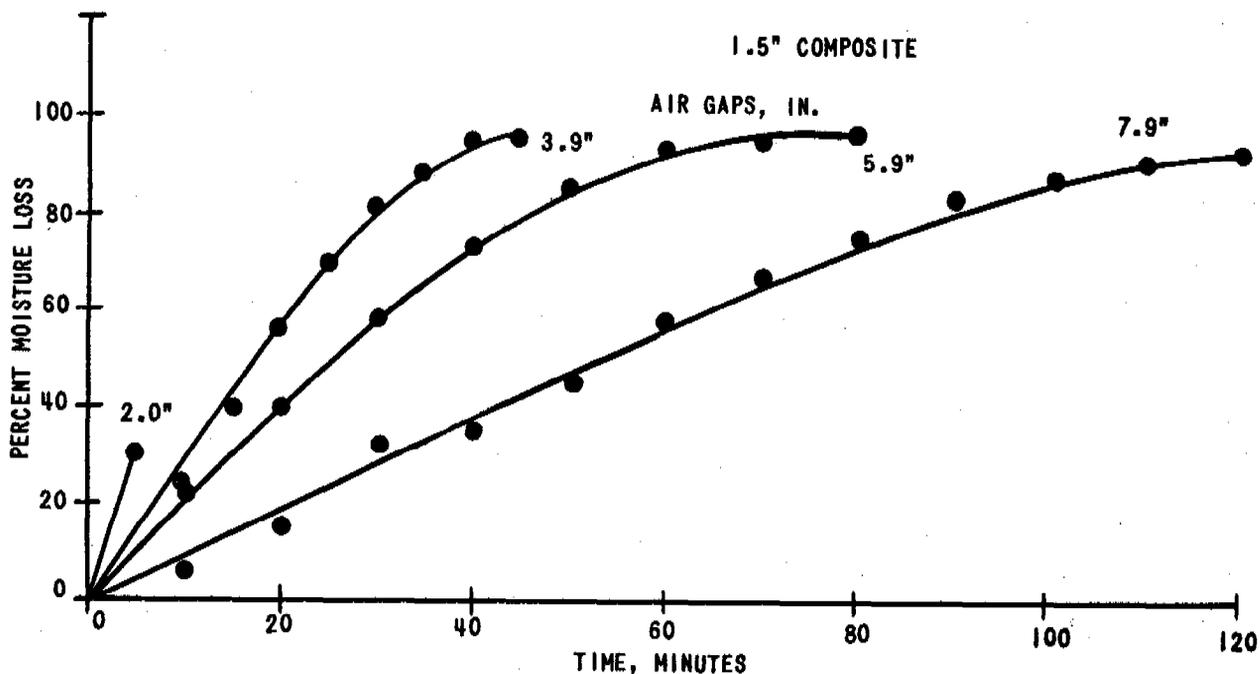


FIGURE 9: PERCENT MOISTURE LOSS VERSUS TIME AT SEVERAL AIR GAPS

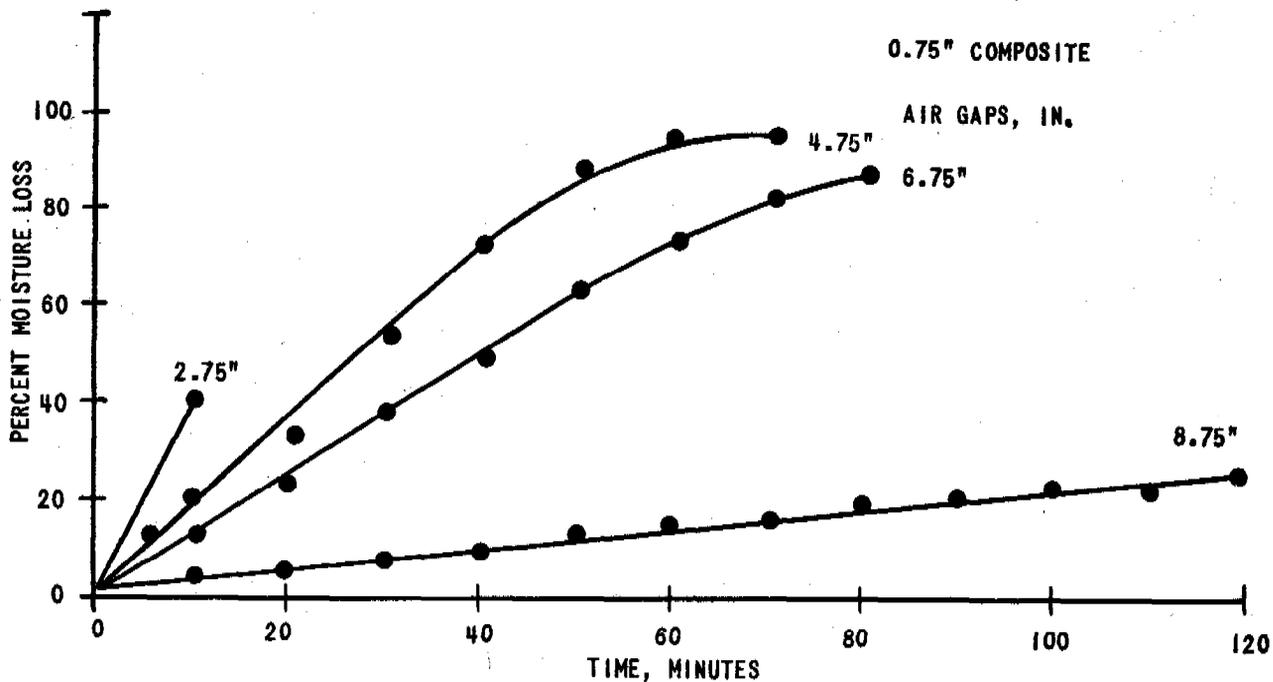


