INFRARED DRYING OF GRANULAR SOLIDS

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James Eric Feltham

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INTRODUCTION

In 1935 a United States Patent was issued for the infrared drying of paints and lacquers on metallic objects. (Groven (1935)). This patent was really the beginning of a new and highly successful drying technique. It was not long after the issuance of the patent that infared drying was applied to granular solids. (Stout, et al. (1945)). However, in this field the method has not been nearly so successful since the standard methods of drying granular solids such as drum dryers, tray dryers, and rotary kilns are considered less expensive.

Most of the research work concerning infrared drying of granular solids has been performed with commercial infrared lamps. There are numerous disadvantages to infrared lamps of this type, and some of these may account for the limited number of applications to date. These lamps operate at a filament temperature of approximately 4800 degrees Fahrenheit. They are commonly called near-infrared lamps because so much of the radiation produced is in the short wave length region of the infrared spectrum. Furthermore, any far-infrared radiation that is produced is absorbed by the glass that protects the filament. The shape and the size of the bulb limit the intensity of radiation that can be applied.

Recently a new type of infrared heater has been placed on the market which has several important advantages over the infrared lamps. These heaters are CHROMALOX heaters manufactured by the Edwin L. Wiegand Company of Pittsburgh, Pennsylvania. They have no glass to shield the filament and operate at a maximum temperature of 1000 degrees Fahrhenheit. The most important result of these changes is to produce a considerable portion of the radiation in the far-infrared region of the spectrum. Far infrared radiation is usually more easily absorbed by the material being dried, and hence should result in more efficient operation.

It is the purpose of this study to determine the mechanism and characteristics of far-infrared drying of granular solids. Drying rates of various granular solids are obtained as a function of a number of operating variables. The results are compared with those of convection drying as obtained either in this study or by other investigators.

INSTRUMENTATION AND EQUIPMENT

The basic piece of experimental equipment was a laboratory dryer manufactured by the Proctor and Schwartz Company, Philadelphia, Pennsylvania. See Diagram 1 in the Appendix. This dryer is of a compartment-tray design and is heated by a Trane steam heater. It was necessary to equip the dryer with five CHROMALOX Infrared Heaters for this investigation.

The drying compartment measures 24x24x48 inches. The necessary humidification is supplied by an open steam humidifier. Baffling arrangements and dampers on either side of the drying compartment permit various methods of air circulation.

The relative humidity in the dryer is regulated by a wet and dry bulb recorder-controller manufactured by the Foxboro Company, Foxboro, Massachusetta. The wet bulb is the porous-sleeve type.

Air is circulated through the dryer by a fan which is driven by a one and a half horsepower electric motor. The fan is connected to the motor through a variable speed drive.

Mounted on top of the dryer is a TOLEDO scale equipped with its hook suspended in the drying compartment. The scale is manufactured by the Toledo Scale Company, Toledo, Ohio. The scale is equipped with three beams, one blank and two of which have one ounce graduations. There is also a five pound chart with one one-hundredth of a pound graduations. In order to achieve greater accuracy, the scale was used as a balance. A set of brass weights calibrated in grams served as the means of weight determination.

The infrared heaters were manufactured by the Edwin L. Wiegand Company of Pittsburgh, Pennsylvania. They consist of an alloy-sheathed heating element with a parabolic shaped aluminum reflector. See Diagram 3 in the Appendix. The CHROMALOX heaters, catalogue number RAD 2083, were the 800 watt, 220 volt size. An extruded aluminum casing was constructed to enable the heaters to be fastened near to each other. This close connection achieved a reasonably uniform intensity of radiation across the drying surface. When the heaters were on the entire operating time, the filament temperature was 1000 degrees Fahrenheit. The energy spectral distribution curve for this situation is shown in Figure 1.

The intensity of radiation was measured with a General Electric Infrared Meter, type DW-69. This meter has been calibrated directly in watts per square inch and indicates the radiation with a wave length between 3,000 and 35,000 Angstroms. It is obvious from the energy spectral distribution curve shown in Figure 1 that the infrared meter did not register a considerable portion of the incident radiation that was emitted by the heaters. The method used in determining the actual quantity of incident radiation is discussed in the section on experimental procedure. The meter is accurate to plus or minus five per cent of the full scale reading which is 10 watts per square inch.

Leeds and Northrup copper-constantan duplex wire thermocouples were used to measure the temperature at various depths in the bed. The leads, size 24 B&S gauge, were insulated with a double layer of silicone resin impregnated fibre glass. The thermocouples were calibrated in a constant-temperature, Dowtherm-A bath using a mercury thermometer which had been calibrated by the National Bureau of Standards. The thermometer was graduated in tenths of a degree from 0 to 200 degrees Centigrade. The calibration data are given in Table 1 in the Appendix. Diagram 2 in the Appendix shows the thermocouple circuit arrangement. The thermocouple leads were connected to a number 820, twenty point thermocouple selector switch manufactured by the Wheelco Instruments Company, Chicago, Illinois.

A potentiometer was used to measure the thermocouple emf. The potentiometer, model number 8657-C, was manufactured by the Leeds and Northrup Company, Philadelphia, Pennsylvania. The accuracy of this instrument is specified to be plus or minus 50 microvolts. The reference junction was maintained at 0.00 degrees Centigrade with distilled water and ice in a Dewar flask.

Since the top surface of the drying tray is exposed to such a high intensity of radiation, it is not practical to measure the surface temperature of a granular bed such as was encountered in this work. To reduce the effect of random arrangements of particles around the thermocouple, a small piece of sheet copper measuring 1/4x1/4 inches was soldered to the copper-constantan junction. To compensate for the effect of radiation on the thermocouple, one layer of Reynolds Metal Company, Louisville, Kentucky, aluminum foil was placed on the copper sheet. The top thermocouple in the bed of solids was not actually located at the surface of the bed but was placed to enable a thin layer of solids to cover the piece of copper sheet. This layer of solids on top of the copper was made as thin as was practical.

The thermocouple leads were brought into the bottom of the pan to avoid direct exposure to the infrared heaters. As an added precaution, the leads were wrapped with two layers of aluminum foil and placed in flexible electrical conduit.

The drying pan was constructed of galvanized sheet metal with a half inch layer of sheet asbestos serving as insulation. Another piece of the sheet metal was also placed outside of the insulation. The dimensions of the pan were 10x12x1 inches.

A steel rack to support the drying pan was also constructed. The rack was designed to connect the pan to the scales and to permit continuous water evaporation determinations without interrupting the drying experiment. It also permitted the pan to be placed at various distances from the infrared heaters.

The materials used in this investigation were silicon carbide, manganese dioxide, and marble dust. The five particle sizes (grit numbers 46, 100, 220, 400, and 600) of silicon carbide were purchased from the Carborundum Company. The manganese dioxide was donated by the Tennessee Corporation, while the marble dust was donated by the Georgia Marble Company of Tate, Georgia. It was necessary to screen the manganese dioxide and marble dust to obtain the desired particle size range. Microscopic particle size analyses were performed on each of the materials.

EXPERMIENTAL PROCEDURE

The standard procedure for setting up a convection drying rate expermient had to be modified slightly to compensate for the effects of the intense infrared radiation. A typical experiment will be described in order to explain how the drying rate data were obtained.

The granular solids were placed in a shallow pan and completely covered with water to be sure they were saturated with water. The solid was then agitated in the water and allowed to soak for at least twelve hours with intermittent mixing.

Before a run was started, the infrared heaters were heated to their maximum operating temperature. While the heaters were warming up, the wet solid was placed in the drying pan by hand. When the pan was full, it was then shaken and tapped until the solid had completely settled. More solid was then placed in the pan and the process was repeated until a full, firmly packed pan was obtained. It is believed that this technique gave uniform packing and produced comparable drying rate data.

Before the drying pan was placed in the oven, a radiation intensity measurement was made with the infrared meter. The pan was then placed at the correct level in the drying rack, and the scales were adjusted to the zero mark. The oven was then completely closed and an attempt was made to regulate the humidity. The time usually required to reach the constant rate period was thirty to forty minutes; therefore, no readings were made during the first fifteen minutes. It also required about forty minutes for the humidity to reach the desired level.

During the course of an experimental run, the temperature of the air steadily increased due to the heating effect of the infrared heaters. No attempt was made to control the dry bulb temperature of the air as this was impossible in the completely closed dryer. The wet bulb temperature was controlled by the addition of steam through the steam spray. At the start of a run, the humidity was always greater than the thirty five per cent relative humidity desired. By the time the constant rate period was reached, the humidity was very close to the desired level. The effect of a variation in humidity is discussed in the section on results. All values for the humidity were obtained from humidity charts of the Foxboro Company, Foxboro, Massachusetts.

Data were recorded every five minutes throughout most of the run. When the solid was completely dry, the heaters were turned off and the solid removed from the drying pan and weighed. Since the temperature of the solid at the end of a run was always higher than 300 degrees Fahrenheit, there was no equilibrium moisture retained by the solid. The zero equilibrium moisture content was checked by placing a sample of dried material in an oven at 105 degrees Centigrade for 24 hours during which no change in weight could be detected.

As previously mentioned, the infrared meter only indicated radiation having a wave length between 3,000 and 35,000 Angstroms. To determine the actual intensity of radiation, it was necessary to perform a graphical integration of the spectral energy distribution curve shown in Figure 1. The calculations were made in this manner:

Area A = Area from 3,000 to 35,000 Angstroms
Area B = Area beyond 35,000 Angstroms
Total Radiation = Area A + Area B
Area A = Meter Reading
Ratio Area B/Area A = 3.30
Intensity of Radiation = A + (A) (B/A)
Intensity of Radiation = (Meter Reading) + (Meter Reading)(3.30)

The accuracy of this method depends upon the meter reading and the spectral energy distribution curve. This distribution curve was provided by the Edwin L. Wiegand Company. A check on this curve was made through data given by Zamzow (1952) and was found to be very reliable. As mentioned previously, the infrared meter is accurate to plus or minus five per cent of the full scale reading.

THEORETICAL CONSIDERATIONS

Convection Drying Theory. The drying of solids refers to the removal of a liquid from a solid phase, such as the removal of water from sand. Convection drying refers to the removal of a liquid from a solid by vaporization when the liquid is in contact with an atmosphere of unsaturated air usually in motion.

In granular solids, the flow of moisture resulting from evaporation is induced by gravitational or capillary forces. Caeglske (1937) and Kiesling (1940) observed that when the pore space within a granular solid is only partly filled with water, a suction is produced which depends upon the surface tension of the liquid and the radius of curvature of the air-water interface. Within an unsaturated granular solid, the liquid will move in the direction of increasing liquid curvatures under the force of capillary action. Caeglske (1937) demonstrated experimentally that the flow of water in a granular solid is not a diffusional process, but rather a capillary one. The actual moisture distribution depends upon the size and distribution of particles and pores.

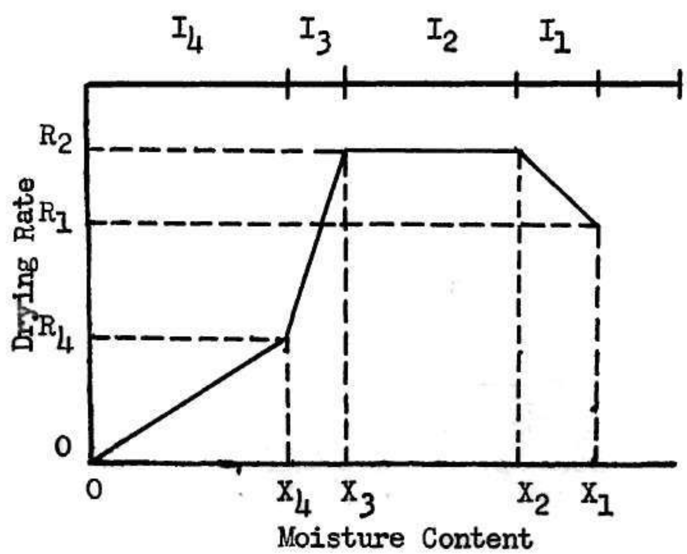
The actual mechanism for the air drying of a solid is a complicated process. Even though it has been established that the mechanism for the flow of moisture to the surface is capillary action, it is necessary to consider some of the other factors that effect the rate of moisture removal.

The rate of moisture removal is dependent upon two groups of factors. The first group comprises all of the variables that are external to the material being dried. These include the temperature, relative humidity, and velocity of the circulating air, and the relative geometrical arrangement of the drying substance. The second group includes the internal factors such as the chemical nature, pore structure, moisture content, and equilibrium moisture content of the material.

To study the effects of some of these variables, it is convenient to consider the case of drying a horizontal layer of granular solid.

It will be assumed that the solid is completely saturated with water, and only the top surface is exposed. The humidity will be assumed to be constant throughout the experiment. All of the heat required for the vaporization of the water and for the heating of the solid is supplied directly by heat transfer to the solid from the hot drying medium.

The data that are usually obtained from such an experiment are represented by a graph such as the one below:



This indicates the drying rate (expressed as pounds per hour per square foot of surface) as a function of the moisture content (expressed as pounds of water per pound of dry solid). This is a typical drying rate curve. Such a curve may be divided into several distinct sections.

<u>Period I_1.</u> This period corresponds to the initial heating up that occurs when a cold, wet solid is placed in the hot drying medium.

<u>Period I_2.</u> This period is known as the constant drying period. It is characterized by a uniform rate of drying which is not a function of the free moisture content. Both the rate of drying and the duration of this period are determined by the mechanism by which moisture flows to the surface.

<u>Period I_3.</u> This section is known as the first falling rate period. In many cases the rate of drying is a linear function of the moisture content. The rate of drying is reduced because the wetted area exposed at the surface has been decreased.

<u>Period I_4.</u> This period corresponds to the second falling rate period. It begins when capillary flow to the surface has ceased. Air actually enters the pores of the solid and vaporization proceeds to take place in the bed of solid. As this zone of vaporization receeds into the solid, heat must be transferred through an increasing thickness of partially dried stock.

McCormack (1940) and Shepherd (1938) state that the rate of drying during the constant rate period is dependent only upon drying conditions and not upon the thickness of the layer. Badger and McCabe (1936) and Shepherd (1938 have shown that the rate of drying during the constant rate period is proportional to the 0.8 power of the air velocity. Badger and McCabe (1936) have also shown that the constant drying rate is proportional to the difference in humidity between the stagnant air film and the body of the air.

The rate of drying during the first falling rate period depends upon the same conditions as the constant rate period. In addition, it falls off with decreasing moisture content. (Gilliland (1938)). The temperature of the stock gradually increases during this period with the temperature gradient increasing toward the heating surface.

According to Shaaban (1945), the second falling rate period begins when the curvatures at the surface become so great that the continuity of the water film is broken. Drying proceeds by diffusion of vapor through the dried portion of the solid and the surface air film. The rate of Drying is no longer effected by air velocity and rapidly falls off to zero as the entire solid layer becomes dry.

Radiant Drying Theory. The theory of radiant drying of granular solids is not nearly so well understood as the theory of convection drying. Stout (1945) and Wingard (1953) concluded that the mechanism of drying using radiant heat is no different from that in convection drying. The validity of this conclusion will have to be born out by future work. At any rate, there is no accepted method for predicting the drying rate of granular solids using infrared radiation. There is also no explanation of the effect of many of the variables commonly encountered in drying experiments.

At the present time, two types of infrared sources are on the market. The oldest, and the one most used by investigators, is the near-infrared lamp. These lamps operate at a temperature of approximately 4,800 degrees Fahrenheit and are enclosed in a glass case.

The other type of infrared heater is the far-infrared heater which operates at a filament temperature of approximately 1,000 degrees Fahrenheit. The characteristics of this radiation are shown in Figure 1. A considerable portion of the radiation from the far-infrared heater is well beyond the range covered by the near-infrared heater. The longer wave length radiation is more easily absorbed by most materials and it should serve to increase the efficiency of infrared drying.

