CONDUCTION DRYING OF SHELLED CORN

by

GLENN E. HALL

AN ABSTRACT

Submitted to the College of Agriculture of Michigan State University of Agriculture and Applied Sciences in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

Approved by Carl W. Hall

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ABSTRACT

The drying characteristics obtained by conduction heating in comparison with convection heating of a thin layer of shelled corn were obtained. Kernels of corn were cut up before and during drying to determine where the moisture was concentrated and the direction of movement during drying.

A heated plate with temperatures of 229, 189, 144 and 104°F was used for conduction drying and air flows of 25, 50 and 100 fpm were used over the heated plate in addition to the natural air current to carry moisture away.

The rate of drying was higher during the first part of drying by convection, but the conduction drying rate was higher during the later part of drying. Drying from 56 percent, d.b., to 15 percent, d.b., moisture content was faster for all four plate temperatures. Conduction drying from 56 to 15 percent, d.b., at 229°F required 49 minutes while convection drying required 54 minutes, or a saving of 10.2 percent in time. Conduction drying from 56 to 15 percent, d.b., at 189°F required 96½ minutes while convection drying required 111 minutes, or a saving of 15.1 percent in time.

The drying rate, which was directly related to the plate temperature, of the kernel was the same whether the

white or yellow side was against the heated plate. The tip of the kernel contained the highest moisture content of any part of the kernel, while the white side had a higher moisture content than the yellow side. Moisture movement was mainly from the head of the kernel to the tip. The drying period, which was divided into four falling rate periods, was defined by the equation $\frac{M-Me}{Mo-Me} = e^{-k\theta}$.

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SUMMARY

The drying rate was directly related to the plate temperature, with the faster drying rates on the higher plate temperatures. The drying rate was the same whether the kernel was lying with its white or yellow side against the heated plate.

The natural air current rising from the plate due to the heat was sufficient to carry away the moisture as it was evaporated from the kernel since added forced air did not increase the drying rate.

Moisture movement was mainly from the head of the kernel to the tip.

The tip of the kernel contained the highest moisture content, 85 percent d.b., of any part of the kernel. The white side of the kernel had a higher moisture content, 68 percent d.b., than the yellow side, which was about 45 percent d.b.

The drying period could be divided into four falling rate periods with each successive period having a slower rate of drying.

Conduction drying is faster than convection drying when drying from 56 percent d.b. to 18.3 and 15 percent d.b. for the $229^{\circ}F$, $189^{\circ}F$ and $144^{\circ}F$ temperatures and to 18.3 percent d.b. for the $105^{\circ}F$ temperature. Drying from

56 percent d.b. to 15 percent d.b., with conduction results in a time saving over convection of 10.2 percent for 229°F, 15.1 percent for 189°F, 16.5 percent for 144°F and 3.2 percent for 104°F.

The equation which can be used to define drying of shelled corn by conduction drying is as follows:

$$\frac{M-Me}{Mo-Me} = e^{-k\theta}$$

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INTRODUCTION

The major portion of drying farm crops in the past has been with the use of forced air through the product. There are a few isolated cases of drying grain with the use of conduction heating of the product, but the studies were so limited that conclusive results were not reached. A considerable amount of information is available on the use of conduction heating for drying non-hygroscopic material such as sand.

According to Hall (1957) 10 percent of the grain crops in the United States are lost between harvesting and consumption. If better and more convenient means are made available to dry grains the practice of drying may become more widespread and result in a large saving by less spoilage and earlier harvest. With a suitable means of drying, crops could be harvested earlier with less shattering, shelling and quality deterioration.

A machine which harvests and dries in one operation would be the ideal situation and might be a reality when a means is available to dry grain rapidly and safely.

The aim of this investigation was to determine the rate of drying obtained by conduction heating of shelled corn in comparison with convection air drying considering, (1) the effect of the temperature and air flow on the rate of drying, and (2) the development of an equation which will apply to conduction drying.

REVIEW OF LITERATURE

The process of drying occurs when the vapor pressure of the product to be dried is higher than the vapor pressure of the surroundings, causing the moisture to move outward. The vapor pressure of the product is increased by heating the product by conduction, convection and/or radiation. Jakob (1949) defined heat conduction as a process of heat transmission due to the elastic impacts of molecules of gases, to longitudional oscillations in solid non-conductors of electricity, and to the motion of electrons in metals. He defined heat convection as the transportation and exchange of heat due to the mixing motion of different parts of a fluid. He defined heat radiation as being identical with light radiation.

Hukill (1948) wrote that in evaporating moisture from grain it is necessary to supply the heat necessary for evaporation. Evaporation from a free water surface requires less heat per pound of water evaporated than evaporation of moisture from grain. The amount of moisture evaporated from grain is proportional to the amount of heat delivered to the grain. The higher the temperature the more readily the moisture leaves the grain. To dry at a faster rate it is necessary to heat the grain to a higher temperature since the drying rate is directly dependent on the temperature of the grain.

Robertson (1959) compared conduction drying with convection drying, both at 135°F, and found that after 10 minutes the heated surface dried shelled corn at a faster rate than the forced heated air. Any moisture content desired which required more than 30 minutes drying time would be obtained in less time by using conduction rather than convection drying since the two curves crossed at 30 minutes.

Kelly (1941) heated wheat by conduction in a cement mixer, placed the wheat in other containers and forced air through the wheat. Fifty-seven percent to 60 percent of the moisture loss took place in the first minute of forced air drying with 43 percent of the temperature drop. Four minutes after the start of forced air through the wheat the rate of drying was very slow. An additional eight minutes was used to reduce the temperature to a level safe for storage. Approximately 18 percent moisture content w.b. wheat was used with a moisture loss of about two percent when heating the wheat to 150°F and exposing it to 12 minutes of forced unheated air in six inch layers. He found that the thinner the layer during the air drying and the higher the temperature to which the grain was heated, the greater the drying rate for a given air flow.

Information concerning the use of conduction heating for drying porous substances such as grain is limited. There is extensive data on the use of conduction heating to dry non-porous products such as sand and pulp. This material is presented since it is related to the problem under investigation by the method of heat transfer to the product. The difference between the drying of porous and non-porous products is related in the articles by Corbin and Newith (1955), Hall (1957), and Sherwood (1936).

Haines (1927) explanation of moisture movement stages in a solid started with a dry bed of soil or sand. To this he added a small amount of water so that the points of contact of the particles held a small volume of moisture. This was called the pendular stage. Next, more water was added until each particle had a complete film of moisture around it and the film was continuous through the bed. This was called the funicular stage. Finally, water was added until all the pore space between the particles was filled. This was called the capillary stage.

Corbin and Newith (1955) showed that the drying characteristics of beds of moist porous granular material are consistent with the capillary theory of drying, the movement of moisture to the drying surface being governed by the surface tension, gravity and friction forces acting on the liquid in the pores and voids of the bed. The form of drying rate curves differed from those for corresponding beds of non-porous granular materials mainly through the capillary action of the internal pores of the granules in conveying water to the surface during the pendular state. Thus the rate of drying during the constant rate period is higher for porous than for non-porous material, and after the critical moisture content is reached there follows an initial period having a very rapid reduction in drying rates and a prolonged second period in which the drying rate falls slowly. Other differences in drying during the various stages can be attributed to the water carrying capacity of the porous granules.

Hall (1957) wrote that there are two major drying periods, the constant rate period and the falling rate period. In the constant rate period the drying takes place on the surface and is influenced by the surrounding conditions. The constant rate period continues as long as the internal moisture moves to the surface as fast as surface moisture is evaporated. The constant rate period is short in duration and is dependent upon the area exposed, differences in humidity between the air stream and wet surface, coefficient of mass transfer and velocity of the drying air. The falling rate period, which is generally the whole range of drying, is influenced by the product, diffusion of moisture to the surface and removal of moisture from the surface. The falling rate period for shelled corn is divided into four periods for corn above 25 percent d.b. This can be explained as follows: the surface area of the micropores of wet corn are covered with water; the thickness of the water is directly proportional to the moisture content. The thickness of a water molecule is about 3×10^{-8}cm. With four layers of water molecules there would be four falling rate drying periods because the drying constant changes as each layer is removed. Drying of corn involves two fundamental processes: (1) there is a transfer of heat to evaporate the kernel moisture and (2) there is a movement of water as a liquid and/or vapor from the kernel. The equation representing moisture movement during the falling rate period is based on Newton's cooling equation, which, in integrated form is $\frac{t-te}{to-te} = e^{-k\theta}$. Substituting M for t results in $\frac{M-Me}{Mo-Me} = e^{-k\theta}$. When $\frac{M-Me}{Mo-Me}$ is plotted against θ on semi-logarithmic paper, k is the slope of the line. The rate of drying can be found by differentiating $\frac{M-Me}{Mo-Me} = e^{-k\theta}$ with respect to θ or by multiplying the mass transfer coefficient by the effective area and the vapor pressure driving force. The vapor pressure driving force is the vapor pressure of the grain minus the vapor pressure of the air.

Sherwood (1936) developed a theory which suggested three drying periods in the drying process. These three periods were: (1) a constant rate drying period during which the surface remains completely wet, the rate of evaporation being the same as that from a constant area free water surface; (2) a first falling-rate period during which there is a decrease of wetted surface with the drying rate being directly proportional to the percent of surface that is wet; and (3) a second falling rate period during which the drying rate is proportional to the rate of water transfer to the surface. He further designated the moisture content at the end of the constant rate period as the critical moisture content. If the critical moisture content is less than the required moisture content all the drying will be in the constant rate period, and by the same token, if the critical moisture is greater than the initial moisture content the whole drying process will occur in the falling rate period.

Tambling (1953) in drying 0.75 inch thicknesses of sand on a hot surface, reported four periods during the drying process: (1) a heating up period during which the temperature of the sand reached a maximum with flash vaporization taking place when the sand slab was placed on the plate; (2) a constant rate period during which the temperature gradient was constant and the moisture was distributed evenly through the slab; (3) a transition period during which the zone of vaporization moved toward the top surface of the slab; and (4) a falling rate period during which the temperature started to increase after reaching a minimum and the moisture was distributed in a bell shaped curve. He found that the higher the plate temperature the greater the drying rate and that there were two zones of vaporization, one starting at the hot plate interface and the other starting at the open face. The water movement was mainly toward the heated plate.

Ludt (1957) in drying sand on a hot surface, found that three drying periods were present, namely, (1) constant drying-rate period, (2) first falling rate period and (3) second falling rate period. Constant layer moisture at the hot surface was instrumental in maintaining the constant drying rate. The first falling rate begins when a constant hot surface moisture can no longer be maintained. The second falling rate begins when the pendular state of water is reached. He found that the constant rate period was from 23 to 10 percent moisture content, d.b., with the falling rate starting between 10 and 6 percent moisture.

Retford (1957) dried sand on a 220°F heated surface and found that maximum drying rate and heat transfer coefficients were obtained with a one-half inch layer as compared with one or one and one-half inch layers. The heat transfer coefficient was correlated with the drying rate between moisture contents of two to ten percent, d.b. The drying rate of the one-half inch layer of sand was 6.9 pounds water per hour sq. ft., while that for a one inch layer was 6.2 pounds water per hour sq. ft. The one and one-half inch layer had the same rate as the one inch layer. The change in the heat transfer coefficient seemed to be controlled by the area of wetted surface.

Ceaglske and Hougen (1937) showed that moisture flow in granular non-hygroscopic solids such as sand was due mainly to capillary forces. They showed data which indicated movement of moisture from an area of low concentration to an area of high concentration, which was not possible considering only diffusion forces.

McCready (1935) has shown that pulp slabs in contact with a hot surface dried at a constant rate for an interval of time and then experienced a falling rate period. A constant temperature occurred in the slab until the critical moisture was reached and then the temperature decreased. In the first period of falling-rate drying, the rate of drying, heat transfer from plate to slab and the temperature of the slab decreased. This indicated an increased resistance between the slab and hot surface due to the drying at the hot surface. In later parts of the falling-rate period there was an increasing temperature difference across the zone of vaporization with a decreasing temperature difference between the hot plate and slab. He showed that the temperature and relative humidity of supplementary air had very little effect on the drying rate as the heat of vaporization is supplied by the hot plate. The thickness of the pulp slabs and the temperature of the hot surface were the major factors which influenced the drying rate.

