DIELECTRIC DRYING OF WHEAT

by

DENNIS EUGENE DRAYER

B. S., South Dakota School of Mines and Technology, 1952

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1954

TABLE OF CONTENTS

INTRODUCTION

The purpose of this project was to investigate the process of drying wheat with high frequency electrical energy. In this investigation emphasis was placed upon studying the relative merits of drying wheat dielectrically while in admixture with various solid desiccants. Minor emphasis was placed upon studying the mechanism of dielectric drying. Resistance measurements of samples dried with high-frequency energy and with hot air were taken in an effort to determine the relative movement of surface moisture.

REVIEW OF LITERATURE

No study of the specific nature of this project has been found in the literature. However, published accounts of related investigations have appeared in recent years. The potentialities of the industrial uses of dielectric drying have been studied with reference to the food, wood, and plastics industries.

The process of dielectric drying is a means of generating heat within a material by subjecting it to a high-frequency electrostatic field. The heating effect, which is nearly uniform throughout the material, is caused by repeated orientations of the molecules within the material.

The process of drying by air or hot gas involves contacting the surface of the material with the drying medium. The heating effect, which is not uniform throughout the material, is accomplished through the transfer of heat by convection and radiation.

Drying wheat by air or hot gas is a process whereby heat must be transferred from the gas to the surface and from the surface of the kernel inward. Since the amount of moisture removed is proportional to the heat supplied, any method of increasing the rate of heat addition would be desirable provided that parts of the kernel do not become overheated. Sherman (23) found that the rate of water removal during electronic heating was ten times faster than with conventional drying methods.

Major advantages of radio-frequency heating, according to Mann et al. (13), include the following:

The heat can be generated rapidly and uniformly throughout the material or concentrated in portions of highest loss factor, eliminating the necessity of heating the entire body.

The amount of heat is easily varied and controlled. The process is adaptable to automatic control.

The generating equipment presents an economy of space and flexibility of adaptation, is simple to operate and easy and economical to maintain, assuming a reasonable tube life.

The method achieves results not possible with other processes and can increase the speed of a process, thereby decreasing labor costs.

An added advantage, as stated by Proctor and Goldblith (Mrak et al. 14) is that the moisture content of a material can be reduced below five percent without obtaining the case hardening which usually results when conventional drying means are used. Dennis, entymologist for the United States Department of Agriculture in Manhattan, Kansas, stated that wheat treated with radio-frequency energy shows indications of faster sprouting and growing.[1]

---

[1] Norman Dennis, Private Communication.

Major disadvantage of radio-frequency heating include high power costs, high equipment costs, and problems associated with keeping the load "in tune" with the generator.

Wide applications of radio-frequency heating were found in the literature. Stephens (25) reported that radio-frequency heating is adaptable for the drying of pottery and for rayon cord. Various electrode arrangements are shown for drying different shaped objects. Stephens also stated that various powders, pharmaceutical granules, and tablets can be dried by passing them along a belt through an electrostatic field of suitable strength. The efficiency of a large installation, as reported by Stephens, is to be taken as fifty percent.

Proctor and Goldblith (Mrak et al., 14) reported that the rice weevil in wheat can be destroyed by radio-frequency energy at forty to fifty megacycles. Hartshorn (7) pointed out the advantages of using radio-frequency heating for sterilizing food.

Langton (12) summarized various dielectric heating applications with reference to the heat treating of thermoplastics and the gluing of plywood.

Nicol (18) employed radio-frequency heating techniques in drying granular solids. As concluded by Nicol, when wet materials are heated, the heat is generated in the liquid, or the solid, or both; and in each case the mechanism may be either purely resistance heating or dielectric loss.

The mechanism of dielectric drying was studied by Mann et al. (13) and was found to be the same as for conventional drying methods. The drying curves obtained for sand showed four portions common to conventional drying curves: the increasing-rate period; the constant-rate period; the uniform falling-rate period; and the accelerated falling-rate period.

During the constant-rate period, the majority of the capillaries maintain their liquid at the surface. At the start of the uniform falling-rate period, the liquid level in the capillaries recedes. The evaporation of the liquid takes place within the body of sample during the accelerated falling-rate period. Because the liquid movement is of the same type and because the drying curves are of a general shape, the authors concluded the mechanism is the same.

Brown et al. (4) reported that a rayon cake can be dried in about one hour by radio-frequency heating whereas conventional methods require about one hundred hours. Rayon dried in this manner was not subjected to internal strains often set up in yarn. Bulk-reduction for penicillin, pasteurization of milk and beer, and other applications of radio-frequency heating were also discussed.

In all cases where radio-frequency energy was used for dehydration, air was employed to remove the moisture. The literature surveyed presented no method of using a solid desiccant in conjuction with radio-frequency drying. However, Oxley (20) suggested the possibility of mixing damp grain with a granular absorbent. The primary objective of such a method of drying was to eliminate the application of heat.

Bosomworth (3), Sherman (23), and Rushton (Mrak et al.,14) have listed other adaptations of radio-frequency energy for dehydration purposes.

In drying processes where large amounts of water must be removed, the volume of air required is large. The use of a solid desiccant in contact with the wet material eliminates the need for air. The choice of desiccant would depend upon its regeneration characteristics, physical structure, and moisture-carrying capacity. Minor thermal benefits in the form of heats of wetting would result from the use of powdered desiccants.

Certain inconsistencies in explaining the mechanism of radio-frequency heating appeared in the literature. Perry (21) reported that the heating is nearly uniform throughout the thickness of material and that the heating was caused by frictional stresses. Nicol (18) expressed that the mechanism was either resistance heating or dielectric loss or both. Most investigators have described the mechanism by one of these methods. However, Langton (12) stated that recent discoveries indicate that the charge resides in a surface film on the dielectric.

Because of the apparent possibilities of radio-frequency heating, the relative newness of the approach, and the lack of published material on the specific nature of this project, it was deemed desirable to further investigate this process.

THEORY OF DIELECTRIC DRYING

Dielectric heating is defined as the heating of a nominally insulating material due to its own dielectric losses when the material is placed in a varying electrostatic field. Dielectric heating can be applied to insulating materials such as ceramics, plastics, and other nonconducting materials. The material to be heated is placed in a strong electrostatic field produced by a high-frequency voltage. Frequencies usually used in dielectric heating vary from 1 to 100 megacycles.

Two metallic plates similar to the plates of a capacitor are used as electrodes. The material to be heated is placed between the electrodes. Mann, et al. (13) state that materials composed of polar molecules are best suited for dielectric heating purposes. As shown by Fig. 1 in Plate I the material forms the dielectric of the capacitor.

The molecules of the material are first stressed toward one electrode and later toward the other electrode. Under the influence of a high-frequency voltage, the molecules tend to reorient themselves several million times a second. The rapidity of molecular reorientation depends upon the frequency of the impressed voltage. Heating of the material is caused by "molecular friction". Presented in Fig. 2 of Plate I is a simplified diagram showing the effect of electrode polarity on the position of the molecular charges. The positive charges of the molecules are attracted to the negative electrode and the negative charges to the positive electrode. An excellent theoretical treatment of the dielectric properties of insulating materials has been presented by Murphy and Morgan (15) (16) (17).

Another common explanation of the heating of a material in an electrostatic field is that the heat generated is partially due to resistance heating.

The thermal power generated in a dielectric material may be expressed as

$$\text{Thermal power (Kilowatts)} = 1.76 \times 10^{-2} MC\Delta T \qquad (1)$$

where M = mass rate of heating, pounds per minute

C = specific heat of the material, Btu per pound per $^{\circ}F$

ΔT = temperature rise desired, $^{\circ}F$.

This formula gives the amount of power required to raise a specified quantity of material a certain number of degrees per minute.

In order to produce the desired heat in the material, a specified

EXPLANATION OF PLATE I

Fig. 1 Dielectric heating.

Fig. 2 Reversal of charges on particles in electrostatic field.

PLATE I

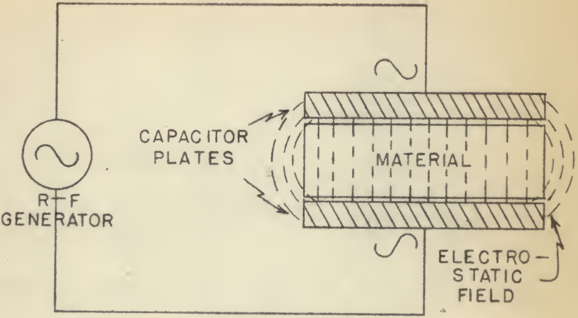


FIG. 1

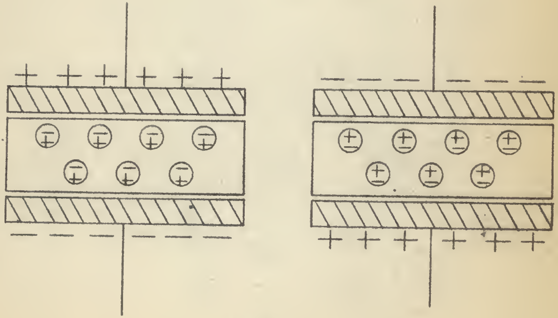


FIG. 2

voltage capable of causing sufficient current flow must be maintained. The voltage required may be determined by the formula

$$E_1 = \sqrt{\frac{W_1}{1.4 \times 10^{-12}(f)(\epsilon'')}} \qquad (2)$$

where E_1 = voltage gradient, volts per inch

f = frequency of generator, cycles per second

ϵ'' = loss factor

= power factor x dielectric constant

= $(p.f.)(\epsilon')$

W_1 = heat required, watts per cubic inch of material.

Equation (2) was derived from the basic dielectric heating formula

$$W = 1.41 \times 10^{-12} E^2 f \epsilon'' \frac{A}{d} \qquad (3)$$

where W = heat generated, watts

E = total voltage across material, volts

f = frequency, cycles per second

ϵ'' = loss factor

A = area to which voltage is applied, square inches

d = thickness of material between electrodes, inches

$E_1 d$ can be substituted for E in Equation (3). This substitution, together with rearrangement of Equation (3), gives

$$\frac{W}{Ad} = 1.41 \times 10^{-12} E_1^2 f \epsilon'' = P \qquad (4)$$

where P = heat generated per unit volume of material, watts per cubic inch.

Another useful formula, used for determining the current through the load, is

$$I = 1.41 \times 10^{-12} E \epsilon' f \frac{A}{d} \qquad (5)$$

where I = current through load, amperes.

In the previous equations, the loss factor e'' is difficult to predict mathematically with any accuracy. Temperature, moisture content, frequency, and composition all affect the value of e''. A method described by Brown et al. (4) permits the evaluation of the loss factor by means of a Q-meter.

The frequency used is limited by two factors: voltage distribution and oscillator design. For a given electrode size the higher the frequency, the greater is the possibility of unequal voltage distribution. The voltage applied across a material should not be so high as to promote arcing between the electrodes. As pointed out by Mann, et al. (13) the choice of frequency and voltage gradient should be made only after considering the dielectric properties of the material. Because of the difficulty of generating sufficient power at high frequencies, radio-frequency generators used for heating purposes are limited to a maximum frequency of one hundred megacycles.

According to the Westinghouse Instruction Book for Radio Frequency Generators (10), the spacing of the electrodes is important in the final analysis of a specific dielectric heating application. If the electrodes rest on the material, if the area of each electrode is equal to the area of the material, and if the thickness of the material is such that the two electrodes are parallel, uniform heating will result if the voltage across the electrodes is uniform and the material is homogeneous. Uneven heating results if the electrodes are not parallel. Jordon (11) pointed out that the electrodes should be in contact with the material; otherwise, any air gap present produces a series-capacitor effect which lowers the voltage gradient.

The voltage at which arcing is produced across the material is to be avoided. The possibility of arcing can be reduced by lowering the voltage or increasing the thickness of material. The decrease in heating rate, due to the lowering of the voltage, can be offset by employing a higher frequency (Equation 4). The Westinghouse Instruction Book (10) has specified that for porous materials the voltage gradient is generally kept below 2000 volts per inch while a gradient less than 5000 volts per inch may be used for homogeneous materials.

The selection of equipment for a given heating application is influenced by each of the theoretical factors mentioned. Not only are the electronic characteristics important, but also the physical and electrical properties of the material must be considered when investigating a given application.

NATURE OF THE STUDY

The nature of this study was exploratory in character. Various schemes of utilizing the high-frequency energy were studied. In each case the ultimate objective was to determine which scheme gave the fastest drying rate. In nearly all of the experiments, the maximum temperature was limited to 180°F because of the reported harmful effects to the germination properties of wheat on heating above that temperature.

In each of the schemes studied, wheat was heated while in admixture with a solid desiccant. Alumina, Florite, and silica gel were the principal desiccants used. Each of these desiccants were compared from the standpoints of moisture capacity, heat losses, and electrical characteristics.

Minor emphasis was placed upon studying the mechanism of dielectric drying. Any drying mechanism is concerned with the movement of moisture. The relative amounts of surface moisture present during the various stages of drying were determined by resistance measurements.

The remainder of the study was concerned with the determination of the overall thermal efficiency of the dielectric drying process and with a study of combination dielectric-and air-drying methods.

The flexibility of operation of the equipment permitted several variations in the manner of heating. The speed of the dielectric drying process was such that several trials could be carried out in a relatively short period of time.