Naturally the fraction of radiation that is absorbed by the material being dried is of the utmost importance as far as the rate of drying is concerned. However, since a layer of water covers most of the drying surface for a considerable portion of the drying experiment, the actual quantity of radiation absorbed depends upon that absorbed by the water as well as the solid. Ickis (1939) stated that radiation having wave lengths longer than 14,000 Angrstroms will be completely absorbed by water having a thickness of 0.5 millimeters. During the constant rate period and the first falling rate period, water will usually exist in layers more than a half millimeter thick. This would tend to make the efficiency of drying high regardless of the solid being dried.

The flow of radiant heat from the infrared heaters to the bed of moist solid can be represented by the following equation:

$$qr = \sigma A \epsilon (Tr^4 - Ts^4) \quad (1)$$

Convection heat transfer can be represented by the following equation:

$$qc = h_c A(t_a - t_s) \quad (2)$$

If forced convection is used, the value of h_c, the convection heat transfer coefficient, will tend to increase as the velocity of the air increases. However, in radiant drying, the solid will usually be at a higher temperature than the air: hence, the term $(t_a - t_s)$ will be negative.

PREVIOUS WORK IN INFRARED DRYING OF GRANULAR SOLIDS

Stout, Caplan, and Baird (1945) have reported the most significant results concerning infrared drying of granular solids. They used a bank of nineteen near-infrared lamps with sand and magnesium stearate. They succeeded in achieving constant drying rates up to 1.90 pounds of water per hour per square foot.

Stout's work also investigated the effect of air velocity and bed thickness. He reported that increasing the air velocity from 0 to 450 feet per minute decreased the constant drying rate approximately thirty per cent. The thickness of the drying solid was found to have no effect on the rate of drying. Bed thicknesses up to one inch were investigated.

No attempt was made to control the humidity; hence, no definite conclusions could be made concerning what effect it had on the drying rate.

Wingard and Rozier (1952) studied the drying of wood and sand with infrared radiation. The equipment was similar to that of Stout's and the results obtained substantiated the results reported by Stout.

PRESENTATION AND DISCUSSION OF RESULTS

The results of the experimental runs are presented as a series of drying rate curves plotted as a function of moisture content.

The drying rate of silicon carbide is presented as a function of the intensity of radiation, particle size, air velocity, and relative humidity. The drying rates of manganese dioxide and marble dust are presented as functions of the intensity of radiation. The silicon carbide results are presented in Figures 2 through 7. The results for manganese dioxide are presented in Figure 8. The results for the marble dust are shown in Figure 9. All of the results are presented in tabular form in the Appendix in Tables II through VI. Tables VII through XXXII present the experimental data as it was taken in the laboratory.

All of the drying rate curves exhibited characteristic properties of the typical drying rate curve discussed in the section on convection drying theory. In all of the experimental runs, the solid passed through an initial heating period during which the drying rate was rapidly increasing. The actual time required by this initial period depended on the intensity of radiation. At least thirty minutes were required in all cases.

Although bed thickness was not a variable in this investigation, it is evident that the thickness of the drying solid will affect the time required by the heating period. In some applications, thirty minutes may be too long. Considering the mechanism of drying, it becomes evident that a thin bed of solid could substantially reduce the time required to reach the constant rate period. In some of the high radiation intensity runs, the warming up period required more time than did the constant rate period.

After the warming up period, the drying solid entered the constant rate period. Values for the constant rate of drying are tabulated in the Appendix in Tables II through IV. The values for the constant rate period will be the criteria used to evaluate the effects of many of the variables that were studied.

At some critical moisture content, the constant drying rate period ended and the falling rate period started. Initially the rate of drying decreased very rapidly - almost a linear function of the moisture content. This period corresponds to the first falling rate period described in the section on convection drying theory. Then, at some new critical moisture content, the drying rate entered a period corresponding to the second falling rate. Finally, the drying rate approached zero as the moisture content was reduced to zero.

The constant drying rate as a function of the intensity of radiation for silicon carbide is shown in Figure 10. The same result was found for marble dust. Figure 10 shows that the constant drying rate is proportional to the intensity of radiation. This proportionality indicates that the flow of radiant heat to the bed of moist solid is the controlling factor in determining the rate of drying. Evidently the driving force for the flow of moisture, capillary action, is sufficient to maintain the high flow rates encountered in this intestigation.

Manganese dioxide gave constant drying rates equal to silicon carbide and marble at radiation intensities of 5.5 and 6.4 watts per square inch. However, the drying rate at an intensity of 7.7 watts per square inch was approximately seventeen per cent less. This indicates that some resistance to the flow of moisture has started to play an important part at the high radiation intensity values.

This resistance could possibly be due to some special attractive force between the manganese dioxide and the water. Manganese dioxide forms a mono-hydrate which could have had an effect upon the rate of moisture removal. Another possibility is the relative surface area between the three solids investigated. A decreased pore space could conceivably reduce the capillary action driving force. The work in this investigation does not attempt to offer the solution to this problem. The suggestions listed above are only a few of many possibilities. Typical samples of the three solids were viewed under the microscope to study the shape and form of the particles. Pictures were taken and can be seen in Figures 16, 17, and 18 in the Appendix.

During the constant rate period, the temperature near the top, the middle, and the bottom of the bed of solid was essentially uniform. Not until the constant rate period ended did the temperatures at the various levels begin to separate. This uniform temperature must be due to the moisture transferring the heat by conduction and convection throughout the bed. The surface is obviously cooled by the high rate of evaporation of the moisture. The surface temperature during the drying operation for the three materials is shown in Figures 13 through 15. It is interesting to note the sharp rise in temperature exactly coinciding with the end of the constant rate period. A technique such as this could be used in determining critical moisture contents.

Figure 11 shows the silicon carbide drying rates obtained at air velocities of 0-, 1200-, and 1700- feet per minute. Within experimental error, the drying rate is uneffected by the air velocity. Stout in 1945 observed decreasing drying rates with increasing air velocities. However, this difference is understandable when one considers the intensities of radiation used in the two experiments. Considerably higher intensity values were used in this investigation. Evidently the heat that is removed by convection, represented by this equation

$$Qc = h_c' A(t_a - t_s)$$

is so small compared to the heat absorbed by radiation that the overall effect is negligible. In addition, the temperature difference, $(t_a - t_s)$, is usually about five degrees Fahrenheit in this study. Stout maintained the temperature difference considerably greater than this, and as a result succeeded in removing more heat from the pan of solid.

Table II best shows the effect of particle size upon the drying rate. Caeglske (1937) investigated the effect of particle size in convection drying of sand. He found the rate of drying increased slightly as the particle size increased. In this investigation, drying rates were determined for silicon carbide having an average particle size of 530-, 200-, 90-, 17-, and 8- microns. The results indicate that the rate of drying is not effected by the particle size of the solid. This statement seems to be in line with the conclusion previously stated that the controlling factor is the rate of heat transfer to the moist solid.

Figure 12 shows the drying rates for silicon carbide at 35-, 50-, and 60- per cent relative humidity. Constant drying rates of 2.48-, 2.37-, and 2.30- pounds of water per hour per square foot of surface area were obtained. The slight decrease in drying rate with increasing relative humidity is significant and is beyond any possible experimental error.

According to Manders (1947/1948) the triatomic water molecule will absorb radiation. This absorption is especially pronounced at wave lengths of 15000-, 20000-, 30000-, 47500-, and 6000- microns. Since the infrared heaters in this experiment are emitting radiation in this region, some absorption of radiation by the water vapor would be expected. As the humidity is increased, the amount of radiation absorbed will also increase. This absorption would have a net effect of reducing the rate of drying.

The efficiency of drying is usually expressed as a ratio of the heat required for the drying. Similar calculations made for this investigation reveal some interesting results. For calculation purposes, consider the drying of silicon carbide which has an average particle size of 530 microns. The intensity of radiation was 7.7 watts/square inch and the relative humidity was 35 per cent. The constant drying rate under these conditions was 2.48 pounds per hour per square foot.

Input: $4{,}000 \text{ watts} \times 3.413 \ \underline{\text{BTU/Hr.}} = 13{,}652 \text{ BTU/Hr.}$ (1)

Received by Drying Pan:

$$7.7 \frac{\text{Watts}}{\text{In.}} \times 120 \text{ In.}^2 \times 3.413 \frac{\text{BTU/Hr.}}{\text{Watt}} = 3150 \text{ BTU/Hr.} \quad (2)$$

Heat required to vaporize water:

$$2.48 \frac{\text{Pounds}}{\text{Hr. Ft.}^2} \times 972 \frac{\text{BTU}}{\text{Pound}} \times 120 \text{ Ft.}^2 = 2010 \text{ BTU/Hr.} \qquad (3)$$

Overall Efficiency: $E = \frac{(3)}{(1)} \times 100 = \frac{2010}{13,652} \times 100 = 14.7\%$

Actual Efficiency: $E = \frac{(3)}{(2)} \times 100 = \frac{2010}{3150} \times 100 = 63.8\%$

The low overall efficiency of drying does not indicate a true picture. Considerable heat was lost due to the tremendous overlapping of the drying pan that was necessary to achieve a reasonable uniform intensity of radiation. The actual efficiency is a much more representative figure since in an actual operation no overlapping would be necessary. A well designed system could attain values of the overall efficiency approaching the actual efficiency.

The author realizes that this thesis has not progress far toward the explanation of the mechanism of infrared drying. However, it is hoped that this work has uncovered some of the possibilities that lie ahead and will help guide future work in this field.

CONCLUSIONS AND RECOMMENDATIONS

1. Drying rates of granular solids are as much as eight times that obtained in ordinary convection drying methods.

2. The particle size of the granular solid does not effect the rate of infrared drying.

3. The constant rate of drying with infrared radiation is proportional to the applied intensity of radiation.

4. An increase in the relative humidity of the atmosphere decreases the rate of drying.

5. The effect of air velocity is negligible if the intensity of radiation is in the range of 7.7 watts per square inch.

6. Thin beds of granular solids decrease the total time required for drying. The initial heating period is decreased and the process enters the constant rate period in a shorter time.

7. Thermocouples placed near the surface of a bed of granular solids serve as an accurate means for determining the critical moisture content.

8. The efficiency of infrared drying of granular solids may be defined as the ratio of the heat required for vaporization of the moisture to the heat actually incident upon the surface of the bed of solid.

NOMENCLATURE

A	Area, Square Feet
E	Efficiency, Per Cent
h_c	Convection Heat Transfer Coefficient, BTU per Hour per Square Foot per Degree Fahrenheit
I	Intensity of Radiation, Watts per Square Inch
q_c	Rate of Heat Transfer by Convection, BTU per Hour
q_r	Rate of Heat Transfer by Radiation, BTU per Hour
R	Drying Rate, Pounds Water per Hour per Square Foot
T_r	Absolute Temperature of Infrared Radiator, Rankine
T_s	Absolute Temperature of Surface, Rankine
t_a	Temperature of Air, Fahrenheit
t_s	Temperature of Surface, Fahrenheit
X	Moisture Content, Pounds Water per Pound of Dry Solid

Greek Letters

ϵ	Emissivity, Dimensionless
σ	Dimensional Constant in Stefan-Boltzmann Law, 0.173×10^{-8} BTU per Square Foot per Hour per Degree Rankine^4

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APPENDIX

TABLE I

Calibration of Thermocouples
Copper Constantan Thermocouples
Reference Junction: 0.00 Degrees Centigrade

Thermometer Reading C	Corrected Value C	EMF VALUES Couple Number 1	2	3	4	5
60.40	60.30	2.50	2.50	2.50	2.50	2.50
63.80	63.70	2.61	2.61	2.61	2.61	2.61
75.30	75.20	3.11	3.11	3.11	3.11	3.11
85.30	85.20	3.59	3.59	3.59	3.59	3.59
111.25	111.35	4.82	4.82	4.82	4.82	4.82
124.90	125.10	5.48	5.48	5.48	5.48	5.48
156.45	156.65	7.02	7.02	7.02	7.02	7.02
195.30	195.50	9.04	9.04	9.04	9.04	9.04

TABLE II

Constant Drying Rates of Silicon Carbide
35 Per Cent Relative Humidity

Air Velocity: 0 Ft/Minute

Intensity of Radiation Watts/Square Inch	Particle Size Microns	Drying Rate Lbs. Water / Hour Square Foot
7.7	8	2.46
7.7	17	2.35
7.7	90	2.43
7.7	200	2.50
7.7	530	2.48
6.4	8	1.75
6.4	17	1.67
6.4	90	1.80
6.4	200	1.70
6.4	530	1.80
5.5	8	1.36
5.5	17	1.40
5.5	90	1.32
5.5	200	1.36
5.5	530	1.34

TABLE III

Constant Drying Rates of Manganese Dioxide
35 Per Cent Relative Humidity

Air Velocity: 0 Ft/Minute

Intensity of Radiation Watts/Square Inch	Particle Size Microns	Drying Rate $\frac{\text{Lbs. Water}}{\text{Hour Square Foot}}$
7.7	310	2.06
6.4	310	1.60
5.5	310	1.44

TABLE IV

Constant Drying Rates of Marble Dust
35 Per Cent Relative Humidity

Air Velocity: 0 Ft/Minute

Intensity of Radiation Watts/Square Inch	Particle Size Microns	Drying Rate $\frac{\text{Lbs. Water}}{\text{Hour Square Foot}}$
7.7	390	2.46
6.4	390	1.74
5.5	390	1.31

TABLE V

Air Velocity Studies
Constant Drying Rates of Silicon Carbide
35 Per Cent Relative Humidity

Intensity of Radiation Watts/Square Inch	Particle Size Microns	Air Velocity Ft/Minute	Drying Rate Lbs. Water / Hour Square Foot
7.7	530	0	2.48
7.7	530	1200	2.32
7.7	530	1700	2.42

TABLE VI

Humidity Studies
Constant Drying Rates of Silicon Carbide
Air Velocity: 0 Ft/Minute

Intensity of Radiation Watts/Square Inch	Particle Size Microns	Relative Humidity Per Cent	Drying Rate Lbs. Water / Hour Square Foot
7.7	530	35	2.48
7.7	530	50	2.37
7.7	530	60	2.30

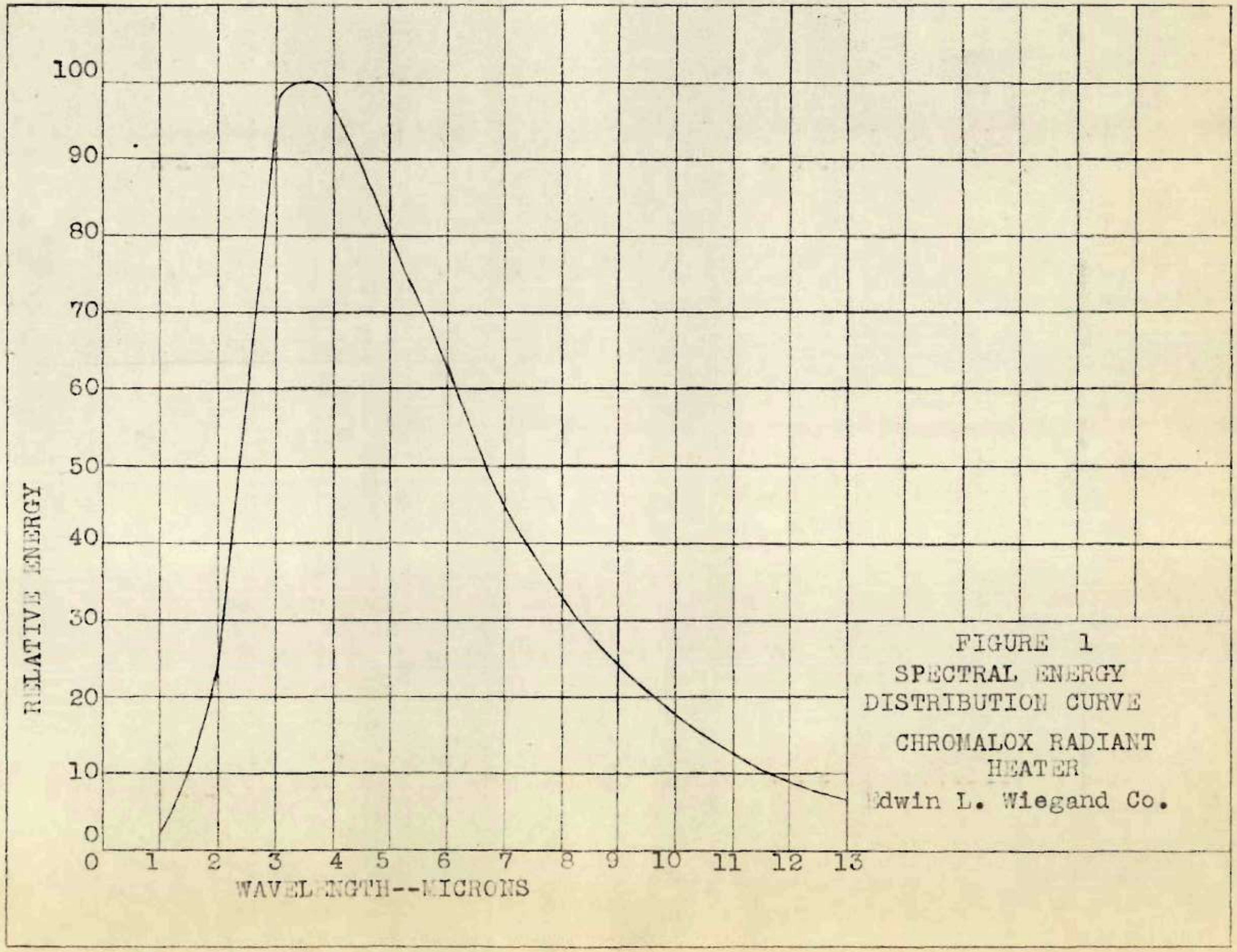

FIGURE 1
SPECTRAL ENERGY
DISTRIBUTION CURVE
CHROMALOX RADIANT
HEATER
Edwin L. Wiegand Co.

