DRYING CERAMIC PRODUCTS USING INDUCED ULTRA-HIGH FREQUENCY ELECTRICAL ENERGY

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by

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I. INTRODUCTION

In the drying of ceramic products it is desirable to remove the moisture as rapidly as possible without endangering the structure by uneven shrinkage.

The principle method of drying clay products at the present time consists of passing hot, humid air over the damp, clay pieces. Both the humidity and the temperature of the air in contact with the clay ware must be accurately controlled to prevent any drying action at the surfaces of the clay pieces before their interiors become heated. If the outside layer of any individual piece dries before all of the water has been expelled from its interior, stresses will be set up, and as a consequence the piece tends to crack or warp. In addition, a dry layer at the surface of the piece tends to retard the further passage of moisture from the center to the outside.

The ideal condition for drying clay wares is to heat the piece at its center first, and keep the center at a higher temperature than the material toward the outside. This condition will produce a high vapor pressure within the piece which will cause forced diffusion of the moisture to the surface, replacing the moisture as it is evaporated from the surface.

It is very difficult to obtain this ideal condition

with the conventional methods of drying ceramic products. Therefore, this investigation was conducted to determine the possibility of drying by heating the ware from the center first, using ultra-high frequency induced electrical energy.

II. REVIEW OF LITERATURE

There are two essential factors in the drying of any clay product which are pointed out by Norton[1]: "First, the rate of evaporation from the surface which is governed by the temperature, velocity, and humidity of the drying air; and second, the rate of diffusion of moisture through the material to be dried, which depends upon the temperature of the material, the shape and size of the pores, the moisture gradient, and the amount of moisture". The rate of diffusion is not constant throughout the drying cycle.

The total shrinkage is not influenced by the rapidity of drying[2], that is, long drying does not tend to bring about greater shrinkage nor does more rapid drying tend to bring about smaller shrinkage. The total shrinkage is proportional to the water content of the clay, and therefore the drying time depends largely upon the water content.

Cracks developed during drying are due to tension which reaches a maximum at the surface. It is pointed out by Phillips[3] that as water evaporates from the surface

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[1]F. H. Norton, "Refractories," Chapter VI, p. 129 - 142.

[2]R. F. Geller, "Note on the Effect of Time on Drying Shrinkage of Clays," Jour. Amer. Ceram. Soc., 4, p. 282 - 287 (1921).

of the formed piece, the movement of water from the interior is retarded by the impervious structure of the mass. The surface shell becomes quickly almost bone dry, while the interior retains much of its original water content, and consequently a characteristic form of extreme cracking is set up.

Extreme care must be exercised to prevent cracking in the drying of shapes having thin, quickdrying portions joined to a heavy body. As pointed out by Norton[1], a humidity- controlled dryer is best for this condition because the moisture content of the whole shape can be gradually lowered by reducing the humidity in the drying chamber.

Lindsay[4] states that in the drying of any clay body, the rate of evaporation of moisture from the surface relative to its replacement by diffusion from within, is the all-important factor.

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[1]Ibid.

[3]J. G. Phillips, "Improving the Properties of Clays and Shales," Canadian Dept. of Mines and Resources, Bull. No. 793, p. 9.

[4]D. C. Lindsey and W. H. Wadleigh, "Some Observations on the Drying Properties of Clays," Jour. Amer. Ceram. Soc., 8, p. 677-693 (1925).

III. EXPERIMENTAL

A. Procedure of Investigation

The test specimens (2-1/4 inch cubes) were formed by means of a Bonnot V-60 auger extrusion machine. As nearly as possible the same percentage of water of plasticity was used in making up all of the test specimens.

Each specimen was introduced into the humidity dryer between the two 2-1/2 inch square copper plate electrodes, which were placed 3-1/4 inches apart, so that heat could be applied either by (1) induced eddy currents, or by (2) preheated, humid air, or by (3) combinations of the two.