FIGURE 10: PERCENT MOISTURE LOSS VERSUS TIME AT SEVERAL AIR GAPS

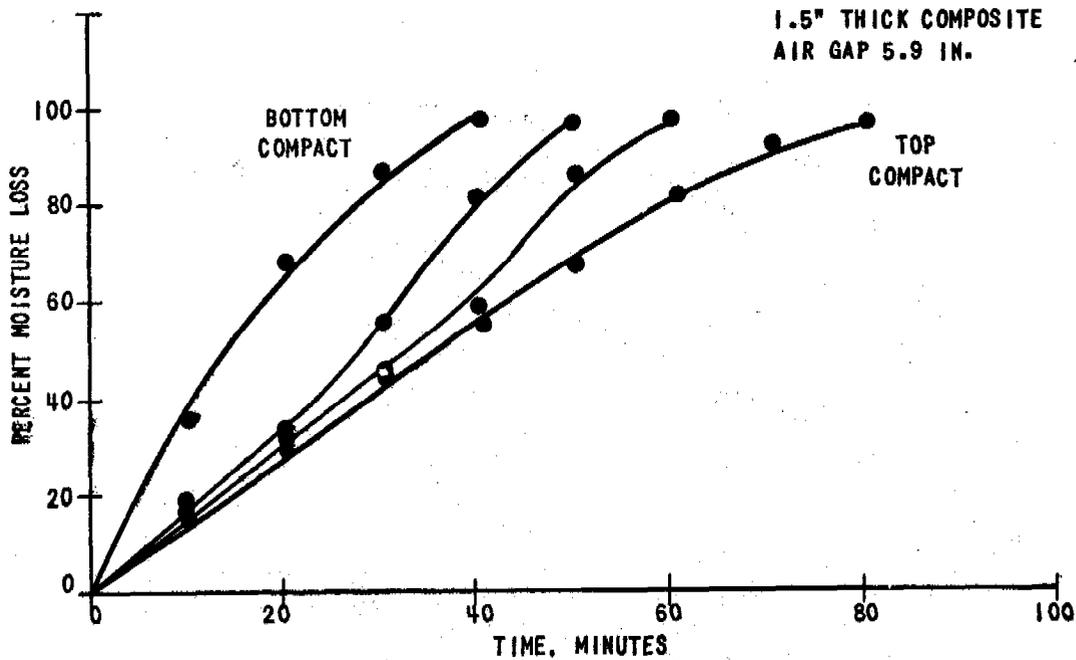


FIGURE 11: MOISTURE DISTRIBUTION DURING DRYING CYCLE FOR CERAMIC COMPOSITE (A/t 2.05)