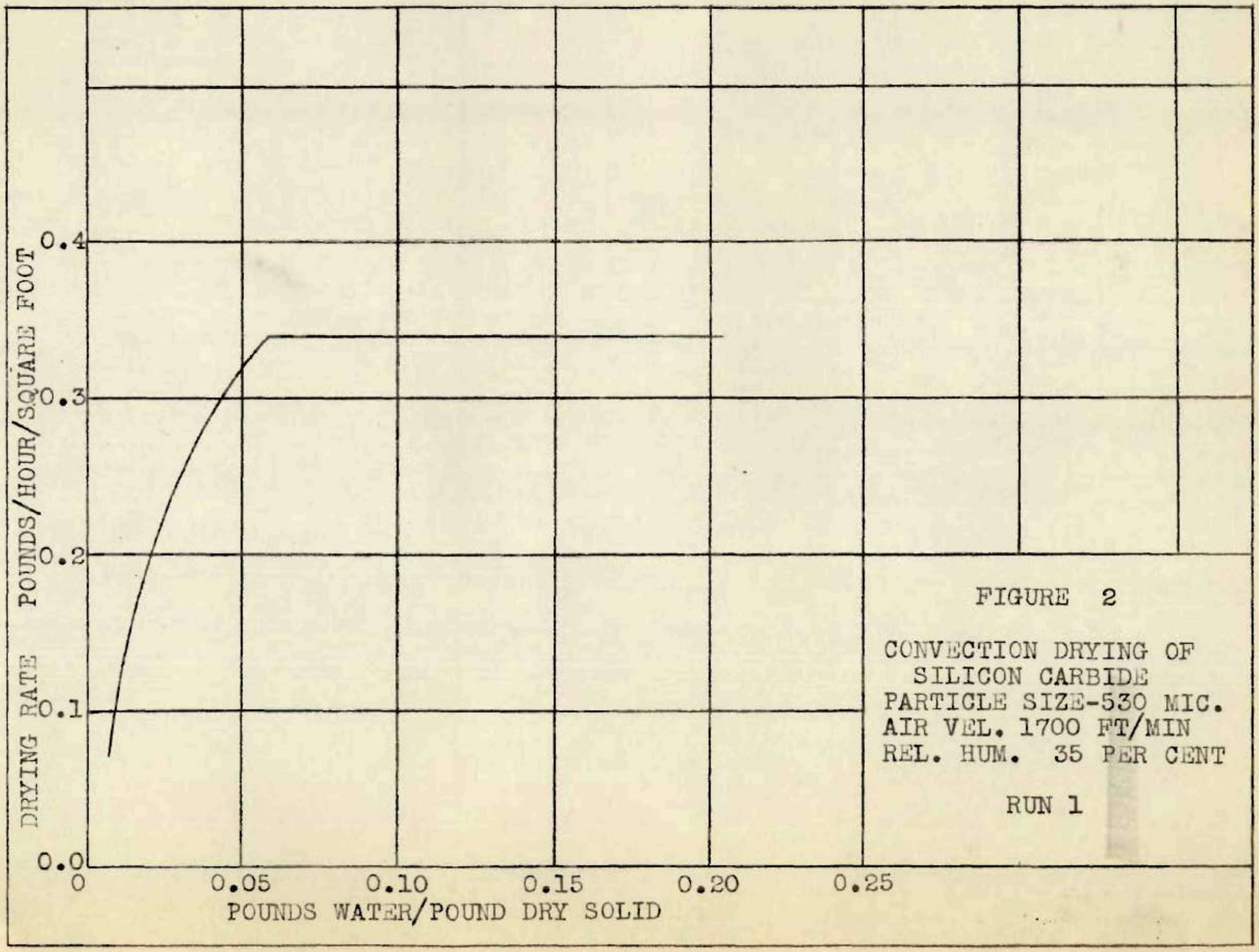

FIGURE 2

CONVECTION DRYING OF
SILICON CARBIDE
PARTICLE SIZE-530 MIC.
AIR VEL. 1700 FT/MIN
REL. HUM. 35 PER CENT

RUN 1

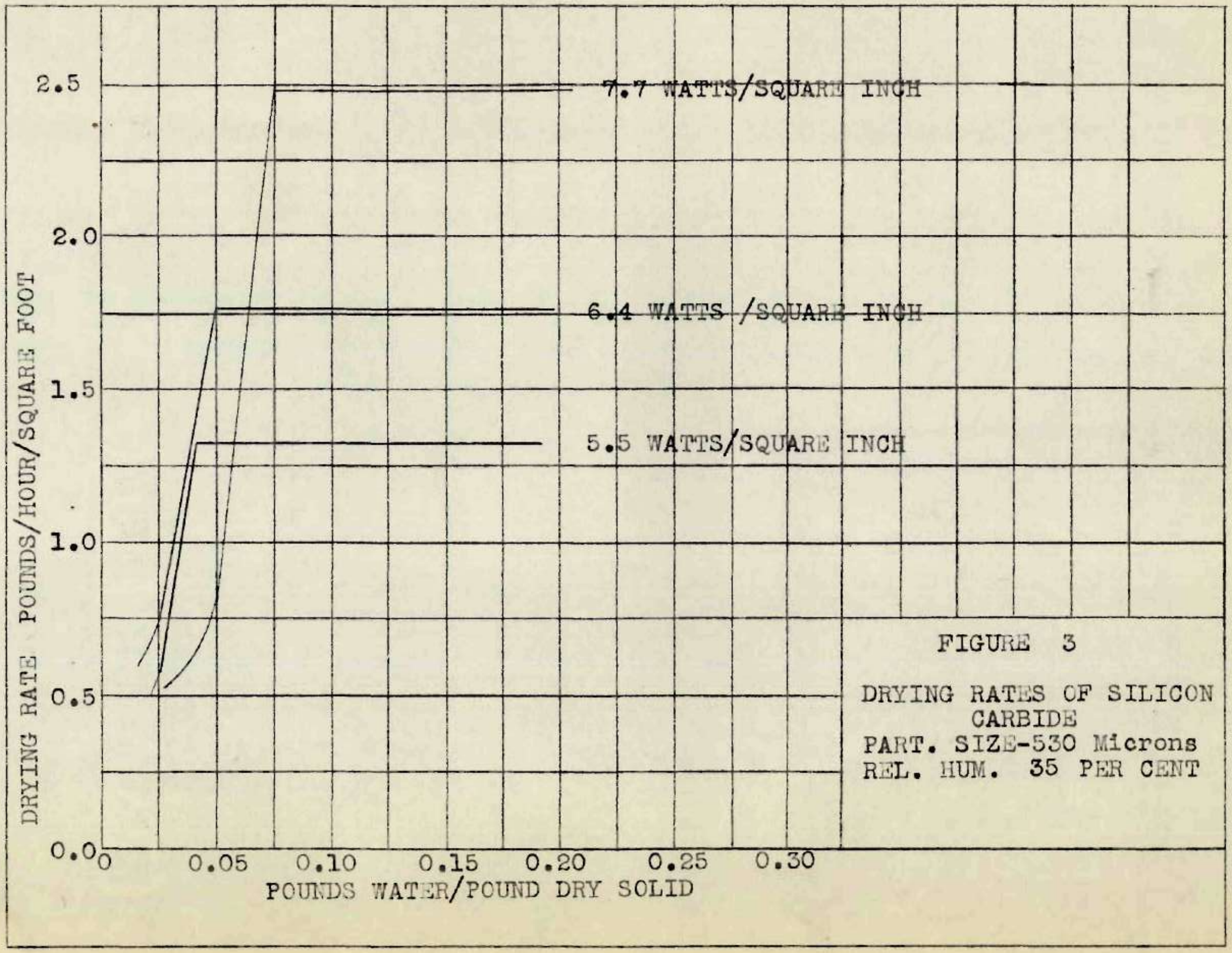

FIGURE 3

DRYING RATES OF SILICON CARBIDE
PART. SIZE-530 Microns
REL. HUM. 35 PER CENT

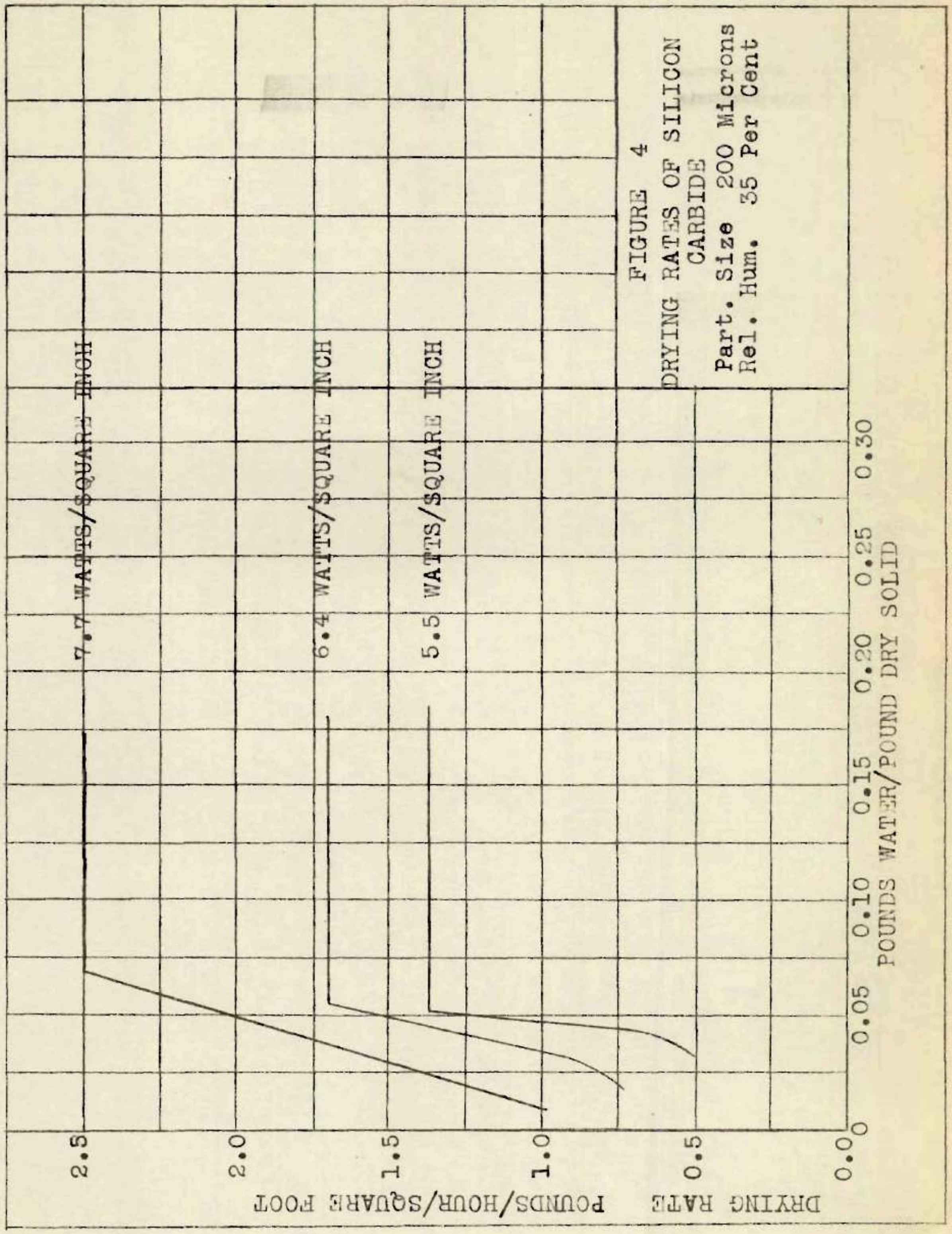

FIGURE 4
DRYING RATES OF SILICON CARBIDE
Part. Size 200 Microns
Rel. Hum. 35 Per Cent