Description of Equipment

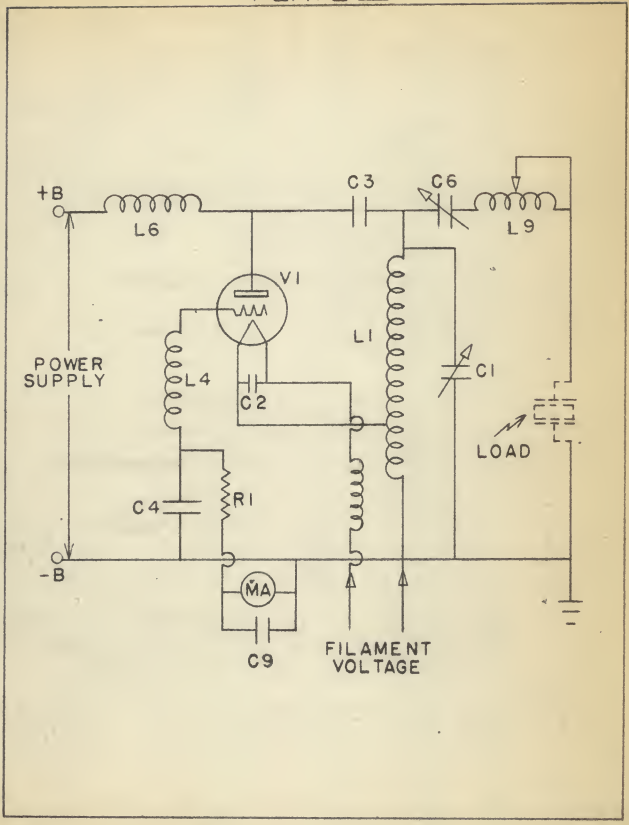
The radio-frequency generator used for this study was a Westinghouse, one-kilowatt, industrial radio-frequency generator (Westinghouse style number 867692). This generator consists of a radio-frequency oscillator with two circuits. One circuit was tuned to produce an output of 300 kilocycles; this circuit was used for induction heating. The other circuit was tuned to 10 megacycles and was used for dielectric heating. Each circuit used a common power supply and the same oscillator tube. A simple switching operation transfered the generator from an induction heater to a dielectric heater. A simplified schematic diagram of the 10 megacycle oscillator circuit is shown in Plate II. The functions of the

EXPLANATION OF PLATE II

Simplified Schematic Diagram of Oscillator Circuit

V1	Oscillator tube
MA	Milliammeter
R1	Grid resistor
C2, C3, C4, C9	Fixed capacitors
C1, C6	Variable tuning capacitors
L1, L4, L6	Inductances
L9	Variable inductance

PLATE II


+B
L6
C3
C6
L9
V1
L1
C1
POWER
SUPPLY
L4
C2
LOAD
C4
R1
-B
MA
C9
FILAMENT
VOLTAGE

various components shown in Plate II are not explained in this report.

Metering instruments included with the generator are the following: input voltmeter; power-supply voltmeter; grid-current ammeter; and plate-current ammeter.

The generator is put into operation by the following series of steps: first, the filament voltage is applied; second, after the tube warm-up period is completed, high voltage from the power supply is applied to the oscillator tube; and third, the plate voltage is increased, together with the load coupling, to give the desired voltage drop across the load.

Load voltages were measured with a vacuum-tube voltmeter constructed especially for this generator by the Electrical Engineering Department of Kansas State College.

The load, which consisted of mixtures of wheat and desiccant, was contained between two parallel plate electrodes. The electrodes were made of aluminum and were 4 inches by 5 inches by 3/8 inch. An enclosure made of Lucite was constructed about the electrodes to contain the wheat and desiccant.

Auxiliary equipment used included the following: radio-frequency ammeters; Westinghouse type G-40 recording wattmeter; portable General Electric wattmeter; Weston model 769 electronic analyzer; Kodak timer; vacuum oven and pump; laboratory balance; and alcohol and mercury thermometers. The load current was measured by a radio-frequency ammeter. The input power to the generator was measured by the recording wattmeter. The resistances of the dried wheat samples were measured by the Weston electronic analyzer. The rest of the auxiliary equipment was used during the actual drying studies. The equipment described is shown in Plate III.

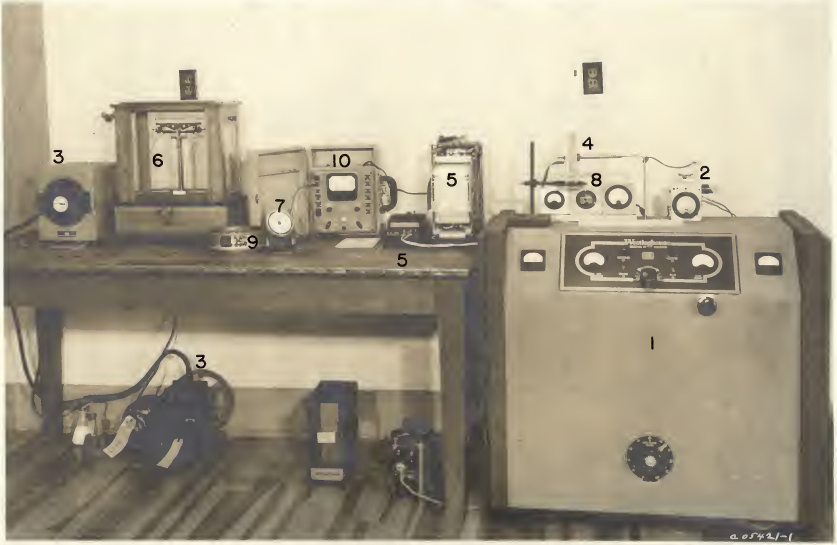
EXPLANATION OF PLATE III

Photograph of Equipment

1. Generator
2. Vacuum-tube voltmeter
3. Vacuum oven and pump
4. Electrodes
5. Wattmeters
6. Balance
7. Timer
8. Ammeters
9. Sieve
10. Ohmmeter

NOTE: Shielding between electrodes and voltmeter is not shown.

PLATE III



Materials Used

The wheat used in this project was obtained from the Milling Department of Kansas State College. Being composed of several Kansas varieties, the wheat could not be classified into one predominate variety.

The solid desiccants used for the sorption of moisture were silica gel, activated alumina, Florite, Drierite, and anhydrous calcium chloride. Factors governing the choice of desiccant were regeneration, activity, separation, and arcing. The majority of the drying studies were conducted using silica gel as the drying agent.

Cobaltous chloride, a visual indicator of moisture, was used in studying the water migration which occurred during drying.

Description of Procedure

All wheat used for the drying investigations had an initial moisture content in the vicinity of eighteen percent on the dry basis.[1] The wheat, as obtained, varied from twelve to fourteen percent moisture. Small quantities of the original wheat were moistened with a predetermined amount of water to bring the moisture content to approximately eighteen percent. The choice of eighteen percent moisture as an initial water content for the wheat was for the purpose of simulating conditions that might be expected following harvest. Early experiments showed that, under identical drying conditions, different varieties of wheat dried at different rates.

---

[1] All moisture contents referred to in this report are on the dry basis.

However, the differences in drying rates that did exist between the varieties tested were small.

Moisture determinations were made on the wheat before drying by heating the samples in a vacuum oven at a temperature of 105°C for a period of four to five days. The wheat so dried was in the form of kernels. A check on the reliability of drying wheat in the kernel form for purposes of moisture determination was made against drying the wheat in the form of ground samples. No appreciable difference in the calculated moisture contents occurred between the two methods.

Next, approximately twelve grams of desiccant were mixed with one hundred grams of wheat. Mixing was done by pouring the weighed sample of wheat and the desiccant simultaneously into the electrode chamber. A mercury-filled thermometer was inserted into the mixture to measure the temperature rise. The upper opening of the electrode chamber, or cell, was closed off by a section of Lucite. The electrode chamber used is shown in Plate IV.

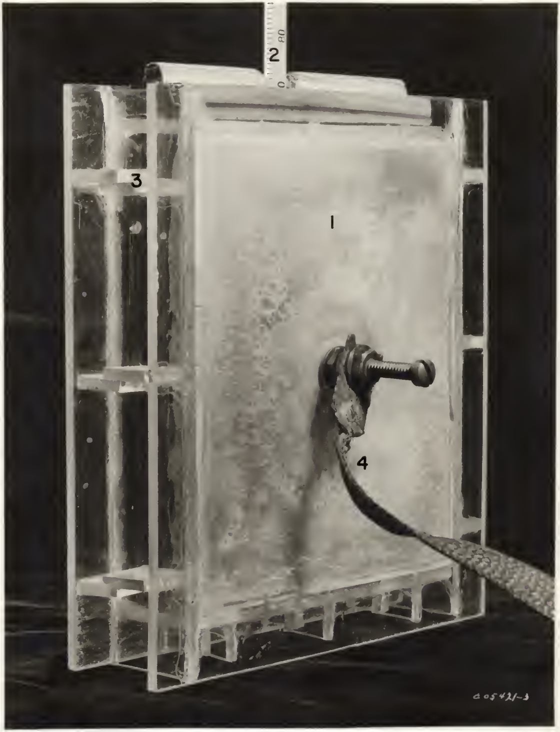
Three general schemes of applying the high-frequency power were utilized. One method, which hereafter will be referred to as "constant-power-setting" runs, was to apply the high-frequency energy by manipulation of the "loading" to give the desired initial voltage gradient. The second method employed, referred to as "constant-temperature" runs, involved the maintaining of a constant sample temperature of 160°F following the heating period. The third method, referred to as "constant-voltage-gradient" runs, involved the maintaining of a constant voltage gradient across the sample throughout the period of heating. Voltage gradients of 1160, 1280, 1400, and 1520 volts per inch of thickness were maintained by manual regulation of the plate-voltage-control dial on the generator.

EXPLANATION OF PLATE IV

Electrode Chamber

1. Aluminum electrodes
2. Thermometer
3. Lucite enclosure
4. Generator lead

PLATE IV



The sample, after being dried according to one of the three schemes described, was removed from the electrode chamber and separated from the desiccant by a simple screening operation. Knowledge of the initial moisture content and of the weight after drying permitted calculation of the final moisture content.

Repetition of this method for different intervals of time gave values of moisture content and time which were used to establish the drying curves. Various desiccants were used in each series of runs for the purpose of determining the most suitable moisture absorbing agent.

Various schemes of intermittent drying were investigated for the purpose of determining whether or not a rest interval between periods of dielectric heating would result in the removal of more moisture for a given period of energy application. As before, wheat samples of known moisture content were mixed with the desiccant; the resulting mixture was subjected to short intervals of dielectric heating followed by an interval of rest.

Intermittent Drying Runs. In the first series of runs, the wheat and desiccant were left in contact with each other between the electrodes; no separation was performed after the heating cycle. In the second series of runs, the wheat and desiccant were separated during the rest period.

In the first series of runs, dielectric heat was applied for 15 seconds; rest periods of 15 seconds, 45 seconds, and 2 minutes and 45 seconds were allowed in different trials.

In the second series of intermittent heating trials (where the wheat and desiccant were separated during the rest period), mixtures were heated through two temperature spans. Moisture removed during the heating of samples from 80°F to 160°F was compared with the amount removed in heating samples from 20°F to 100°F. In each case, following the attainment of the desired maximum temperature, the wheat and desiccant were separated; the wheat was allowed a rest period of thirty to forty minutes before being reheated. Drying curves were thus established for each different method of intermittent heating.

Alternate Dielectric- and Air-Drying Cycles. Since dielectric heating reportedly generates thermal energy within a material, the transfer of internal moisture to the surface of a solid would be expected to be at a higher rate than under conventional air-drying methods. Possibly some method of applying intermittent applications of high-frequency energy followed by a drying period using hot air would result in a faster overall drying process. Investigations with this thought in mind were conducted.

Samples of wheat with a known initial moisture content were subjected to alternate air- and dielectric-drying cycles. The sample was first spread over a screen to a depth of one to two kernels. Hot air at a temperature of 250°F was passed through the bed for 15 seconds. Upon removal from the drier, the sample was weighed and then mixed with silica gel and placed between the electrodes of the dielectric-heating apparatus. (A period of approximately five minutes elapsed between the removal of the wheat from the drier using heated air and the subsequent application of the high-frequency energy.) The wheat was heated for 30 seconds in the high-frequency field. Following the heating, the mixture was removed from the electrode chambers, the wheat was separated from the silica gel, and the weight of the dried sample was obtained.

The above procedure was then repeated, using hot air as a drying medium and then high-frequency energy. Three applications of heated air in 15 second periods each and two applications of high-frequency energy for intervals of 30 seconds each constituted the method utilized to study this drying process.

Air-Drying Runs. Samples of wheat were dried solely by using hot air at a temperature of 250°F. The purpose of these trials was to determine whether or not the application of high-frequency energy had any effect on the amount of moisture removed in a subsequent air-drying interval. In this particular phase of the investigation, hot air served as the drying medium. The amount of water removed during the air-drying interval which was preceded by a dielectric-drying interval (described above) was compared with the amount removed in the air drying interval not preceded by an application of dielectric energy.

The apparatus used for all of the air-drying cycles consisted of a cylindrical, electrically-heated air drier constructed by W. J. Beane.[1] As before, the sample of wheat was spread in a thin layer on a wire screen and hot air was passed through the bed.

Mechanism of Dielectric Drying. Unexpected variations in the amount of moisture removed during the alternate dielectric- and air-drying intervals prompted a series of investigations which dealt with a study of the mechanism of dielectric drying.

The approach used in studying the mechanism of dielectric drying was to investigate the movement of water within the wheat kernels. One method

---

[1] Wendell J. Beane, Dehydration of Alfalfa with Superheated Steam, p. 12, Unpublished M. S. Thesis, Kansas State College, 1953.

employed to indicate the relative amount of moisture present on the surface or skin of the wheat was to use cobaltous chloride, a visual indicator of moisture. Predetermined amounts of a cobaltous chloride solution were added to dry wheat to obtain the desired initial moisture content. Upon drying, the original red (wet) surfaces changed to varying shades of blue (dry). This method, however, proved unsatisfactory.

The method used to study the movement of the moisture within the kernels was to measure the direct-current (d-c) resistance of the sample after it was subjected to various drying schemes.[1]

Samples of wheat were first dried, either by dielectric energy or by hot air, and then the resistance was measured. Inasmuch as only a very small current flows through the sample during the resistance measurement, it was concluded that the current would follow the skin or kernel surface in its flow from one contact to the next. Hence, the opposition that the current met was limited to the surface of the kernels. In effect, then, the resistance indicated by the ohmmeter gave a relative measure of the moisture on the outer surface of the kernel.

Previous theories about dielectric drying suggest that moisture would be driven to the surface of an object more readily than if the object were dried by hot air. If one sample of wheat could be dried by hot air and another by high-frequency energy and each sample could be dried to the same extent, that is, each would have been supplied the same amount of energy, theoretically each sample then should be at the same final moisture

---

[1] Many instruments used by the grain industry for moisture analysis are based upon the fact that the moisture content of grain is inversely proportional to its d-c resistance.

content. However, the sample that had been dried by dielectric heating could be assumed to have a higher concentration of surface moisture than the air-dried sample by virtue of the fact that dielectric heating heats the sample from within, driving the moisture to the surface of the particle.

The study of the mechanism of dielectric drying was centered around these previous suppositions. The actual study itself consisted of drying samples of wheat by the application of high-frequency energy, hot air, or combinations of both in the form of alternating periods of each, and the measurement of the resistance of the samples following the application of heat. Resistance measurements were made by placing the sample in a cell similar to the electrode cell. The Weston analyzer was used to measure the resistance. Presented in Plate V is a picture of the resistance cell and the ohmmeter which were used for all resistance measurements.