Tests were made, first, using high frequency as the only means of heating the specimens; second, using the resistance wire coils as the only source of heat; third, using a combination of the two sources of heat throughout the entire drying period; and fourth, using a combination of the two sources of heat for the first thirty-six minutes, and the heating coils only for the completion of the drying period. In each case the air velocity was held constant at 120 feet per minute, and the humidity was controlled throughout. The fastest drying schedule possible was developed. In the various methods of drying used, many preliminary tests were made to determine the fastest possible rate of drying without damage to the test specimens. Three test specimens were dried under each method of drying.

The linear shrinkage at two minute intervals was recorded when ultra-high frequency current was used as the source of heat. Readings were taken at five minute intervals when the heating coils were used as the only source of heat. The critical period during the drying of any ceramic material occurs while the shrinkage water is being expelled. After the shrinkage has stopped, all danger of cracking is ended, although the material is not throughly dry. For this reason, only the shrinkage period was considered in the tests conducted.

The power input for the oscillator and for the heating coils was determined on all of the tests.

After all of the test specimens had been completely dried, compressive strength determinations were made.

In order to determine the way in which heating takes place within a test specimen, an egg was placed between the electrodes, and the position of the first evidence of cooking noted.

A two-inch cube was bored with a 1-inch hole and placed in the high frequency field to determine if heating would be evenly distributed throughout the cross section of the piece.

B. Material

One clay was used throughout this investigation. It was a fine-grained, alluvial type clay with a high drying shrinkage and strong tendency to laminate when formed by the auger extrusion method. All these properties tended to produce specimens that were very difficult to dry.

C. Apparatus

1. Humidity Dryer

A laboratory dryer similar to the one described by Norton[5] (Figs. 1 and 2) in which the temperature, humidity, and velocity of the air could be controlled, was constructed. Fig. 2 shows (F,M), a direct driven fan with which the velocity of air passing from the right-hand to the left-hand compartment is controlled. Heat is supplied to the moving air by the introduction of steam at point (S_1), located directly above the resistance wire coils.

The sample is suspended on a glass rod support from a balance (B), placed on the top of the dryer. A dial micrometer is placed between the point of suspension of the glass support and the sample so that the linear shrinkage of the piece at definite intervals throughout the drying period could be obtained.

The arrows of Fig 2 show the direction of air travel from the fan (F) located below the right-hand compartment. The air then passes through the heating coils (C,C) and over the top of the partition which

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[5] F. H. Norton, "Some Notes on the Nature of Clay, II," Jour. Amer. Ceram. Soc., 16, 86 - 92 (1933).

separates the two compartments of the dryer. As shown by the arrows, the air then passes over the wet and dry bulb thermometers (W and D), around the test specimen and through the hole in the floor, back to the fan.

Plate electrodes (P,P) are placed on each side of the position for the sample (S). Ultra-high frequency, electric current is induced in the sample by means of these electrodes.

Fig. 1. Front view of experimental dryer with oscillator.