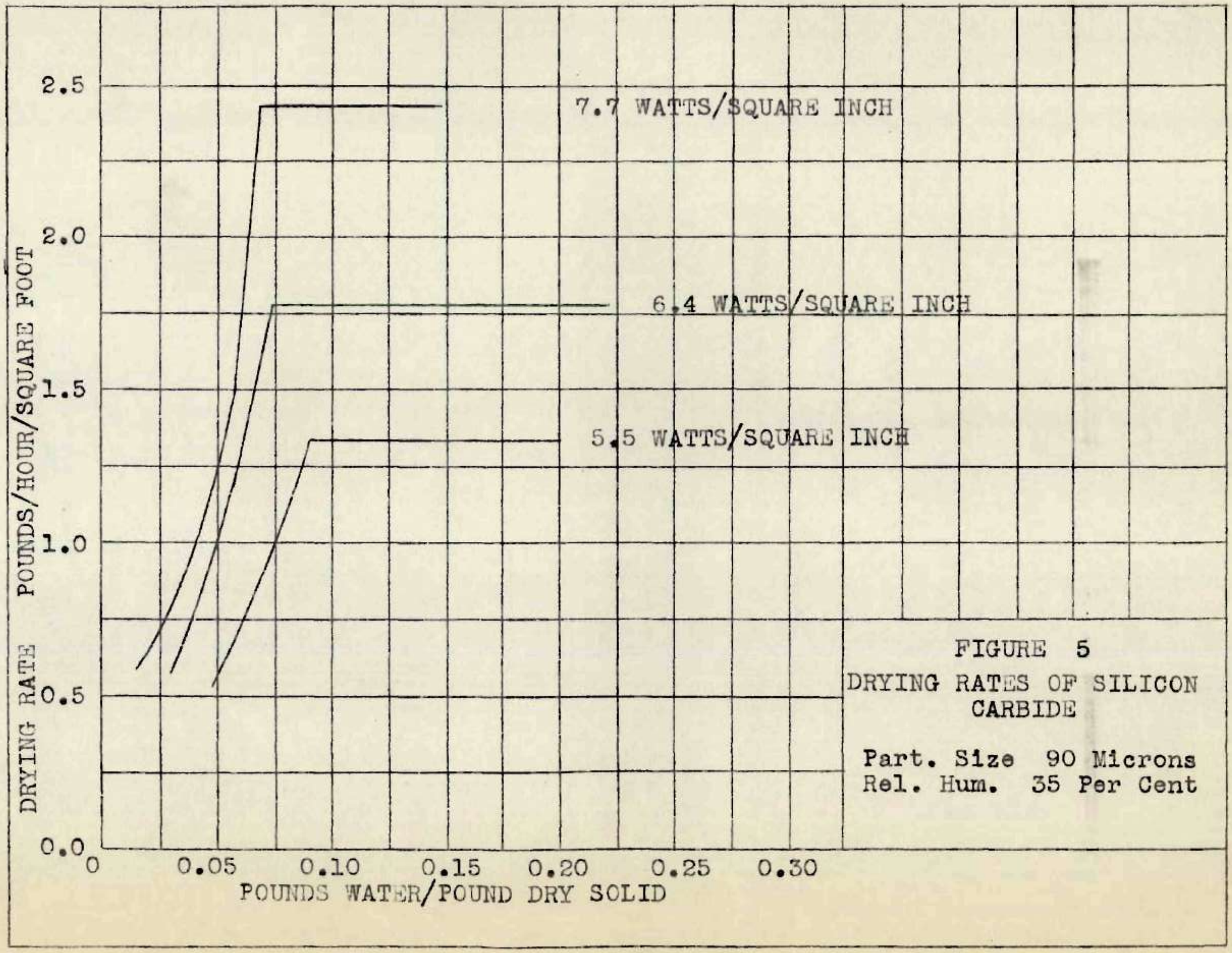

FIGURE 5
DRYING RATES OF SILICON CARBIDE

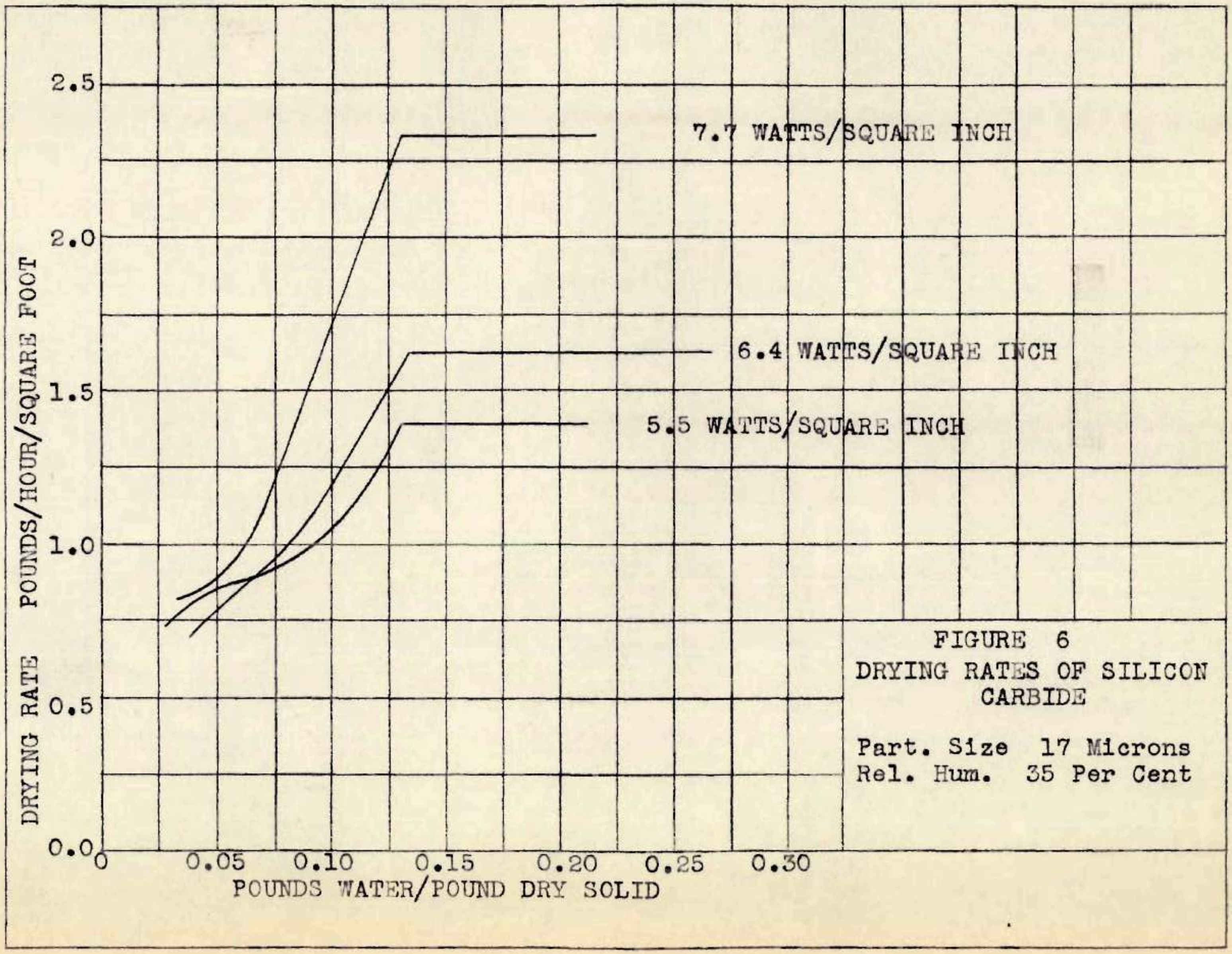

FIGURE 6
DRYING RATES OF SILICON CARBIDE

Part. Size 17 Microns
Rel. Hum. 35 Per Cent

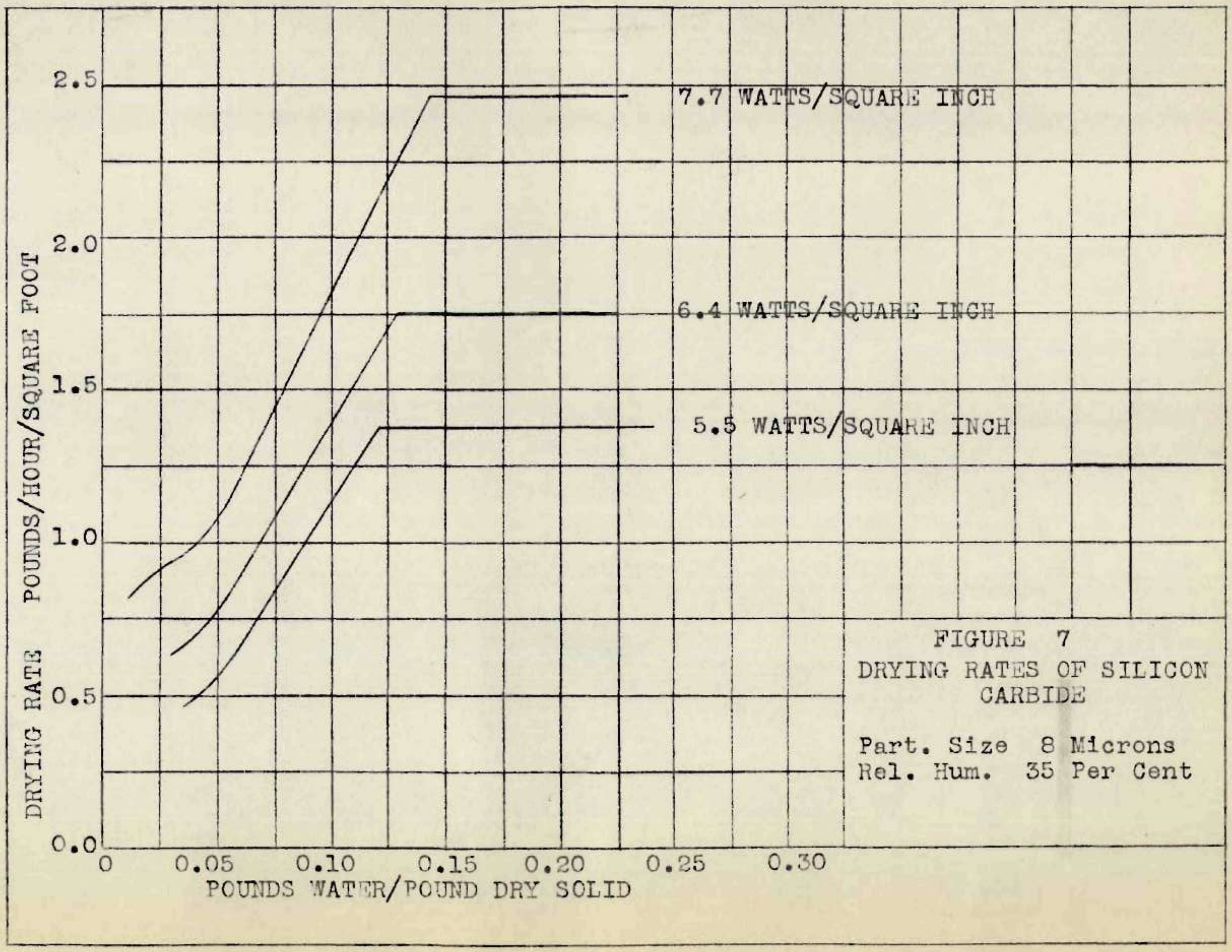

FIGURE 7
DRYING RATES OF SILICON CARBIDE

Part. Size 8 Microns
Rel. Hum. 35 Per Cent

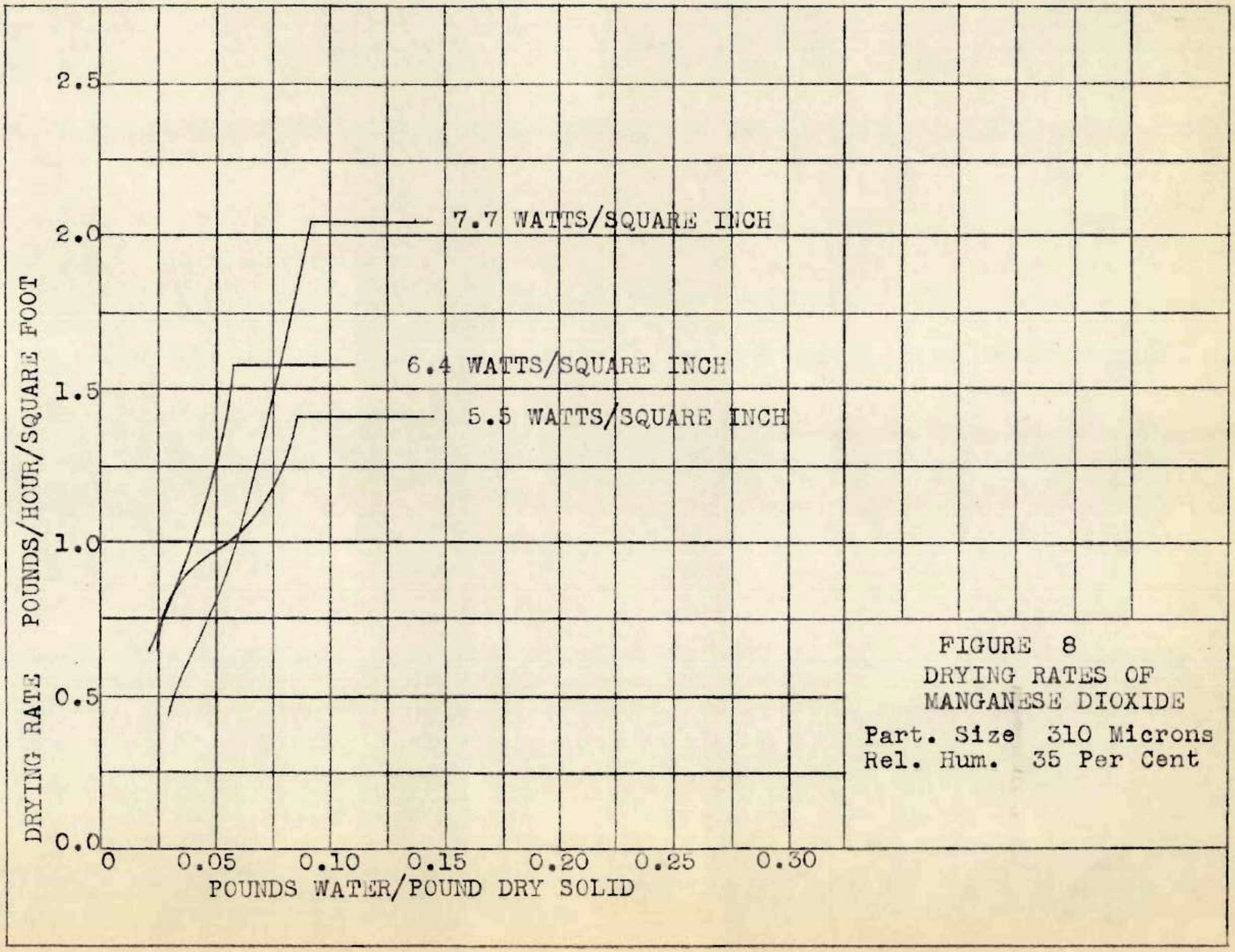

FIGURE 8
DRYING RATES OF
MANGANESE DIOXIDE
Part. Size 310 Microns
Rel. Hum. 35 Per Cent