Efficiency of Dielectric Drying. The next major portion of the investigation was centered about determining the efficiency of dielectric drying. The efficiency of the drying process was found by calculating the heat required to produce a given temperature rise in the sample and to vaporize the given amount of moisture and by measuring the energy input to the generator. The Westinghouse recording wattmeter was inserted in the power circuit supplying the generator to measure the input energy. Application of the high-frequency energy to the wheat for a given period of time vaporized an amount of water which could be calculated by weight loss. A knowledge of the specific heat of wheat and of the heat of vaporization of moisture from wheat permitted the calculation of the heat

EXPLANATION OF PLATE V

Resistance Measurement Equipment

1. Resistance cell
2. Weston analyzer (ohmmeter)

PLATE V


1
2
OHMS
DC PROBE
DC VOLTS
GROUND
AC PROBE
WESTON
ELECTRONIC
VOLT OHM
MILLIAMMETER
DC CURRENT
AC VOLTS
DC VOLTS
c 05421-2

utilized during the drying process. Efficiencies were found for both "constant-power-setting" runs and for "constant-voltage-gradient" runs. The energy curves recorded by the wattmeter were graphically integrated by means of a planimeter to find the input power to the generator.

Effect of Desiccant Particle Size. The possibility that a different particle size desiccant might facilitate the removal of moisture was investigated. Previously, all desiccants used had a particle size of minus 200 mesh, U. S. Standard Sieve Series. In this phase of the study, silica gel, in sizes ranging from +20 to +325 mesh, was mixed with the sample of wheat; the mixture, being composed of wheat and one particular size of desiccant particle, was heated for two minutes. The heating procedure was repeated using a different particle-size desiccant but maintaining the same length of drying time and the same power setting as previously used. The different size desiccant particles used included nine mesh ranges: -10 +20, -20 +30, -30 +40, -40 +50, -50 +70, -70 +100, -100 +140, -140 +200, and -200 +325. For purposes of further comparison, samples of wheat and desiccant in one of the above size classifications were heated for time intervals of four and six minutes, in addition to the two minute interval mentioned previously. The underlying objective in this phase of the study was to determine what size of desiccant particle would lend itself to the removal of the largest amount of moisture during the drying of the wheat; the results of this study coupled with problems of separating the wheat and desiccant led to the prediction of the choice of the size desiccant which would be used if a continuous process were developed.

Minor Points of Interest. The remaining work done was concerned with minor points of interest which were essential to any study of this sort. Each point is here presented with little mention of the actual procedure used. Most of these areas of investigation are self explanatory.

(a) The moisture adsorbed by the desiccant in contact with the wheat with no application of heat was determined. The desiccant and wheat were left in contact for nearly two hours in a closed container.

(b) Varying amounts of silica gel were mixed with the wheat and dried dielectrically under otherwise identical conditions to determine the optimum amount of desiccant required for removal of the greatest amount of moisture.

(c) The initial moisture content of the silica gel used was determined by drying samples of the gel in a vacuum oven. This moisture content presented a view as to how much water the desiccant could sorb during the drying step.

(d) Separation of the wheat and desiccant was not complete. Three desiccants were separately mixed with wheat samples in weighed amounts and then dried. After drying, a simple screening operation was performed to separate the wheat and desiccant. The percentage loss of each of the three desiccants, silica gel, alumina, and Florite, was found.

(e) For determining whether or not the generated high-frequency power was concentrating itself in the wheat or in the desiccant, a quantity of silica gel with no wheat present was exposed to high-frequency energy between the electrodes. The indicated temperature rise was noted.

(f) In the event that some future combination of dielectric- and air-drying could be used, samples of wheat alone were heated dielectrically to determine for how long an interval high-frequency energy could be applied without arcing occurring. Previous experiments showed that when insufficient desiccant was present arcing tended to occur along paths of moisture condensation.

(g) The final phase of the project dealt with determining the dielectric constant of wheat. From Equation (4), it is seen that to determine the power generated in the load requires knowledge of the dielectric constant. The ratio of the capacity current through the material to the capacity current which would flow if the same field intensity were applied to free space is called the dielectric constant. Hence, from field voltage and current measurements, the dielectric constant of wheat was found. Relatively few determinations of the dielectric constant were made. To be useful for purposes of calculation, extensive data would have had to have been collected because the dielectric constant of wheat varies with moisture content.

Because of the rapidity with which the individual runs could be completed, numerous determinations of a varied nature were made.

RESULTS

For purposes of referring to the data collected for each different type of run, the following resume of the various points covered during the investigation is presented. The investigation has been divided into ten classifications. Tabulated data will be grouped into one of these classifications and designated, for instance, as 1-1, 4A-1, 4A1-1, etc., to correspond to a given area of investigation and a given run.

Classification of Data

1. Constant-power-setting runs
2. Constant-temperature runs
3. Constant-voltage-gradient runs
4. Intermittent drying runs
    A. Wheat and desiccant in contact during rest period
        1. Heat applied for 15 seconds, rest 15 seconds
        2. Heat applied for 15 seconds, rest 45 seconds
        3. Heat applied for 15 seconds, rest 2 minutes and 45 seconds
        4. Constant temperature-span runs
    B. Wheat and desiccant separated during rest period
5. Alternate intervals of air and dielectric drying
6. Drying with hot air
7. Study of mechanism of drying
    A. Use of cobaltous chloride
    B. Resistance measurements

8. Efficiency of dielectric drying
9. Water removal and size of desiccant particle
10. Miscellaneous
    - A. Moisture removed by desiccant with no high-frequency energy applied
    - B. Use of varying amounts of desiccant
    - C. Loss of desiccant
    - D. Moisture content of desiccant
    - E. Heating desiccant alone in high-frequency field
    - F. Heating wheat alone in high-frequency field
    - G. Temperature measurement with alcohol and mercury thermometers
    - H. Determination of dielectric constant

Experimental Data and Calculations

The data taken for each of the classified areas of investigation are presented in Tables 1 through 10H. The Tables are numbered to correspond with the major points of interest mentioned above.

The principal desiccant used during the project was silica gel of -200 mesh. In most trials, the weight of desiccant was not accurately known but was approximately twelve grams. Each trial in Runs 1-1 through 3-4 was performed by starting with a sample of wheat at the specified moisture content and drying it a given time by one of the three methods of power utilization described. At the end of that trial, the loss in weight was determined and also the final moisture content. This process was repeated using a sample of the original wheat. The major calculation involved in these runs was the calculation of the final moisture content. As an illustrative example, the method of calculation of the final moisture content of Run 1-1, entry number 1, is here illustrated:

Initial weight wheat (wet) = 107.9348 gm.

Initial percent H_2O (D. B.) = 15.07

$$\frac{\text{Wt. } H_2O}{\text{Wt. dry wheat}} = 0.1507, \text{ and Wt. } H_2O + \text{Wt. dry wheat} = 107.9348$$

1.1507 (Wt. dry wheat) = 107.9348

Wt. dry wheat = 93.7992 gm.

Wt. initial H_2O = 107.9348 - 93.7992 = 14.1356

Final weight wheat (wet) = 106.1928 gm.

Moisture lost on drying = 107.9348 - 106.1928 = 1.7420 gm.

Moisture remaining = 14.1356 - 1.7420 = 12.3936 gm.

$$\text{Final percent } H_2O \text{ (D. B.)} = \frac{12.3936}{93.7992} \times 100 = 13.21\%$$

Thus, moisture-content-versus-time-of-drying curves were established.

The resistance values tabulated in Table 5 were used only for purposes of comparison of the surface moisture of the sample when dried under different conditions; these values are not intended to be absolute resistances for wheat samples at different moisture levels. Also, in Table 5 it is to be noted that resistances were measured of wheat samples with and without the presence of desiccant dust. The dust referred to is the desiccant which adhered to the kernel and was thus unrecovered during screening of the mixture.

Tabulated in Table 8 is the energy input to the generator in kilo-

Table 1. Constant-power-setting runs.

Run Number	Desiccant and mesh	Initial Weight Wheat (gm)	Initial Moisture Content (% D.B.)	Drying Time (min.)	Final Temp. (°F)	Final Weight Wheat (gm)	Final Moisture Content (% D.B.)	Comments
1-1	Silica Gel (200)	107.9348	15.07	1	126	106.1928	13.21	Initial temp. = 80°F
	"	102.8918	"	2	182	99.4069	11.17	--
	"	104.0803	"	3	266	96.9948	7.23	Steam escaped at 260° F
	"	104.9525	"	4	310	89.1287	4.16	--
	"	101.2712	"	5	334	90.3607	2.67	--
	"	106.0416	"	6	325	83.9067	1.65	--
	"	91.8705	"	7	350	80.5480	0.89	--
	"	106.0980	"	8	360	84.1355	0.24	--
	"	91.2065	"	9	355	79.3517	0.11	Some decomposition of wheat.
1-2	Alumina (200)	95.7636	15.87	1	170	93.2553	12.83	Initial temp. = 80°F
	"	98.6175	"	2	270	93.7060	10.09	--
	"	96.3561	"	3	298	87.3988	5.09	--
	"	88.9236	"	4	342	77.9942	1.63	--
	"	89.9812	"	5	340	78.2808	0.80	--
1-3	Silica Gel (200)	96.7182	13.33	1	164	93.5593	9.63	Initial temp. = 80°F
	"	96.0634	"	2	260	90.7565	7.07	--
	"	97.6640	"	4	316	85.7662	0.48	Steam evolved at 270°F
	"	96.4646	"	6	338	83.5596	1.83	--
	"	93.9180	"	8	350	80.7400	2.57	--
	"	93.5145	"	10	362	82.5152	3.16	Some charred kernels.

Table 1. (Concl.)

Run Number	Desiccant and mesh	Initial Weight Wheat (gm)	Initial Moisture Content (% D.B.)	Drying Time (min.)	Final Temp. (°F)	Final Weight Wheat (gm)	Final Moisture Content (% D.B.)	Comments
1-4	Silica Gel (200)	94.9085	17.93	1	152	92.3520	14.75	Initial temp. = 80° F
	"	97.8844	"	2	240	92.5412	11.49	--
	"	93.9668	"	3	292	85.8861	7.80	Steam at 290°
	"	97.1159	"	4	310	86.0705	4.52	--
	"	94.8481	"	5	328	81.8200	1.73	--
	"	97.0595	"	6	341	82.6247	0.39	--
	"	96.2541	"	8	350	81.4896	-	Decomposed.
1-5	Alumina	94.6519	17.93	1	198	92.1809	14.85	Initial temp. = 80°F
	"	94.0069	"	2	276	89.2902	12.01	--
	"	95.6571	"	3	296	88.0089	8.50	--
	"	94.5213	"	4	324	83.6746	4.40	--
	"	94.7679	"	5	346	82.3103	2.43	--
	"	94.3230	"	6	362	80.3512	0.46	--
1-6	Florite (200)	109.1132	16.47	1	150	107.4807	14.73	Initial temp. = 100°F
	"	111.5539	"	2	212	107.7649	12.51	--
	"	103.3264	"	3	280	95.6298	8.85	Steam at 250°F.
	"	99.4067	"	4	318	89.8762	5.30	Florite was easier to
	"	95.3581	"	5	327	84.9158	3.72	recover from wheat
	"	92.6256	"	6	348	81.7778	2.83	than silica gel or alumina.

Table 2. Constant temperature runs.

Run Number	Desiccant and mesh	Initial Weight Wheat (gm)	Initial Moisture Content (% D.B.)	Drying Time (min.)	Final Temp. (°F)	Final Weight Wheat (gm)	Final Moisture Content (% D.B.)	Comments
2-1	Silica Gel (200)	101.9919	16.23	1	164	100.2063	14.89	Initial Temp.=80°F
	"	103.0203	"	2	160	100.6255	13.53	--
	"	98.9968	"	3	160	95.8526	12.54	--
	"	103.9581	"	5	160	100.5178	12.16	--
	"	101.2467	"	10	160	97.4977	11.92	--
	"	101.6087	"	15	160	97.7127	11.77	--
	"	98.0321	"	20	160	93.4913	10.84	--
	"	97.7188	"	25	160	93.2287	10.88	--
2-2	Alumina (200)	93.9052	15.87	2	162	91.3904	12.77	Initial temp.=80°F
	"	99.6296	"	3	160	96.8626	12.65	--
	"	95.9792	"	5	160	93.5164	12.89	--
	"	95.6198	"	10	161	92.9976	12.69	--
	"	97.6942	"	15	160	94.7356	12.36	--
	"	94.5959	"	20	161	91.5832	12.18	--
	"	94.8335	"	25	160	91.9480	12.34	--
2-3	Silica Gel (200)	101.3541	17.62	1	160	99.0366	14.93	Initial temp.=80°F
	"	97.5750	"	2	160	94.8938	14.39	--
	"	98.9380	"	3	160	96.3283	14.52	--
	"	99.6775	"	5	160	96.8405	14.27	--
	"	100.3971	"	10	160	97.0444	13.69	--
	"	100.7806	"	20	160	97.1021	13.33	--
	"	103.3001	"	25	160	99.2891	13.05	--

Table 2. (Concl.)

Run Number	Desiccant and mesh	Initial Weight Wheat (gm)	Initial Moisture Content (% D.B.)	Drying Time (min.)	Final Temp. (°F)	Final Weight Wheat (gm)	Final Moisture Content (% D.B.)	Comments
2-4	Alumina (200)	100.7236	17.62	1	160	98.8052	15.38	Initial temp.=80°F
	"	99.8836	"	2	160	97.6138	14.97	—
	"	102.0862	"	3	160	99.8291	15.02	—
	"	101.6752	"	5	160	99.2916	14.86	—
	"	99.2711	"	10	160	96.6893	14.56	—
	"	100.8282	"	15	160	98.1103	14.45	—
	"	98.6153	"	20	160	95.5464	13.96	—
	"	99.8708	"	25	160	97.1670	14.44	—

Table 3. Constant voltage-gradient runs.