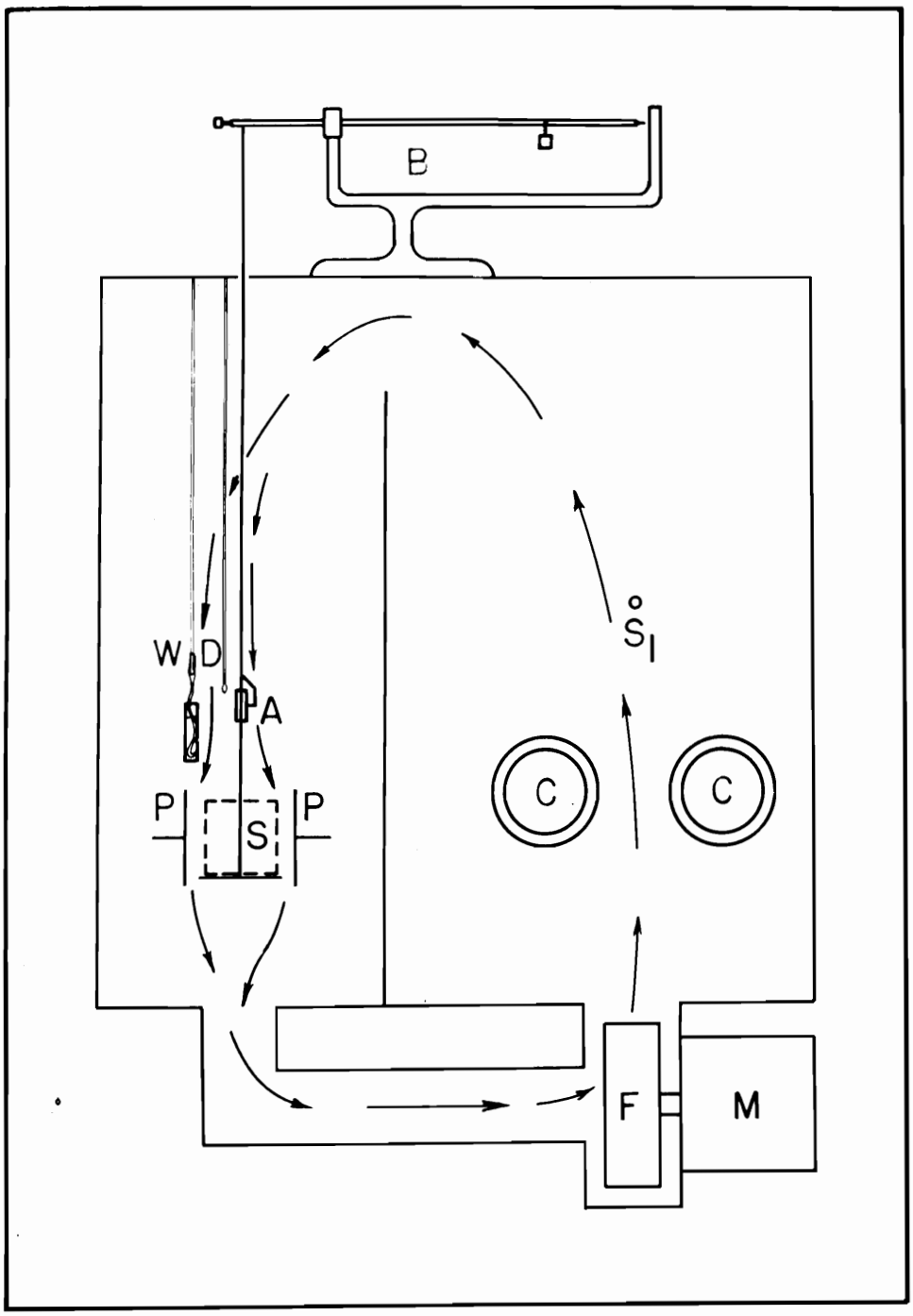

FIG. 2. DIAGRAMMATIC SKETCH OF EXPERIMENTAL DRYER

2. Oscillator

A push-pull type power oscillator is used for the source of high frequency potential between the two plates. Fig. 4 shows schematically the oscillator circuit, input meters, and the load. The parts of this circuit are described as follows:

L_1 - Plate Tank - 1/2 in. copper tubing. 4 turns 3-1/2 in. diameter, 3-1/2 in. long.

L_2 - Grid Tank - 1/8 in. copper tubing. 4 turns 1-1/2 in. diameter, 4 in. long.

L_5 - Load Coils - 1/4 in. copper tubing. Each coil 3 turns 1-1/2 in. dia., 1-1/2 in. long.

L_3 & L_4 - Choke Coils - No. 14 copper wire. 38 turns 1/2 in dia., 2-3/4 in. long.

R - 5000 ohms. 50 ma.

C - 48 m.m.f. Variable Condenser.

T_1 - Filament Transformer - 110 to 10 volts, 10 amps.

T_2 - Plate Transformer - 110 to 2300 volts, 0.5 amps.

M - 500 ma. D.C. Plate Meter

A - 10 amp. A.C. Input Meter

W - 500/1000 Input A.C. Wattmeter

V_1 - 150 volt A.C. Input Voltmeter

V_2 - Three Electrode Vacuum Tubes. The rating of each tube is as follows:

Plate Potential (RMS) (A.C.)	2500 volts
Plate Current (D.C.)	0.200 amp.