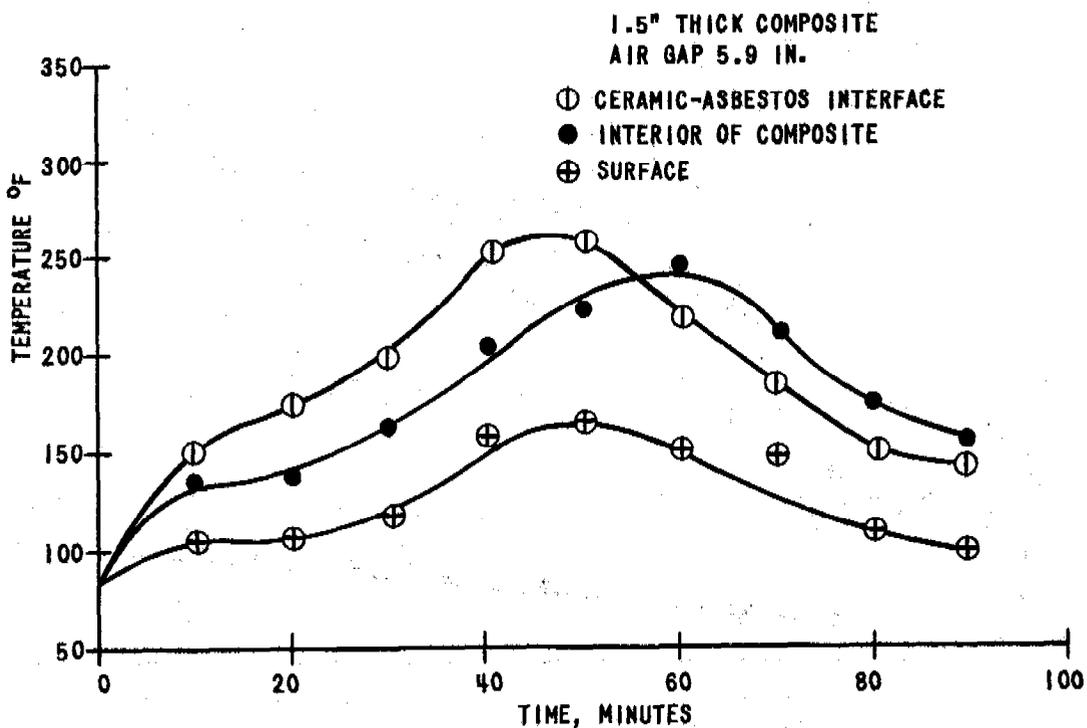


FIGURE 12: TEMPERATURE DISTRIBUTION DURING DRYING CYCLE FOR CERAMIC COMPOSITE (A/t 2.05)