Run Number	Desiccant and mesh	Initial Weight Wheat (gm.)	Initial Moisture Content (% D.B.)	Load Voltage (volts)	Drying Time (min.)	Final Temp. (°F)	Final Weight Wheat (gm.)	Final Moisture Content (% D.B.)	Comments
3-1	Silica Gel (200)	88.5652	17.04	400	1	107	88.0810	16.40	Initial temp.=90°F
	"	88.1434	"	"	2	128	86.9722	15.49	—
	"	88.3610	"	"	3	164	86.4721	14.54	—
	"	88.6447	"	"	4	180	85.9318	13.46	—
	"	90.0232	"	"	5	222	86.2002	12.07	—
	"	88.7756	"	"	6	234	83.7782	10.45	—
3-2	Silica Gel (200)	90.0486	17.04	440	1	116	89.4563	16.27	Initial temp.=90°F
	"	87.3408	"	"	2	144	85.7577	14.92	—
	"	88.0814	"	"	3	187	84.6250	12.45	—
	"	88.7208	"	"	4	273	83.2510	9.82	—
	"	88.2220	"	"	5	265	82.1874	9.03	—
	"	87.8535	"	"	6	269	81.0111	7.92	—
3-3	Silica Gel (200)	87.5145	17.04	480	1	122	86.6663	15.91	Initial temp.=94°F
	"	87.9114	"	"	2	160	85.1781	13.40	—
	"	88.6385	"	"	3	242	84.2598	11.26	—
	"	89.6769	"	"	4	290	82.4318	7.58	—
	"	85.5486	"	"	5	294	77.5872	6.15	—
	"	88.9715	"	"	6	301	80.2396	5.55	—

Table 3. (Concl.)

Run Number	Desiccant and mesh	Initial Weight Wheat (gm.)	Initial Moisture Content (% D.B.)	Load Voltage (volts)	Drying Time (min.)	Final Temp. (° F)	Final Weight Wheat (gm.)	Final Moisture Content (% D.B.)	Comments
3-4	Silica Gel (200)	88.0026	17.04	520	1	140	86.6755	15.27	Initial temp.=92°F
	"	84.9240	"	"	2	192	81.6752	12.56	—
	"	86.8826	"	"	2-3/4	234	81.6052	9.93	Arcing

Table 4. Intermittent drying. Wheat and silica gel left in contact during rest period.

Run Number	Length Of Heating Cycle (sec.)	Length of Rest Cycle (sec.)	Total Heating Time (min.)	Initial Weight Wheat (gm.)	Initial % H_2O (D.B.)	Final Temp. (°F)	Final Weight Wheat (gm.)	Final % H_2O (D.B.)	Comments
4A-1	180	0	3	98.9494	17.24	282	93.2366	10.47	No rest periods
	15	15	3	98.4695	"	232	93.5594	11.39	Less kernel expansion
	15	30	3	99.9247	"	223	95.8815	12.50	—
	15	45	3	99.2434	"	220	94.8617	12.06	—
	15	60	3	99.2503	"	214	95.5111	12.82	—
	15	90	3	99.1491	"	180	95.4779	12.90	—
	15	120	3	99.0554	"	187	95.3127	12.81	—
	15	150	3	98.6851	"	160	95.2276	13.13	—
	15	180	3	98.8582	"	162	95.5612	13.33	—
4A1-1	15	15	1	95.5908	15.94	140	93.1957	13.03	—
	"	"	2	96.7252	"	204	91.9329	10.19	—
	"	"	3	96.0688	"	280	87.8614	6.03	—
	"	"	4	99.5587	"	288	89.2158	3.89	—
	"	"	5	96.7283	"	312	85.7195	2.74	—
	"	"	6	96.6786	"	314	83.5800	0.23	—
4A1-2	15	15	1	101.2938	16.96	135	100.1279	15.61	New electrode casing used.
	"	"	2	96.9173	"	189	94.2116	13.69	—
	"	"	3	97.3382	"	249	92.9063	11.63	—
	"	"	4	97.8217	"	290	90.5506	8.27	—
	"	"	5	97.2909	"	290	88.1486	5.97	—
	"	"	6	96.5911	"	305	87.5244	5.98	—

Table 4. (Concl.)

Run Number	Length of Heating Cycle (sec.)	Length of Rest Cycle (sec.)	Total Heating Time (min.)	Initial Weight Wheat (gm.)	Initial % H_2O (D.B.)	Final Temp. (°F)	Final Weight Wheat (gm.)	Final % H_2O (D.B.)	Comments
4A2-1	15	45	1	96.4458	15.94	145	93.8680	12.83	—
	"	"	2	98.7797	"	196	94.2623	10.63	—
	"	"	3	94.3300	"	250	86.6391	6.49	—
	"	"	4	96.9283	"	274	86.8503	3.88	—
	"	"	5	96.3849	"	258	84.8809	2.10	—
4A2-2	15	45	1	96.2845	16.96	141	94.7301	15.07	Different electrode cell than run 4A2-1
	"	"	2	93.2989	"	197	90.3990	13.32	
	"	"	3	90.5359	"	237	86.0837	11.21	—
	"	"	4	94.5018	"	251	89.0234	10.18	—
	"	"	5	95.7882	"	264	88.9717	8.64	—
	"	"	6	94.5614	"	270	86.6946	7.23	—
4A3-1	15	165	1	97.7204	20.58	139	93.6618	15.57	Alcohol thermometer used to measure T.
	"	"	2	95.5104	"	184	88.5610	11.81	—
	"	"	3	99.2515	"	206	91.0370	10.60	—
4A3-2	15	165	1	94.4254	16.96	126	93.1994	15.44	New electrode spacing
	"	"	2	93.1678	"	146	90.8766	14.08	—
	"	"	3	91.6111	"	170	88.5266	13.02	—
	"	"	4	91.1148	"	175	87.5588	12.40	—
	"	"	5	91.9666	"	188	88.0168	11.94	—
	"	"	6	92.6176	"	198	88.4527	11.70	—

Table 4A. Intermittent drying. Wheat and silica gel left in contact during rest period. Sample allowed to cool to room temperature between heating cycles.

Run Number	Initial Weight Wheat (gm.)	Initial % H_2O (D. B.)	Final Temp. (°F)	Drying Time (min.)	Final Weight Wheat (gm.)	Final % H_2O (D. B.)	Comments
4A4-1	106.2840	15.87	160	1.30	103.7014	13.05	One sample used all the way; sample cooled after attainment of 160°F. Same silica used for all trials.
	103.7014	"	160	1.08	102.2413	11.46	
	102.2413	"	160	1.08	101.3486	10.49	
	101.3486	"	160	1.16	100.5074	9.57	
	100.5074	"	160	1.00	99.9346	8.95	

Table 4B. Intermittent drying. Wheat and silica gel separated during rest period. Sample heated over constant-temperature range.

Run Number	Initial Wheat Weight (gm.)	Initial % H_2O (D.B.)	Initial Temp. (° F)	Drying Time (min.)	Rest Time (min.)	Final Temp. (°F)	Final Weight Wheat (gm.)	Final % H_2O (D.B.)	Comments
4B-1	100.5453	18.42	80	1.17	40	160	97.2986	14.59	One sample used all the
	97.1676	14.44	80	1.22	40	160	95.4410	12.41	way. Cooled to room
	95.3802	12.34	80	0.95	30	160	94.6982	11.53	temp. after each heating.
	94.6656	11.49	80	1.25	90	160	93.7878	10.46	Some moisture lost during
	93.7480	10.42	80	0.75	30	160	93.4365	10.05	cooling period.
	93.4344	10.04	80	0.75	0	160	93.1829	9.75	
4B-2	101.5929	18.42	20	0.92	240	100	99.8768	16.42	One sample used all the way.
	99.8768	16.42	20	0.75	60	100	99.0137	15.41	Assumed negligible moisture
	99.0137	15.41	20	0.92	60	100	98.3398	14.63	lost during cooling.
	98.3398	14.63	20	1.0	60	100	97.8330	14.04	
	97.8330	14.04	20	1.10	60	100	97.1061	13.19	--
	97.1061	13.19	20	0.95	60	100	96.6635	12.67	--
	96.6635	12.67	20	0.70	60	100	96.3903	12.35	--
	96.3903	12.35	20	0.37	60	60	96.2374	12.18	Temp. span decreased.
	96.2374	12.18	20	0.30	0	60	96.1060	12.02	--

Table 5. Alternate intervals of air and dielectric drying. Air-drying intervals were of 15 seconds duration; dielectric-drying intervals were 30 seconds.

Run Number	Weight Wheat		Type of Drying	Temperature		% H_2O		Resistance	
	Initial (gm.)	Final (gm.)		Air Used (°F)	Sample after Dielectric drying (°F)	Initial (D.B.)	Final (D.B.)	Without Desiccant Dust (Megohms)	With Desiccant Dust (Megohms)
5-1	97.9261	—	—	—	—	22.18	—	6	22
	97.9261	96.0980	Air	300	—	22.18	19.90	—	6
	96.0980	95.1518	Dielectric	—	116	19.90	18.71	—	80
	95.1518	93.6194	Air	300	—	18.71	16.81	—	24
	93.6194	93.0653	Dielectric	—	119	16.81	16.11	—	800
	93.0653	92.6603	Air	300	—	16.11	15.61	—	175
	92.6603	92.3475	Dielectric	—	116	15.61	15.22	—	1000
						on standing,Final R=200			
5-2	99.4081	—	—	—	—	22.18	—	5.5	21
	99.4081	98.0421	Air	300	—	22.18	20.50	—	5
	98.0421	97.0127	Dielectric	—	120	20.50	19.23	—	85
	97.0127	95.9423	Air	300	—	19.23	17.92	—	22
	95.9423	95.3645	Dielectric	—	120	17.92	17.21	—	375
	95.3645	94.5074	Air	300	—	17.21	16.16	—	47
	94.5074	94.0724	Dielectric	—	122	16.16	15.62	—	750
						on standing,	Final R =	90	
5-3	104.8681	—	—	—	—	22.18	—	6.5	22
	104.8681	103.7840	Air	300	—	22.18	20.92	—	4.8
	103.7840	102.5779	Dielectric	—	120	20.92	19.51	—	54
	102.5779	101.9215	Air	300	—	19.51	18.75	—	40
	101.9215	101.0801	Dielectric	—	118	18.75	17.77	—	150
	101.0801	100.4764	Air	300	—	17.77	17.06	—	61
	100.4764	100.0184	Dielectric	—	134	17.06	16.53	—	900
						on standing,	Final R =	100	

Table 5. (Cont.)

Run Number	Weight Wheat Initial (gm.)	Weight Wheat Final (gm.)	Type of Drying	Temperature Air Used (°F)	Temperature Sample after Dielectric drying (°F)	% H_2O Initial (D.B.)	% H_2O Final (D.B.)	Resistance Without Desiccant Dust (Megohms)	Resistance With Desiccant Dust (Megohms)
5-4	102.9128	—	—	—	—	22.18	—	3	13
	102.9128	102.0392	Air	250	—	22.18	21.14	—	3
	102.0392	100.5162	Dielectric	—	132	21.14	19.33	—	36
	100.5162	99.9203	Air	250	—	19.33	18.63	—	25
	99.9203	98.9180	Dielectric	—	138	18.63	17.44	—	500
	98.9180	98.4529	Air	250	0	17.44	16.88	—	60
	98.4529	97.9550	Dielectric	—	130	16.88	16.29	—	200
5-5	102.5583	—	—	—	—	22.18	—	2.3	11
	102.5583	101.5807	Air	250	—	22.18	21.02	—	4.5
	101.5807	100.0271	Dielectric	—	136	21.02	19.16	—	40
	100.0271	99.3375	Air	250	—	19.16	18.34	—	42
	99.3375	98.5136	Dielectric	—	137	18.34	17.36	—	135
	98.5136	98.0460	Air	250	—	17.36	16.84	—	60
	98.0460	97.4370	Dielectric	—	140	16.84	16.08	—	200
5-6	104.0869	—	—	—	—	22.18	—	3.4	18
	104.0869	103.2890	Air	250	—	22.18	21.22	—	7.3
	103.2890	101.9074	Dielectric	—	130	21.22	19.62	—	60
	101.9074	101.3572	Air	250	—	19.62	18.97	—	30
	101.3572	100.4348	Dielectric	—	132	18.97	17.89	—	130
	100.4348	100.0247	Air	250	—	17.89	17.41	—	80
	100.0247	99.3303	Dielectric	—	132	17.41	16.59	—	120
5-7	94.8642	—	—	—	—	18.78	—	2000	2000
	94.8642	94.4202	Air	235	—	18.78	18.22	—	100

Table 5. (concl.)

Run Number	Weight Wheat		Type of Drying	Temperature		% H_2O		Resistance	
	Initial (gm.)	Final (gm.)		Air Used (°F)	Sample after dielectric drying (°F)	Initial (D.B.)	Final (D.B.)	Without Desiccant Dust (Megohms)	With Desiccant Dust (Megohms)
	94.4202	93.7604	Dielectric	—	122	18.22	17.40	—	200
	93.7604	93.3817	Air	235	—	17.40	16.92	—	275
	93.3817	92.9061	Dielectric	—	118	16.92	16.33	—	
	92.9061	92.5655	Air	235	—	16.33	15.90	—	750
	92.5655	92.1970	Dielectric	—	118	15.90	15.44	—	
5-8	95.1968	—	—	—	—	16.47	—	140	200
	95.1968	94.7336	Air	250	—	16.47	15.93	—	50
	94.7336	94.0918	Dielectric	—	123	15.93	15.12	—	2000
	94.0918	93.6065	Air	250	—	15.12	14.52	—	200
	93.6065	93.1718	Dielectric	—	128	14.52	13.99	—	2000
	93.1718	92.8768	Air	250	—	13.99	13.63	—	400
5-9	95.2613	—	—	—	—	16.47	—	65	200
	95.2613	94.8182	Air	250	—	16.47	15.93	—	38
	94.8182	94.1393	Dielectric	—	128	15.93	15.10	—	1000
	94.1393	93.6969	Air	250	—	15.10	14.56	—	200
	93.6969	93.2161	Dielectric	—	137	14.56	13.97	—	2000
	93.2161	92.8930	Air	250	—	13.97	13.57	—	350
5-10	95.4212	—	—	—	—	16.47	—	90	210
	95.4212	95.0366	Air	250	—	16.47	16.00	—	50
	95.0366	94.4034	Dielectric	—	129	16.00	15.23	—	1000
	94.4034	94.0321	Air	250	—	15.23	14.77	—	150
	94.0321	93.5502	Dielectric	—	138	14.77	14.19	—	1400
	93.5502	93.1543	Air	250	—	14.19	13.70	—	420

Table 6. Drying wheat solely with hot air.