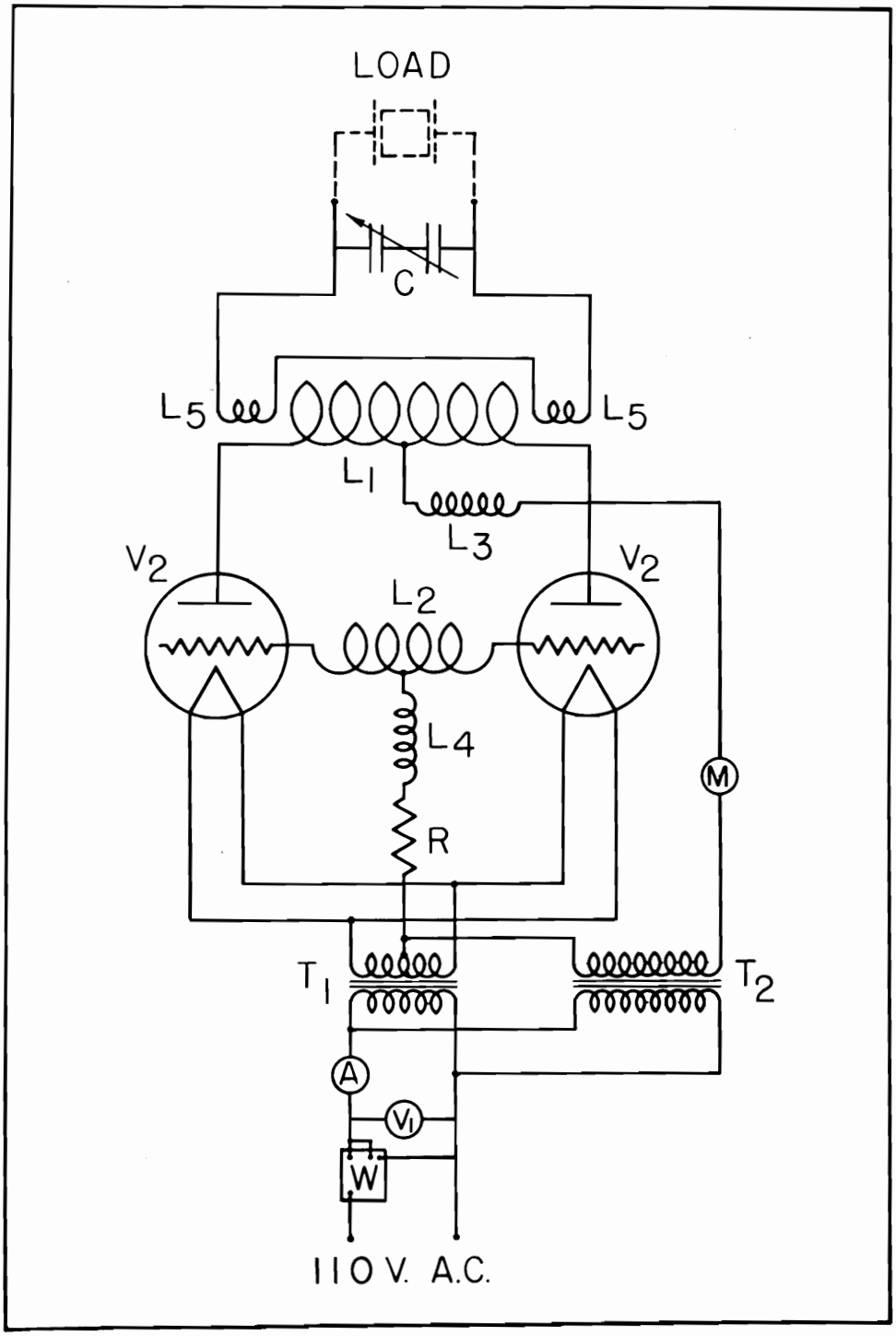

FIG. 3. CIRCUIT DIAGRAM OF THE OSCILLATOR

Plate Input	550 watts
Plate Dissipation	150 watts
Grid Potential (D.C.)	-500 volts
Grid Current (D.C.)	0.060 amp.
Grid Current (R.F.)	8.0 amp.
Grid Potential (R.F.)	750 volts

A great advantage of this type of circuit lies in the fact that alternating current is used for the plate supply. Practically any A.C. voltage can be obtained by a simple transformer, whereas high voltage D.C. is difficult to obtain without expensive and special apparatus. The tubes in this oscillator are of the three-electrode type, designed especially for electro-therapy work.