Shroff (1949) in drying 0.17 to 0.20 inch thick laminations of paper pulp found that flash vaporization took place on the 240°F heated surface. The temperature of the sheet rose to the boiling point of water while the temperature of the plate decreased. Both temperatures then decreased to a minimum, then continually increased with the plate temperature attaining its original value. The period of falling temperatures includes the falling rate period during which drying begins. The interval of increasing temperature constitutes the rest of the falling rate period which is controlled by internal diffusion. The moisture content of the sheets decreased very rapidly, with the thinner sheets drying at a faster rate than thicker sheets. The controlling mechanisms during drying were (1) unsaturated surface drying, (2) internal liquid diffusion and (3) diffusion from the interior of the fiber. The rate of drying depends on the amount of heat transferred to the pulp which in turn is controlled by the coefficient of heat transfer and the resistance of heat flow in the material. As the sheet dries the resistance to heat flow is increased and the drying rate decreases. The coefficient of heat transfer between the plate and sheet varied from 122 Btu/hr. sq. ft. ^{o}F at time zero to 0.9 Btu/hr. sq. ft. ^{o}F at the end of seven minutes, at which time the diffusion of moisture from within the fibers seemed to be the controlling factor.

Ernst, Ardern, Schmiel, Tiller (1938) found that in drying Prussian Blue, a gelatinous solid that adheres firmly to the drying plate, the drying rate proceeded normally at first and at the end of the initial period suddenly decreased. The rate then rose sharply and fell off gradually as during a normal falling-rate period. Drying proceeded normally at first while surface moisture and internal reservoirs were being emptied. After this the only moisture being evaporated was held in the capillaries themselves. The liquid then began to rise in the capillaries causing a vacuum since the Prussian Blue adhered to the plate and prevented the water from rising to the surface, thus the sudden decrease in drying rate. The solid, which had been drying at the heated surface finally broke away from the surface and air entered the capillaries. Drying then resumed as normally expected.

King and Newitt (1955) dried non-porous granular glass beads on a heated plate under various conditions and found that there was an initial heating period during which the drying rate was constant and the conductivity of the drying bed did not change. This was followed by a pseudo-constant rate period of a slowly decreasing drying rate which is similar in duration to the constant rate period for normal convection air drying and in the period during which the surface of the bed is sufficiently wet to maintain the air film in contact with it in a saturated condition. The constant rate period was followed by a first falling rate period during which the rate fell rapidly and a second falling rate period during which the rate decreased slowly. The heat conductivity of the bed decreased as the bed dried, since the conductivity is a function of the moisture content, resulting in a decreasing drying rate.

They also used forced air of varying velocities and temperatures across the heated plate and found that the higher the temperature and velocity of the air the faster the drying rate. Also, the higher the plate temperature the faster the drying rate.

Ernst, Ridgway and Tiller (1938) stated that drying in a vacuum could be used to dry substances that decompose or undergo undesirable physical changes at high temperature. Their results indicated that there was little change in the rate of drying when the vacuum was changed, when there is a large difference between the boiling point of the water at the drier pressure and the plate temperature. The rate of drying depended more on the plate temperature than on the vacuum.

EQUIPMENT

The shelled corn was dried on a 0.040 inch thick steel plate suspended above a 220 volt hi-speed calrod burner hot plate. The plate temperature was regulated by changing the height of the heated plate above the burner. Five light bulbs were connected in parallel and operated through an electrical volt meter to control the voltage to the hot plate and thus provide a control of the temperature by changing the size of the light bulbs.

The temperature was measured by a thermometer set in a 1/4 inch piece of steel drilled out to the size of the thermometer bulb and placed on the heated plate.

The samples removed during drying were weighed before and after oven drying on a Mettler Analytical Balance.

After the initial weighing the samples were dried in a Precision Scientific Air-oven.

Air from a compressed air line was dispersed in a 9 inch x 16 inch x 20 inch plenum chamber before being blown 2 inches above and parallel to the corn for several of the runs. The air velocity was controlled by a valve in the line and measured with a Hastings Air Meter.

The experimental set-up is shown in Figure 1.

EQUIPMENT LIST

Hot plate (to heat the drying plate)
  Hi-speed calrod burner
  Size: 220 volt

Plenum Chamber (to get uniform air flow)
  9 inches x 16 inches x 20 inches

Air Meter (to measure rate of air flow)
  Make: Hastings
  Model: G-5
  Manufacturer: Hastings Instrument Co., Hampton, Virginia

Volt-Amp Meter (to maintain constant voltage to hot plate)
  Make: Weston Industrial Analyzer
  Model: 639
  Type: 2
  Number: 4161
  Manufacturer: Weston Electrical Instrument Corporation, Newark, New Jersey

Analytical Balance (to weigh samples)
  Make: Mettler
  Accuracy: 0.00005 gram
  Manufacturer: Mettler Instrument Corporation, Highstown, New Jersey

Drying Air-oven (for removal of moisture in samples)
  Type: Air
  Manufacturer: Precision Scientific Co., Chicago, Illinois

Variac (to regulate heating for convection drying)
  Size: 0-130 Volts

Hair Dryer (for convection drying)
  Make: Kenmore
  Model: 559830

Psychrometer (to obtain relative humidity)
  Type: sling

Thermometers (for temperature measurement)
  Size: 0-230°F

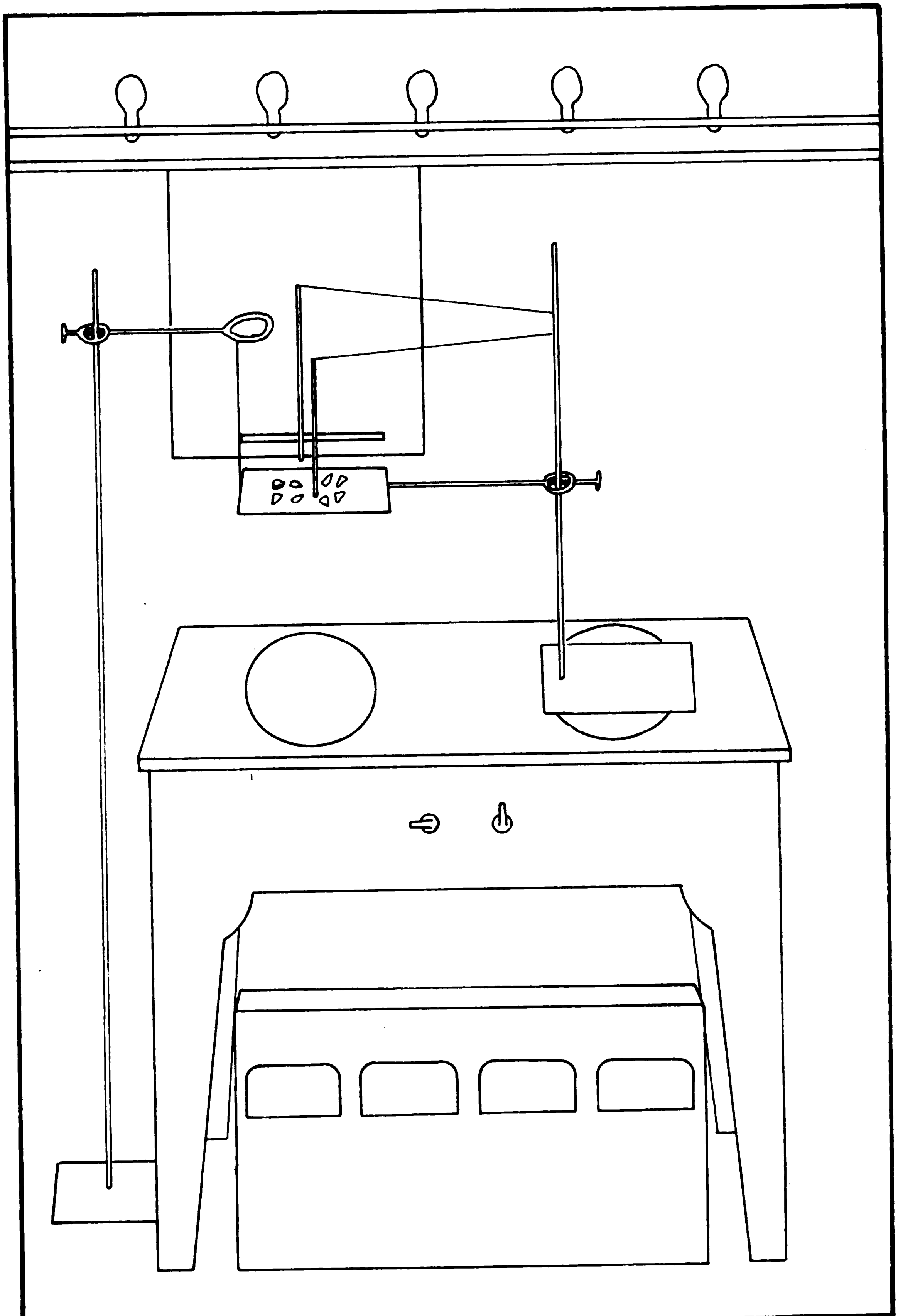


Figure 1. Sketch of experimental set-up used for conducting the investigation.

PROCEDURE

All corn used in the drying portions of this experiment was hand shelled Pfister's Hybrid 244P yellow dent corn. It was shelled on 12 September 1959, when it contained approximately 56 percent moisture, d.b., and placed in a zero degree Fahrenheit cold storage box. One week prior to being used in the experiments, the corn was placed in the 40°F cold storage box.

The corn was removed from the 40°F box and placed on the heated plate. A 10 second time period was allowed before starting the time for drying during which the kernels were flattened on the hot plate in a single layer. At each time interval a sample of six kernels selected randomly were removed. The sample was placed in a closed metal container and allowed to cool 10 minutes before weighing on the analytical balance. After weighing, the sample was placed in a 212°F drying oven for 72 hours. After oven drying, 10 minutes were allowed to permit the sample to cool before reweighing to get the dry matter weight. This procedure was repeated for each sample. Four runs were made for each drying condition.

Air from a compressed air line was used to increase the velocity across the shelled corn while drying for some of the runs.

Samples from several of the runs were cut into various parts after drying to determine the drying effect throughout the kernel. The notation for each part of the kernel is shown in Figure 2. Runs were also made to determine if the drying rate was the same whether the kernel was lying with its white or yellow side against the heated plate.

The equilibrum moisture contents for the four plate temperatures were found by drying the shelled corn on the heated plate until no further significant amount of moisture was lost by the sample.

In order to obtain the drying rates the data obtained from the drying runs was plotted on semi-logarithmic graph paper. Values of moisture content ratio, $(M-M_e)/(M_o-M_e)$, were plotted as the ordinate on the logarithmic scale against drying time on the arithmetic scale. The plots resulted in straight lines over limited portions of the curve with sharp changes in the slope between the straight line portions of the curve. The results show that the drying of shelled corn by conduction heating obeys the equation $(M\text{-}Me)/(Mo\text{-}Me)=e^{-k\theta}$, which is analogous to Newton's law of cooling, where k is valid over limited ranges of moisture content.

The drying rate expression is obtained by differentiating with respect to time the equation:

$$(M\text{-}Me)/(Mo\text{-}Me) = e^{-k\theta} \tag{1}$$

$$(M\text{-}Me) = (Mo\text{-}Me)e^{-k\theta} \tag{2}$$

$$M = (Mo\text{-}Me)e^{-k\theta} + Me \tag{3}$$

$$\frac{dM}{d\theta} = -k\ (Mo\text{-}Me)\ e^{-k\theta} \tag{4}$$

Substituting equation (2) into equation (4) results in:

$$\frac{dM}{d\theta} = -k\ (M-Me) \qquad (5)$$

which states that the drying rate is directly related to the free moisture content and the drying constant k, where k is the slope of the straight line portions of the semi-logarithmic plots. The values of k were calculated for the four plate temperatures and are listed in figure 3. The values of k were generally higher for the higher plate temperatures. The discovery of four falling rate periods, corresponding to the four k values agreed with Hall (1957) who first reported that corn above 25 percent d.b. moisture content has a falling rate period of drying subdivided into four periods.

To compare conduction drying with convection drying, corn of the same variety and moisture content was dried in thin layers by the use of convection heating in runs 88-95. This was accomplished by forcing air at the rate of 235 fpm through the single layer of corn with a hair dryer. The temperature was controlled by a Variac controlling the voltage to a heating element which heated the inlet air to the dryer to get the 229°F and 189°F air temperatures. The 144°F and 104°F air temperatures were obtained by controlling the hair dryer heating element with a Variac. A sample of approximately 10 grams was placed in a wire basket suspended in the heated air stream. The basket was removed from the air stream and weighed periodically during the drying process.

After the heated air drying process the samples were placed in the air oven for 72 hours so the weight of dry matter of the sample could be determined. The times for drying by convection were the same as those used for the conduction drying.