Run Number	Weight Wheat (gm.)		Temp. of Air (° F)	Time of Interval (sec.)	% H_2O (D. B.)		Resistance (Megohms)
	Initial	Final			Initial	Final	
6-1	100.4731	---	---	---	22.18	---	5.6
	100.4731	99.4236	250	15	22.18	20.90	3.0
	99.4236	98.5496	"	"	20.90	19.84	17
	98.5496	98.0194	"	"	19.84	19.19	33
6-2	100.5698	---	---	---	22.18	---	4.9
	100.5698	99.7906	250	15	22.18	21.23	3.9
	99.7906	99.0072	"	"	21.23	20.28	6.4
	99.0072	98.3167	"	"	20.28	19.44	12
6-3	100.2796	---	---	---	22.18	---	3.6
	100.2796	99.4006	250	15	22.18	21.11	2.5
	99.4006	98.6228	"	"	21.11	20.16	5.2
	98.6228	97.9584	"	"	20.16	19.35	15
6-4	111.1768	---	---	---	16.47	---	120 - no gel
							250 - gel dust
	111.1768	110.3812	220	15	16.47	15.64	40
	110.3812	109.7730	"	"	15.64	15.00	89
	109.7730	109.3171	"	"	15.00	14.52	210
6-5	108.8640	---	---	---	16.47	---	130 - no dust
							390 - dusted
	108.8640	108.2494	220	15	16.47	15.81	70
	108.2494	107.7296	"	"	15.81	15.26	125
	107.7296	107.3748	"	"	15.26	14.88	350

Table 6. (concl.)

Run Number	Weight Wheat (gm.)		Temp.of Air (°F)	Time of Interval (sec.)	% H_2O		Resistance (Megohms)
	Initial	Final			(D.B.) Initial	(D.B.) Final	
6-6	108.3936	--	--	--	16.47	--	160 - no dust
							200 - dusted
	108.3936	107.8194	220	15	16.47	15.85	70
	107.8194	107.3605	"	"	15.85	15.36	115
	107.3605	106.8241	"	"	15.36	14.78	250
6-7	95.9210	--	--	--	16.47	--	175 - no dust
							200 - dusted
	95.9210	95.4759	250	15	16.47	15.93	46
	95.4759	95.0602	"	"	15.93	15.42	70
	95.0602	94.5857	"	"	15.42	14.85	120
6-8	96.1473	--	--	--	16.47	--	135 - no dust
							300 - dusted
	96.1473	95.7117	250	15	16.47	15.94	56
	95.7117	95.1921	"	"	15.94	15.31	73
	95.1921	94.7982	"	"	15.31	14.84	150
6-9	95.8710	--	--	--	16.47	--	100 - no dust
							250 - dusted
	95.8710	95.4194	250	15	16.47	15.92	50
	95.4194	94.9440	"	"	15.92	15.34	80
	94.9440	94.5366	"	"	15.34	14.85	150

Table 7A. Dielectric drying mechanism studies. Use of cobaltous chloride as moisture indicator.

Run Number	Cumulative Dielectric Drying Time (sec.)	Weight of Wheat after Drying Interval (gm.)	Wheat Temp. after Interval (°F)	% H_2O of Sample (D.B.)	Resistance of Mixture (Megohms)	Color of Wheat	Comments
7A-1	0	95.1632	83	19.68	1.2	Broken Kernels were pink	Wheat became blue on mixing with SiO_2
	15	93.9893	106	18.20	0.013	Lt. blue	—
	30	93.0510	122	17.02	0.05	Blue	--
	40	92.5872	121	16.44	0.20	Dark blue	—
	60	92.0194	137	15.73	0.14	Sample became progressively darker blue	
	120	90.3028	190	13.56	0.13	"	
	180	88.4092	240	11.19	0.15	"	

Table 7B. Dielectric drying mechanism studies. Resistance of sample exposed to alternate intervals of hot-air blast and cold storage.

Run Number	Weight of Wheat (gm.)			Temperature (°F)		Time		Resistance (megohms)
	Start (22.18% H_2O)	After Air	After Cold Storage	Hot Air	Cold Air	Hot Air Applied (sec.)	Cold Air Applied (hrs.)	
7B-1	104.5457	--	--	--	--	--	--	7.5
	--	103.7226	--	300	--	15	--	7.7
	--	--	103.3764	--	4	--	2.5	2000
	--	102.9972	--	300	--	15	--	18.5
	--	--	102.4973	--	4	--	18.5	1500
	--	102.1356	--	300	--	15	--	38
	--	--	101.9467	--	4	--	4.5	Infinite
	--	101.6170	--	300	--	15	--	87

Table 8. Determination of efficiency of dielectric drying.

Run Number	Type of Run	Length of Run (min.)	Weight of Wheat (gm.)		% H_2O (D.B.)		Final Temp. (°F)	Generator Input (kwhr.)	Desiccant Used
			Initial	Final	Initial	Final			
8-1	'constant-power'	3.25	81.0336	76.6066	17.35	9.49	258	0.0683	Silica gel
	'constant-potential' (400 volts)	3.25	85.3791	83.2152	17.35	14.38	166	0.0385	"
	'constant-potential' (440 volts)	3.25	83.8979	80.3596	17.35	12.40	214	0.0499	"
	'constant-potential' (480 volts)	3	85.7971	81.5983	17.35	11.61	224	0.0549	"
	'constant-potential' (520 volts)	2.58	86.1309	81.4439	17.35	10.96	226	0.0566	"
8-2	'constant-power'	2	93.8729	90.8661	17.35	13.59	214	0.0366	Silica gel
	"	2	105.0564	101.3137	17.35	13.17	247	0.0425	Alumina
	"	2	100.2027	96.9180	17.35	13.50	195	0.0370	Florite
8-3	'constant-power'	4	100.4274	92.8585	17.35	8.51	316	0.0807	Silica gel
	"	4	99.7026	91.7223	17.35	7.96	283	0.0884	Alumina
	"	3.6	101.2541	95.5502	17.35	10.74	295	0.0736	Florite
8-4	'constant-power'	6	98.6682	88.0048	17.35	4.67	330	0.1134	Silica gel
	"	6	100.8149	89.2790	17.35	3.92	362	0.1192	Alumina
	"	6	97.4223	87.0318	17.35	4.83	304	0.1090	Florite

Table 9. Moisture adsorption and size of desiccant (silica gel) particle.

Run Number	Heating Time (min.)	Particle Size (mesh)	Weight of Wheat (gm.)		Final Temp. (°F)	Weight Desiccant Used (gm.)	% H_2O (D.B.)		Generator Input (kwhr.)
			Initial	Final			Initial	Final	
9-1	2	325	95.5060	91.3622	214	18.4780	17.31	12.23	Average of all
	2	200	97.9678	93.4563	212	20.8460	17.31	11.91	two-minute runs
	2	140	97.8041	93.3537	220	21.4160	17.31	11.97	was 0.0361
	2	100	98.2000	93.7912	198	21.1446	17.31	12.04	"
	2	70	98.9982	94.9629	205	19.6605	17.31	12.53	"
	2	50	97.9356	94.0292	190	20.1689	17.31	12.63	"
	2	40	96.5049	92.5160	197	20.1893	17.31	12.46	"
	2	30	98.3190	94.4826	204	19.9046	17.31	12.73	"
	0.75	20	98.2580	97.2168	112	21.6077	17.31	16.07	—
9-2	4	325	97.0196	89.0338	306	13.1722	17.31	7.65	Average of all
	4	200	99.7806	91.3698	310	12.9809	17.31	7.42	four-minute runs
	4	140	98.7204	90.1602	314	14.3954	17.31	7.14	was 0.0827
	4	100	97.0590	88.3464	300	15.6075	17.31	6.78	"
	4	70	97.2989	88.7621	317	14.6166	17.31	7.02	"
	4	50	99.0417	90.4464	314	16.3330	17.31	7.13	"
	4	40	97.5595	89.5071	310	17.7417	17.31	7.63	"
	4	30	88.3993	81.1120	305	16.6360	17.31	7.64	"
	3.25	20	85.3531	79.9603	280	18.7498	17.31	9.90	"

Table 9. (concl.)

Run Number	Heating Time (min.)	Particle Size (mesh)	Weight of Wheat (gm.)		Final Temp. (°F)	Weight Desiccant Used (gm.)	% H_2O (D.B.)		Generator Input (kwhr.)
			Initial	Final			Initial	Final	
9-3	6	325	96.6256	85.4800	330	13.4562	17.24	3.72	Averages of all
	6	200	99.7642	88.6638	329	12.9905	17.24	4.20	six-minute runs
	6	140	99.2992	88.3072	319	15.6261	17.24	4.26	was 0.1186
	6	100	100.5410	89.4578	329	16.3674	17.24	4.32	"
	6	70	97.2229	86.0628	315	16.4867	17.24	3.78	"
	6	50	98.7117	87.8185	330	18.1040	17.24	4.30	"
	6	40	100.1817	89.1489	326	18.4291	17.24	4.33	"
	6	30	98.7614	87.9310	327	16.1983	17.24	4.38	"

Table 10. Moisture removed from wheat by silica gel at 80°F.

Run Number	Weight of Wheat (gm.)		% H_2O (D.B.)		Time of Exposure (min.)
	Initial	Final	Initial	Final	
10A-1	99.2659	98.5602	18.42	17.58	5
	100.5086	99.4733	"	17.20	10
	99.9642	99.1269	"	17.43	15
	98.7828	97.7119	"	17.60	20
	100.4422	99.3919	"	17.18	25
	95.0440	91.9565	13.33	9.65	106

Table 10A. Effect of amount of silica gel used versus moisture adsorbed. All runs at equal power-settings and equal time intervals (1 min. 15 sec.).

Run Number	Weight Silica gel (gm.)	Final Temp. (°F)	Weight of Wheat (gm.)		% H_2O (D.B.)		Wt. silica gel / Wt. wet wheat
			Initial	Final	Initial	Final	
10B-1	5.156	162	102.9163	99.5645	18.42	14.56	0.050
	10.533	170	101.3656	97.5990	"	14.02	0.104
	20.709	180	88.1204	84.2232	"	13.18	0.235
	40.262	208	70.4559	66.1303	"	11.15	0.571
	80.484	230	35.6891	33.1860	"	10.11	2.255

Table 10B. Effect of amount of silica gel used versus moisture adsorbed. All runs were terminated at a maximum temperature of 160°F.

Run Number	Weight Silica Gel (gm.)	Drying Time (sec.)	Weight of Wheat (gm.)		% H_2O (D.B.)		Wt. silica gel / Wt. wet wheat
			Initial	Final	Initial	Final	
10B-2	6.2395	65	100.8902	98.4676	18.92	16.06	0.062
	11.4657	64	102.6247	99.8680	"	15.73	0.112
	22.3923	60	88.7838	86.4276	"	15.76	0.252
	37.2916	77	65.9687	63.1337	"	13.81	0.565
	78.9401	72	51.4628	48.7506	"	12.65	1.534

Table 10C. Desiccant lost when heated with wheat.

Run Number	Desiccant (-200 mesh)	Heating Time (min.)	Weight of Desiccant (gm.)		% Loss
			Initial	Final (wt. H_2O included)	
10C-1	Silica gel	0	16.1261	15.7620	2.73
	Alumina	0	20.6913	20.2477	3.02
	Florite	0	21.4391	21.2750	1.47
10C-2	Silica gel	2	13.0807	13.7722	17.70
	Alumina	2	20.9211	20.4288	20.24
	Florite	2	20.8061	21.3775	13.04
10C-3	Silica gel	4	17.8043	19.5921	32.47
	Alumina	4	26.4661	26.3546	30.63
	Florite	4	19.7126	20.8114	23.36
10C-4	Silica gel	6	17.0718	17.7460	58.51
	Alumina	6	25.8163	24.3182	40.49
	Florite	6	21.7304	21.7823	47.58

Table 10D. H_2O content of silica gel used in all trials. Determinations made by heating in vacuum oven at 100°C.

Run Number	Weight Initial gel (gm.)	Weight Final gel (gm.)	Loss in Weight (gm.)	% H_2O (Based on wt. dry gel and water of constitution.)
10D-1	28.6632	27.5883	1.0749	3.89
	26.1285	25.1735	0.9550	3.79
	35.5746	34.3343	1.2403	3.61
			Average --	3.76

Table 10E. Heating of silica gel (-200 mesh) in dielectric field.

Run Number	Heating Time (min.)	Temp. of gel (°F)
10E-1	0	80
	10	94

Table 10F. Heating of wheat (16.28% H_2O) in dielectric field.

Run Number	Heating Time (min.)	Temp. of Wheat (°F)
10F-1	0	80
	1	132
	2	188

Table 10G. Comparison of alcohol and mercury thermometer readings in a dielectric field.

Run Number	Temperature, °F	
	Alcohol	Mercury
10G-1	88	88
	98	100
	105	108
	117	120
	127	130
	138	140
	149	150
	161	160
	173	170
	184	180
	195	190
	204	200
	213	210
	221	219

Table 10H. Dielectric constant determination. Field intensity maintained constant. Field current with air as dielectric as noted.

Run Number	Mixture Temp. (°F)	Heating Time (sec.)	Load Current (amps)	$K = \frac{I_{Load}}{I_{Air}}$
10H-1	76	0	--	--
($I_{air} = 0.60$)	90	5	2.30	3.83
	100	18	2.37	3.95
	110	22	2.38	3.97
	130	32	2.80	4.67
	140	36	2.82	4.70
10H-2	88	0	--	--
($I_{air} = 0.65$)	102	30	2.60	4.00
	124	60	2.71	4.17
	151	90	2.88	4.43
	190	120	3.10	4.77
	264	180	3.20	4.92

watt-hours as calculated by using the recording wattmeter and the planimeter. The input energy in kilowatts versus time was recorded; graphical integration of the recorded curve gave the power consumed. For purposes of illustration, Plate VI, showing the recorded energy versus time curve, was included.

Correlation of Results

Drying curves were established from the previous data for each of the three desiccants used. For purposes of comparison, representative "constant-power-setting", "constant-temperature", "constant-voltage-gradient", and various intermittent-drying runs were selected to show the relative speed with which water was removed. Curves relating percent H_2O (dry basis) as a function of dielectric drying time were plotted.

Plate VII shows the drying curves for the various runs. "Constant-power-setting" runs using silica gel, alumina, and Florite gave the fastest rate of water removal. However, in these runs, the temperatures attained by the wheat was well in excess of 180°F; any industrial application would necessarily be required to limit the final temperature of the wheat to 180°F because of injurious effects to the wheat kernel. The three curves designated as "constant-power-setting" runs were established from Runs 1-4, 1-5, and 1-6, for silica gel, alumina, and Florite, respectively.