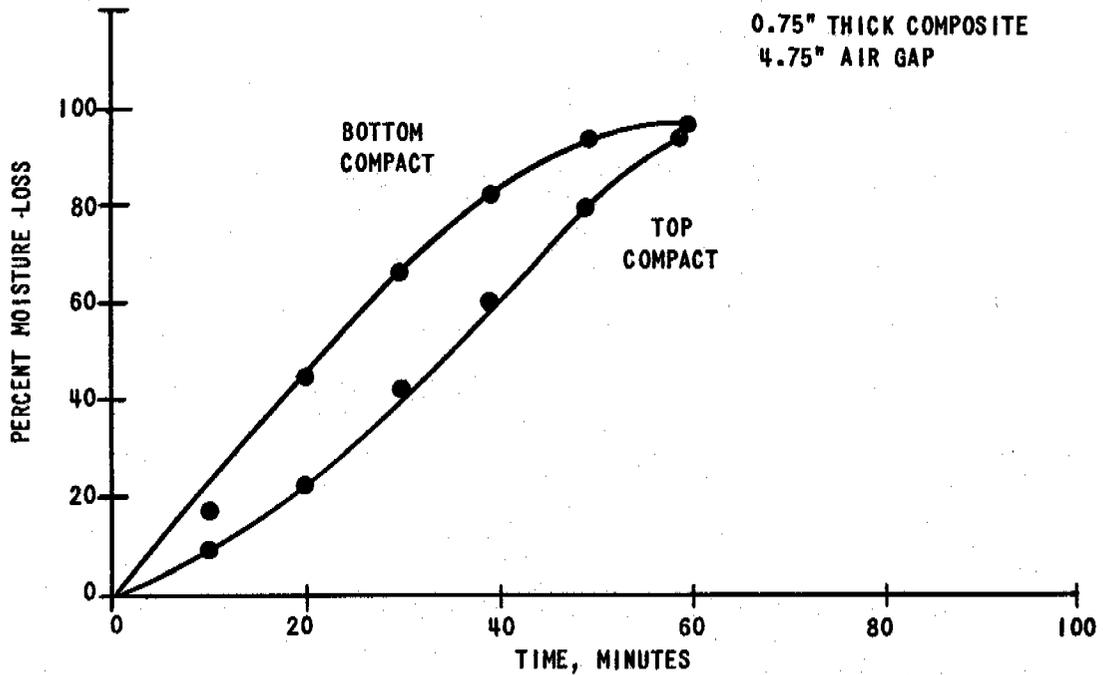


FIGURE 13: MOISTURE DISTRIBUTION DURING DRYING CYCLE OF CERAMIC COMPOSITE (A/t 1.50)

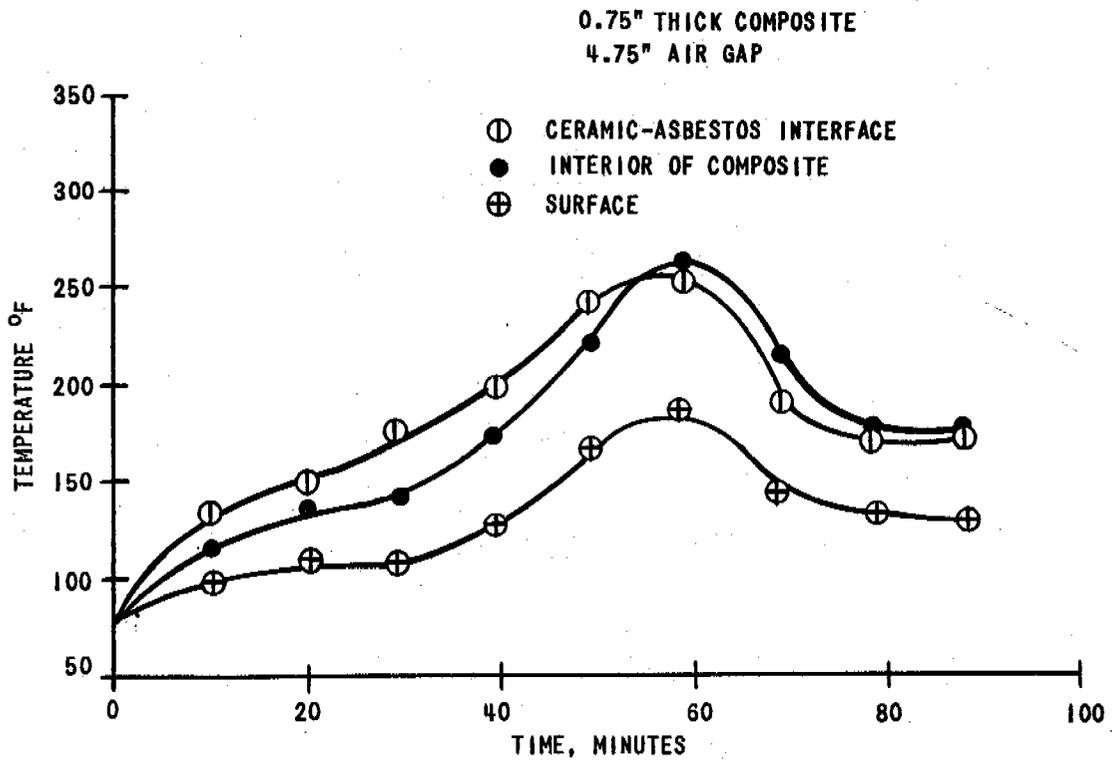


FIGURE 14: TEMPERATURE DISTRIBUTION DURING DRYING CYCLE OF CERAMIC COMPOSITE (A/t 1.50)