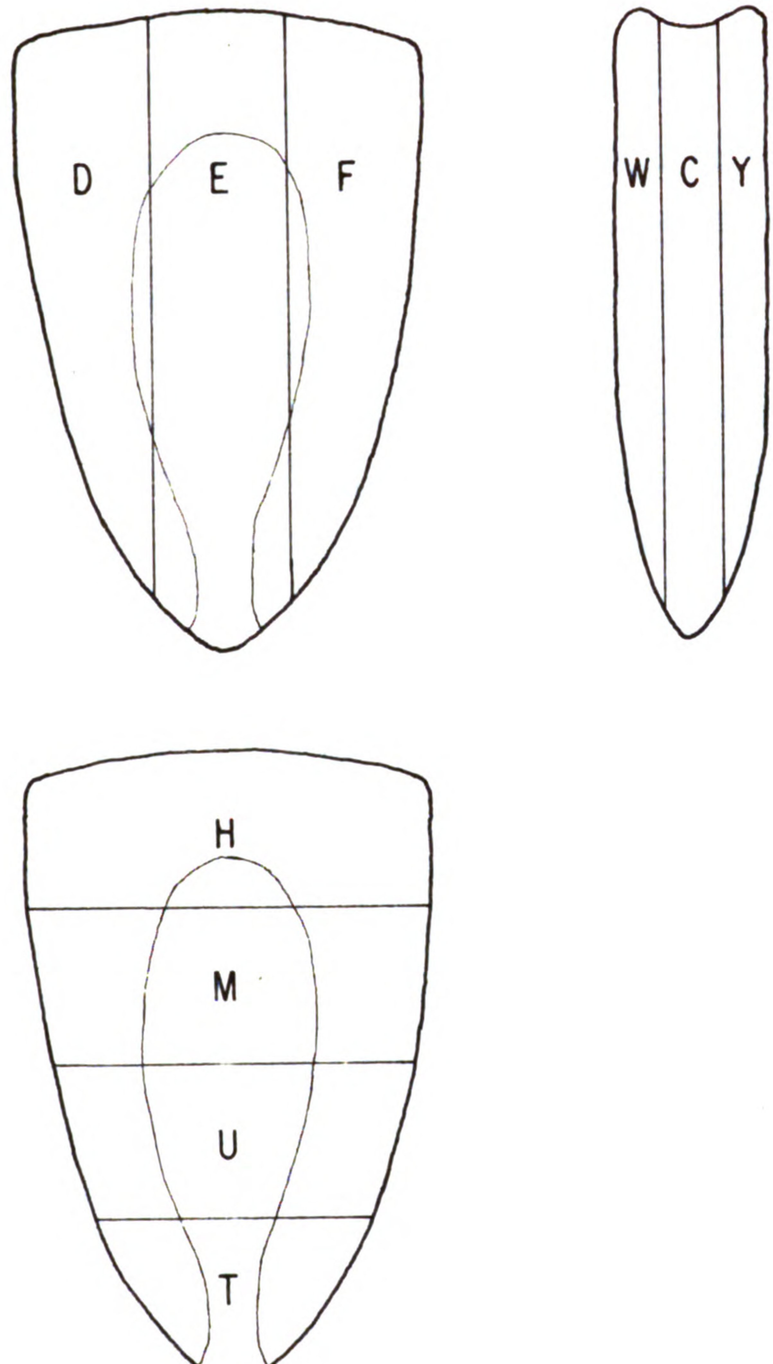


Figure 2 Sketch of kernel as divided into parts during the investigation.

DISCUSSION AND RESULTS

The drying rate periods consisted of four falling rate periods. This was in agreement with Hall (1957), who stated that the initial moisture content is usually less than the critical moisture content, therefore, all the drying would take place in the falling rate period.

Runs one through four at 229°F plate, runs five through nine at 189°F plate, runs 10-13 at 144°F plate and runs 14-17 at 104°F plate gave quite consistent results within each group.

Runs 18-21 had 100 fpm forced air of about 35 percent relative humidity parallel and two inches above the 229°F plate and did not dry as rapidly as runs 22-25 with 50 fpm or runs 26-29 with 25 fpm. This was caused by the high velocity air cooling the plate off and allowing less heat to be transferred to the kernel. The 229°F plate runs with forced air at 100 fpm never came back up to 229°F after the initial drop to 154°F in plate temperature, but attained a temperature of approximately 186°F. The 229°F plate temperature after the initial drop in plate temperature to approximately 173°F which was the same as for the zero fpm runs. Using forced air at 100 fpm was, in effect, the same as using a lower plate temperature. The work done by King and Newitt (1955) showed that a faster rate of drying was obtained by using forced air across the product in combination with the conduction heating. This occurred because they maintained a constant temperature on the plate by supplying more energy during the drying periods which would cause the plate temperature to decrease. The runs without any forced air across the 229°F plate dried as fast as those with air. This would indicate that the convection current set up by the 229°F plate was sufficient to carry away the moisture as fast as it was evaporated from the kernel.

Runs 30-33 with forced air at 25 fpm and runs 35-38 with forced air at 50 fpm dried at the same rate as runs five-nine which didn't have forced air across the 189°F plate. This indicated the moisture was carried away rapidly enough by the natural convection current at 189°F. Runs 34 and 39 with forced air at 100 fpm dried at a slower rate than those without forced air: here again, the additional air flow did not have the drying capacity to make up for the loss of heat from the plate. The 189°F plate runs with forced air at 100 fpm had an initial drop in plate temperature to 143°F and then attained a maximum of 171°F. The 50 fpm runs cooled the plate below the 189°F set point, but still dried as fast as the 25 fpm and natural convection runs at 189°F plate. The 189°F plate runs with forced air at 50 fpm had an initial drop in plate temperature to 149°F and then attained a maximum of 183°F. The 189°F plate with forced air at 25 fpm had an initial drop to 154°F and then attained the 189°F temperature.

Using the 144°F plate, the runs from 40 through 43 with 25 fpm forced air dried at the same rate as the runs without forced air. The 144°F plate runs with forced air at 25 fpm had an initial drop in plate temperature to 120°F and then attained the 144°F temperature. The 144°F plate runs with forced air at 50 fpm had an initial drop in plate temperature to 112°F and then attained a plate temperature of 131°F with the drying rate less than that obtained with natural convection.

With the 104°F plate it was not necessary to use forced air as the runs 48 through 51 with 25 fpm forced air dried at a slower rate than runs 14 through 17 in which the natural convection was not supplemented with forced air. The 104°F plate runs with forced air at 25 fpm had an initial drop in plate temperature to 91°F and then attained the 104°F temperature.

In all cases, the natural convection currents rising from the heated plate were sufficient to carry the moisture away as fast as it was being evaporated from the kernel. When the corn was placed on the plate there was an immediate drop in the temperature of the plate to a minimum and then a continuous rise till the original plate temperature, or a lesser value in some of the forced air runs, was reached with the temperature remaining constant during the remainder of the drying period. Shroff (1949) and Tambling (1953) experienced the falling temperature and then the rising temperature, after drying had progressed, that was experienced in all the drying runs.

The question of whether the drying rate was affected by the position of the kernel was investigated next. Using whole kernel samples in runs 52, 53, 56 and 57, it was found that the drying rate was not affected whether the W or Y side was against the heated surface. This promoted the theory that the moisture moved from head end to tip end to get out of the kernel during the drying process. This theory was substantiated visibly by putting hot kernels in colodium; moisture bubbles could be seen leaving the kernel from the tip end.

An additional plate was placed on top of the kernels being dried in runs 60-61 to try to utilize more of the heat from the lower plate. The drying rate was increased, but excessive discoloration of the kernels resulted. In runs 62-63, a screen with 50 percent openings was placed on top of the kernels which resulted in a small increase in drying rate over runs 5, 6, 7, and 8, but there was still excessive discoloration of the kernels.

During the course of the investigation an attempt was made to determine where the moisture was concentrated in the kernel and the effect of this on the drying rate. Undried kernels were cut into three parts, W, C, and Y, as shown in Figure 2. It was found that the W side contained the highest moisture content with about 68 percent moisture content d.b. and the Y side the least with 45 percent d.b. The C portion contained approximately 55 percent d.b. Other undried kernels were cut into four parts, H, M, U, and T, as shown in Figure 2. These results showed that the T portion contained the highest percentage of moisture with U, H, and M, following in decreasing order. The T part contained 85 percent d.b., the U had approximately 60 percent d.b., H had approximately 46 percent d.b., and M had approximately 42 percent d.b. Several other varieties of yellow dent corn were examined by the same methods with similar results. When the kernels were cut into portions D, E, and F, (figure 2) the E portion had a considerable higher moisture content than the D and F sections. This was expected since the E portion contained most of the T part and the wetter part of the W side. For approximately 56 percent d.b. corn, side D and F contained about 40 percent moisture content and the E portion contained approximately 64 percent d.b. The next step was to cut up kernels during the drying operation to see which part of the kernel dried the fastest and how the moisture moved through the kernel, whether from the heated side upward or from end to end.

Runs 54, 55, 58, 59, 65, 74, 75, 78, 80 and 82 through 87 were to determine the drying rate of the various parts of the kernel. The drying rates of the H, M, U, and T, parts were uneffected regardless of whether the white or yellow side was against the heated plate. With the white side in contact with the heated plate, the white side, which had the highest moisture content originally, had a faster drying rate and dried to a lower moisture content than the yellow side by approximately 5 percent, d.b. When the drier yellow side was in contact with the heated plate the drying rate of the two sides were almost equal with the yellow side being the driest, at the end of the drying period, by about 1 percent, d.b.

From the drying curve of the parts of the kernel it would seem that the moisture moves from the H section to the T section. On the composite plot of the H, M, U, and T, sections of runs 75, 79, 83, and 87, it can be seen that at the end of 20 minutes the H portion had dried at a faster rate than the U and M portions and is the driest of all 4 portions of the kernel. The T portion, containing material more conducive to drying, has the lowest moisture content of the sections after about 1 hour. The H section is drier than the M and U section until 2 hours, after which the 3 portions are at approximately the same moisture content.

Figure 3 shows the semi-logarithmic plot of conduction versus convection drying and lists the k-values. The range of applicability of the k-value for conduction drying are as follows:

Table 1. Range of applicability (percent, d.b.) of the k-value for conduction drying.

	229°F	189°F	144°F	104°F
k_1	54.9-43.12	55.42-45.36	55.88-48.09	56.03-49.50
k_2	43.12-26.59	45.36-29.34	48.09-31.87	49.50-31.85
k_3	26.59-16.68	29.34-16.76	31.87-20.70	31.85-13.71
k_4	16.68-8.51	16.76-9.16	20.70-10.90	13.71-8.88

Figure 4 shows that convection drying was faster, at the beginning of drying, than conduction, but was slower after a certain time had elapsed. For the 229°F temperature, conduction drying was faster than convection drying after 20 minutes, for 199°F after 64 minutes, for 144°F after 116 minutes and for 105°F after 10 hours. The saving of time for drying to 18.3 percent, d.b. and 15 percent, d.b., which are the moisture contents generally accepted for selling and storage, respectively, are listed in Table 6. With the exception of drying to 18.3 percent, d.b. from approximately 56 percent, d.b. at 104°F, conduction drying is faster than convection drying at the same temperature. Robertson (1959) experienced the same crossing of the conduction and convection drying curves at a temperature of 135°F.

Tables 2 through 5 summarize the data obtained with the four plate temperatures at zero fpm. additional air flow.

Figures 5 through 15 are a graphical representation of the data taken during the conduction drying part of the investigation.

Table 2. Summarization of Moisture Contents from the Data

		229°F Plate		No Forced Air		
Time min.	Plate °F	Run 1 d.b.	Run 2 d.b.	Run 3 d.b.	Run 4 d.b.	Average d.b.
0	229	54.16	54.96	54.92	55.92	54.99
1	172	51.31	48.59	48.09	52.65	50.16
3	185	53.21	49.59	47.21	46.96	49.24
5	190	43.06	44.31	44.66	41.68	43.43
7	201	43.14	42.01	42.95	36.99	41.27
10	210	36.42	33.52	37.05	39.92	36.73
15	219	32.49	31.93	29.02	31.35	31.20
20	225	28.00	25.68	26.77	27.66	27.03
25	227	28.04	26.29	22.11	26.67	25.78
30	229	23.18	22.72	20.34	22.46	22.18
40	230	17.43	19.51	15.88	16.39	17.30
50	228	15.25	16.09	13.87	14.00	14.80
60	229	13.47	11.38	11.59	11.54	12.00
80	230	10.60	8.47	10.25	13.20	10.63
100	229	10.01	8.85	6.83	8.35	8.51

Me = .17 percent d.b.