The intermittent-drying trials in which the wheat was heated to 160°F, cooled to room temperature, and reheated to 160°F, etc., gave the next fastest rate of water removal of the curves presented on Plate VII. Run

EXPLANATION OF PLATE VI

Reproduced Section of Chart from Recording
Wattmeter

PLATE VI

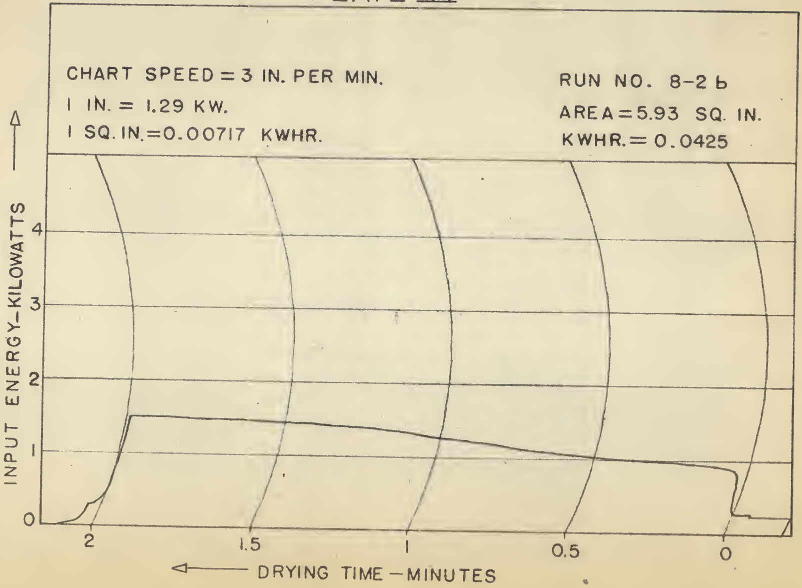


CHART SPEED = 3 IN. PER MIN.
1 IN. = 1.29 KW.
1 SQ. IN. = 0.00717 KWHR.
RUN NO. 8-2 b
AREA = 5.93 SQ. IN.
KWHR. = 0.0425
INPUT ENERGY-KILOWATTS
0
1
2
3
4
2
1.5
1
0.5
0
DRYING TIME - MINUTES

EXPLANATION OF PLATE VII

Drying Curves - % H_2O vs. Time

Curve: 1. "Constant-power-setting" run using silica gel

2. "Constant-power-setting" run using alumina

3. "Constant-power-setting" run using Florite

4. Intermittent-heating run; heat from 80° to 160°F and repeat

5. Intermittent-heating run; heat from 20° to 100°F and repeat

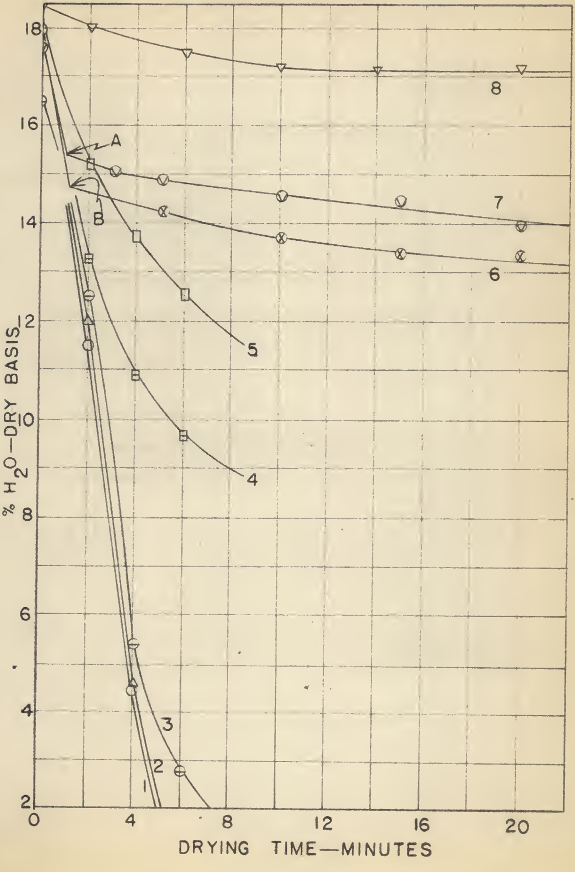
6. "Constant-temperature" run using silica gel

7. "Constant-temperature" run using alumina

8. No heat applied; moisture loss due solely to silica gel

Points A and B. End of heating-up period for constant-temperature runs.

PLATE VII


18
16
14
12
10
8
6
4
2
0
4
8
12
16
20
% H_2O—DRY BASIS
DRYING TIME—MINUTES
A
B
1
2
3
4
5
6
7
8

No. 4B-1 was used to obtain this curve.

Next in the speed of water removal was the intermittent run in which the wheat was heated from 20° to 100°F; this procedure was identical with the one from 80° to 160°F except for the initial and final temperature limits. Run No. 4B-2 gave this curve on Plate VII.

The data from Runs 2-3 and 2-4 were plotted on Plate VII to show the comparative rates of the "constant-temperature" trials.

The uppermost curve on Plate VII is for the drying of wheat solely by the use of silica gel; no heat was applied. Run No. 10A-1 provided the data for this curve.

Presented in Plate VIII are the results of the "constant-voltage-gradient" runs. The lower portion of the 1520 volts-per-inch curve was arrived at by extrapolation. Arcing prevented heating of the sample beyond 2-1/2 minutes at this gradient. The four curves presented were derived from the data of Runs 3-1, 3-2, 3-3, and 3-4.

Plate IX shows the results of Run 4A-1 where the periods of rest between the intermittent drying cycles were varied from 0 to 3 minutes. The total heating time in each trial was constant and equal to 3 minutes.

The effect of a rest period between short intervals of heating as compared to a continuous-heating run on the speed of drying is shown in Plate X. Three intermittent drying runs of different length rest cycles were compared. Data used came from Runs 4A1-2, 4A2-2, and 4A3-2.

The efficiencies of different dielectric drying runs were calculated by knowing the integrated area of the input-energy-versus-time curve. The calculated efficiencies were defined by the following equation:

$$\text{Overall Efficiency} = \frac{\text{Heat to vaporize } H_2O + \text{Increase in sensible heat of wheat and desiccant}}{\text{Total heat input}} \times 100$$

EXPLANATION OF PLATE VIII

Drying Curves - %H_2O vs. Time

"Constant-voltage-gradient" runs

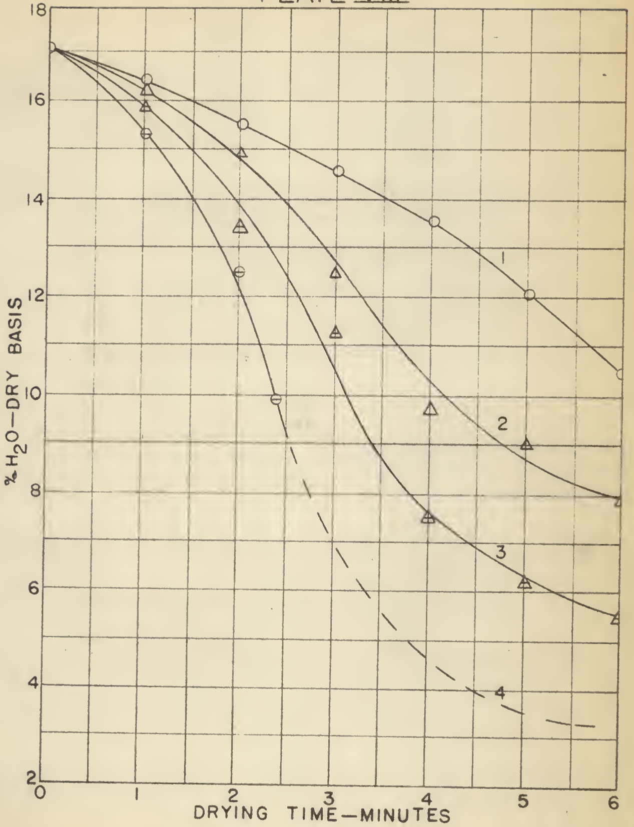
Curve: 1. Voltage gradient of 1160 volts per inch

2. Voltage gradient of 1280 volts per inch

3. Voltage gradient of 1400 volts per inch

4. Voltage gradient of 1520 volts per inch

PLATE VIII

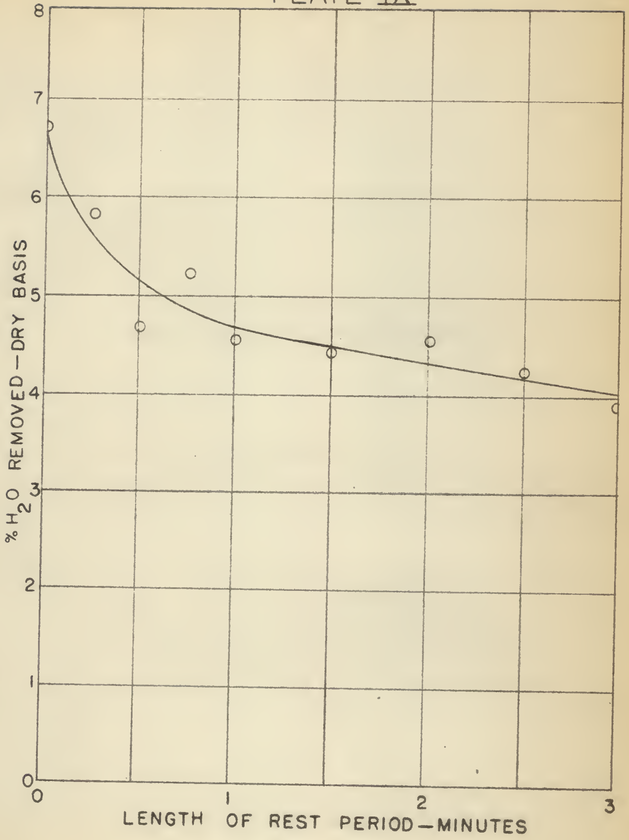

18
16
14
12
10
8
6
4
2
% H_2O—DRY BASIS
0
1
2
3
4
5
6
DRYING TIME—MINUTES
1
2
3
4

EXPLANATION OF PLATE IX

Percent H_2O Removed at a Function of Time

Total Drying Time Constant

PLATE IX



8
7
6
5
4
3
2
1
0
% H_2O REMOVED – DRY BASIS
0
1
2
3
LENGTH OF REST PERIOD – MINUTES

EXPLANATION OF PLATE X

Intermittent Drying with Various Periods of Rest

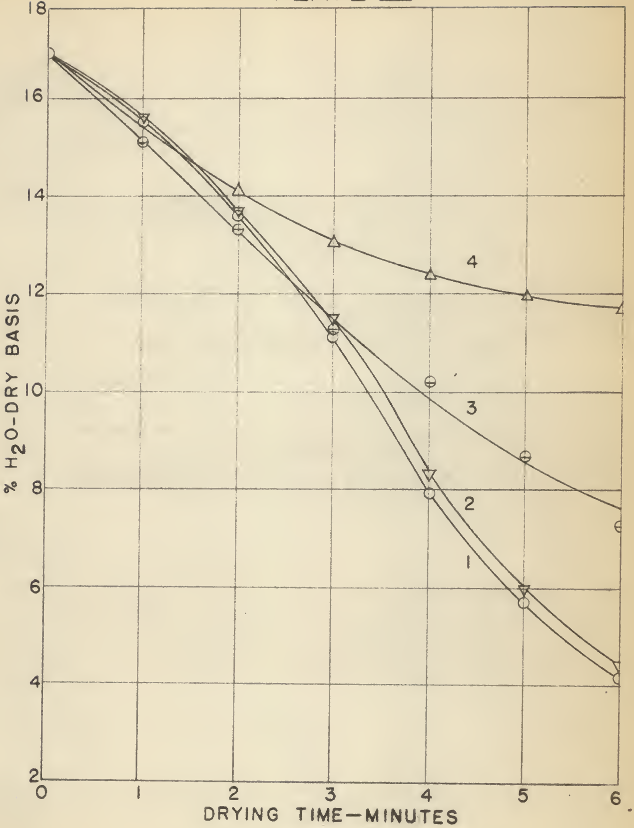
Curve: 1. Continuous heating - no rest period

2. Alternate cycles of 15 seconds heating and 15 seconds rest

3. Alternate cycles of 15 seconds heating and 45 seconds rest

4. Alternate cycles of 15 seconds heating and 2 minutes and 45 seconds rest

PLATE X


18
16
14
12
10
8
6
4
2
% H_2O-DRY BASIS
0
1
2
3
4
5
6
DRYING TIME—MINUTES
1
2
3
4

By assuming that the heat of vaporization of water from wheat was 1100 Btu per lb. and that the specific heats of silica gel, alumina, and Florite were approximately the same (0.3 Btu per (lb.)(°F)), the overall efficiency was calculated. The specific heat of wheat, as given by Oxley (20), p.9, is 0.40 to 0.45 Btu per (lb.)(°F). Thus, the efficiency equation becomes as follows:

$$\text{Efficiency} = \frac{(1100)(x) + (t_2 - t_1)(C_W W_W + C_D W_D)}{(453.6)(3413)\ Y}(100)$$

$$= \frac{1100x + \Delta t\ (0.40\ W_W + 0.30\ W_D)}{(453.6)\ (3413)\ Y}\ (100) \qquad (6)$$

where x = water removed during drying, gms
t_2 = final temperature of wheat, °F
t_1 = initial temperature of wheat, °F
C_W = Specific heat of wheat, Btu per (lb.)(°F) = 0.40
W_W = Weight of wheat, gms
C_D = Specific heat of desiccant, Btu per (lb.)(°F) = 0.30
W_D = weight of desiccant, gms
Y = calculated power input, kwhr
Δt = temperature difference, °F = $t_2 - t_1$

This equation is realized as not being rigorously correct because of the variation in the heat of vaporization with moisture content and because of the variation of the specific heats with temperature. However, these variations are small and for all practical purposes can be taken as constant. The efficiencies so calculated serve as a basis for judgment of the process.

Presented in Table 11 is the data used to calculate the percent efficiencies from Equation (6).

Plate XI shows the effect of size of desiccant particle on the amount of moisture removed during a given drying time. Data for this plot was taken from Table 9, Runs 9-1, 9-2, and 9-3.

Table 11. Efficiency of dielectric drying.