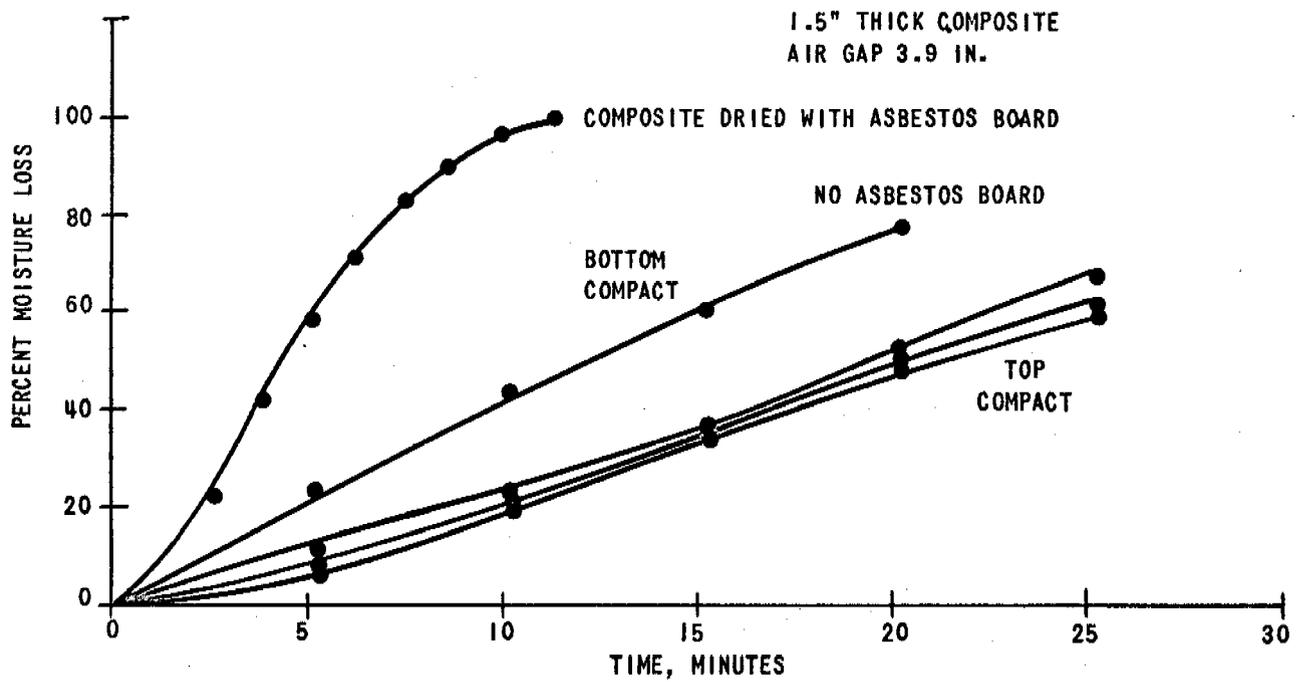


FIGURE 15: DRYING RATES FOR COMPOSITES DRIED WITH AND WITHOUT ASBESTOS PLATE

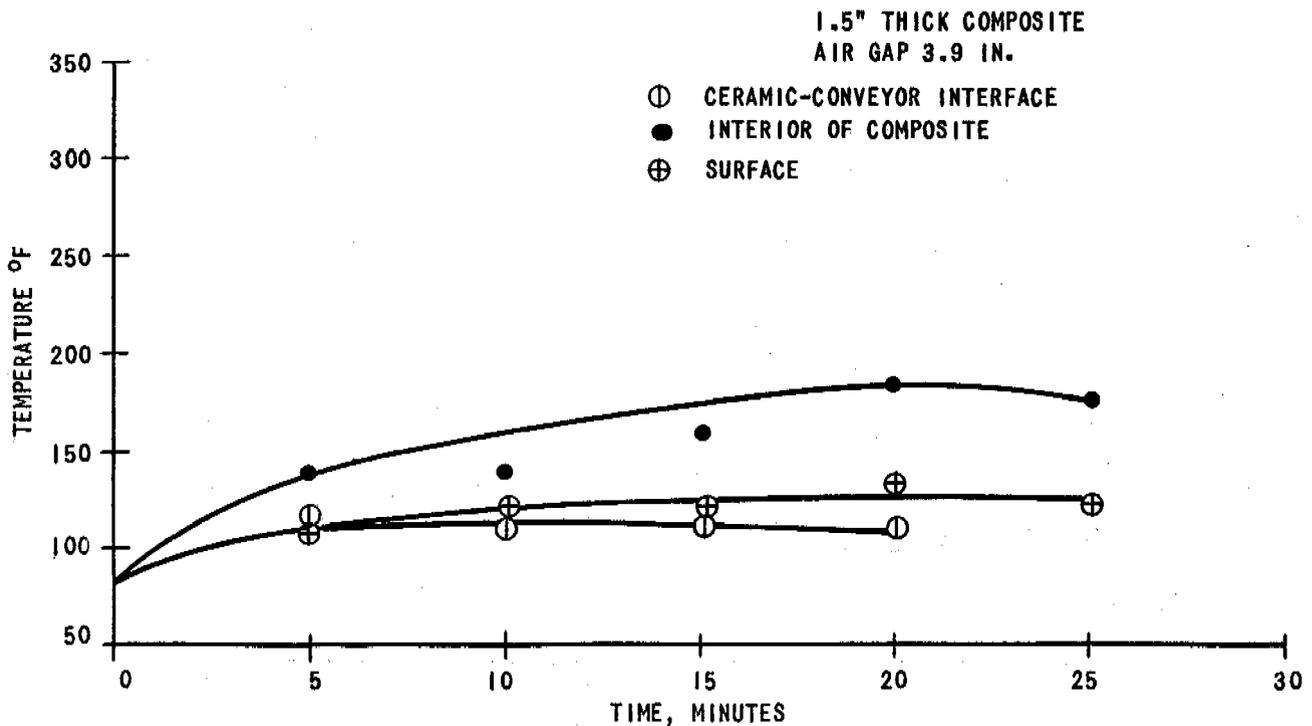


FIGURE 16: TEMPERATURE DISTRIBUTION