The output frequency is determined by the reactive constants of the circuit, which include the load and the inter-electrode capacitance of the tubes. The heating effect due to eddy currents, varies as the square of the frequency[6] which was approximately 43 megacycles or seven meters. The heating effect due to resistance of the clay is independent of frequency, and varies as the square of the current[7].

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[6]H. Pender and W. A. Del Mar, "Electrical Engineers' Handbook," Section 3 p. 21.

[7]R. G. Hudson, "The Engineers' Manual," p. 205.

D. Results

The per cent linear shrinkage of the test specimens dried by each method, together with the drying schedules and plate currents used for each method of drying are shown in Tables 1, 2, 3, and 4.

Time (Min.)	Dry Bulb (Deg.C.)	Wet Bulb (Deg.C.)	Plate Current (M.A.)	% Linear Shr. (Ave. of 3 Tests)
0	36	35	0	0.00
2	38	37	0	-0.58*
4	40	39	250	-1.90
6	41	40	230	-5.40
8	43	42	210	-1.73
10	44	43	190	2.36
12	45	44	190	6.00
14	46	45	190	9.66
16	47	46	190	13.90
18	48	47	190	18.28
20	49	47	190	22.65
22	49	48	190	26.74
24	50	48	190	31.40
26	50	49	190	36.24
28	51	50	190	40.62
30	51	50	190	45.58
32	52	51	200	50.84
34	52	51	200	56.10
36	52	51	210	61.36
38	52	51	210	66.62
40	53	52	210	71.58
42	53	52	220	76.39
44	53	52	220	80.90
46	53	52	220	84.23
48	53	52	230	87.71
50	51	52	230	90.46
52	50	50	240	93.21
54	49	48	240	95.52
56	49	47	250	97.40
58	48	46	250	98.69
60	48	45	250	99.85
62	48	45	250	99.99
64	47	44	250	100.00

Table 1. Average results obtained using ultra-high frequency without resistance heating coils, together with the drying schedule and values of the plate current used with this method of heating.

*Minus signs indicate expansion.

Time (Min.)	Dry Bulb (Deg.C.)	Wet Bulb (Deg.C.)	Plate Current (M.A.)	% Linear Shr. (Ave. of 3 Tests)
0	45	40	0	0.00
2	52	44	250	-1.25*
4	57	47	230	-4.94
6	60	49	200	-7.72
8	65	52	200	-8.80
10	69	54	200	-8.96
12	72	56	200	-8.69
14	75	58	200	-7.40
16	75	59	200	-5.76
18	75	59	200	-3.75
20	75	59	200	-0.76
22	75	59	200	2.39
24	75	59	200	5.30
26	75	59	200	8.38
28	75	60	200	13.04
30	75	60	200	17.03
32	75	60	200	21.51
34	75	60	200	26.10
36	75	60	210	30.75
38	75	60	210	35.49
40	75	60	220	40.47
42	75	60	220	45.47
44	78	61	220	50.17
46	80	62	220	55.13
48	82	63	230	60.21
50	84	64	230	65.20
52	86	65	240	70.04
54	90	65	240	75.15
56	90	65	250	79.97
58	90	65	250	84.25
60	90	65	250	88.17
62	90	65	250	91.77
64	90	63	250	94.55
66	90	60	250	98.22
68	90	58	250	99.10
70	90	56	250	99.63
72	90	54	250	100.00

Table 2. Average results obtained using a combination of ultra-high frequency and resistance heating coils throughout the entire shrinkage period, together with the drying schedule and values of the plate current used.

*Minus signs indicate expansion.