Run Number	Initial Weight Wheat (gms.) (W_W)	Weight H_2O Removed (gms.) (x)	$t_2 - t_1$ (°F) (t)	Weight of Desiccant (gms.) (W_D)	Power Input (kwhr.) (Y)	Calculated Overall Efficiency (%)
8-1a	81.0336	5.4270	174	15	0.0683	11.7
8-1b	85.3791	2.1639	80	15	0.0385	9.2
8-1c	83.8979	3.5383	127	15	0.0499	11.3
8-1d	85.7971	4.1980	159	15	0.0549	11.8
8-1e	86.1309	4.6870	161	15	0.0566	12.2
8-2a	93.8729	3.0068	134	13.08	0.0366	15.8
8-2b	105.0564	3.7427	161	20.92	0.0425	17.7
8-2c	100.2027	3.2847	109	20.81	0.0370	14.8
8-3a	100.4274	7.5689	232	17.80	0.0807	14.9
8-3b	99.7026	7.9983	199	26.49	0.0884	12.8
8-3c	101.2541	5.7039	211	19.71	0.0736	13.4
8-4a	98.6682	10.6634	242	17.07	0.1134	12.7
8-4b	100.8149	11.5359	272	25.82	0.1192	13.5
8-4c	97.4223	10.3905	213	21.73	0.1090	12.3
9-1b	97.9678	4.5115	132	18.48	0.0361	19.2
9-2b	99.7806	8.4108	228	12.98	0.0827	15.1
9-3b	99.7642	11.1004	243	12.99	0.1186	12.5

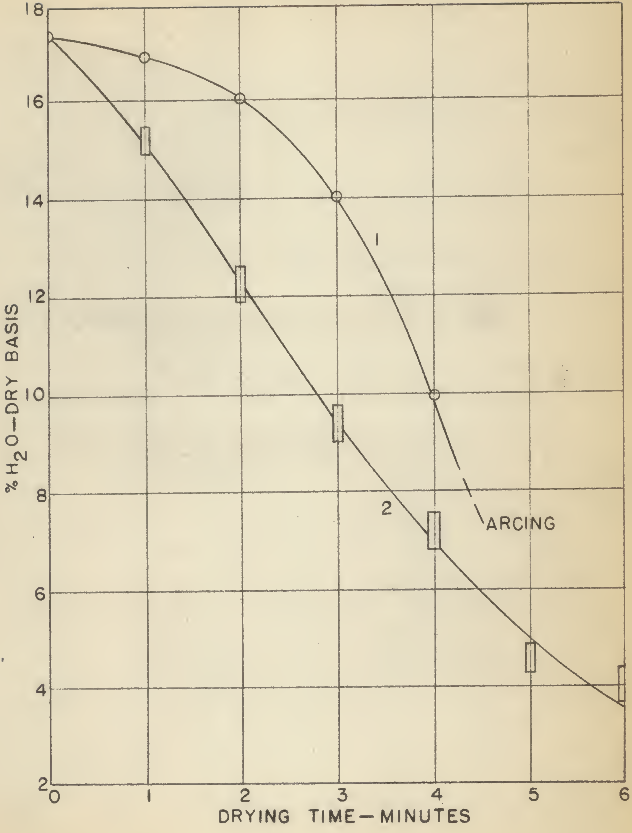
EXPLANATION OF PLATE XI

Effect of Desiccant Particle Size on Moisture Removal

Curve 1. Drying curve using +20 mesh silica gel

Curve 2. Averaged drying curve using +30 mesh through +325 mesh

PLATE XI


18
16
14
12
10
8
6
4
2
% H_2O—DRY BASIS
0
1
2
3
4
5
6
DRYING TIME—MINUTES
1
2
ARCING

Shown in Plate XII is the relationship between the percent H_2O removed versus the amount of silica gel present during dielectric drying. The two curves relate the amount of moisture removed under conditions of equal drying times and of equal temperature rise to the weight ratio of desiccant to wheat.

The resistance-measurement studies concerned with the mechanism of dielectric drying are discussed in the following section.

DISCUSSION OF RESULTS AND CONCLUSIONS

The drying curves obtained showed the typical periods common to other forms of drying; the heating-up period, the constant-rate period, and one or more falling-rate periods. Only curves relating percent moisture content versus time were established for the data. The slopes of these curves could easily be determined to establish the rates of drying; however, no other rates were available for comparison so this was not done.

An analysis of the data presented indicates that the relative rate of dielectric drying is quite rapid. The application of high-frequency energy to the drying of wheat showed that such a process is easily controlled and is flexible in operation.

"Constant-Power-Setting" Runs

Typical drying curves were obtained in the "constant-power-setting" runs. In each case the heating period was very short; no changes in the

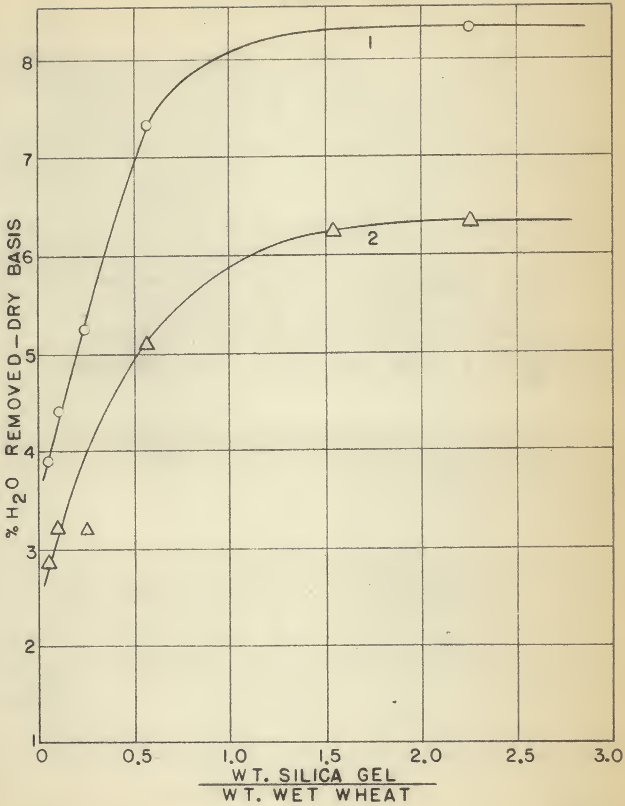
EXPLANATION OF PLATE XII

% H_2O Removed versus Amount of Silica Gel Used

Curve 1. All samples heated for an equal time interval

Curve 2. Samples heated through an equal temperature span

PLATE XII


% H_2O REMOVED – DRY BASIS
1
2
3
4
5
6
7
8
0
0.5
1.0
1.5
2.0
2.5
3.0
1
2
WT. SILICA GEL
WT. WET WHEAT

curvature of the drying curves were found between "zero" drying time and the constant-rate period. The "constant-power-setting" runs were made at the same control settings initially and no adjustment of the controls was made during the runs. Curves 1, 2, and 3 of Plate VII have the greatest slope of the curves there presented; hence, the "constant-power-setting" runs gave the fastest rate of drying. However, this type of run was injurious to the wheat because the specified maximum safe-drying temperature of 180°F was exceeded. These "constant-power-setting" curves were useful, however, in that they indicated the maximum rate that wheat could be dried with the equipment used. (Somewhat higher rates could have been attained for shorter periods, but the tendency for arcing to occur would have been increased.) Other types of runs which did not exceed 180°F were judged upon how close their drying curves approached the curves of the "constant-power-setting" runs.

The "constant-power-setting" runs were not runs in which the rate of heat input was constant. Variations in the dielectric constant of the load, in the frequency of the generator, and in the voltage-gradient were evidenced during the drying experiments. Ideally, for comparison of dielectric drying with other methods, the rate of heat input should be constant. Supplying heat at a constant rate through dielectric heating would require some means of maintaining the product of the variables in Equation (4) constant. No high-frequency wattmeter was found that would measure the instantaneous power delivered to such a load.

"Constant-Temperature Runs

Curves 6 and 7 of Plate VII were the results of two of the "constant-temperature" runs. Points A and B on these curves mark the point at which the power output of the generator was reduced in order to maintain the temperature constant at 160°F. From "zero" time to these points, the power was applied using the same control settings as with the "constant-power-setting" runs. This fact accounts for the steepness of the initial portion of Curves 6 and 7.

As the heating was continued beyond Points A and B, the power output of the generator was continually reduced. The dielectric properties of the load were changing in such a manner as to require less heat input to maintain the 160°F temperature.

The slopes of Curves 6 and 7 indicate that the drying rate was extremely slow in comparison to the rates indicated by Curves 1, 2, and 3 of Plate VII.

"Constant-Voltage-Gradient" Runs

The results of the "constant-voltage-gradient" runs as presented in Plate VIII show the effect of electrode potential on the rate of drying. An increase in the potential causes the slope of the curve to increase. Equation (4) shows that the amount of heat generated per unit volume of material is directly proportional to the square of the voltage gradient. Of all the variables in Equation (4) that influence the generated power, the voltage gradient is the most effective. The final drying temperature for each of these runs exceeded 180°F. Arcing occurred during drying with a voltage gradient of 1520 volts per inch. In a few instances where the rate of power application was high, some kernels exploded or popped. The appearance of these kernels was similar to popped corn.

Intermittent Drying Runs

The intermittent drying runs were of interest in that one of these runs produced a drying curve which had a slope during the initial portion that was almost as great as the slope of the "constant-power-setting"type curves. Curve 4, Plate VII, is the result of heating the sample at a power level equal to the maximum limit used until the sample reached 160°F. After 160°F had been reached, the sample was allowed to cool to room temperature and then the process was repeated. This run had the advantage over other runs in that the temperature of 180°F was not exceeded while at the same time the power was being applied at the maximum rate.

The drying of wheat to the reportedly safe moisture content of ten percent could be done in the above manner without injuring the wheat. Of all the methods of dielectric heating investigated, this method appeared best from a practical standpoint.

Curve 5, Plate VII, was plotted from the results of trials similar to those for Curve 4 except that in this case the initial temperature was 20°F and the final was 100°F. The fact that a lower drying rate results from Curve 5 than from Curve 4 can be explained by the fact that at lower temperatures the dielectric constant of wheat is less than at higher temperatures. Hence, at the same power settings, less heat was developed at the lower temperatures.

Alternate periods of heating and resting proved of no beneficial aid to moisture removal. Plate IX shows that the maximum amount of moisture removed for a given total heating time occurred when no alternate rest cycles were used. The purpose of the intermittent drying schemes was to devise, if possible, another method of drying the wheat and not exceed 180°F during the process. The purpose of utilizing a rest period between short heating cycles was to determine if: first, the temperature of the wheat could be kept lower; and second, a rest period would be advantageous to any moisture diffusion process within the kernel. However, as shown by Plate X, as the rest periods were increased the amount of moisture removed in a given drying time decreased. The rate of drying in these cases is apparently determined solely by the rate of power input; diffusion is not a controlling step during this drying process.

Air- and Dielectric-Drying

Analysis of the data of Tables 5 and 6 indicates that an intermediate drying step using dielectric energy does not promote the removal of more moisture during the following air-drying step. In other words, the inclusion of a dielectric drying step between two air-drying intervals does not facilitate the removal of any more moisture in the second air-drying step than if the dielectric drying interval had been omitted.

Examination of the moisture contents after drying showed no appreciable difference in the amount of water removed when the wheat was dried by air alone or by alternate intervals of dielectric- and air-drying. These comparisons aere made at equal intervals of drying time.

Possibly dielectric heating could be utilized in conjunction with some other form of heating. The alternate air- and dielectric-drying intervals, under certain conditions of temperature and length of application, might prove to be a feasible process for drying wheat; in the experiments mentioned in this report, the variables time and temperature were not fully investigated. If dielectric heating could be used only for a short interval for the purpose of driving the internal moisture to the surface, then a less expensive means of drying, such as hot air, could be used to remove the surface moisture.

Resistance Variation During Drying

The data presented in Table 5 are noteworthy from the standpoint of resistance variation. An inverse relationship exists between the resistance of the grain and the moisture content. While this relationship holds true for equilibrium conditions, it does not hold true for a sample of wheat that is alternately subjected to air and dielectric drying with the resistance being measured immediately after each process. Table 5 shows the following resistance-variation pattern: the resistance of the sample decreases following an air-drying cycle from what the value was following the previous dielectric-drying cycle. Dielectric drying increases the resistance; air drying decreases it. During this series of alternate cycles, the sample was progressively becoming drier; hence, its resistance should increase.

Langton (12) stated that recent discoveries indicate that in dielectric heating the charge resides in a layer near the surface of the object being heated. The above resistance variation conforms to this supposition; an interval of dielectric heating causes the surface of the kernel to become severely dried and increases the resistance. During a subsequent air-drying step, moisture is removed from the kernel but at the same time the once-dried surface layer becomes more moist due to the transfer of moisture within the kernel. The resistance of the sample is lowered from its preceeding value. Run numbers 5-1 through 5-10 illustrate this identical resistance pattern.

Table 6 shows that when wheat was dried solely with hot air the resistance steadily increased as more moisture was removed. This resistance pattern is such as would be expected. Drying with dielectric energy and with hot air in effect gave a variety of resistances for one definite moisture content.

Efficiency of Dielectric Drying

Table 11 shows the calculated overall efficiencies for several dielectric-drying runs. In general, the efficiency, as defined by Equation (6), varied from ten to twenty percent. This range is somewhat lower than the values reported by Stephens (25). Efficiencies reported in the literature varied from 35 to 75 percent. Differences may be due to what is considered as useful heat. Possibly larger installations could be operated more efficiently. Major losses noted during the project are summarized by Langton (12) and include the following effects: conductor, radiation, corona, support, conductance, and dielectric. The first four items are reported to comprise 5 to 10 percent of the total loss. The conductance loss was probably the major item of concern to the project. The electrodes were constructed of aluminum which has a relatively high thermal conductivity; this fact caused conductance losses to be high. Heat lost to the electrodes was evidenced by the temperature rise of the electrodes during drying. Of the losses mentioned, the dielectric loss pertains to the energy actually used in heating the material. Radiation (electromagnetic) losses were noticeable in that the vacuum-tube voltmeter had to be shielded from the exposed electrode connections in order to prevent the voltmeter tube from burning out; excessive currents flowed in the vacuum tube when the meter was not shielded.

The heat required to vaporize water from wheat was assumed to be 1100 Btu per lb. If the heat of vaporization was larger than this, the efficiencies as calcualted by Equation (6) would be higher. Gallaher (6) has developed a method for determining what he calls the "latent heat of wheat". Ratios of the latent heat of vaporization of water from wheat to the latent heat of vaporization of free water were shown as a function of the moisture content of the wheat. This ratio had the value of 1.01 at 20 percent H_2O (dry basis) and the value of 1.42 at 10 percent H_2O (dry basis).

Acceptance of the above information showed that the value of 1100 Btu per pound for the heat of vaporization to be in the correct range. Efficiencies were calculated merely to obtain some idea of the performance of the process.

The highest efficiency of heating would require some type of electrical network whereby the generator could constantly have been kept in "tune". As heating progressed, the change in the dielectric properties of the load caused the load impedance to change and thus, the generator became slightly "detuned".