IN COMPOSITE DRIED WITHOUT ASBESTOS PLATE

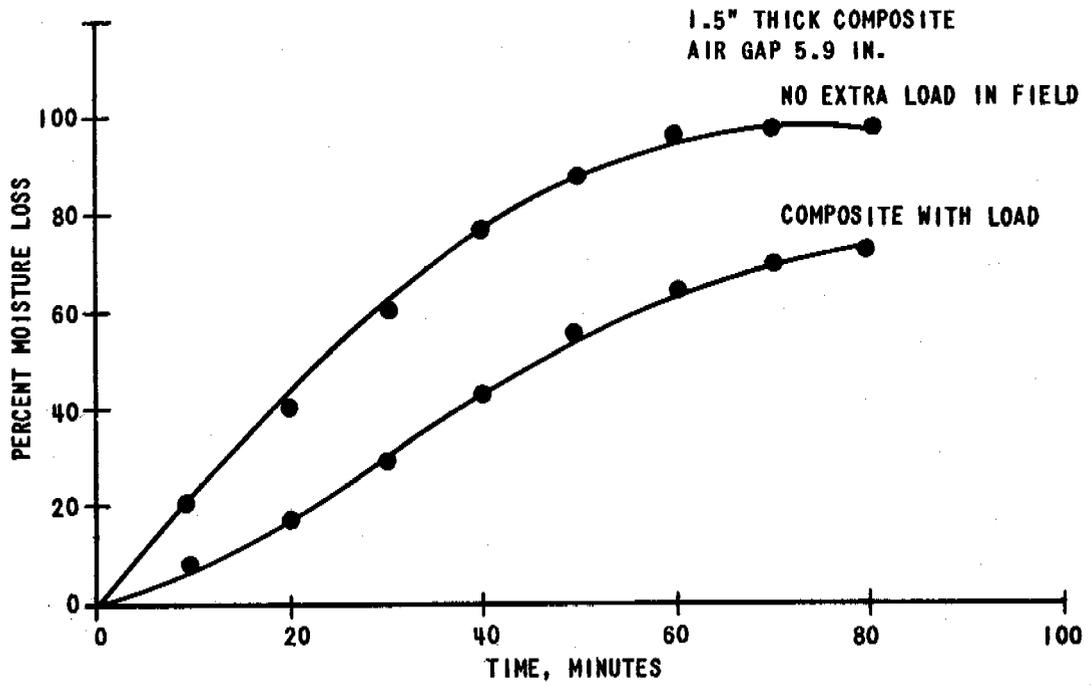


FIGURE 17: EFFECT OF DRYING COMPOSITE WITH AND WITHOUT ADDITIONAL LOAD IN THE ELECTRIC FIELD