Time (Min.)	Dry Bulb (Deg.C.)	Wet Bulb (Deg. C.)	Plate Current (M.A.)	% Linear Shr. (Ave. of 3 Tests)
0	45	40	0	0.00
2	52	44	250	-0.37*
4	57	47	230	-2.71
6	60	49	200	-4.57
8	65	52	190	-5.44
10	69	54	190	-5.81
12	72	56	190	-5.69
14	75	58	190	-5.32
16	75	59	190	-4.72
18	75	59	190	-2.95
20	75	59	190	-0.75
22	75	59	190	1.63
24	75	59	190	4.09
26	75	60	190	7.05
28	75	60	190	10.10
30	75	60	190	13.51
32	75	60	190	16.82
34	75	60	190	20.21
36	75	60	0	25.77
40	80	61	0	34.71
45	85	63	0	41.24
50	90	64	0	45.78
55	90	60	0	50.21
60	90	56	0	55.36
65	90	49	0	61.34
70	90	47	0	67.97
75	90	45	0	74.42
80	90	44	0	80.26
85	90	44	0	85.60
90	90	44	0	90.10
95	90	44	0	93.46
100	90	44	0	96.10
105	90	44	0	97.95
110	90	44	0	99.29
115	90	44	0	99.88
120	90	44	0	100.00

Table 3. Average results obtained using a combination of high-frequency and heating coils for first thirty-six minutes, and heating coils only to complete the test, together with the drying schedule and values of plate currents used.

*Minus signs indicate expansion.

Time (Min.)	Dry Bulb (Deg.C.)	Wet Bulb (Deg.C.)	% Linear Shr. (Ave. of 3 Tests)
0	35	33	0.00
5	45	42	-0.85*
10	50	45	-4.10
15	55	49	-6.84
20	60	52	-8.77
25	65	54	-10.25
30	70	57	-11.56
35	75	59	-12.25
40	75	59	-12.50
45	75	59	-11.14
50	75	59	-9.23
55	75	59	-6.99
60	75	59	-4.76
65	75	59	-2.16
70	75	59	1.33
75	75	59	4.63
80	75	59	7.50
85	75	59	11.16
90	75	59	15.11
95	75	59	18.23
100	75	59	21.79
105	77.5	60	25.35
110	80	61	28.66
115	82.5	61	32.09
120	85	61	35.52
125	87.6	62	39.09
130	90	62	42.60
135	90	63	46.01
140	90	64	50.03
145	90	64	54.04
150	90	63	58.46
155	90	61	63.79
160	90	57	69.68
165	90	53	75.37
170	90	50	80.57
175	90	47	85.28
180	90	45	89.30
185	90	44	92.58
190	90	43	95.04
195	90	42	96.81
200	90	41	98.06
205	90	41	99.01
210	90	40	99.61
215	90	40	99.99
220	90	40	100.00

Table 4. Average results obtained using resistance heating coils as the only source of heat, together with the drying schedule followed for these tests.

*Minus signs indicate expansion.

Fig. 4 shows the plotted results obtained from the data of Tables 1, 2, 3, and 4. These curves illustrate the relation between the per cent linear shrinkage and time. Curve No. 1 shows the result obtained by the use of induced, ultra-high frequency electrical energy as the only source of heat. Curve No. 2 shows the effect of using a combination of high frequency and preheated air to heat the sample. Curve No. 3 was obtained in a similar manner as curve No. 2 up to the point (A), where the high frequency current was cut off and the drying continued with external heat only. Curve No. 4 was obtained by the conventional method of drying ceramic products in which preheated, humid air was passed over the piece.