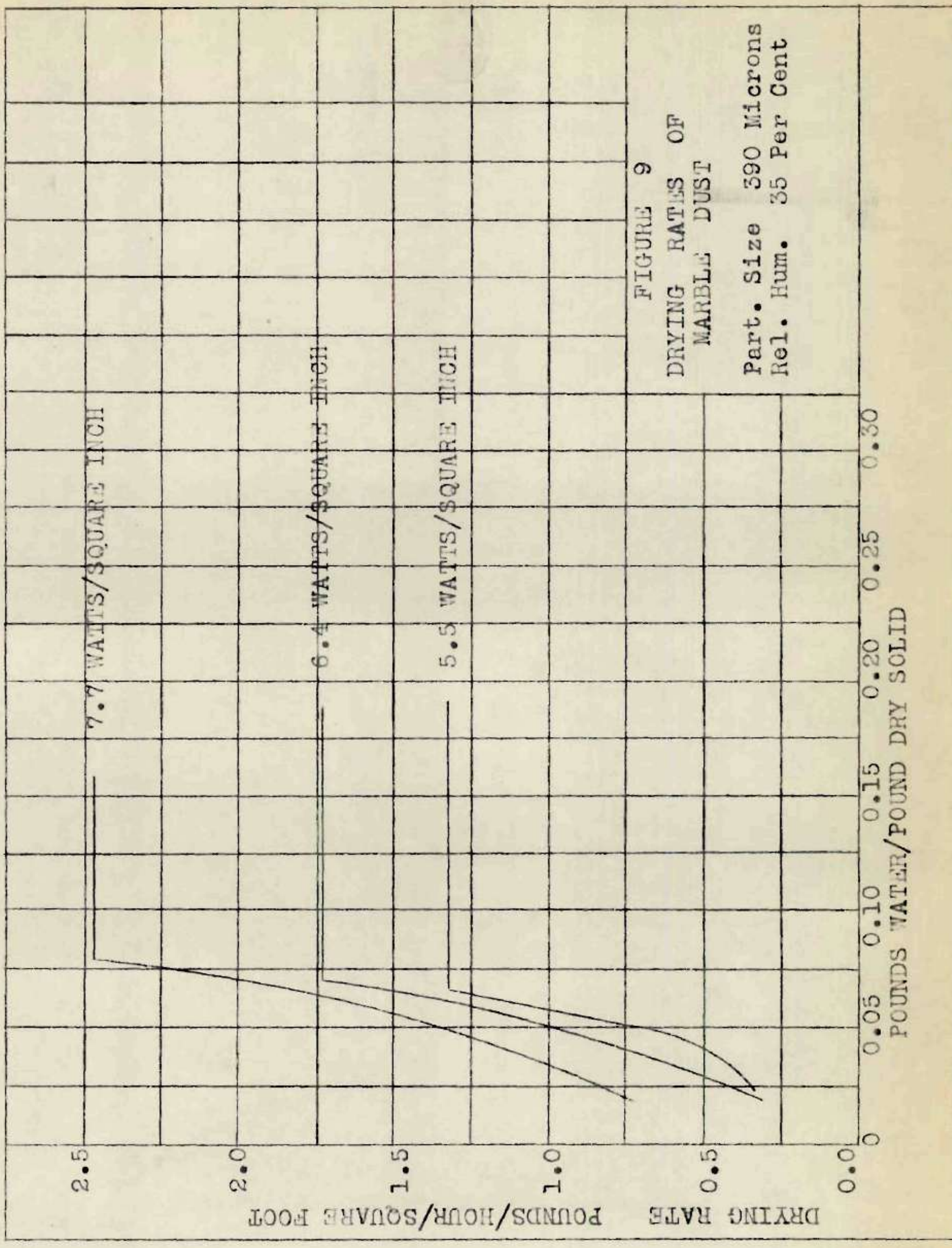

FIGURE 9
DRYING RATES OF MARBLE DUST

Part. Size 390 Microns
Rel. Hum. 35 Per Cent

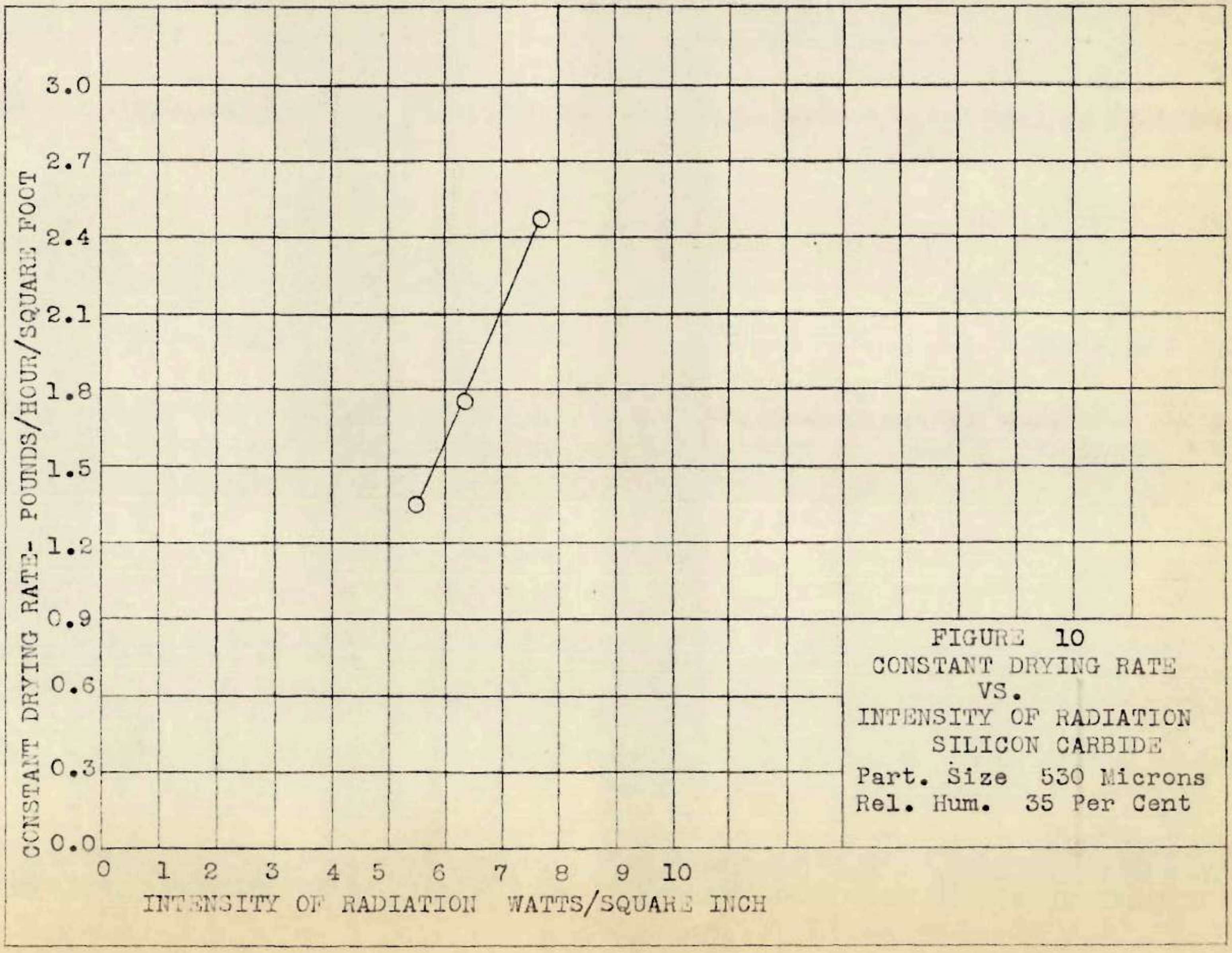

FIGURE 10
CONSTANT DRYING RATE
VS.
INTENSITY OF RADIATION
SILICON CARBIDE
Part. Size 530 Microns
Rel. Hum. 35 Per Cent

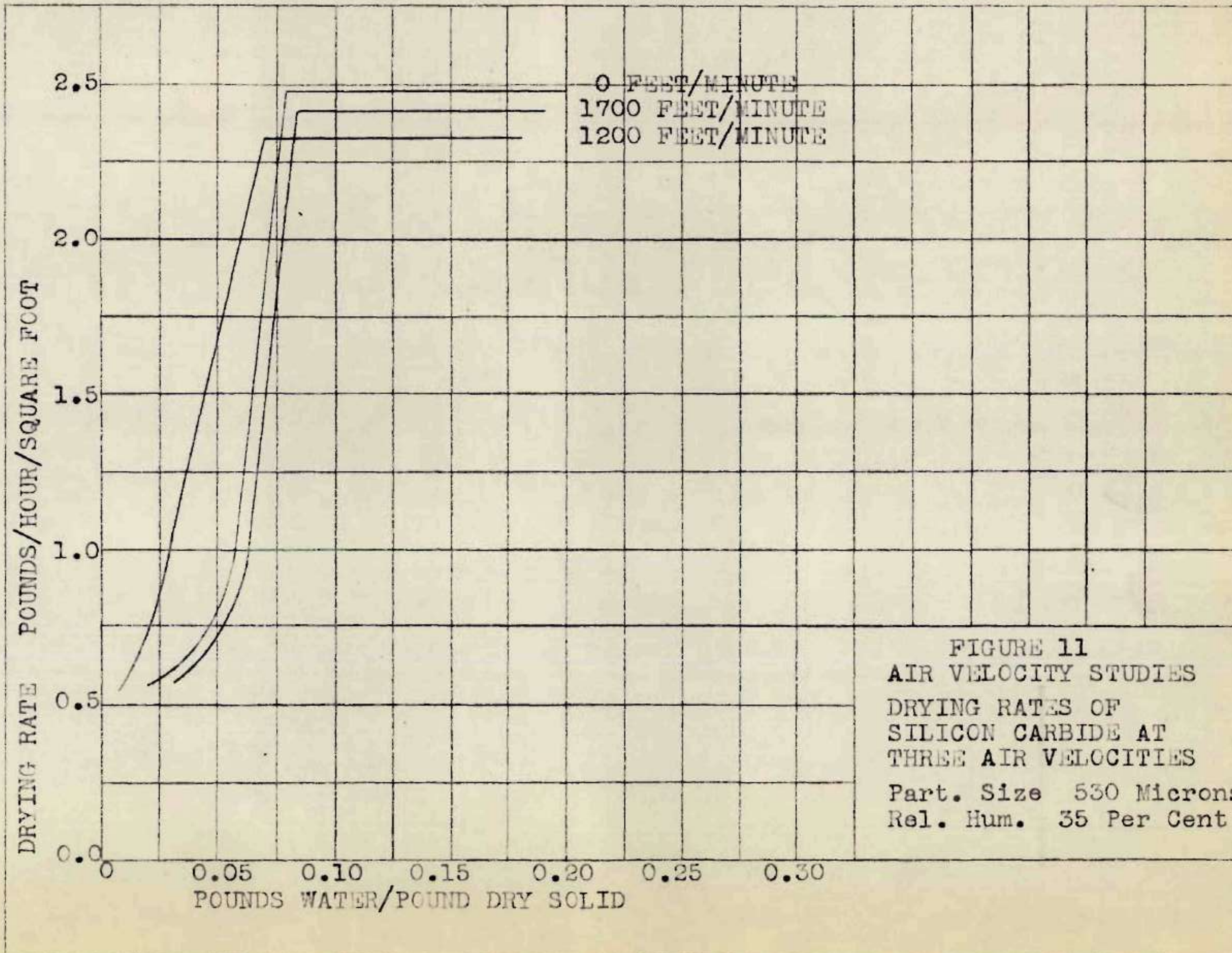

FIGURE 11
AIR VELOCITY STUDIES

DRYING RATES OF
SILICON CARBIDE AT
THREE AIR VELOCITIES

Part. Size 530 Microns
Rel. Hum. 35 Per Cent

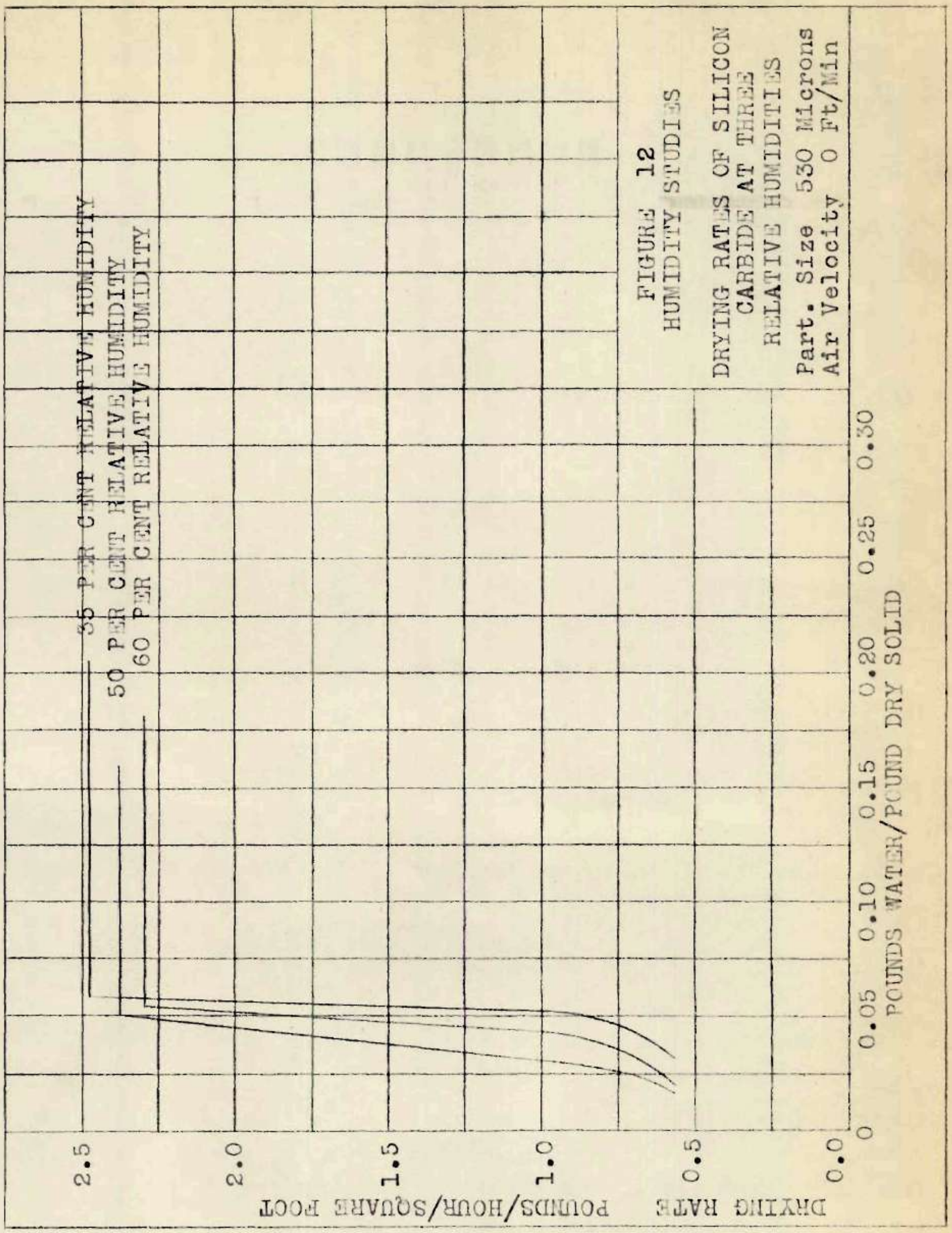
FIGURE 12
HUMIDITY STUDIES
DRYING RATES OF SILICON
CARBIDE AT THREE
RELATIVE HUMIDITIES
Part. Size 530 Microns
Air Velocity 0 Ft/Min
35 PER CENT RELATIVE HUMIDITY
50 PER CENT RELATIVE HUMIDITY
60 PER CENT RELATIVE HUMIDITY
DRYING RATE POUNDS/HOUR/SQUARE FOOT
0.0
0.5
1.0
1.5
2.0
2.5
POUNDS WATER/POUND DRY SOLID
0
0.05
0.10
0.15
0.20
0.25
0.30

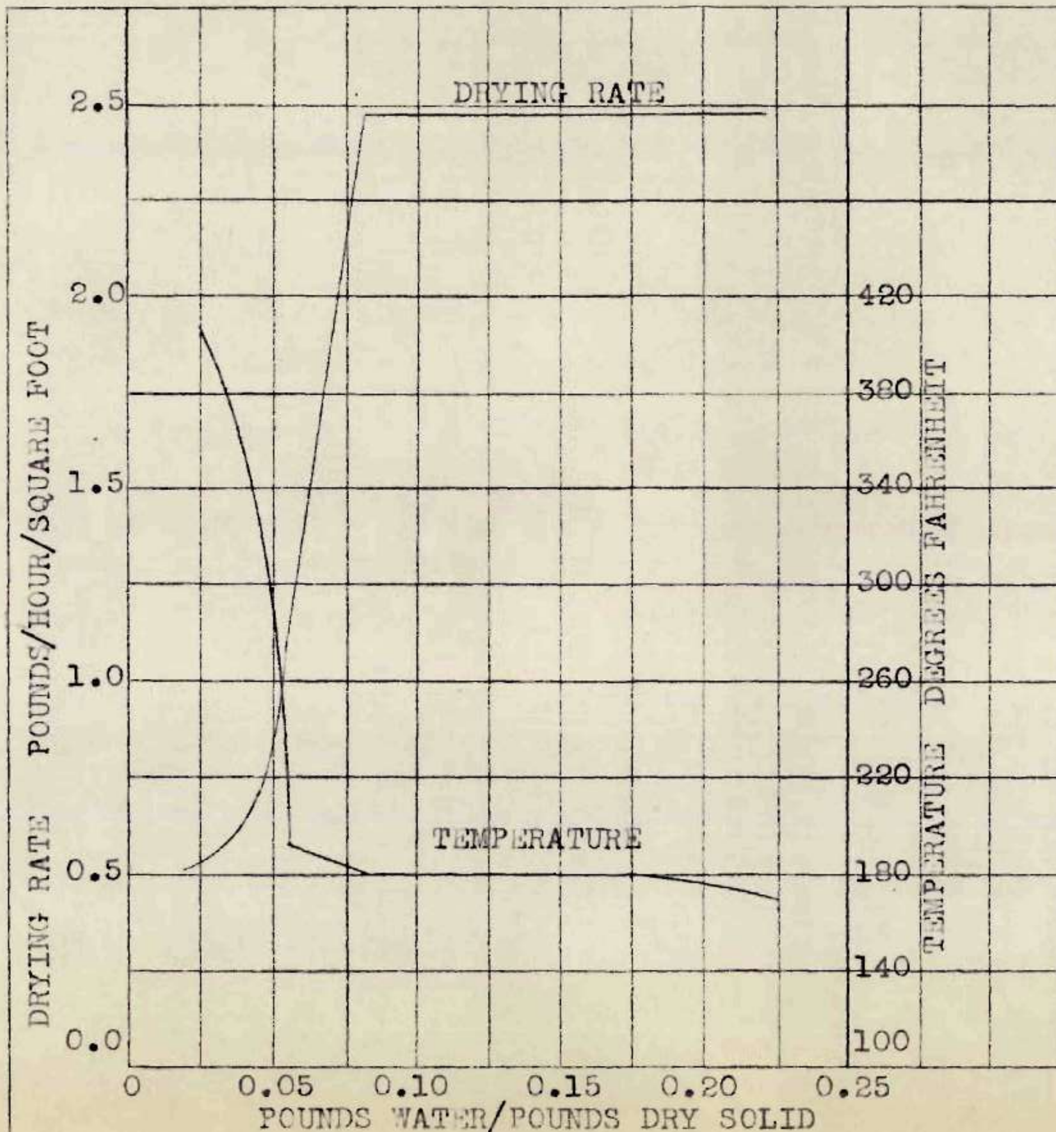

FIGURE 13
DRYING RATE AND SURFACE TEMPERATURE FOR SILICON CARBIDE
7.7 Watts/Square Inch
530 Microns Part. Size
0 Ft/Min. Air Velocity
35 Per Cent Rel. Hum.