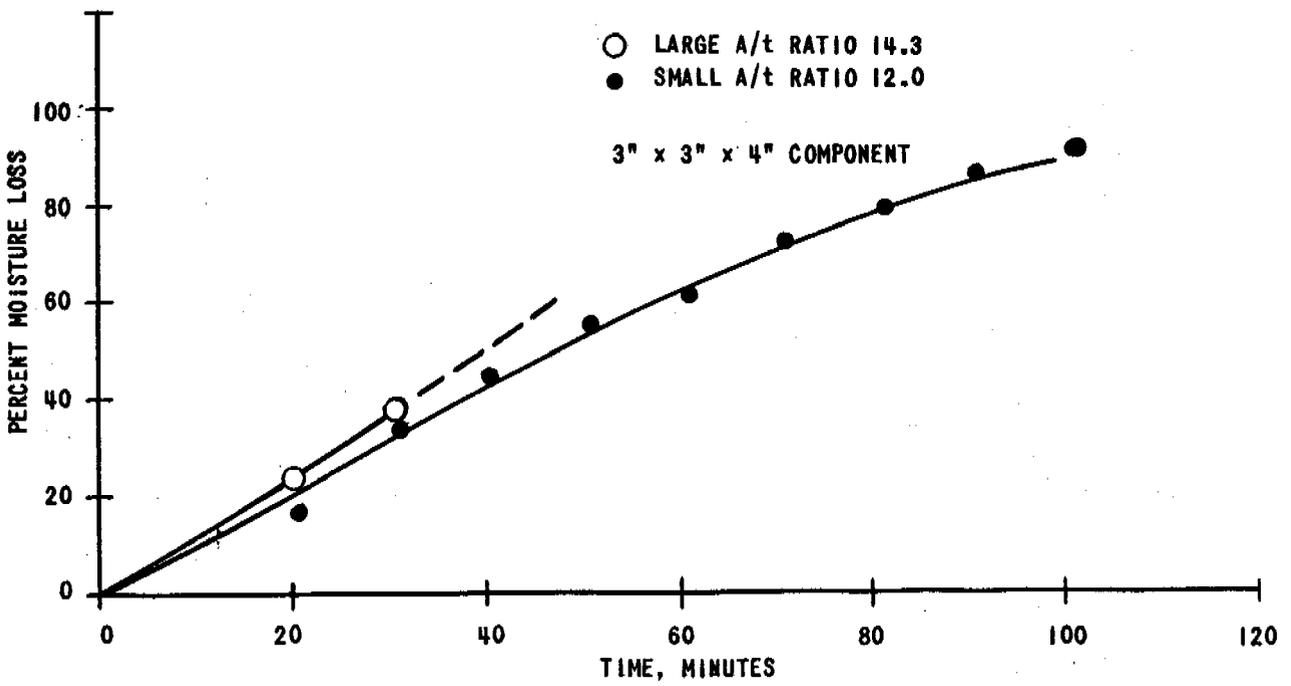


FIGURE 18: EFFECT OF UTILIZING DIFFERENT COMPONENT ORIENTATION TO YIELD INCREASED A/t RATIOS FOR A GIVEN SPECIMEN

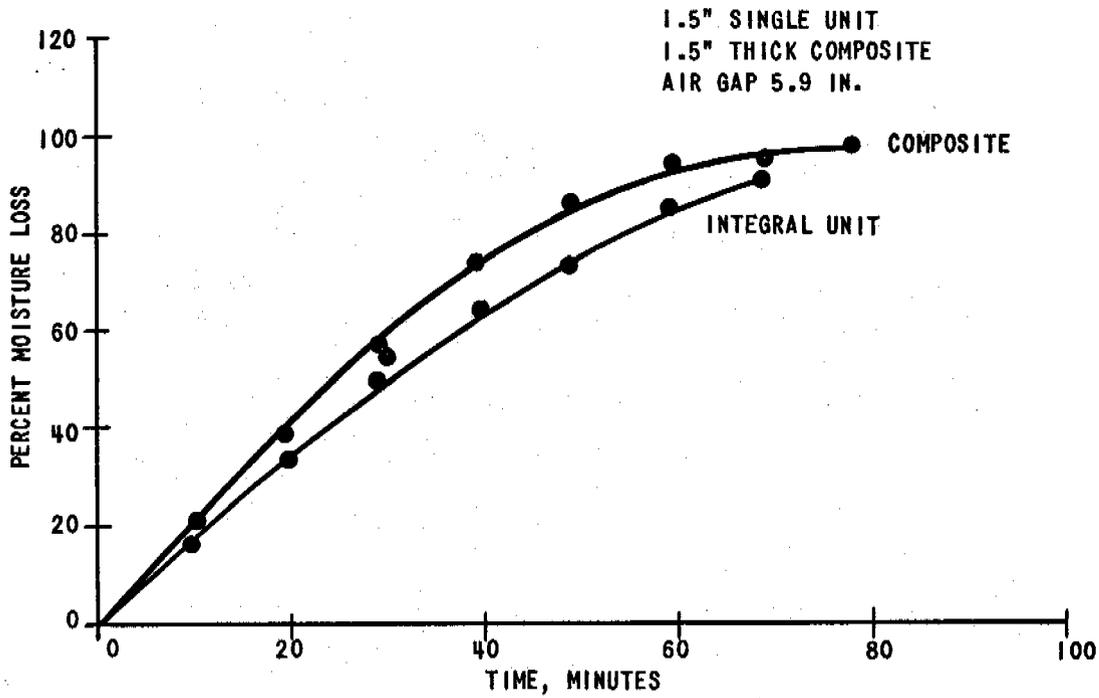