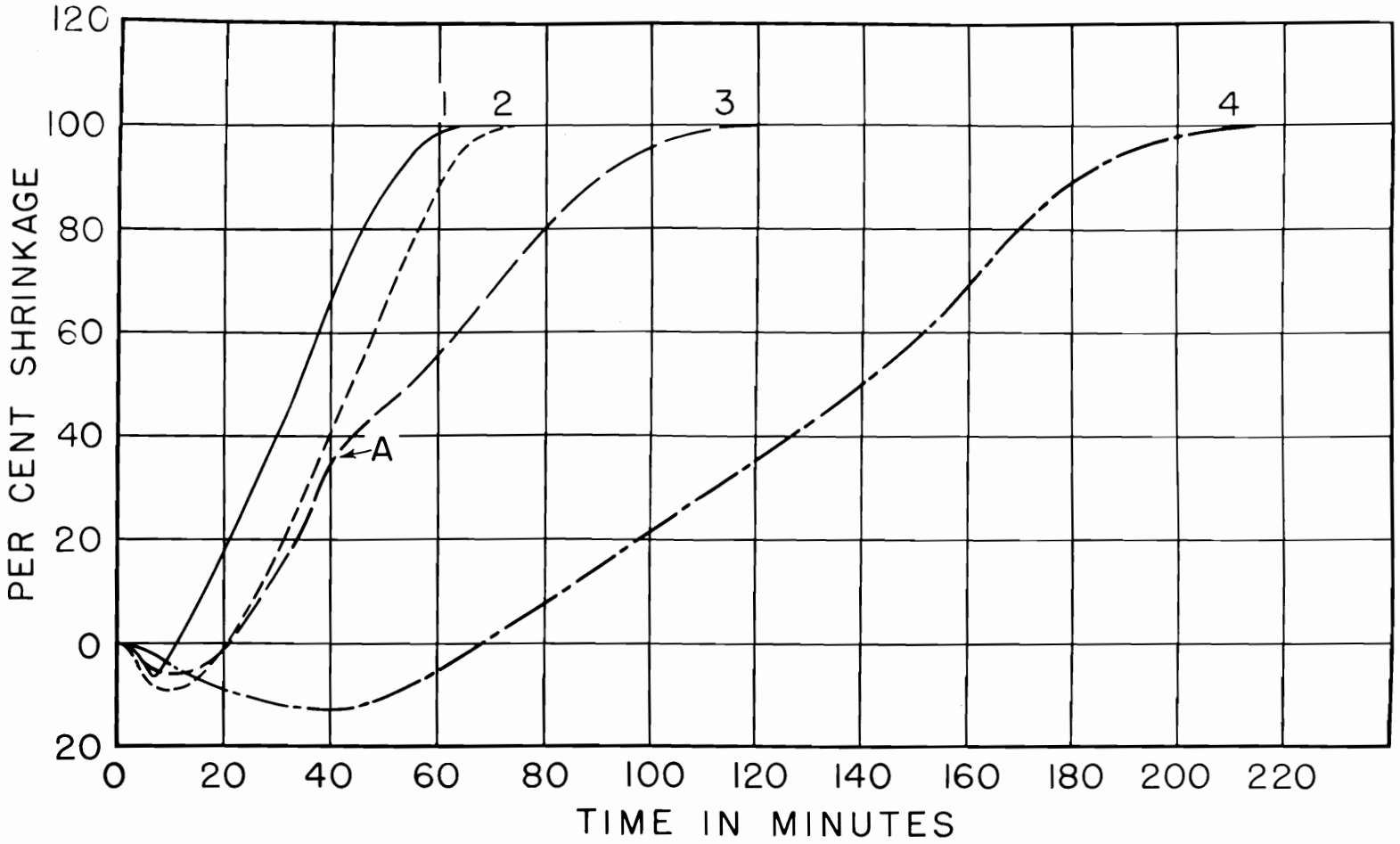

FIG. 4. CURVES SHOWING SHRINKAGE RATE UNDER VARIOUS DRYING METHODS

The averages of the compressive strength determinations are given in Table 5.

Sample Dried by Process No.	Compressive Str. Lbs./Sq.in.
I	421
II	458
III	440
IV	484

Table 5. Average values for compressive strength determinations.

The average power input for the method of drying in which ultra-high frequency alone was used, proved to be only 26% of the power input required when the resistance heating coils alone were used for the particular dryer in which these tests were conducted.

The power input for the high frequency method varied from 405 to 530 watts. The average input power was 450 watts. The average power factor of the total load at the input was 58%. The frequency was practically constant, varying from 42.2 to 43.2 megocycles in a typical test made with no external heat applied.