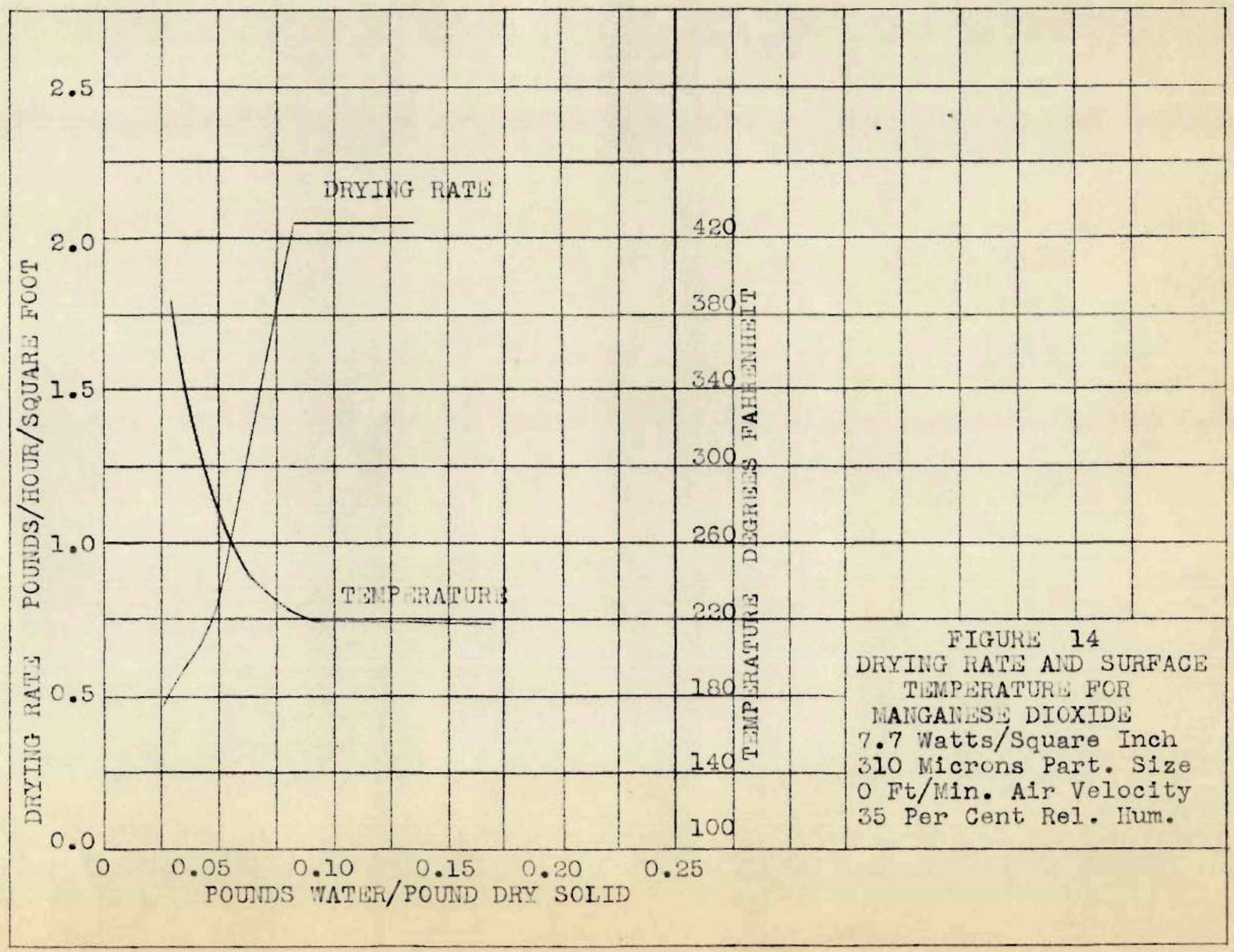

FIGURE 14
DRYING RATE AND SURFACE TEMPERATURE FOR MANGANESE DIOXIDE
7.7 Watts/Square Inch
310 Microns Part. Size
0 Ft/Min. Air Velocity
35 Per Cent Rel. Hum.

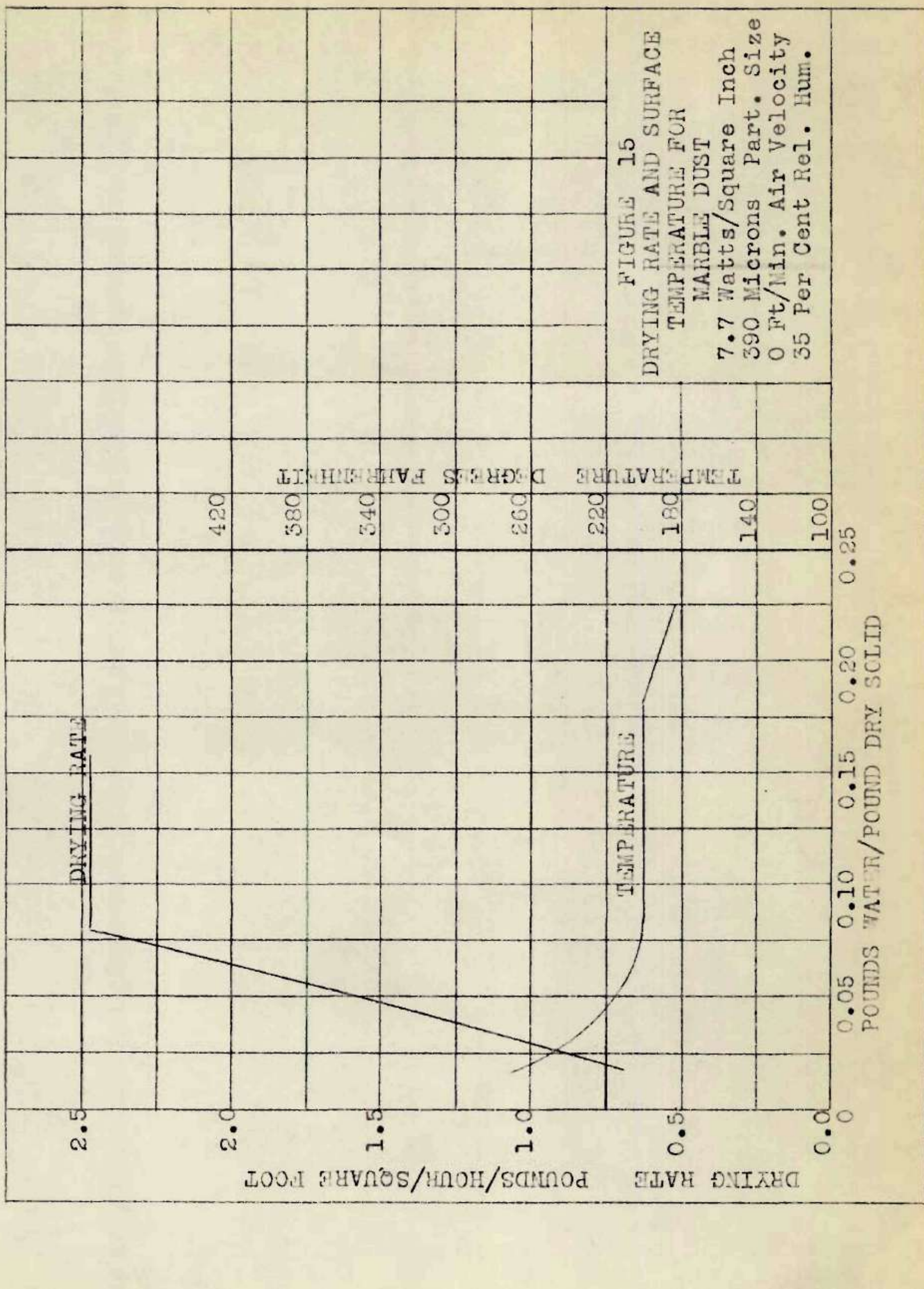

FIGURE 15
DRYING RATE AND SURFACE
TEMPERATURE FOR
MARBLE DUST
7.7 Watts/Square Inch
390 Microns Part. Size
0 Ft/Min. Air Velocity
35 Per Cent Rel. Hum.

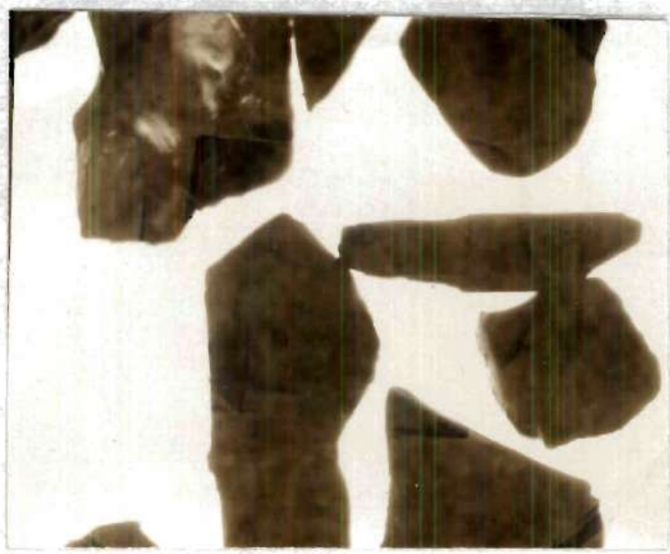

Figure 16
Silicon Carbide
68.2 X

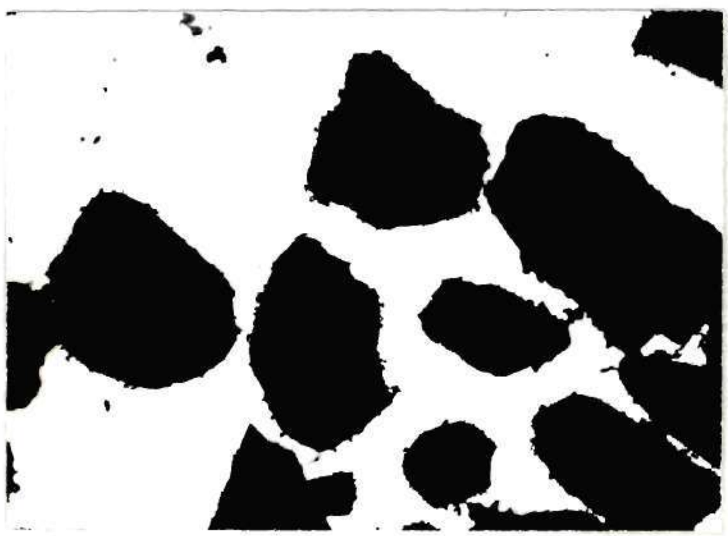

Figure 17
Manganese Dioxide
100 X

Figure 18
Marble Dust
100 X

TABLE VII

Run 1

Material: Silicon Carbide
Air Velocity: 1700 Ft/Minute
Convection Drying Only
Weight of Dry Solids: 7.36 Pounds

Particle Size: 530 Microns
Relative Humidity: 35 Per Cent
Dry Bulb: 170 Degrees Fahrenheit

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0	0.256	114	114	114
10	0.072	0.253	121	121	121
20	0.10	0.249	124	124	124
40	0.14	0.244	128	128	128
60	0.23	0.235	128	128	128
80	0.25	0.226	127	127	127
100	0.27	0.216	128	128	128
120	0.34	0.203	130	130	130
140	0.34	0.191	130	130	130
160	0.34	0.178	129	129	129
180	0.34	0.165	129	129	129
200	0.34	0.156	130	130	130
220	0.34	0.143	128	128	128
250	0.35	0.120	127	127	127
270	0.32	0.105	127	127	127
280	0.33	0.099	126	126	126
300	0.32	0.087	127	127	127
320	0.33	0.074	128	128	128
340	0.35	0.061	129	129	129
360	0.29	0.050	132	132	131
380	0.30	0.039	133	133	133
400	0.26	0.029	132	132	132
420	0.24	0.020	136	136	136
440	0.18	0.013	141	141	141
460	0.11	0.009	150	149	149
480	0.07	0.006	154	154	151
500	0.08	0.003	156	156	152
520	0.07	0.0006	157	157	153
555	0.00	0.000	158	157	157
570	0.00	0.000	160	160	159

TABLE VIII

Run 2

Material: Silicon Carbide — Particle Size: 530 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute — Relative Humidity: 35 Per Cent
Weight of Dry Solids: 6.77 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0	0.34	89	86	82
10	0.61	0.33	138	137	128
15	1.10	0.32	154	154	146
20	1.91	0.30	162	162	158
25	1.97	0.28	167	167	166
30	2.14	0.25	170	170	169
35	2.40	0.23	170	170	170
40	2.52	0.20	173	173	173
50	2.30	0.16	180	180	180
55	2.74	0.13	180	180	180
60	2.42	0.11	180	180	180
65	2.45	0.08	181	181	181
70	1.75	0.063	186	186	186
75	0.70	0.055	260	228	186
80	0.60	0.049	316	278	192
85	0.57	0.043	352	314	224
90	0.63	0.037	379	338	236
95	0.79	0.029	385	342	245
100	0.60	0.026	397	356	267
105	0.79	0.029	410	372	292
115	0.49	0.006	440	400	322
125	0.19	0.002	464	429	365
135	0.03	0.001	490	464	408
155	0.015	0.000	515	490	458

TABLE IX

Run 3

Material: Silicon Carbide   Particle Size: 530 Microns
Intensity of Radiation: 6.4 Watts/Square Inch
Air Velocity: 0 Ft/Minute   Relative Humidity: 35 Percent
Weight of Dry Solid: 7.53 Pounds

Time Min.	Drying Rate $\frac{\text{Lbs. Water}}{\text{Hour Ft.}^2}$	Moisture Content $\frac{\text{Lbs. Water}}{\text{Lbs. Dry Solid}}$	Temperatures °F Surface	Middle	Bottom
0	0	0.260	93	93	93
10	0.43	0.251	150	150	145
20	1.10	0.232	173	173	172
30	1.57	0.203	182	182	182
35	1.72	0.187	185	185	185
40	1.65	0.172	186	186	186
45	1.69	0.156	189	189	189
50	1.78	0.140	190	190	190
55	1.75	0.124	190	190	190
60	1.81	0.107	192	192	192
65	1.78	0.091	194	194	194
70	1.78	0.074	194	194	194
80	1.64	0.044	199	199	199
95	0.72	0.024	243	226	208
100	0.48	0.020	269	241	217
110	0.43	0.012	302	274	258
130	0.28	0.002	361	330	320
140	0.08	0.000	386	369	365
150	0.00	0.000	408	396	394