Table 3. Summarization of Moisture Contents from the Data

Time min.	Plate °F	189°F Plate Run 5 d.b.	Run 6 d.b.	No Forced Air Run 8 d.b.	Run 9 d.b.	Average d.b.
0	189	54.65	56.47	55.95	54.61	55.42
1	140	53.66	55.57	51.88	50.52	52.91
3	146	51.62	50.37	52.65	49.29	51.98
5	154	50.83	51.77	50.27	51.05	50.98
7	171	47.75	45.60	43.99	49.57	46.73
10	176	47.75	50.93	41.78	42.07	43.13
15	183	41.73	36.89	37.10	38.52	38.56
20	187	39.11	34.35	35.77	35.07	36.08
25	189	33.88	31.35	31.43	-----	32.22
30	189	32.09	28.67	27.09	27.93	28.95
40	189	28.94	26.49	24.84	25.07	26.39
50	190	25.68	22.22	22.03	-----	23.31
60	189	24.23	20.23	20.79	20.88	21.53
80	188	17.71	18.61	15.42	15.73	16.87
100	189	15.56	15.82	14.62	-----	15.33
120	190	-----	-----	12.94	12.37	12.65
160	188	-----	-----	-----	10.07	10.07
200	189	7.76	8.33	8.37	9.67	9.16

Me = 1.06 percent d.b.

Table 4. Summarization of Moisture Contents from the Data

		144°F Plate		No Forced Air		
Time min.	Plate °F	Run 10 d.b.	Run 11 d.b.	Run 12 d.b.	Run 13 d.b.	Average d.b.
0	145	56.07	54.12	56.53	56.79	55.88
2	120	56.09	56.47	53.08	54.72	55.09
5	130	55.52	54.89	56.37	52.87	54.91
10	134	49.42	51.47	48.76	48.59	49.56
15	136	48.06	49.19	46.31	49.06	48.16
30	144	41.78	40.86	37.30	42.79	40.68
45	145	37.77	38.11	33.75	32.94	35.64
60	143	30.05	34.61	32.75	29.59	31.78
75	145	28.55	28.02	30.97	26.49	28.51
90	144	24.60	24.57	27.39	24.97	25.38
120	144	19.34	23.17	20.79	20.60	20.98
150	145	18.37	18.76	17.59	16.59	17.83
180	143	16.07	17.11	16.11	15.42	16.18
210	144	17.64	14.42	13.83	14.67	15.14
240	144	11.89	12.76	13.39	13.31	12.84
310	144	-----	-----	11.62	10.18	10.90

Me = 2.39 percent d.b.

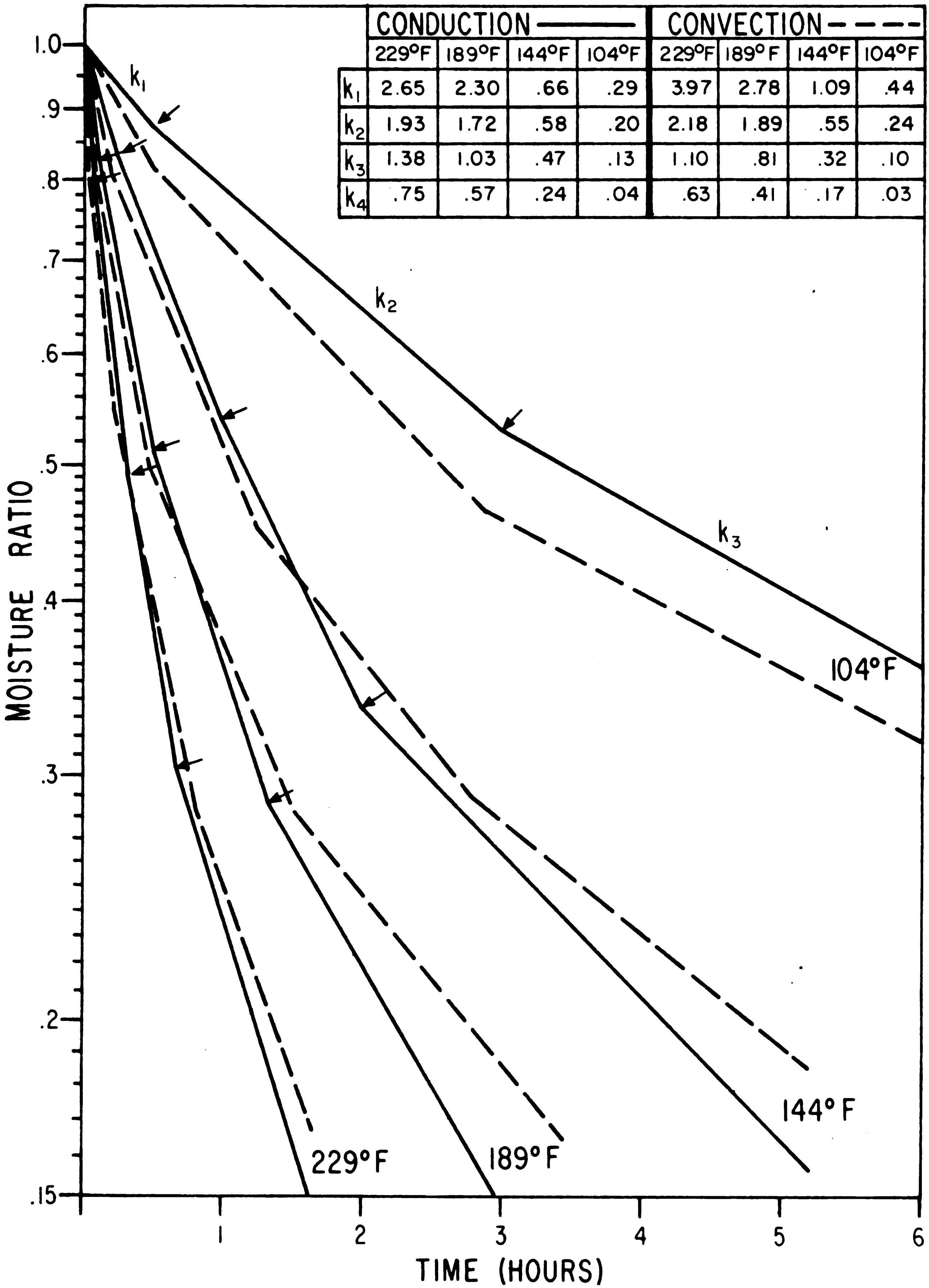
Table 5. Summarization of Moisture Contents from the Data

		104°F Plate		No Forced Air		
Time min.	Plate °F	Run 14 d.b.	Run 15 d.b.	Run 16 d.b.	Run 17 d.b.	Average d.b.
0	104	55.74	54.99	55.80	57.59	56.03
5	94	54.35	51.08	59.87	56.41	55.43
10	99	50.10	54.32	51.33	53.45	52.30
20	101	52.09	52.54	51.30	53.24	52.29
30	104	48.09	50.11	49.44	52.27	47.48
60	103	46.28	48.43	46.72	47.72	47.29
90	105	42.59	39.85	40.22	42.44	41.28
120	104	36.54	38.19	36.32	35.71	36.69
150	105	33.29	34.04	36.06	37.57	35.24
180	104	31.89	31.68	29.76	32.92	31.56
240	103	30.84	27.04	27.42	28.88	28.55
300	104	24.41	24.54	25.82	26.10	25.22
360	104	23.77	20.77	24.03	24.43	23.25
480	105	17.63	20.93	17.07	19.16	18.70
600	105	15.57	14.50	15.10	17.09	15.57
720	104	13.62	11.93	13.25	15.67	13.62
840	103	12.39	10.24	12.30	14.30	12.31
1190	104	12.19	-----	-----	-----	12.19
1440	104	-----	10.37	-----	-----	10.37
1560	103	-----	-----	-----	9.04	9.04
1620	104	-----	-----	8.88	-----	8.88

Me = 4.30 percent d.b.

Table 6. Summarization of the Reduction of Drying Time by Using Conduction Drying to Replace Convection Drying

Temp °F	Condition	From 56% d.b. to % d.b.	Time min.	Reduction in Time Percent
229	Convection	18.3	39	-
229	Convection	15.0	54	-
189	Convection	18.3	79	-
189	Convection	15.0	111	-
144	Convection	18.3	172	-
144	Convection	15.0	226	-
104	Convection	18.3	420	-
104	Convection	15.0	655	-
229	Conduction	18.3	36	8.5
229	Conduction	15.0	49	10.2
189	Conduction	18.3	74	6.7
189	Conduction	15.0	96½	15.1
144	Conduction	18.3	160	7.5
144	Conduction	15.0	194	16.5
104	Conduction	18.3	492	-14.6
104	Conduction	15.0	635	3.2
189	Cond. with plate above	18.3	64	23.4
189	Cond. with plate above	15.0	73	52.1
189	Cond. with screen above	18.3	68	16.2
189	Cond. with screen above	15.0	83	45.8



	CONDUCTION ———				CONVECTION - - -			
	229°F	189°F	144°F	104°F	229°F	189°F	144°F	104°F
k_1	2.65	2.30	.66	.29	3.97	2.78	1.09	.44
k_2	1.93	1.72	.58	.20	2.18	1.89	.55	.24
k_3	1.38	1.03	.47	.13	1.10	.81	.32	.10
k_4	.75	.57	.24	.04	.63	.41	.17	.03

Figure 3. Semi-logarithmic plot comparing conduction and convection drying of shelled corn