It was definitely proved that the interior of the ware was heated first when introduced into the ultra-high frequency field, instead of the outside being heated first as with the conventional method of drying by means of heated air. This was proved when an egg placed between the electrodes cooked first at its center.

Hollow ware pieces placed in the high frequency field are evenly heated through their cross sections, making this type of drying of value for any complicated or intricate shapes.

VI. DISCUSSION OF RESULTS

A. Drying with Ultra-High Frequency Electrical Energy as the Only Source of Heat

During the first seven or eight minutes of the test the specimen expanded approximately six per cent. This was probably caused by the expansion from heating of the water film surrounding the clay particles. With this type of drying there is an abrupt change at the end of seven or eight minutes. This occurs when the rate of evaporation probably exceeds the expansion of the water film. The relation of shrinkage and time is constant from this point until very nearly the end of the shrinkage period. It may be noted that the slope of this curve is very great due to the rapid rate of diffusion caused by the heat developed in the interior of the test specimen by the ultra-high frequency current. As the shrinkage ceases, or when practically all the shrinkage water has been driven off, the curve flattens out.

The time required for completion of the shrinkage of the test specimen with this type of drying was about 30 per cent of the time required with the conventional heated, humid air type of drying.

B. Drying with a Combination of Ultra-High Frequency Electrical Current and External Heating Coils Throughout the Entire Shrinkage Period

From curve No. 2 it is seen that the change from expansion to contraction within the piece was not as abrupt in this case as when the ultra-high frequency current was used without additional heat supplied from the heating coils. This phenomenon was probably due to the fact that the vapor pressure in the drying chamber was increased by the heat from the resistance coils, causing the evaporation of water from the surface of the piece to be more difficult than in the first method in which a lower vapor pressure was maintained in the atmosphere surrounding the specimen. The slope of curve No. 2 after shrinkage began is approximately the same as for curve No. 1 throughout the remainder of the shrinkage period. This indicates that when the temperature of the interior of the test specimen became high enough for the vapor pressure within the piece to overcome the vapor pressure outside, the rate of diffusion became equal to that of the first case.

C. Drying with a Combination of the Two Methods of Heating for the First Thirty-Six Minutes, and Heating Coils Alone for the Remainder of the Shrinkage Period

Since the first portion of the drying procedure as illustrated by curve No. 3 is identical with that of the drying procedure for curve No. 2, it is expected that they would be very similar. At point (A) on this curve, when the ultra-high frequency electrical energy is cut off, and the remaining drying of the shrinkage period is completed by means of heated air, the slope of the curve falls abruptly and the rate of shrinkage is very nearly the same as under the conditions of curve No. 4. Since the time for completion of the shrinkage period under these conditions is approximately one half the time required for the completion of shrinkage under conditions for curve No. 4, it is probable that this procedure might be an economical one for certain types of ceramic products.

D. Drying with Heat Supplied from Resistance Coils Only

Under the conventional drying conditions as used for the tests of curve No. 4, there is a gradual expansion of the piece during the first forty minutes of the test. Probably very little evaporation has taken place prior to this time. It may be noted from the slope of the curve from this point of maximum expansion that evaporation and subsequent shrinkage is going on very slowly for the completion of the test. Since it was determined in the testing that this was the fastest rate possible without damage to the ware, it is evident that diffusion from the interior to the surface was too slow for any greater rate of shrinkage of the piece. Comparing this curve with those of the other types of drying, this method is slower during every portion of the test.

VII. CONCLUSIONS

(a). The time required to dry a test specimen by the use of ultra-high frequency induced current until shrinkage ceases is only thirty per cent of the time required when heat is supplied by resistance wire heating coils.

(b). It is possible, with the use of the ultra-high frequency energy, to dry complicated shapes evenly over their cross sections, which will enable much more rapid and safe drying of these shapes.

(c). The structures of the pieces are not detrimentally affected by induced current, and the rapid drying of this method.

(d). Drying with ultra-high frequency will probably prove to be of economical value in the drying of complicated shapes when additional research has further proved the effectiveness of the use of ultra-high frequency electrical energy.