TABLE X

Run 4

Material: Silicon Carbide — Particle Size: 200 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute — Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.80 Pounds

Time Min.	Drying Rate $\frac{\text{Lbs. Water}}{\text{Hour Ft.}^2}$	Moisture Content $\frac{\text{Lbs. Water}}{\text{Lbs. Dry Solid}}$	Temperatures °F Surface	Middle	Bottom
0	0.00	0.252	93	93	93
10	0.51	0.243	162	162	157
20	1.86	0.215	182	182	181
30	2.48	0.165	186	186	186
35	2.32	0.145	189	189	188
40	2.54	0.122	191	191	191
45	2.52	0.100	193	193	192
50	2.58	0.077	194	194	194
55	2.07	0.059	204	204	201
60	1.49	0.045	219	219	204
70	1.42	0.020	295	273	224
80	0.88	0.005	362	309	291
90	0.25	0.000	411	361	352
100	0.00	0.000	451	413	411

TABLE XI

Run 5

Material: Silicon Carbide Particle Size: 530 Microns
Intensity of Radiation: 5.5 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.17 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.252	86	86	86
10	0.16	0.249	127	125	125
20	0.40	0.239	157	156	155
30	0.99	0.219	170	170	170
40	1.20	0.196	177	177	177
45	1.28	0.184	181	181	180
50	1.28	0.172	182	182	182
55	1.31	0.159	182	182	182
60	1.28	0.147	186	186	186
70	1.35	0.121	189	189	187
80	1.37	0.094	190	190	189
85	1.37	0.081	194	194	192
90	1.34	0.068	196	196	196
95	1.34	0.055	196	196	196
100	1.31	0.043	198	198	198
105	0.80	0.035	203	202	201
110	0.51	0.030	213	205	205
115	0.54	0.025	228	208	206
120	0.41	0.019	250	214	208
130	0.38	0.013	278	243	242
140	0.37	0.006	298	264	264
160	0.10	0.000	344	318	318
170	0.00	0.000	365	349	349

TABLE XII

Run 6

Material: Silicon Carbide Particle Size: 200 Microns
Intensity of Radiation: 6.4 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.58 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.246	98	98	98
10	0.27	0.241	150	146	146
20	0.84	0.218	174	173	172
30	1.48	0.199	182	182	182
35	1.65	0.183	182	182	182
40	1.72	0.168	182	182	182
45	1.65	0.152	188	188	188
50	1.65	0.137	189	189	189
60	1.75	0.105	189	189	189
65	1.75	0.089	192	192	192
70	1.75	0.073	193	193	193
75	1.69	0.058	195	195	195
80	1.47	0.044	205	204	201
85	0.88	0.036	221	209	208
90	0.73	0.030	242	211	208
95	0.70	0.023	276	221	209
100	0.57	0.018	300	242	230
111	0.46	0.009	337	269	263
120	0.30	0.003	368	298	298
130	0.16	0.000	391	331	331
140	0.00	0.000	413	363	363

TABLE XIII

Run 7

Material: Silicon Carbide Particle Size: 90 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.17 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.251	95	95	95
10	0.27	0.245	161	156	150
20	1.80	0.211	181	181	178
35	2.22	0.146	188	188	188
40	2.45	0.122	189	189	189
45	2.48	0.098	190	190	190
50	2.39	0.075	198	197	194
55	1.53	0.060	211	203	201
60	1.28	0.048	242	210	205
65	1.08	0.038	281	225	207
70	0.80	0.030	312	248	208
75	0.64	0.024	334	271	211
80	0.57	0.018	354	287	236
90	0.51	0.008	391	316	276
100	0.32	0.002	426	351	322
110	0.11	0.000	457	399	375
120	0.00	0.000	479	433	414

TABLE XIV

Run 8

Material: Silicon Carbide — Particle Size: 200 Microns
Intensity of Radiation: 5.5 Watts/Square Inch
Air Velocity: 0 Ft/Minute — Relative Humidity: 35 Per Cent
Weight of Dry Solid: 6.93 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.242	96	96	96
10	0.21	0.238	137	133	133
20	0.59	0.226	163	162	161
30	1.02	0.206	174	174	173
40	1.28	0.181	180	180	180
45	1.28	0.168	181	181	181
50	1.31	0.155	184	184	182
60	1.31	0.128	186	186	185
70	1.40	0.100	189	189	186
75	1.43	0.086	190	190	189
80	1.43	0.072	190	190	190
85	1.43	0.057	192	192	190
90	1.12	0.046	192	192	190
95	0.64	0.040	201	198	198
100	0.54	0.034	212	204	202
110	0.57	0.023	246	214	204
120	0.59	0.014	278	241	235
130	0.56	0.003	301	258	262
140	0.14	0.001	328	286	290
150	0.02	0.000	348	318	324
160	0.00	0.000	368	342	352

TABLE XV

Run 9

Material: Silicon Carbide Particle Size: 90 Microns
Intensity of Radiation: 6.4 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.05 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.285	88	88	88
10	0.16	0.281	146	141	139
20	1.32	0.271	169	169	166
30	1.59	0.255	178	178	178
35	1.72	0.223	180	180	180
40	1.85	0.189	182	181	181
45	1.81	0.171	184	184	184
50	1.81	0.153	185	185	185
55	1.81	0.135	186	186	186
60	1.81	0.117	188	188	188
65	1.78	0.099	190	190	190
70	1.75	0.082	193	192	191
75	1.18	0.070	201	198	198
80	1.08	0.060	211	203	201
85	0.96	0.050	231	204	204
90	0.73	0.043	250	208	205
95	0.57	0.038	270	219	206
105	0.57	0.026	302	241	236
115	0.53	0.016	322	254	254
125	0.43	0.007	343	284	284
135	0.24	0.002	362	295	295
145	0.14	0.000	392	337	337
155	0.00	0.000	406	359	359

TABLE XVI

Run 10

Material: Silicon Carbide Particle Size: 90 Microns
Intensity of Radiation: 5.5 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.30 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.265	95	95	95
10	0.16	0.261	140	136	135
20	0.91	0.236	169	169	169
35	1.10	0.215	177	177	177
40	1.24	0.203	179	179	178
45	1.31	0.190	181	181	181
50	1.31	0.178	184	184	182
55	1.31	0.166	186	186	184
65	1.42	0.139	188	188	186
70	1.28	0.127	190	190	188
75	1.40	0.113	192	192	190
80	1.34	0.101	192	192	190
85	1.28	0.089	194	194	192
90	1.12	0.078	196	194	194
95	1.05	0.068	201	201	198
100	0.99	0.059	207	204	201
105	0.83	0.051	216	206	203
110	0.64	0.045	228	209	205
120	0.64	0.033	256	213	207
130	0.54	0.022	275	232	238
140	0.46	0.014	292	242	251
150	0.40	0.006	306	265	273
160	0.32	0.000	327	274	294
175	0.00	0.000	351	313	327

TABLE XVII

Run 11

Material: Silicon Carbide   Particle Size: 17 Microns
Intensity of Radiation: 6.4 Watts/Square Inch
Air Velocity: 0 Ft/Minute   Relative Humidity: 35 Per Cent
Weight of Dry Solid: 6.5 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.351	98	98	98
10	0.30	0.345	144	141	138
20	1.01	0.324	170	170	169
30	1.50	0.292	182	182	181
35	1.56	0.276	181	181	181
40	1.57	0.259	186	186	186
45	1.62	0.242	188	188	188
50	1.69	0.223	190	190	190
65	1.79	0.166	190	190	190
70	1.69	0.149	194	194	194
75	1.59	0.131	196	196	196
80	1.43	0.116	200	200	199
85	1.24	0.103	204	204	203
90	1.12	0.091	202	202	202
95	0.95	0.081	202	202	202
100	0.80	0.072	204	204	202
105	0.83	0.064	205	205	205
115	0.87	0.045	208	206	205
120	0.70	0.038	212	212	206
140	0.48	0.014	277	261	236
150	0.45	0.004	301	281	256
160	0.19	0.000	324	306	288
170	0.00	0.000	355	341	327

TABLE XVIII

Run 12

Material: Silicon Carbide Particle Size: 17 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 6.5 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.320	93	93	93
15	1.01	0.290	172	170	169
20	1.75	0.270	179	179	178
25	1.91	0.250	183	183	183
30	2.13	0.230	186	186	186
35	2.32	0.200	189	189	188
40	2.38	0.176	190	190	190
45	2.32	0.150	194	193	192
55	1.86	0.111	200	200	199
60	1.18	0.099	201	201	201
65	1.59	0.081	205	205	205
70	1.21	0.069	209	205	205
75	1.08	0.057	213	207	206
80	1.10	0.045	221	209	208
85	0.96	0.035	230	207	207
90	0.89	0.025	243	210	209
100	0.60	0.013	298	236	221
110	0.40	0.004	344	271	265
120	0.19	0.000	382	316	316
130	0.00	0.000	421	372	372

TABLE XIX

Run 13

Material: Silicon Carbide　　Particle Size: 8 Microns
Intensity of Radiation: 5.5 Watts/Square Inch
Air Velocity: 0 Ft/Minute　　Relative Humidity: 35 Per Cent
Weight of Dry Solid: 6.7 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.368	95	95	95
15	0.34	0.358	146	144	141
30	1.21	0.328	170	170	170
35	1.02	0.317	174	174	174
40	1.21	0.305	178	178	178
45	1.18	0.293	184	184	184
55	1.24	0.267	186	186	186
65	1.35	0.239	188	188	188
70	1.34	0.225	190	190	190
85	1.34	0.183	194	194	194
90	1.28	0.170	194	194	194
100	1.37	0.141	194	194	194
105	1.40	0.127	194	194	194
110	1.28	0.114	198	198	198
120	1.05	0.091	202	202	202
125	0.89	0.081	202	202	202
135	1.08	0.062	202	202	202
150	0.72	0.041	204	204	204
160	0.54	0.029	210	206	206
170	0.64	0.019	210	206	206
180	0.31	0.009	224	208	208
190	0.29	0.000	259	221	221
200	0.00	0.000	270	223	221

TABLE XX

Run 14

Material: Silicon Carbide
Particle Size: 17 Microns
Intensity of Radiation: 5.5 Watts/Square Inch
Air Velocity: 0 Ft/Minute
Relative Humidity: 35 Per Cent
Weight of Dry Solid: 6.5 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.298	99	99	99
20	0.56	0.275	162	162	162
30	1.18	0.249	172	172	172
40	1.36	0.220	177	177	177
45	1.40	0.205	178	178	178
50	1.40	0.191	180	180	180
55	1.43	0.175	182	182	182
60	1.43	0.160	185	185	185
70	1.39	0.130	189	189	189
75	1.21	0.117	190	190	190
80	1.18	0.105	194	194	194
85	1.05	0.094	197	197	197
90	0.99	0.083	198	198	198
95	0.92	0.073	198	198	198
100	0.89	0.064	199	199	199
105	0.89	0.054	201	201	201
115	0.75	0.038	201	201	201
125	0.62	0.025	217	205	205
135	0.57	0.013	242	206	206
145	0.32	0.006	273	228	217
155	0.29	0.000	295	251	241
165	0.000	0.000	318	278	271

TABLE XXI

Run 15

Material: Silicon Carbide
Particle Size: 8 Microns
Intensity of Radiation: 6.4 Watts/Square Inch
Air Velocity: 0 Ft/Minute
Relative Humidity: 35 Per Cent
Weight of Dry Solid: 6.40 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.369	99	99	99
20	0.58	0.350	162	160	158
30	1.50	0.305	180	180	180
35	1.53	0.288	184	184	184
40	1.56	0.272	187	187	186
45	1.68	0.253	189	189	189
50	1.68	0.234	190	190	190
55	1.75	0.216	190	190	190
60	1.75	0.197	193	193	192
65	1.75	0.178	194	194	193
70	1.75	0.159	196	196	195
75	1.75	0.140	198	198	198
80	1.59	0.123	201	201	200
85	1.34	0.109	204	204	202
90	1.37	0.094	205	205	205
95	1.27	0.079	207	207	205
105	0.96	0.059	208	208	207
110	0.86	0.050	208	208	207
115	0.73	0.042	217	211	209
120	0.70	0.034	219	212	209
130	0.68	0.020	236	219	211
140	0.43	0.010	284	252	235
150	0.27	0.005	328	282	263
160	0.21	0.000	366	322	309
170	0.00	0.000	391	355	351

TABLE XXII

Run 16

Material: Manganese Dioxide Particle Size: 310 Microns
Intensity of Radiation: 5.5 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 8.40 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.218	99	99	99
20	0.79	0.192	162	155	154
25	0.83	0.181	173	166	164
30	0.99	0.177	180	176	173
35	1.21	0.167	186	183	182
40	1.47	0.155	190	189	188
45	1.28	0.145	193	193	190
50	1.43	0.133	195	195	194
55	1.43	0.121	198	198	198
60	1.43	0.109	201	201	200
65	1.43	0.098	209	203	202
70	1.37	0.086	206	206	205
75	1.08	0.077	210	210	209
80	1.02	0.069	217	211	209
85	1.05	0.060	225	211	210
90	1.05	0.052	238	212	211
95	0.95	0.044	249	213	211
105	0.80	0.031	271	217	215
110	0.64	0.025	280	221	218
120	0.56	0.017	298	240	240
130	0.46	0.009	323	262	262
140	0.37	0.003	344	299	299
150	0.16	0.000	369	325	325
160	0.00	0.000	391	357	357

TABLE XXIII

Run 17

Material: Silicon Carbide Particle Size: 8 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 6.60 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.327	99	99	99
15	1.13	0.291	178	176	174
20	2.00	0.270	184	184	183
25	2.38	0.245	188	188	188
30	2.45	0.219	190	190	190
35	2.45	0.194	192	192	192
40	2.45	0.168	194	194	194
45	2.45	0.142	198	198	198
50	2.13	0.120	202	202	201
55	1.66	0.103	201	201	201
60	1.59	0.086	203	203	202
65	1.43	0.071	205	205	205
70	1.24	0.058	205	205	201
75	0.99	0.048	211	204	202
80	0.86	0.039	221	204	202
85	0.83	0.030	243	202	201
90	0.70	0.022	280	206	205
95	0.63	0.016	316	218	205
105	0.40	0.007	374	262	251
120	0.23	0.000	428	343	336
130	0.00	0.000	449	379	380

TABLE XXIV

Run 18

Material: Manganese Dioxide Particle Size: 310 Microns
Intensity of Radiation: 6.4 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 8.45 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.224	86	86	86
15	0.53	0.211	141	137	133
25	1.12	0.192	162	160	158
30	1.21	0.182	168	168	166
35	1.34	0.171	176	176	174
40	1.43	0.160	188	188	182
45	1.37	0.148	210	210	198
55	1.43	0.125	212	212	212
60	1.50	0.113	211	211	211
65	1.59	0.100	212	212	211
75	1.59	0.074	212	212	211
80	1.40	0.062	212	212	211
85	1.15	0.053	212	212	211
90	1.02	0.044	214	213	211
95	0.86	0.037	220	216	211
100	0.80	0.031	228	220	213
105	0.80	0.024	237	220	218
115	0.56	0.015	258	240	234
125	0.45	0.008	280	254	254
135	0.32	0.003	309	282	287
145	0.16	0.000	341	319	325
155	0.00	0.000	357	336	336

TABLE XXV

Run 19

Material: Manganese Dioxide Particle Size: 310 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 8.15 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.253	90	90	90
15	1.22	0.222	166	158	152
20	1.81	0.207	174	169	166
25	1.78	0.192	190	178	174
30	1.81	0.176	212	188	186
35	1.88	0.160	213	205	199
40	1.97	0.144	213	213	213
45	2.04	0.126	213	213	213
50	2.07	0.109	213	213	213
55	2.07	0.091	213	213	213
60	1.50	0.078	224	213	213
65	1.21	0.068	241	213	211
70	0.92	0.060	257	216	211
75	0.80	0.054	278	255	213
85	0.68	0.042	316	252	226
95	0.40	0.035	353	289	276
105	0.27	0.028	388	334	330
125	0.10	0.000	446	409	423
135	0.00	0.000	456	420	420