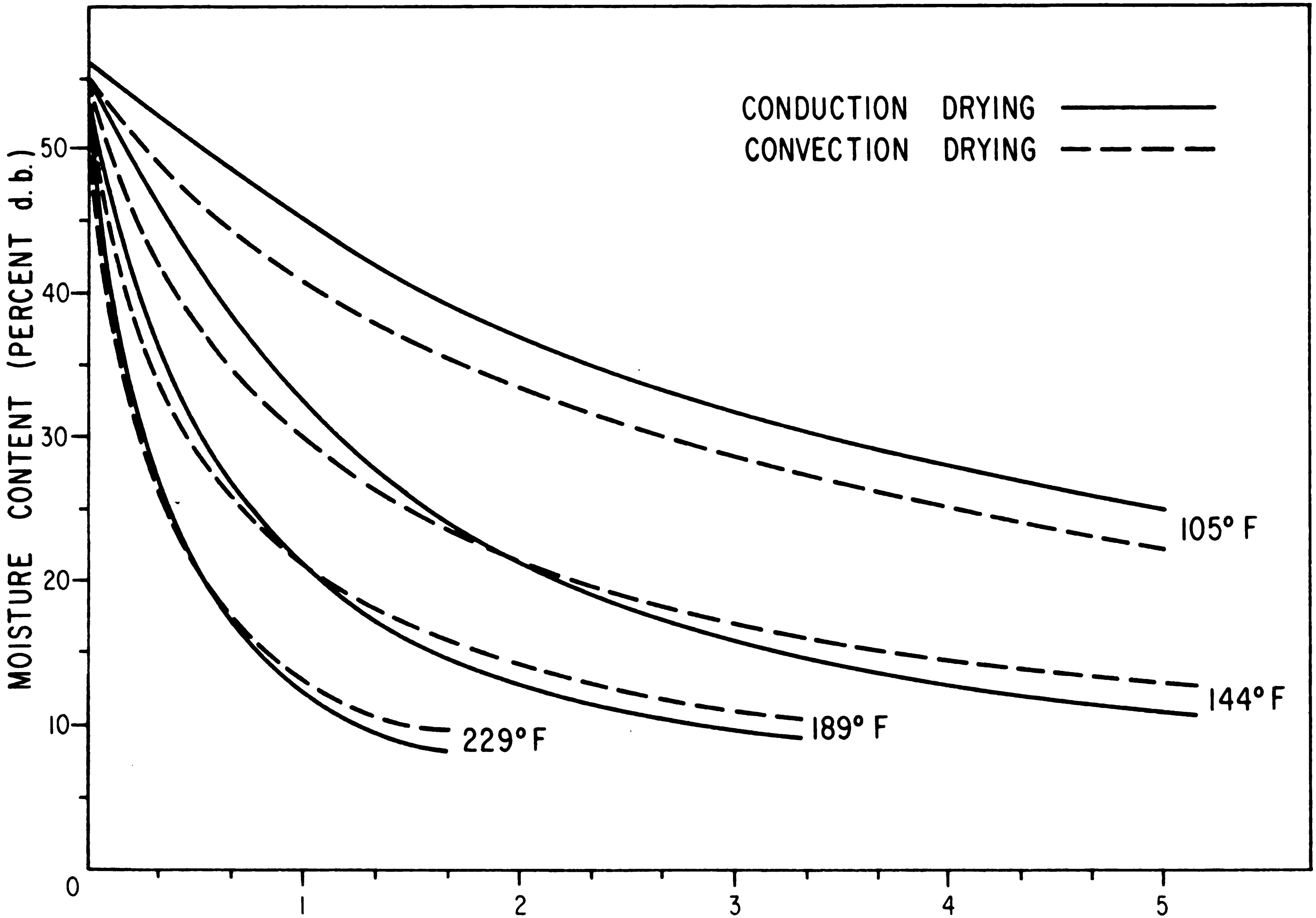


Figure 4. Comparison of conduction and convection drying of shelled corn

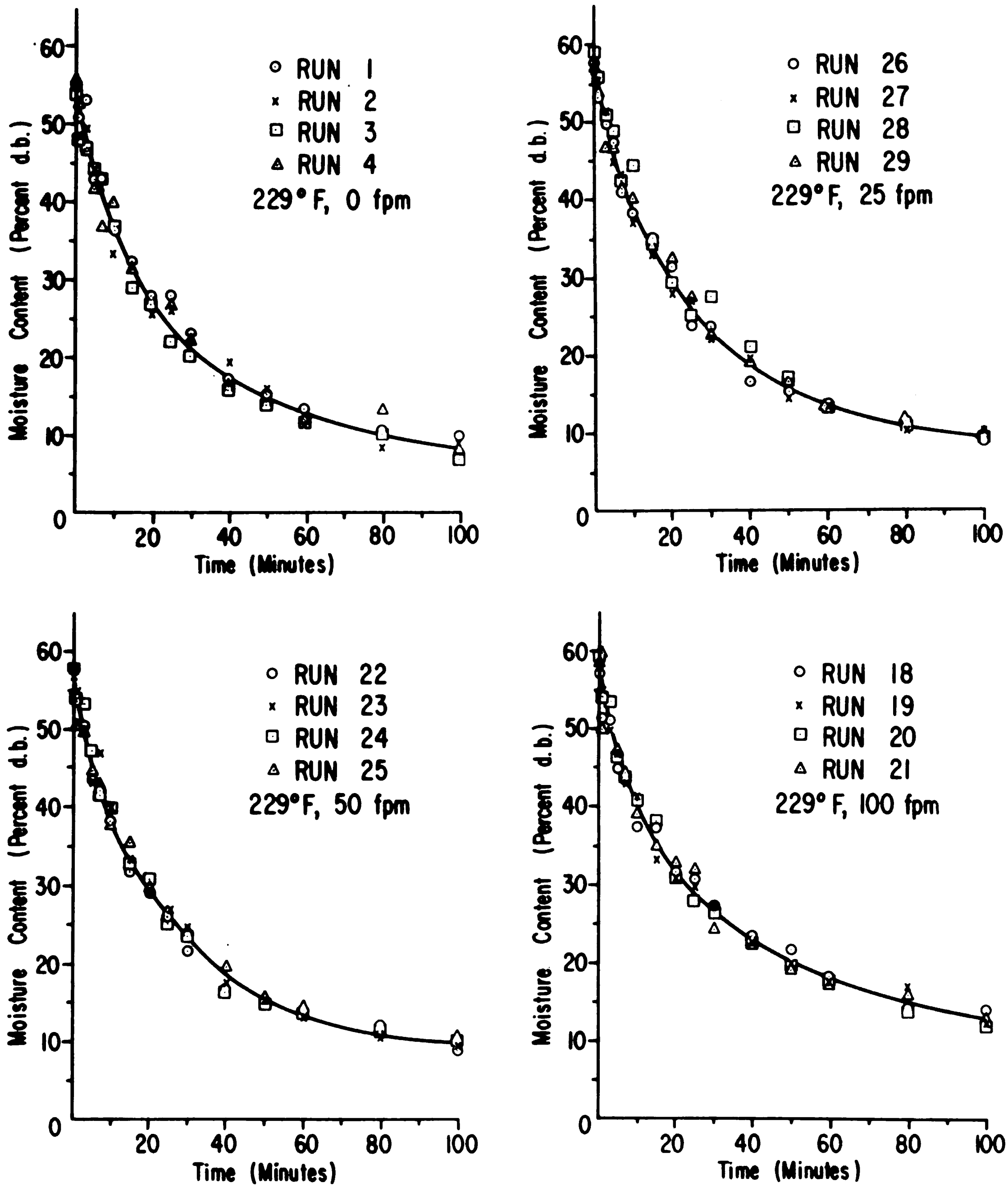


FIGURE 5. DRYING SHELLED CORN WITH 229 °F CONDUCTION HEATING AND 0, 25, 50 AND 100 FPM AIR

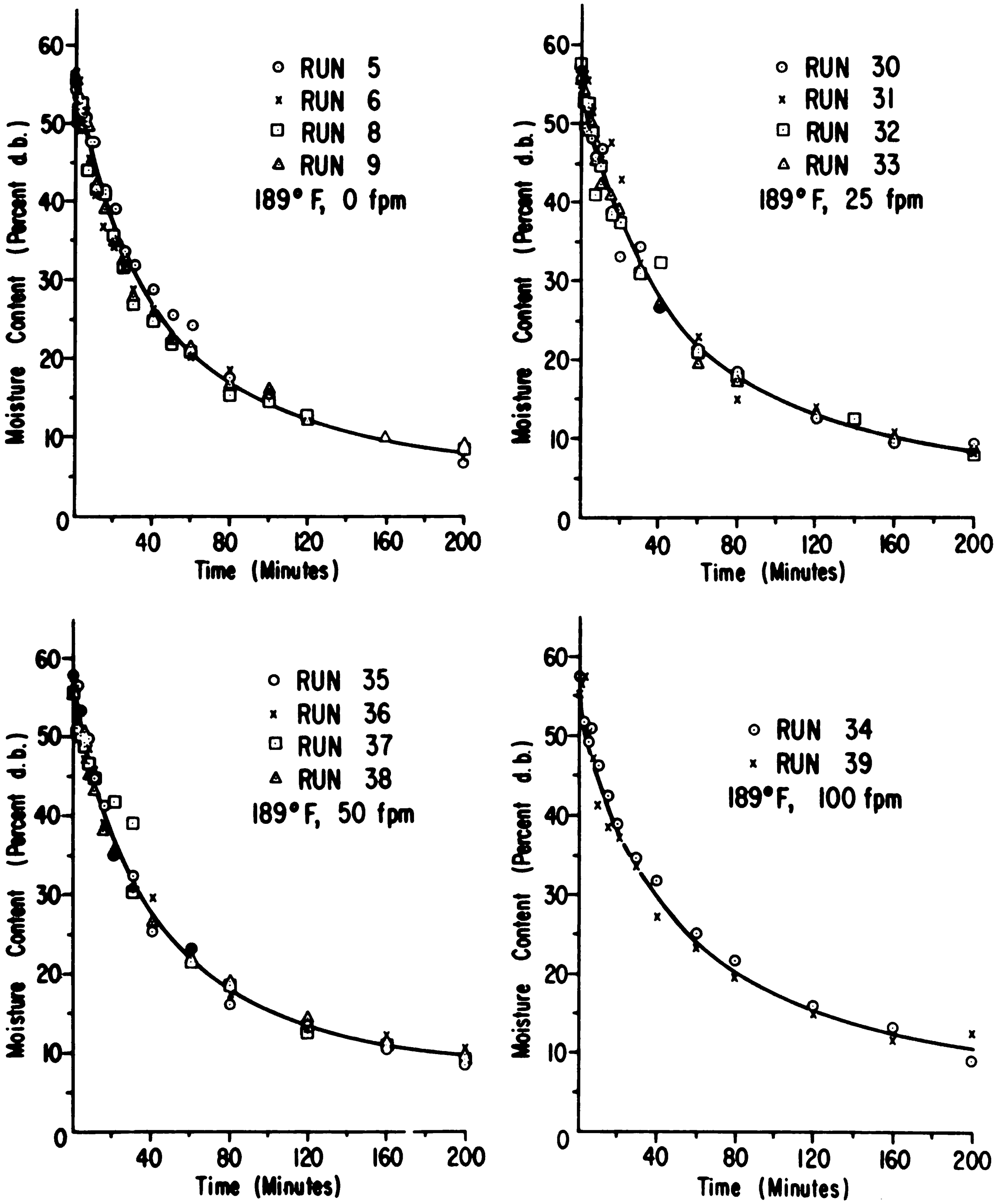


FIGURE 6. DRYING SHELLED CORN WITH 189 °F CONDUCTION HEATING AND 0, 25, 50 AND 100 FPM AIR

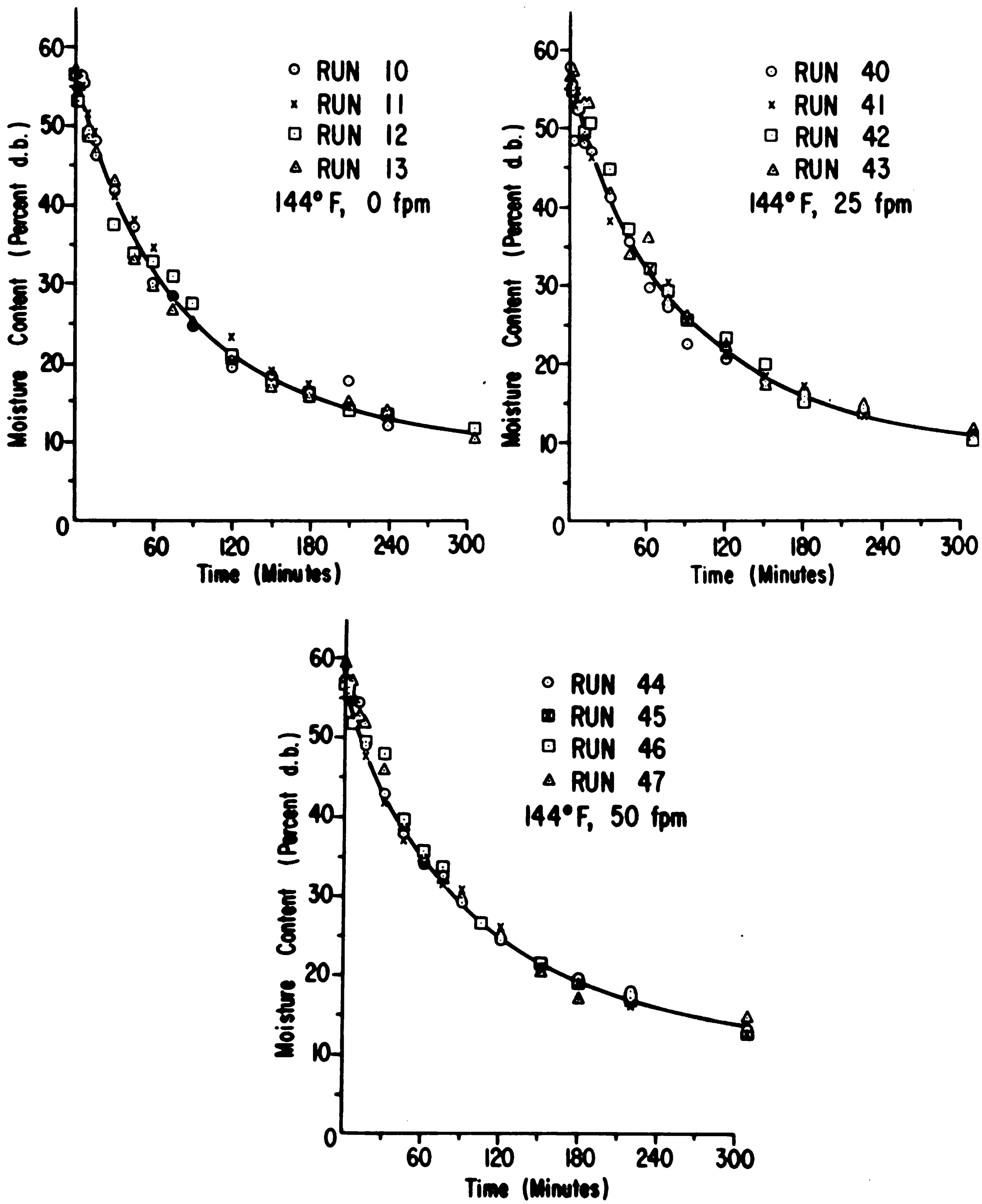
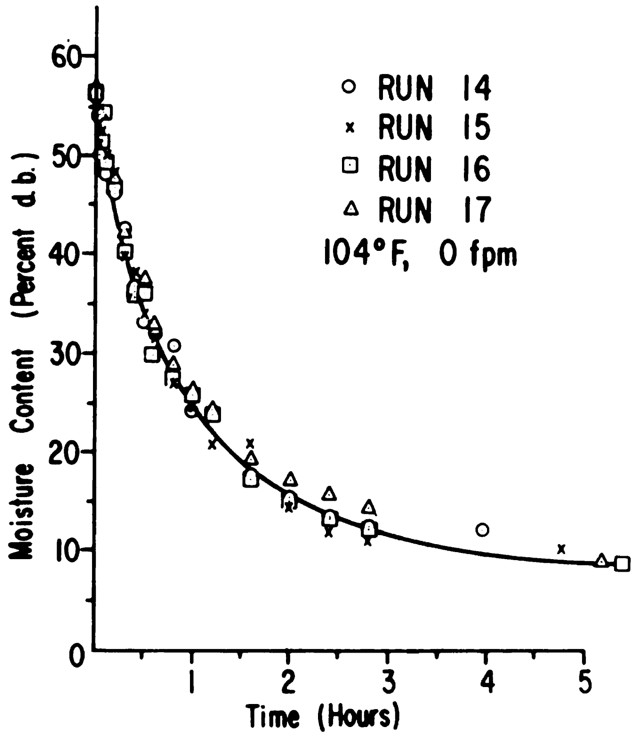