FIGURE 19: RATE OF DRYING FOR COMPOSITE SPECIMENS AND INTEGRAL UNIT

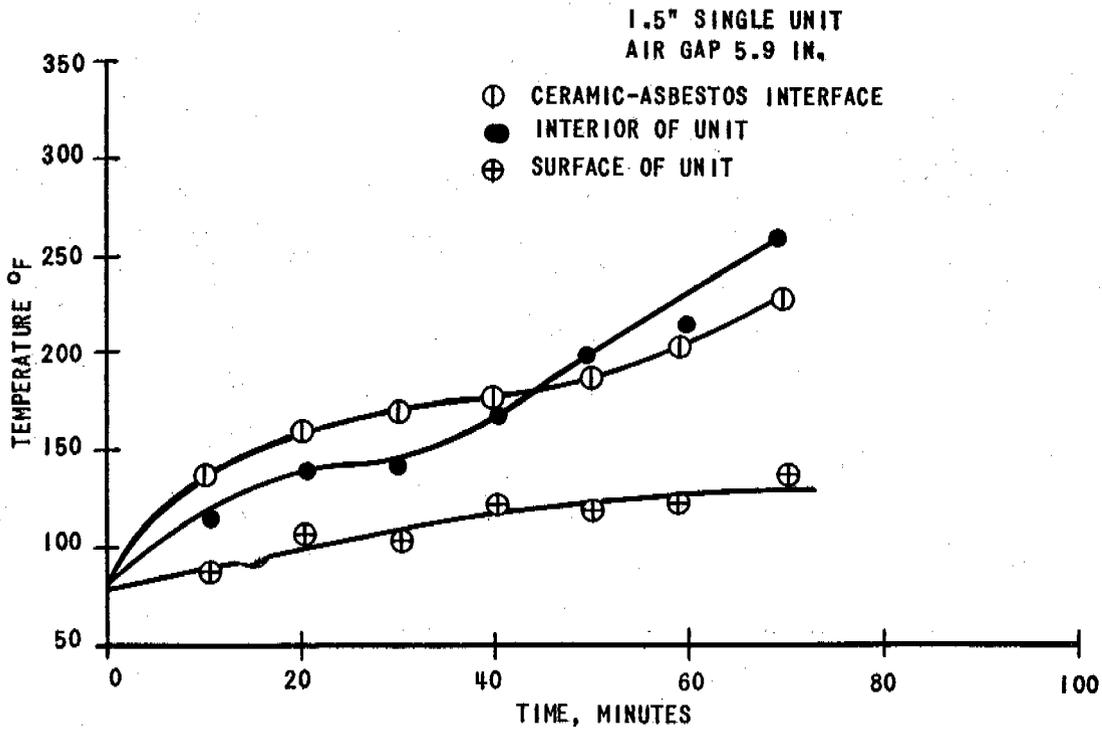


FIGURE 20: TEMPERATURE DISTRIBUTION IN INTEGRAL UNIT

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