TABLE XXVI

Run 21

Material: Silicon Carbide   Particle Size: 530 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 1700 Ft/Minute   Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.75 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.266	95	95	95
15	1.10	0.236	182	170	170
20	2.10	0.218	186	180	180
25	2.38	0.197	190	185	189
30	2.35	0.176	190	189	190
35	2.58	0.153	190	188	190
40	2.45	0.131	194	192	192
45	2.54	0.108	194	194	194
50	2.54	0.086	199	197	198
55	1.50	0.072	205	202	202
60	0.89	0.064	212	206	208
65	0.80	0.057	256	209	212
70	1.05	0.048	277	217	212
80	0.64	0.037	302	241	247
90	0.69	0.025	329	254	259
100	0.60	0.014	355	302	302
110	0.43	0.007	384	339	339
120	0.24	0.008	411	379	379
130	0.16	0.000	432	411	411
140	0.00	0.000	448	430	430

TABLE XXVII

Run 22

Material: Marble Dust Particle Size: 390 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 5.50 Pounds

Time Min.	Drying Rate $\frac{\text{Lbs. Water}}{\text{Hour Ft.}^2}$	Moisture Content $\frac{\text{Lbs. Water}}{\text{Lbs. Dry Solid}}$	Temperatures °F Surface	Middle	Bottom
0	0.00	0.325	108	108	108
15	1.10	0.283	167	158	158
25	2.00	0.232	182	180	180
30	2.23	0.204	189	189	186
35	2.35	0.175	196	196	192
40	2.42	0.144	199	199	196
45	2.51	0.113	198	198	198
50	2.35	0.083	198	198	198
55	1.88	0.059	205	205	204
60	1.28	0.043	209	208	207
65	0.96	0.031	216	213	210
70	0.70	0.022	266	225	212
75	0.41	0.017	286	255	245
80	0.41	0.012	300	277	256
85	0.51	0.006	320	295	271
90	0.44	0.000	333	313	288
95	0.00	0.000	351	327	309

TABLE XXVIII

Run 23

Material: Marble Dust Particle Size: 390 Microns
Intensity of Radiation: 5.5 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 5.45 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.336	80	80	80
15	0.53	0.316	136	130	129
20	0.70	0.306	149	145	142
30	0.99	0.282	162	161	158
35	1.10	0.267	169	166	166
40	1.18	0.252	172	171	170
50	1.24	0.221	178	177	176
60	1.24	0.189	182	182	182
65	1.31	0.173	184	184	182
75	1.35	0.138	186	186	186
80	1.27	0.122	188	188	188
85	1.31	0.105	189	189	189
95	1.35	0.075	193	190	190
100	1.02	0.062	198	196	196
105	0.70	0.053	201	199	199
110	0.57	0.046	205	202	202
120	0.37	0.037	241	216	208
130	0.29	0.029	254	236	236
140	0.32	0.021	262	241	241
150	0.33	0.012	269	245	245
160	0.29	0.005	280	263	263
170	0.21	0.000	297	277	277
180	0.00	0.000	313	295	295

TABLE XXIX

Run 24

Material: Marble Dust Particle Size: 390 Microns
Intensity of Radiation: 6.4 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 5.45 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.316	95	95	95
15	0.74	0.288	147	141	137
25	1.23	0.257	170	165	162
35	1.59	0.217	180	178	178
40	1.69	0.195	182	182	182
45	1.75	0.173	186	186	186
50	1.75	0.151	189	189	189
55	1.75	0.128	190	190	190
60	1.75	0.106	193	193	193
65	1.75	0.084	194	194	194
70	1.53	0.064	196	196	196
75	0.92	0.053	202	202	201
80	0.80	0.043	205	205	205
85	0.57	0.035	213	206	206
90	0.51	0.029	240	213	208
95	0.16	0.027	258	230	230
105	0.38	0.017	274	242	241
115	0.32	0.009	289	262	254
125	0.24	0.003	309	282	280
135	0.11	0.000	336	318	311
145	0.00	0.000	360	351	348

TABLE XXX

Run 25

Material: Silicon Carbide Particle Size: 530 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 60 Per Cent
Weight of Dry Solid: 7.90 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.245	88	88	88
15	0.74	0.223	168	166	165
25	1.64	0.195	186	186	184
30	2.23	0.175	190	190	189
35	2.36	0.154	190	190	190
40	2.36	0.134	192	192	192
45	2.23	0.114	194	194	194
50	2.20	0.095	194	194	194
55	2.32	0.075	196	196	196
60	2.13	0.056	201	201	201
65	0.95	0.048	210	208	208
70	0.82	0.040	211	210	210
75	0.70	0.034	248	212	212
80	0.64	0.029	254	224	214
90	0.56	0.019	280	258	258
100	0.60	0.008	309	268	277
110	0.46	0.000	344	319	319
120	0.00	0.000	377	360	356

TABLE XXXI

Run 26

Material: Silicon Carbide Particle Size: 530 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 1200 Ft/Minute Relative Humidity: 35 Per Cent
Weight of Dry Solid: 7.67 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.²	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.269	86	86	86
15	0.82	0.247	161	161	161
25	1.78	0.215	178	178	178
30	2.00	0.197	181	181	181
35	2.32	0.176	184	184	184
40	2.35	0.155	185	185	185
45	2.20	0.135	186	186	186
50	2.29	0.114	187	187	187
55	2.38	0.093	190	190	190
60	2.29	0.072	190	190	190
65	1.27	0.060	200	199	199
70	1.05	0.054	205	205	205
75	0.64	0.048	212	212	212
80	0.41	0.044	241	224	213
90	0.67	0.032	269	264	260
100	0.56	0.022	280	270	269
110	0.56	0.012	302	302	302
120	0.43	0.004	327	327	327
130	0.24	0.000	372	372	372
140	0.00	0.000	403	403	403

TABLE XXXII

Run 27

Material: Silicon Carbide Particle Size: 530 Microns
Intensity of Radiation: 7.7 Watts/Square Inch
Air Velocity: 0 Ft/Minute Relative Humidity: 50 Per Cent
Weight of Dry Solid: 8.00 Pounds

Time Min.	Drying Rate Lbs. Water / Hour Ft.^{2}	Moisture Content Lbs. Water / Lbs. Dry Solid	Temperatures °F Surface	Middle	Bottom
0	0.00	0.235	108	108	108
15	0.69	0.217	166	166	166
25	1.83	0.185	182	182	182
30	2.13	0.166	186	186	186
35	2.54	0.144	190	190	190
40	2.45	0.123	194	194	194
45	2.39	0.102	194	194	194
50	2.23	0.083	196	196	196
55	2.32	0.063	196	196	196
60	2.23	0.043	201	201	201
65	1.12	0.034	209	209	209
70	0.57	0.029	216	212	212
75	0.60	0.023	243	217	214
80	0.51	0.019	265	245	242
90	0.54	0.010	292	256	251
100	0.40	0.003	325	289	277
110	0.16	0.000	366	332	313
120	0.00	0.000	403	384	367

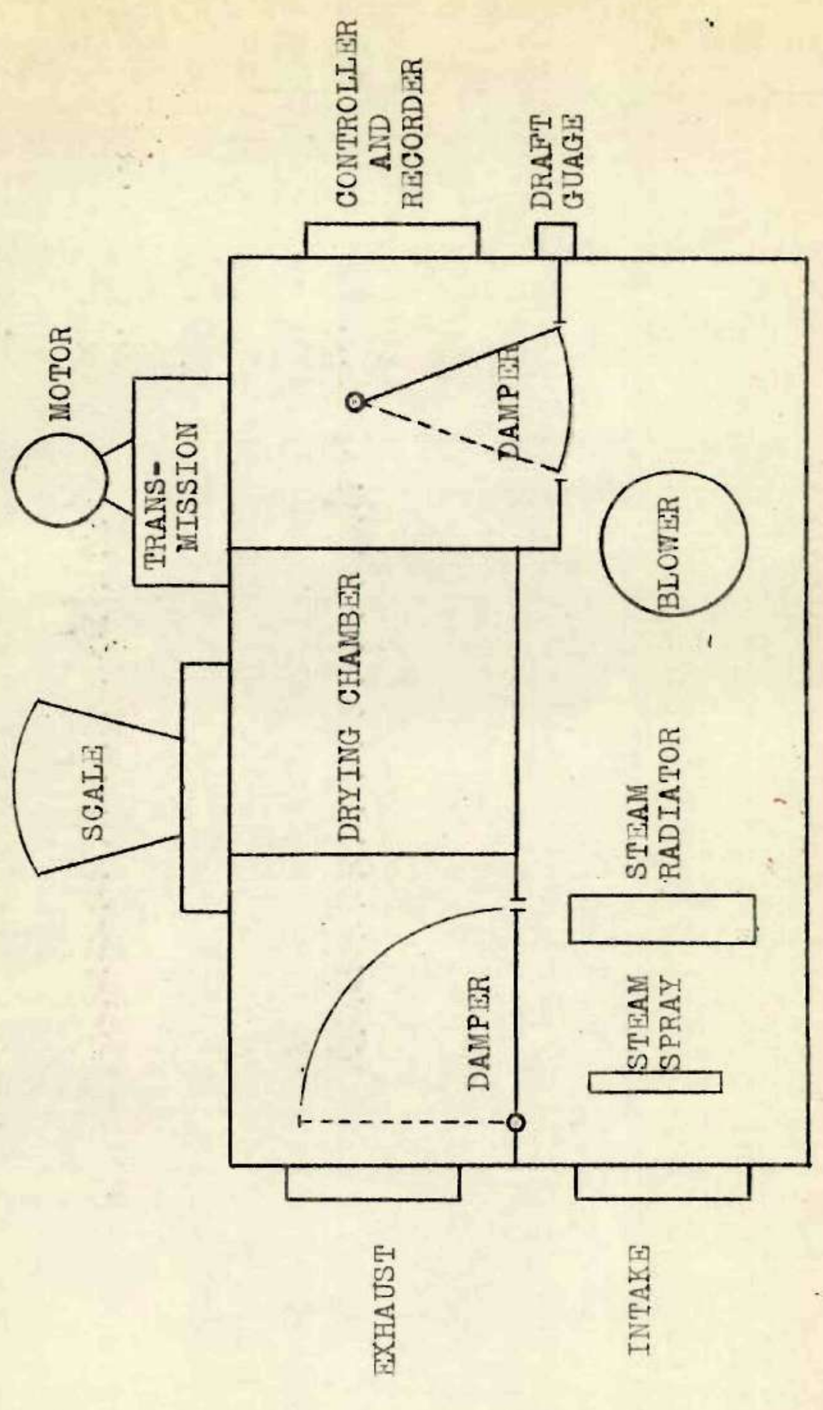

DIAGRAM 1
PROCTOR AND SCHWARTZ
LABORATORY DRYER

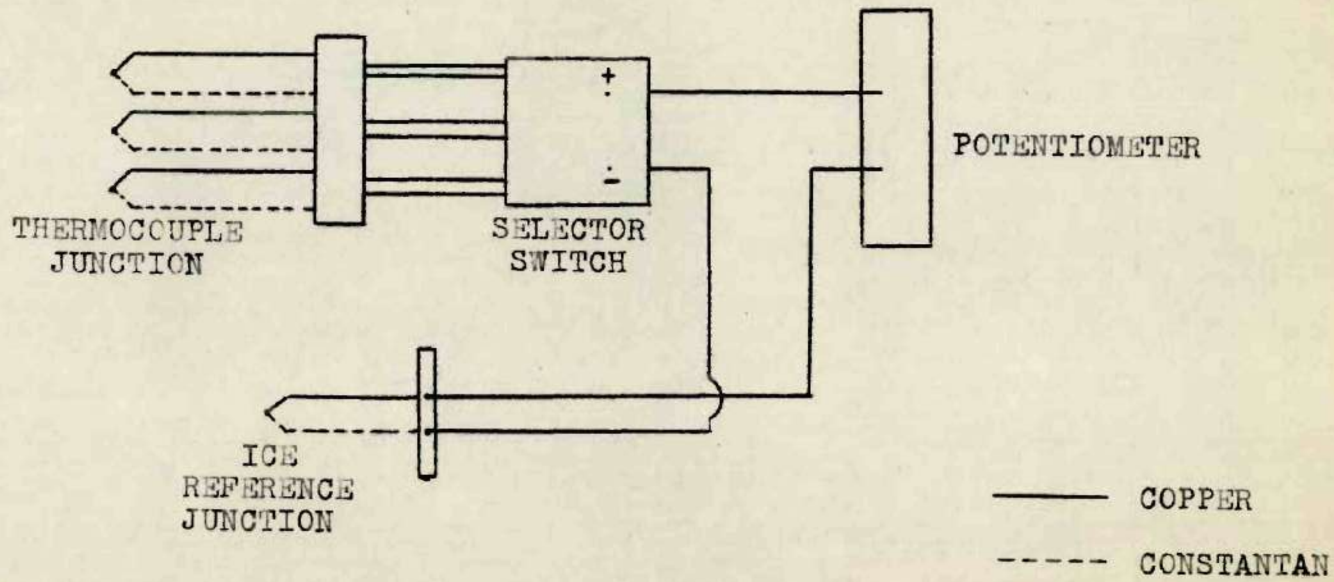

DIAGRAM 2

POTENTIOMETER CIRCUIT

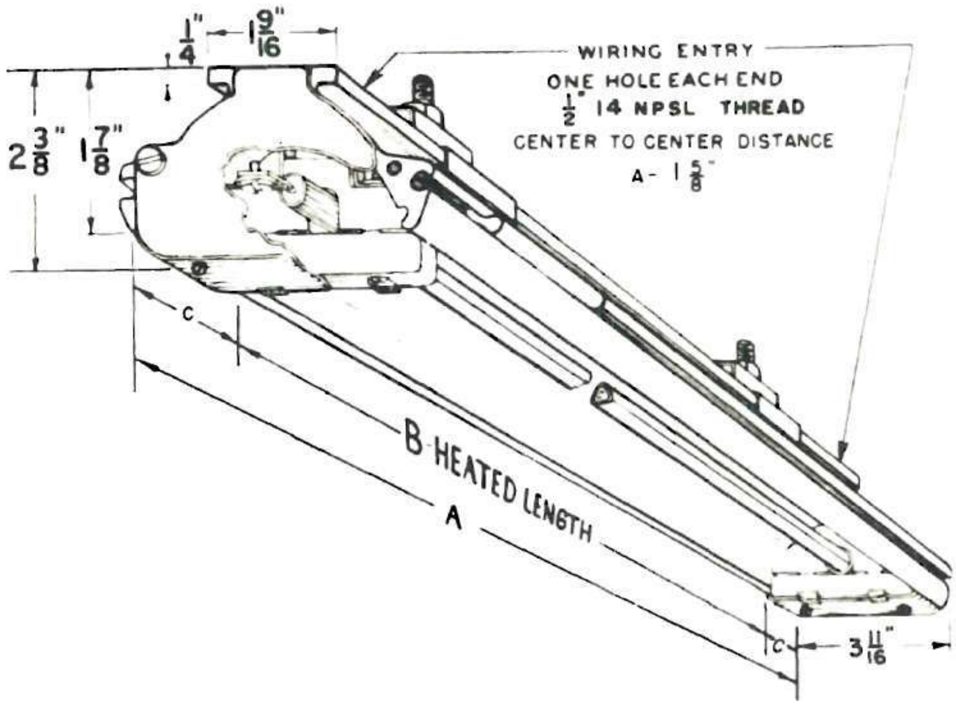

Diagram 3
CHROMALOX Infrared Heater
Edwin L. Wiegand Company
Pittsburgh, Pennsylvania