FIGURE 7. DRYING SHELLED CORN WITH 144 °F CONDUCTION HEATING AND 0, 25 AND 50 FPM AIR



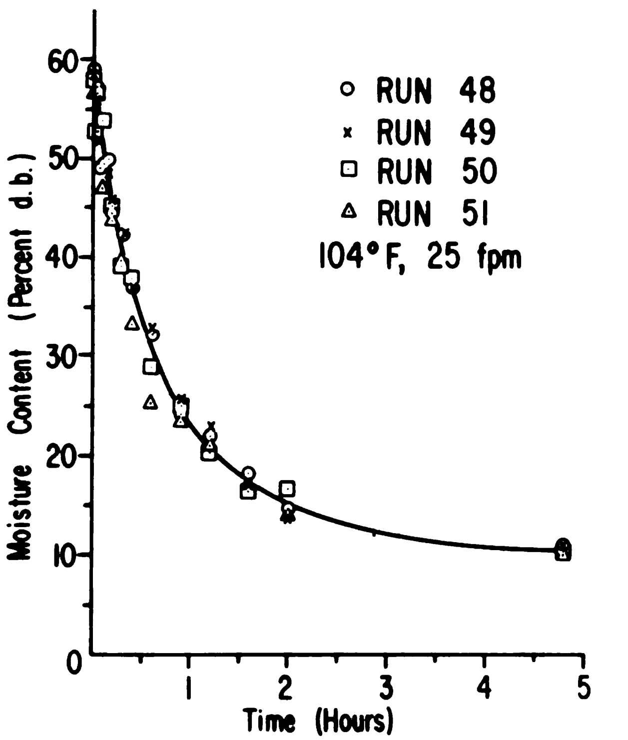
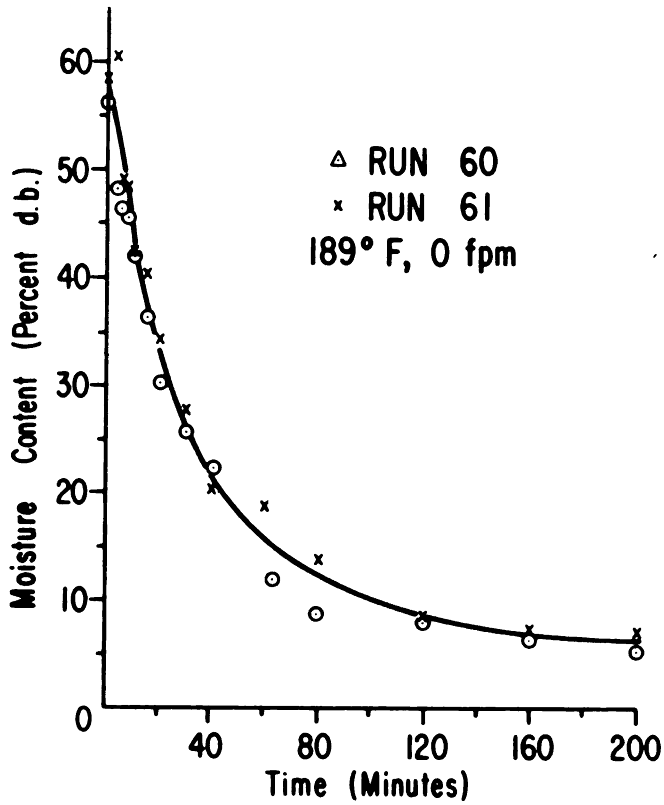


FIGURE 8. DRYING SHELLED CORN WITH 104 °F CONDUCTION HEATING AND 0 AND 25 FPM AIR



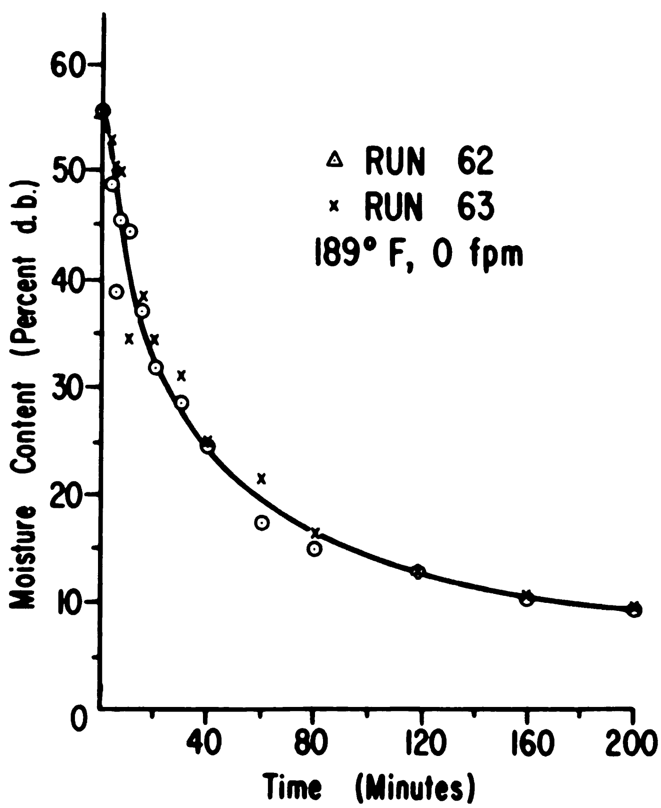


FIGURE 9. DRYING SHELLED CORN ON 189 °F CONDUCTION HEATING PLATE WITH ADDITIONAL PLATE ABOVE KERNELS

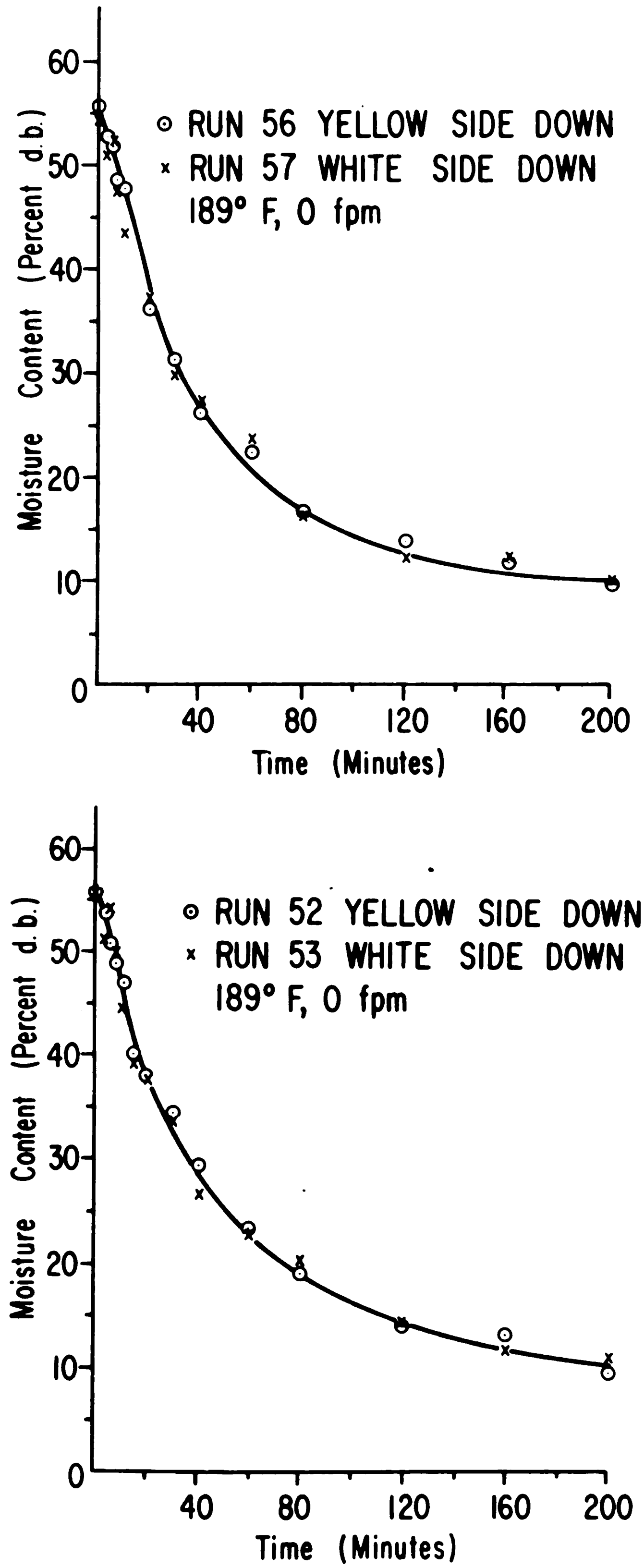


FIGURE 10. DRYING SHELLED CORN ON 189 °F CONDUCTION HEATING PLATE WITH WHITE OR YELLOW SIDE OF KERNEL DOWN

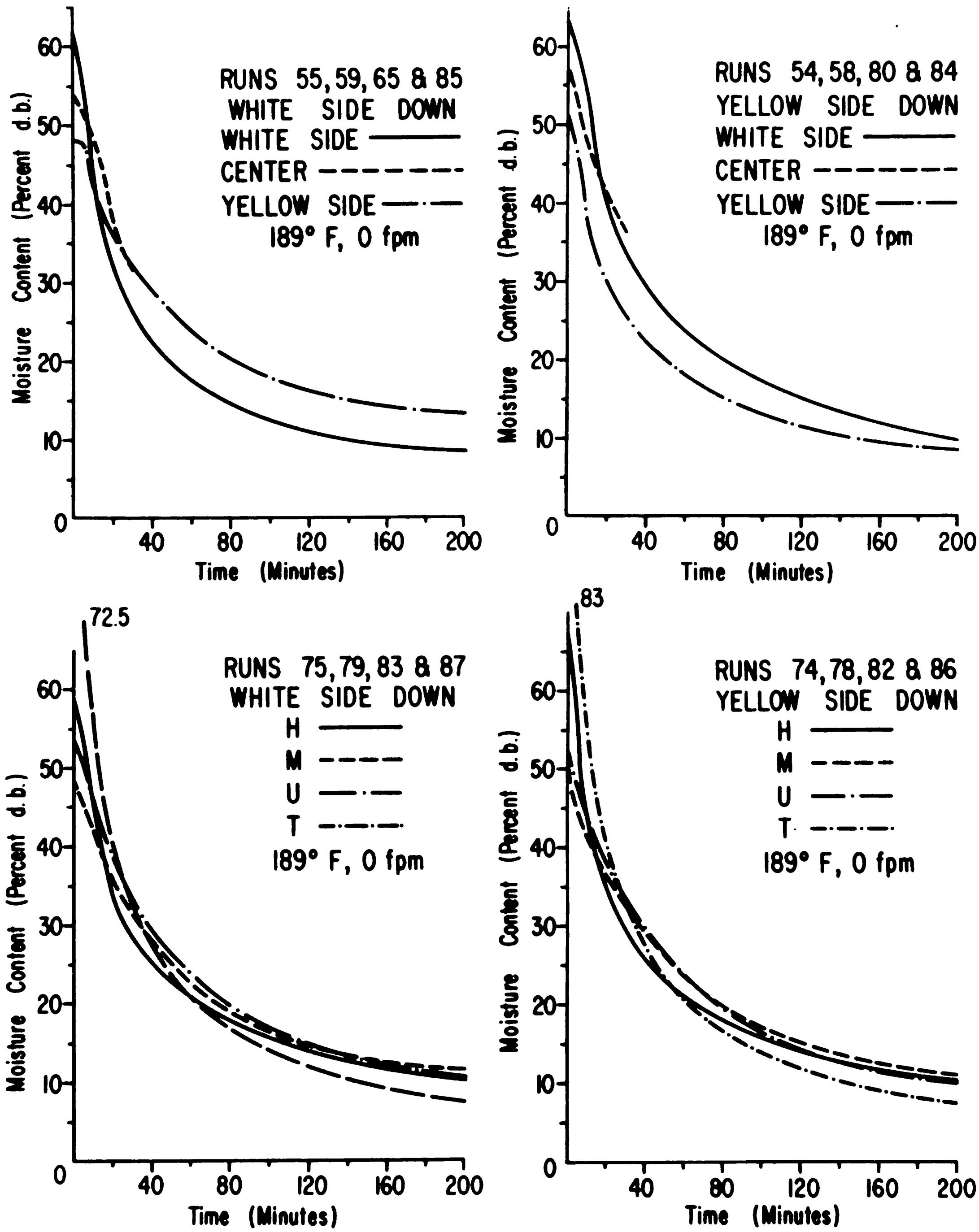


FIGURE 11. DRYING SHELLED CORN ON 189 °F CONDUCTION HEATING PLATE, WHITE OR YELLOW SIDE OF KERNEL DOWN, WITH AVERAGE MOISTURE CONTENTS OF THE VARIOUS SECTIONS OF THE KERNEL DETERMINED