Dielectric heating for the purpose of drying appears to be uneconomical. Low efficiencies for the conversion of power into useful heat and the requirement of large-scale equipment are the most serious drawbacks to dielectric drying.

Desiccant Performance

The differences in the performance of the three desiccants, silica gel, alumina, and Florite, were small, as was expected. As shown by Perry (21), silica gel possesses greater ability to take up water rapidly than does alumina. Experiments involving the use of Florite were included because of the relative newness of this desiccant.

Plate XI shows that the effect of particle size of the desiccant used had little effect on the amount of moisture removed from the wheat. All moisture-content-versus-time curves except for the +20 mesh desiccant fell in a common band on Plate XI. Hougen and Dodge (8) reported that there was little increase in the adsorptive capacity of silica gel for an increase in fineness because of the submicroscopic pore structure of the gel. The run using +20 mesh silica gel was terminated because of arcing. Moisture accumulation on the gel particles caused a low-resistance path to develop and arcing resulted. As shown in Table 9, the power consumption of the generator was approximately the same for all size ranges investigated. There was a slight indication that the runs using the finer desiccant required more power for a given amount of moisture removed.

The loss of desiccant as reported in Table 10C was due partly to the fact that some of the desiccant adhered to the kernel and was thus lost as an unrecoverable dust. Simple hand-screening operations were the only methods used for desiccant recovery. The loss of desiccant reported in Table 10C was as a weight percent of the initial amount used. All drying experiments were conducted with the electrode cell closed at the top by a plate of Lucite. If no water vapor escaped during the heating but was totally retained by the desiccant, the final weight of desiccant would have been the initial weight plus the amount of moisture removed from the wheat. Inasmuch as the electrode chamber was not air-tight, some of the vapor did escape. Hence, the values of percent loss as reported in Table 10C should be recognized as being high.

The drying effect due solely to the presence of the desiccant was shown in Plate VII, Curve 8, for the case of wheat initially at 18.42 percent H_2O in contact with silica gel. At the end of six minutes, approximately 17.50 percent H_2O remained in the sample. If so desired, each of the other curves on Plate VII could be corrected for this desiccant-drying effect. Approximately 0.9 percent H_2O could be added to the values of each of the other runs at the six-minute time line to obtain the net moisture content due solely to the application of dielectric energy.

Plate XII shows the effect of the relative weight of silica gel to wheat upon the moisture content of the sample under various drying conditions. The curves should theoretically pass through zero on the ordinate scale at a value of zero for the ratio if the electrode chamber was completely isolated. However, as discussed before, some water vapor escaped the cell and was not adsorbed by the desiccant. For values of the ratio of 1.0 and greater, little additional moisture was removed for an increase in the amount of desiccant used. In nearly all of the runs conducted, the amount of desiccant present was such that the ratio of the weight of the desiccant to the weight of the wheat had a value of about 0.15. Minor variations in the amount of desiccant used in those cases probably affected the amount of moisture removed only to a small extent.

The initial moisture content of the silica gel used in this project was 0.0376 gms H_2O per gm dry gel. Hougen and Watson (9), p. 294, stated that the heat of complete wetting of silica gel with water was -15.3 calories per gram of dry gel. The heat given off for incomplete wetting would be less than this value. For 15 grams of desiccant initially present, a maximum of about one Btu of heat would be evolved as heat of wetting. Clearly, this adds nothing to the efficiency of the process.

Table 10E showed that silica gel was heated slowly in the dielectric field. Ten minutes of heating produced a temperature rise of only 14°F. Therefore, under the conditions of generator adjustment used, the silica gel did not absorb the high-frequency energy as readily as the wheat did.

Temperature Measurement.

The temperature measurements in the high-frequency field were considered somewhat unreliable. The mercury or alcohol contained in such thermometers should absorb energy from the high-frequency field the same as any load would. However, the thermometer could be expected to absorb the energy at a different rate than the wheat-desiccant mixture because of the difference in dielectric properties. This fact accounts for the unreliability of the temperature readings. Over a period of six minutes, the readings on the mercury and alcohol thermometers increased by 5°F; this small temperature rise was noted when the two thermometers were suspended between the electrodes with only air present as the load. This heating effect was due solely to the development of heat in the thermometer fluid. If, however, the thermometers were immersed in wheat between the electrodes and if the wheat was heated dielectrically, the thermometers would indicate nearly the correct mixture temperature; the heating of the thermometer fluid would be accomplished by conduction from the wheat at a much greater rate than by rate of heat development in the thermometer fluid.

No detailed study was made on the problem of temperature measurement. The only study conducted along these lines consisted of comparing the indicated temperatures of alcohol and mercury thermometers. Table 10G shows the results of this comparison. In some instances the alcohol thermometer gave readings less than the mercury thermometer; in other instances higher readings were noted on the alcohol thermometer. Stephens (25) stated that spirit-filled thermometers were not affected by radio-frequency fields. Thermocouples imbedded in the sample could be effectively used; temperature measurements could then be made after the power was shut off.

Dielectric Constant Determinations

Dielectric constant determinations were made by comparing the load currents that flowed using air as the dielectric medium in one case and using the mixture of wheat and desiccant in the other case. Since the dielectric constant of air is nearly unity, and since the ratio of the load current using air as the dielectric medium to the load current using wheat was known, the dielectric constant was easily found. The values calculated ranged between 3.83 and 4.92. The dielectric constant was found to vary with moisture content and temperature; frequency and pressure also were reported to affect the value of the dielectric constant.

SUMMARY

Of the dielectric schemes investigated, the one that offered the greatest industrial possibilities was the intermittent procedure whereby the wheat was heated at a fast rate to 160°F and was then cooled. This scheme showed that approximately five and one-half minutes were required to dry a sample from eighteen down to ten percent moisture.

The process of the dielectric drying of wheat was concluded to be the same as for other drying processes; however, the indicated mechanism of dielectric heating was that the surface layer of the particles was given a severe dry. This concentration of charges is similar to the mechanism of induction heating at lower frequencies.

Drying wheat solely by dielectric heating is inefficient. The results of this study showed that a combination of air- and dielectric-drying was impractical from the standpoint of drying wheat. No future work along these lines is considered necessary.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to:

Dr. Rollin G. Taecker for giving his advice, counsel, and encouragement during the course of this project.

Dr. Henry T. Ward for his helpful discussions, suggestions, and encouragement.

Professor Raymond C. Hall for his consultation and advice.

The Electrical Engineering Department of Kansas State College for loaning the radio-frequency generator and accessory electrical equipment.

The Chemical Engineering Department as a whole for the use of equipment and materials.

BIBLIOGRAPHY

(1) Babbitt, J. D.,"Observations on the Adsorption of Water Vapor by Wheat", Can. J. Research, F27; 55-72, 1949.

(2) Bock, A. P., "Economics of Radio Frequency Heating", Product Engineering, Vol. 19, No. 1, pp. 118-21, 1948.

(3) Bosomworth, G. P., "High Frequency Heating", Can. Chem. Process Inds., 30, No. 7, 28-34, 47, 1946.

(4) Brown, G. H., M. S. Hoyler, and R. A., Bierwirth, Theory and Application of Radio-Frequency Heating, New York: D Van Nostrand Company, Inc., 1947.

(5) Ceaglske, N. H., and O. A.,Hougen, "Drying Granular Solids", Ind. Eng. Chem., 29: 805-813, 1937.

(6) Gallaher, G. L., "A Method for Determining the Latent Heat of Agricultural Crops", Ag. Eng., 32: 34T, Jan. 1951.

(7) Hartshorn, L., "Radio-Frequency Heating", Nature, Vol. 157, May 11, 1946, pp. 607-610.

(8) Hougen, O. A. and F. W. Dodge, "Drying of Gases". A report for the National Defense Research Committee, 1530 P Street, N. W., Washington, D. C. Section L-8, Division B. Chemical Engineering Department, University of Wisconsin, June 30, 1941.

(9) Hougen, O. A. and K. M. Watson, Chemical Process Principles. Part One. Material and Energy Balances, New York: John Wiley & Sons, Inc., 1943.

(10) Instruction Book for 1-KW Industrial Radio Frequency Generator. Catalogue CF-443-A, Westinghouse Electric and Manufacturing Co., Radio Division, Baltimore, Md.

(11) Jordon, J. P., "The Theory and Practice of Industrial Electronic Heating", General Electric Review, Dec., 3-11, 1943.

(12) Langton, L. L., Radio Frequency Heating Equipment, London: Sir Issac Pitman and Sons, Ltd., 1949.

(13) Mann, C. A., N. H. Ceaglske, and A. C. Olson, "Mechanism of Dielectric Drying", Ind. Eng. Chem., 41: 1686-94, 1949.

(14) Mrak, E. M. and G. F. Steward, (editors), Advances in Food Research, Vol. 3, New York: Academic Press Inc., 1951.

(15) Murphy, E. J. and S. O. Morgan, "The Dielectric Properties of Insulating Materials", Bell System Tech. J., Vol. 16, pp. 493-512, 1937.

(16) ________________, "The Dielectric Properties of Insulating Materials", Bell System Tech. J., Vol. 17, pp. 640-669, 1938.

(17) ________________, "The Dielectric Properties of Insulating Materials. III. Alternating and Direct Current Conductivity", Bell System Tech. J., Vol. 18, pp. 502-537, 1939.

(18) Nicol, D. L., "Drying Granular Solids by High Frequency Heating", The Industrial Chemist, 27: 339-44, 1951.

(19) Oxley, T. A., "Study of Water Content of Single Kernels of Wheat", Cereal Chemistry, 25: No. 2; 111-127, 1948.

(20) ________________, The Scientific Principles of Grain Storage, Liverpool: The Northern Publishing Co., 1948.

(21) Perry, J. H. (editor), Chemical Engineers' Handbook, Third ed., New York: McGraw-Hill Book Company, Inc., pp. 870-874, 1950.

(22) Schutz, P. W. and E. K. McMahon, "Dielectric Heating of Granular Materials -- Aluminum and Silicon Oxides", Ind. Eng. Chem., 43: 179, 1946.

(23) Sherman, V. W., "Electronic Dehydration of Foods", Electronics, 17, No. 2, 94-97, 1944.

(24) Solomon, M. E., "The Use of Cobalt Salts as Indicators of Humidity and Moisture", Ann. Appl. Biol., 32(1): 75-85, 1945.

(25) Stephens, R. L., "Radio Frequency Drying", Trans. Inst. Chem. Engrs., 27: 37-46, 1949.

(26) Veneable, D., "Dielectric Heating Fundamentals", Electronics, 18: No. 11, 120-4, 1945.

DIELECTRIC DRYING OF WHEAT

by

DENNIS EUGENE DRAYER

B. S., South Dakota School of Mines and Technology, 1952

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1954

The nature of this study was exploratory in character. The purpose of the project was to investigate the problems relating to the dielectric drying of wheat. Emphasis was placed upon studying the relative merits of drying wheat while in admixture with various solid desiccants. Minor emphasis was placed upon studying the relative movement of moisture during drying. The actual mechanism of dielectric drying was investigated by taking resistance measurements on wheat samples after various drying intervals. The relative movement of surface moisture was thus determined.

Dielectric heating is defined as the heating of a nominally insulating material due to its own dielectric losses when the material is placed in a varying electrostatic field. The heating of a material when exposed to high-frequency electrostatic fields is said to be accomplished by "molecular friction" due to repeated molecular reorientations or by resistance heating or by both.

The power developed in the material when it is placed between two electrodes is directly proportional to the voltage gradient, the frequency of the oscillating field, and the loss factor of the material.

Various schemes of utilizing high-frequency energy were investigated. The wheat was mixed with one of the desiccants, silica gel, alumina, or Florite, and heated in the high-frequency field for a specified time interval. This general procedure was used to establish moisture-content-versus-time curves for the various drying schemes.

The different drying schemes utilized were classified as "constant-power-setting" runs, "constant-temperature" runs, "constant-voltage-gradient" runs, and "intermittent-drying" runs.

"Constant-power-setting" (not to be confused with constant power input) runs gave the fastest rate of drying. A one-hundred gram sample of wheat was dried from eighteen percent moisture down to a negligible water content in about six minutes. These runs gave information about the maximum drying rate that could be attained with the equipment. The minimum rate determined was for the simple mixing of wheat and desiccant with no power applied. The "constant-temperature" and "constant-voltage-gradient" runs gave intermediate drying rates.

Intermittent drying schemes proved to be the best method of drying the wheat with regards to total drying time and temperature attained. Wheat heated from 80°F to 160°F, then cooled to 80°F, reheated, etc., was dried at a rate that approached the rates of the "constant-power-setting" trials. Harmful effects to the germinating and milling properties of wheat were reported when drying temperatures in excess of 160-180°F were used.

Wheat samples were dried by alternate intervals of hot air and dielectric energy for the purpose of studying the mechanism of dielectric heating. Resistance measurements, which gave indications of the relative movement of surface moisture, were made after each interval. It was found that the instantaneous resistance of a wheat sample did not depend entirely on the moisture content but depended also upon the previous method of drying. An air-drying interval increased the resistance of the wheat; another air-drying interval, while decreasing the overall moisture content, decreased the resistance from what it was following the dielectric-drying step. In effect, several resistance values could be obtained for a given sample of wheat; the magnitude of the resistance was dependent on the moisture content and on the type of drying to which the sample had been subjected. These variations show that the surfaces of kernels were severely dried by the application of dielectric energy. L. L. Langton, in his book entitled Radio-Frequency Heating Equipment, stated that recent theories indicate that the charge resides in a surface film on the dielectric. The variations mentioned above support his theory.

The overall efficiency of the dielectric drying process was found by measuring the total input energy to the generator with a recording wattmeter. The efficiencies calculated expressed the fraction of input energy that appeared in the output as sensible and latent heat. The values calculated ranged between ten and twenty percent. These values were somewhat lower than the 35-75 percent range reported in the literature.

The size of desiccant particle used in admixture with the wheat had little or no effect upon the amount of moisture removed. The loss of desiccant upon separation from the wheat was high in some instances. Mesh sizes from +20 to +140 were recovered easiest. The percent of desiccant lost increased with increasing fineness.

Minor experiments concerned with the variation of the dielectric constant of wheat, the amount of moisture removed versus the amount of desiccant used, temperature measurement in an electrostatic field, and the heating of wheat and of desiccant separately by means of dielectric energy rounded out the project.

The mechanism of drying using dielectric energy was concluded to be the same as for other forms of drying on the basis of the shapes of the drying curves.

The heating mechanism during dielectric drying was found to be such that the surface layers of the kernels were given a severe dry.

The efficiency of drying wheat dielectrically was so low that no further work using dielectric heating is recommended.