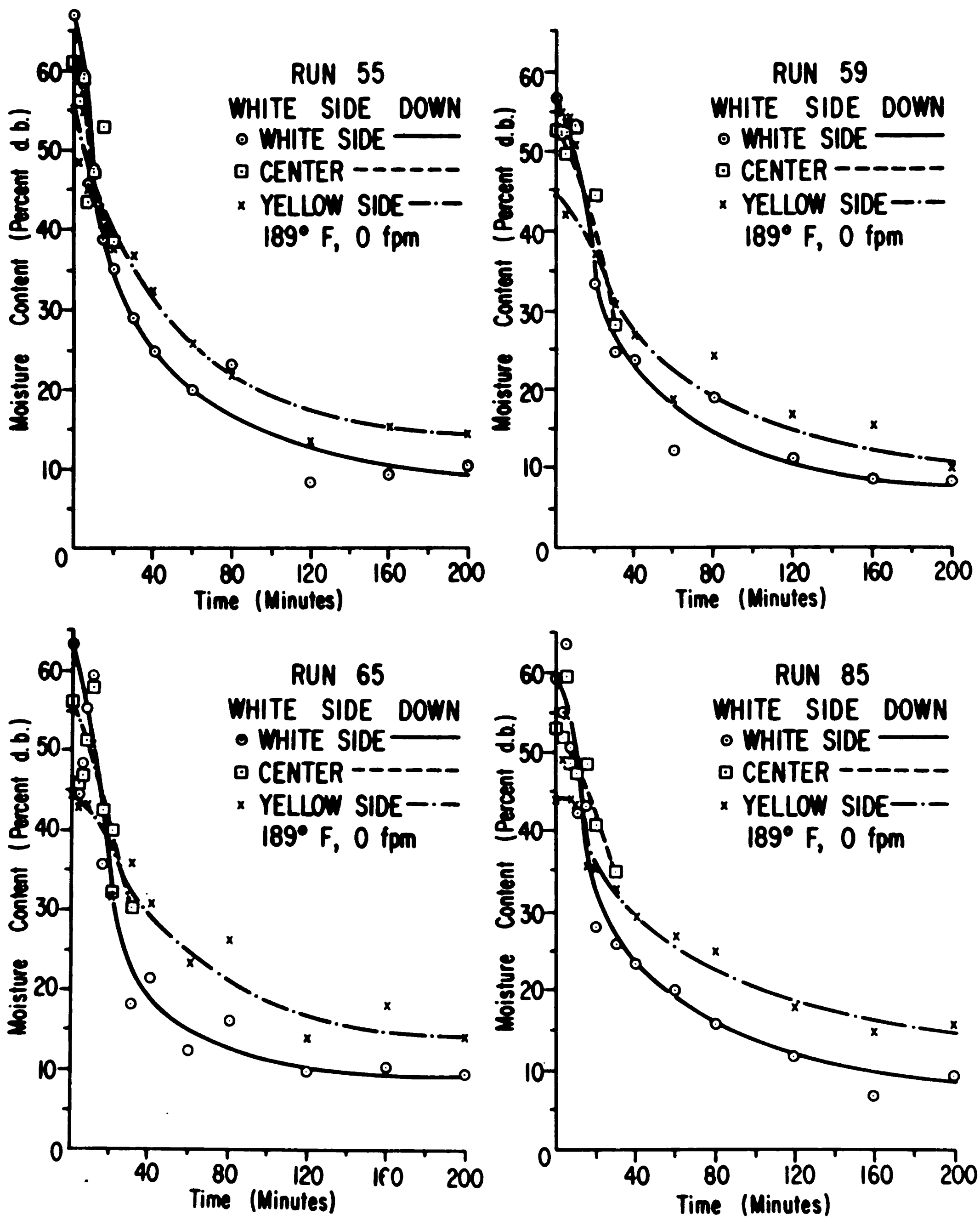


FIGURE 12. DRYING SHELLED CORN ON 189 °F CONDUCTION HEATING PLATE, WHITE SIDE OF KERNEL DOWN, WITH MOISTURE CONTENT OF W, C AND Y SECTIONS OF THE KERNEL DETERMINED

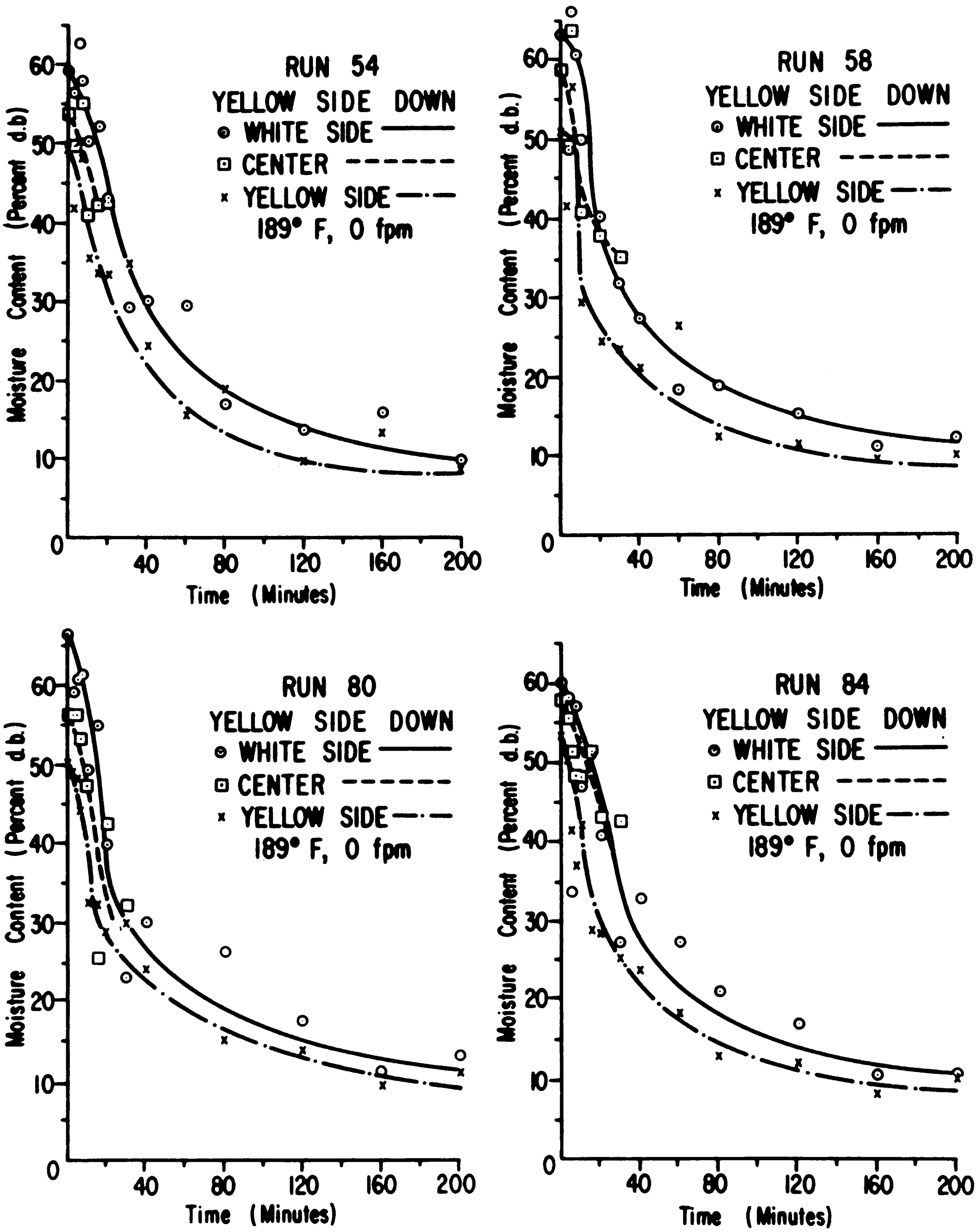


FIGURE 13. DRYING SHELLED CORN ON 189 °F CONDUCTION HEATING PLATE, YELLOW SIDE OF KERNEL DOWN, WITH MOISTURE CONTENT OF W, C AND Y SECTIONS OF THE KERNEL DETERMINED

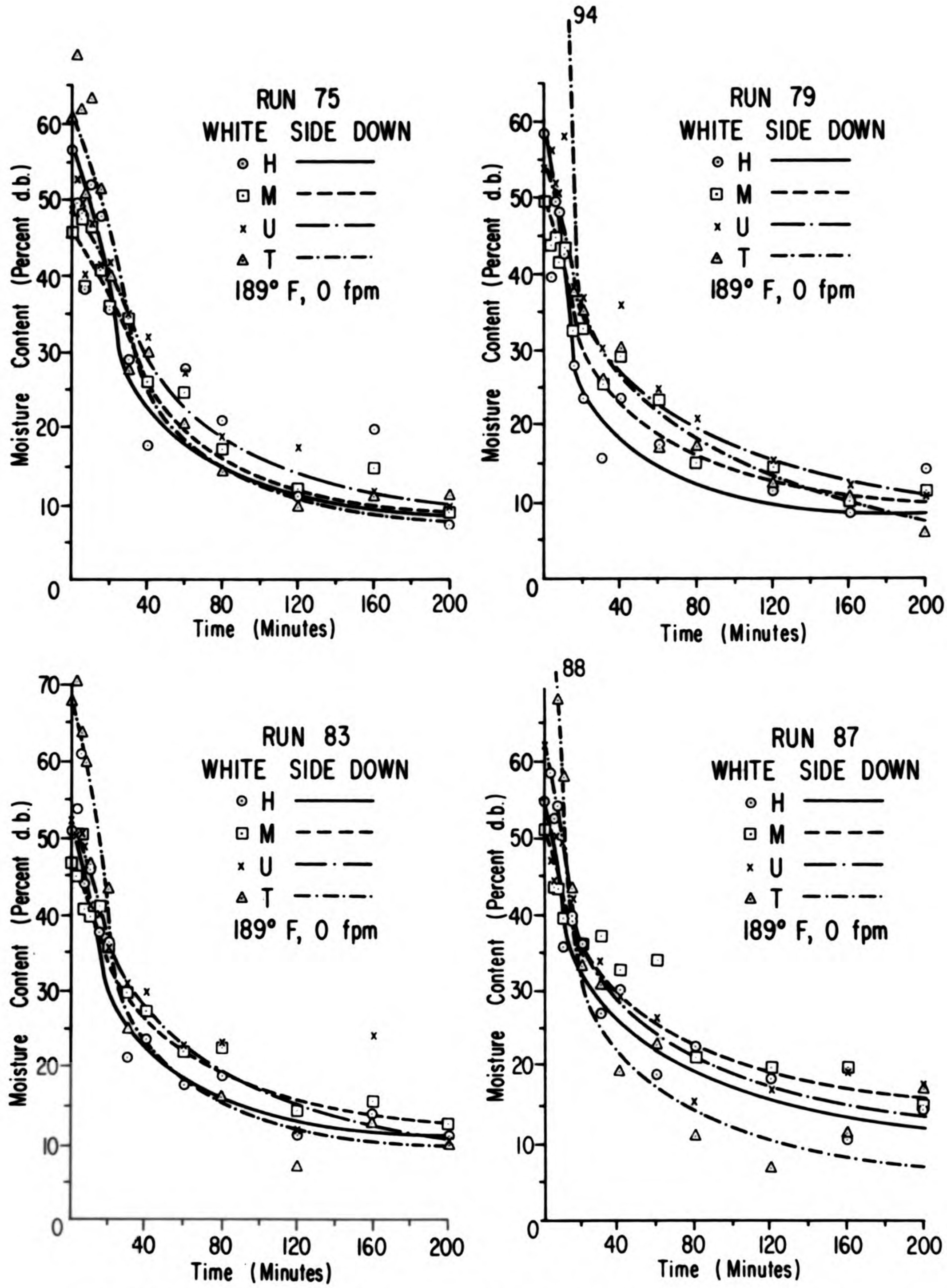


FIGURE 14. DRYING SHELLED CORN ON 189 °F CONDUCTION HEATING PLATE, WHITE SIDE OF KERNEL DOWN, WITH MOISTURE CONTENT OF H, M, U AND T SECTIONS OF THE KERNEL DETERMINED

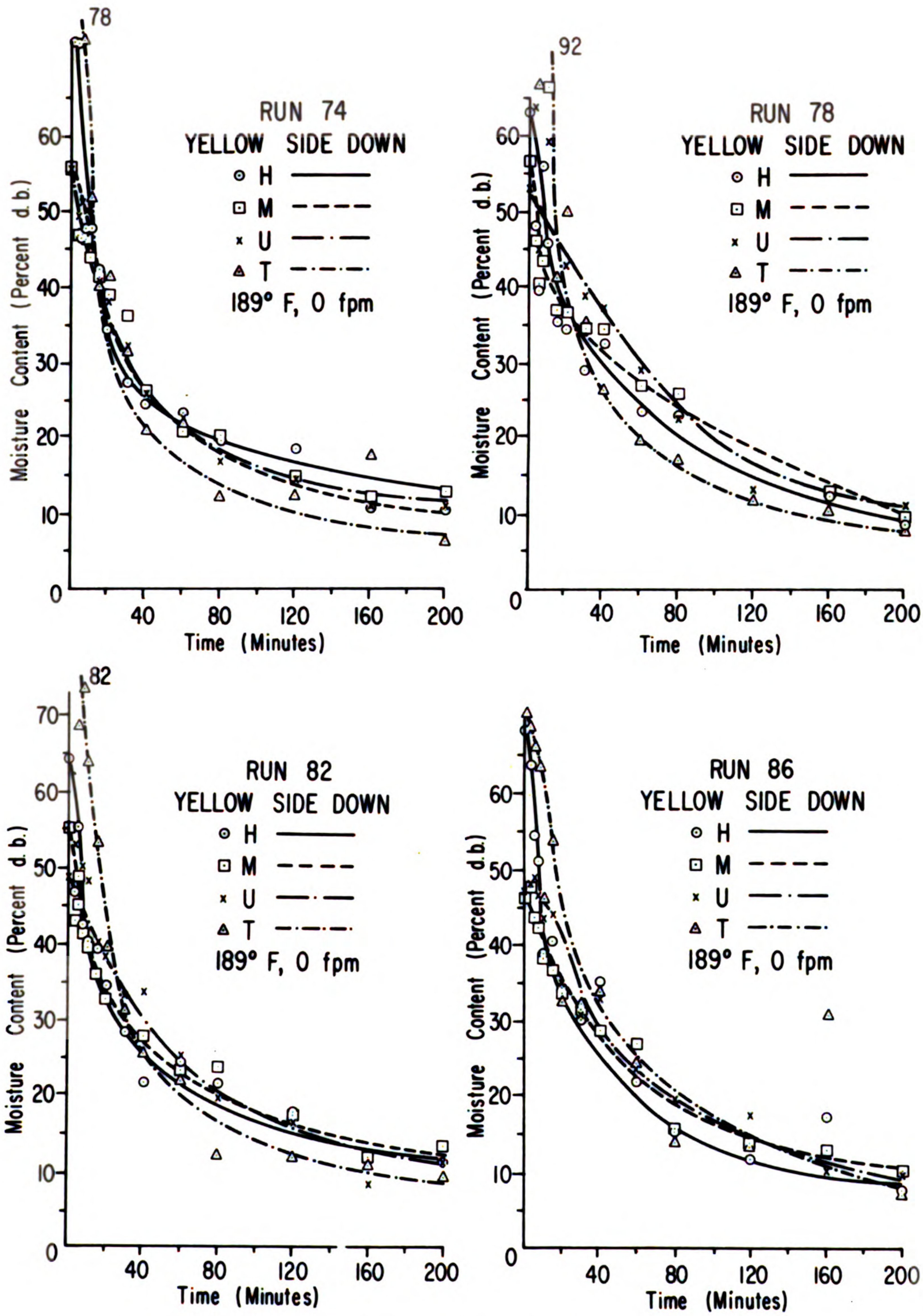


FIGURE 15. DRYING SHELLED CORN ON 189 °F CONDUCTION HEATING PLATE, YELLOW SIDE OF KERNEL DOWN, WITH MOISTURE CONTENT OF H, M, U AND T SECTIONS OF THE KERNEL DETERMINED

CONCLUSIONS

1. The moisture moves mainly from the head to tip sections of the kernel.

2. Natural convection was sufficient to carry away the moisture as vaporization occurred, for conduction drying.

3. The drying rate is the same regardless of which side, white or yellow, of the kernel is in contact with the heated plate.

4. Drying occurred in four falling rate periods for shelled corn at 56 percent d.b., dried to approximately 8 percent d.b.

5. The tip of the kernel contained the highest moisture content of any part of the kernel at the beginning of drying and the lowest after drying to below 22 percent d.b.

6. The higher the plate temperature the faster the rate of drying.

7. The rate of drying by conduction can be defined by the differentiated form of the equation $\frac{M-Me}{Mo-Me} = e^{-k\theta}$ as is used for convection drying.

8. Conduction drying is faster than convection drying for drying 56 percent d.b. shelled corn to less than 26 percent d.b. at 229°F, to less than 20 percent d.b. at 189°F, to less than 22 percent d.b. at 144°F and to less than 15.5 percent d.b. at 104°F.

9. Reducing the plate temperature 40° from 229°F approximately doubled the time required to dry 56 percent d.b. shelled corn to 15 percent d.b. Reducing the plate temperature 85° from 229°F, approximately quadruples the time required to dry shelled corn from 56 percent d.b. to 15 percent d.b. Reducing the plate temperature 125° from 229°F increased the drying time approximately 13 times to dry from 56 to 15 percent d.b.

RECOMMENDATIONS FOR FUTURE STUDY

1. Compare the economics of conduction and convection drying.

2. Determine the effect of conduction drying on milling, flavor, etc.

3. Determine the effect of conduction drying on germination.

4. Determine the drying rates of other products using conduction drying.

BIBLIOGRAPHY

Ceaglske, N. H. and Hougen, O. A. (1937) The Drying of Granular Solids, American Institute of Chemical Engineers, Transactions. 33:283-311.

Corben, R. W. and Newitt, D. M. (1955) The Drying Characteristics of Porous Granular Material, American Institute of Chemical Engineers, Transactions, 33:52-63.

Ellenwood, Frank O. and Mackey, Charles O. (1944) Thermodynamic Charts, Second Bulletin, John Wiley and Sons, Inc., New York, New York.

Ernst, R. C., Ardern, D. B., Schmiel, O.K., and Tiller, F. M. (1938) Drying Prussion Blue on Heated Shelves, Industrial and Engineering Chemistry, 30:1119-1121.

Ernst, R. C., Ridgway, J. W., and Tiller, F. M. (1938) Vacuum Drying of Solids, Industrial and Engineering Chemistry, 30:1122-1124.

Haines, W. B. (1927) Studies in the Physical Properties of Soil, IV, Journal of Agricultural Science, 17:264-290.

Hall, Carl W. (1957) Drying Farm Crops, First Edition, Edwards Brothers, Inc., Ann Arbor, Michigan.

Hukill, W. V. (1948) Types and Performances of Farm Grain Dryers, Agricultural Engineering, 29 (2):53-54, 59.

Jakob, Max (1949) Heat Transfer, Volume One, John Wiley and Sons, Inc., New York, New York.

Kelly, C. F. (1941) Drying Artificially Heated Wheat With Unheated Air, Agricultural Engineering, 22(9):316-320.

King, A. R. and Newitt, D. M. (1955) The Drying of Solids With Heat Transfer by Conduction, Transactions of Institution of Chemical Engineers, 33:64-69.

Ludt, R. W. (1957) Drying of Sand on a Hot Surface, American Institute of Chemical Engineers Journal, (3):343-147.

McCready, D. W. (1935) Drying of Paper and Pulp, Paper Trade Journal, 101(13):66-71.

Retford, David Thomas (1957) Drying Rates and Heat Transfer Coefficients on a Heated Surface for the Drying of Sand, Unpublished Thesis for M.S. Degree, Michigan State University, East Lansing, Michigan.

Robertson, Keith (1959) Drying Single Layers of Shelled Corn on a Heated Surface, Unpublished Report of Special Problem, Michigan State University, East Lansing, Michigan.

Sherwood, T. K. (1936) Air Drying of Solids, American Institute of Chemical Engineers, Transactions, 32:150-68.

Shroff, Phiroze Dhunjishaw (1949) The Drying of Paper Pulp on a Heated Surface, Unpublished Thesis for M.S. Degree, Michigan State University, East Lansing, Michigan.

Tambling, Thomas Noel (1953) A Study of the Mechanism of Drying Sand on a Heated Surface, Unpublished Thesis for M.S. Degree, Michigan State University, East Lansing, Michigan.

APPENDIX

Table 7. Summary of Drying Runs for the Investigation

Run Number	Temperature ^{o}F	Type of Heating	Air Flow fpm	Misc.
1-4	229	Conduction	0	
5-9	189	Conduction	0	
10-13	144	Conduction	0	
14-17	104	Conduction	0	
18-21	229	Conduction	100	
22-25	229	Conduction	50	
26-29	229	Conduction	25	
30-33	189	Conduction	25	
34,39	189	Conduction	100	
35-38	189	Conduction	50	
40-43	144	Conduction	25	
44-47	144	Conduction	50	
48-51	104	Conduction	25	
52,56	189	Conduction	0	Yellow down
53,57	189	Conduction	0	White down
60-61	189	Conduction	0	Plate on top
62-63	189	Conduction	0	Screen on top
54,58, 80,84	189	Conduction	0	Yellow down W,C,Y parts
55,59, 65,85	189	Conduction	0	White down W,C,Y parts
74,78 82,86	189	Conduction	0	Yellow down H,M,U,T parts
75,79, 83,87	189	Conduction	0	White down H,M,U,T parts

Table 7. Continued

Run Number	Temperature °F	Type of Heating	Air Flow fpm	Misc.
88-89	229	Convection	235	
90-91	189	Convection	235	
92-93	144	Convection	235	
94-95	104	Convection	235	

LIST OF SYMBOLS

Btu - British Thermal Units

d.b. - Dry basis

e - 2.7128, natural logarithm base

f - Number which is represented from the origin on the abscissa equal to the width of one cycle on the ordinate on semi-logarithmic graph paper

fpm - Feet per minute

^{o}F - Degrees Fahrenheit

h - Heat transfer coefficient, Btu/hr sq. ft. ^{o}F

hr - Hour

k - Drying constant, 1/hours

M - Moisture content at any time, percent, dry basis

Me - Equilibrium moisture content, percent, dry basis

Mo - Initial moisture content, percent, dry basis

N - Constant

q - Heat flow, Btu/hr.

sq.ft. Square feet

t - Temperature, degrees Fahrenheit

te - Equilibrium temperature, degrees Fahrenheit

to - Initial temperature, degrees Fahrenheit

w.b. - Wet basis

X - Actual distance measured on abscissa

Y - Actual distance measured on ordinate

θ - Time, hours

SAMPLE CALCULATIONS

Calculation of Moisture Content:

$$= \frac{\text{Weight after plate drying-weight after oven drying}}{\text{Weight after oven drying}}$$

$$= \frac{2.0211 \text{ grams} - 1.6804 \text{ grams}}{1.6804 \text{ grams}} \; 100$$

$$= 20.27 \text{ percent d.b.}$$

Calculation of Moisture Ratio:

$$= \frac{M - Me}{Mo - Me}$$

$$= \frac{20.27 \text{ percent d.b.} - 1.06 \text{ percent d.b.}}{55.27 \text{ percent d.b.} - 1.06 \text{ percent d.b.}}$$

$$= \frac{19.21}{54.21}$$

$$= 0.354$$

Calculation of Slope of Line on Semi-log Plot:

$$k = - \frac{Y}{x} \frac{1}{.4343} \frac{1}{f}$$

$$= - \frac{25}{13} \; \frac{1}{.4343} \; \frac{1}{1.667}$$

$$k = -2.65$$