AN EQUATION AND DIMENSIONLESS PARAMETERS DESCRIBING INFRARED VIBRATION DRYING

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ABSTRACT

AN EQUATION AND DIMENSIONLESS PARAMETERS
DESCRIBING INFRARED VIBRATION DRYING

by Verl E. Headley

An investigation was conducted to evaluate the variables involved in infrared vibration drying of high moisture shelled corn. These variables were evaluated and arranged in the dimensionless ratios. These dimensionless ratios were used for defining the drying constant, k.

Frequency variation from 600 to 1450 cycles per minute had essentially no effect on drying rate. Tests were then run at 1000 cycles per minute. The optimum value of amplitude was 3/32 of an inch. Increasing the intensity from 1500 to 4600 Btu/hr.ft^2, increased the value of the drying constant, k. As the wavelength was increased from 1 to 2.5 microns at a constant intensity, there was a linear increase in the drying rate. The drying constant decreased linearly as the velocity was increased at 100 ft/min and greater. The most rapid drying occurred with no forced air while vibrating the product. Depths of one to four inches were dried in the vibrating bed.

Another approach for relating mathematically the variables involved was to derive a prediction equation for

relating the drying constant ratio as a function of the variables involved with infrared vibration drying. The equations were verified using an analysis of variance approach.

The results indicated the prediction equation

$$\tilde{k}' = 2.22 \times 10^5 \left[\left(\frac{FC_d}{V}\right)\left(\frac{I\ \lambda_{max}}{h_t D\ T_{i_R}}\right)\right] + 6.42$$

$$\tilde{k}' - 4.35 < k' < 4.35 + \tilde{k}'$$

as being valid for all grain depths up to and including four inch grain layers, when vibration only (no forced air flow) was used, with an overall correlation coefficient of 0.93 resulting. With forced air flow through the vibrating grain layer this equation was not valid.

The equation for predicting the drying constant can be used to predict the drying rates for shelled corn with initial moisture contents in the range of 35 to 50 per cent dry basis.

Approved Carl W. Hall July 1964

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By

dwin
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ABBREVIATIONS AND SYMBOLS

A	amplitude of vibration
$b_{k'}(\pi_8 \pi_9)$	slope of regression equation
C_d	vertical cycle distance, $C_d = 4A$
C	speed of light in a medium
C_p	heat capacity of grain
C_v	speed of light in vacuum
d	diameter
D_p	diameter of kernel of corn on basis of sphere
D	depth of grain layer
e	base of natural logarithm
E_{b_λ}	monochromatic emissive power of a black body
E_b	emissive power of black body
f	frequency of light wave oscillation
F	frequency of vibration
F_{ratio}	F-test for significant difference
G	air mass flow rate

h_c	convective heat transfer coefficient
h_r	total heat transfer coefficient, $(h_c + h_r)$
I	intensity of infrared radiation received at the surface of grain
k_c	grain thermal conductivity
k	drying constant for shelled corn
k_o	drying constant for shelled corn at reference conditions using vibration without infrared energy
k_a	estimated or predicted value of drying constant using dimensionless ratios
k'	experimental drying constant ratio, k/k_o
$\tilde{k}'$	drying constant ratio by prediction equation, k_a/k_o
$\bar{k}'$	mean value of drying constant ratios
M	moisture content of shelled corn
M_o	initial moisture content of shelled corn
N	total number of observations
$r_{(\pi_8 \pi_9)k'}$	coefficient of linear correlation
T_{o_K}	absolute temperature in Kelvin degrees
T_{o_R}	absolute temperature in Rankine degrees

T_{ioR} initial grain temperature in Rankine degrees

T_i initial grain temperature in Fahrenheit degrees

t_s surface temperature of grain, ^oF

t_∞ temperature of surroundings, ^oF

V air velocity

W moisture content ratio

π pi, signifies a dimensionless ratio

$(\pi_8\pi_9)$ product of dimensionless ratios $\pi_8\pi_9$.

$(\overline{\pi_8\pi_9})$ mean value of products of dimensionless ratios

θ drying time

λ wavelength

λ_{max} wavelength at peak intensity of emitter

σ Stefan Boltzman constant

ρ_o reflectivity

ρ air density

α absorptivity

α_λ monochromatic absorptivity

ϵ emissivity

ϵ_c emissivity of shelled corn

ϵ_λ monochromatic emissivity

τ transmissivity

η refraction index

$S_{(k', \pi_8 \pi_9)}$ standard deviation of sample points from regression line

t statistical t distribution

α level of significance

INTRODUCTION

Artificial drying of agricultural products has expanded rapidly in recent years. Application of better farming principles resulting in increased yields, and improved harvesting methods have created problems in the field to storage operations, primarily in drying. Corn harvesting machines (picker-shellers) harvest high moisture shelled corn more rapidly than conventional heated air grain dryers can reduce the moisture content to facilitate safe storage. Heated-air drying (convection heating) is a relatively inefficient method of energy transfer. Likewise shelled corn is temperature sensitive as far as germination, milling properties, and nutrient value are concerned. These characteristics, along with high initial moisture contents of shelled corn, in some cases require that more than one pass be made through the heated air drying system to reduce the grain to a moisture content low enough to facilitate safe storage, which in the same manner reduces the capacity of the grain dryer.

Infrared radiant energy is a high intensity energy source. The application of infrared energy for the drying of agricultural products received considerable attention in the early 1940's. A misunderstanding of the characteristics of infrared energy transfer resulted in many failures in its early applications to the drying of hygroscopic food products.

The absorption of infrared radiant energy by a product is primarily a surface phenomenon. Infrared rays impinge upon the surface of the product producing a skin heating effect. Thus previous applications of infrared radiant energy for drying agricultural products have been limited to thin layers usually of one inch or less.

Recent satisfactory applications of infrared radiant energy have been reported by vibrating shelled corn layers up to two inches in depth. Proper manipulation of the product sufficient to produce thorough mixing allowed larger grain depths to be satisfactorily dried at increased infrared energy intensities, thus increasing the capacity of an infrared drying unit.

The objective of this investigation was to study infrared vibration drying particularly for drying high moisture shelled corn. This study was made to establish the best combination of the variables involved in infrared vibration drying of high moisture shelled corn, to combine these variables into their proper dimensionless ratios, and to establish a drying equation containing the proper combination of dimensionless ratios incorporated into a drying constant which would best describe infrared vibration drying.

REVIEW OF LITERATURE

History of Infrared Radiant Energy Applications

Excluding the solar source of infrared radiant energy, man first produced this type of energy artificially when he discovered fire in prehistoric times. This he used to warm his body, and thus discovered that infrared does not heat the surrounding air, but only that portion of his body directly exposed to the infrared rays or relatively speaking that portion of his body seeing the infrared radiant energy source.

Infrared radiant energy though generally not recognized has been used in domestic applications for years. The ever popular charcoal grilling of steak relies almost entirely on the radiant energy emitted from the glowing coals for cooking the meat. Food placed in an oven under flames is cooked largely from the absorption of infrared rays. An electric toaster browns bread primarily by the action of infrared radiation as well as naturally convected heat.

Thomas Edison in 1880 perfected the carbon filament lamp which he designed primarily for lighting purposes. This lamp was soon recognized as a means of supplying local heat for therapeutic treatments, thus the carbon filament "infrared" lamp originated.

Industrial applications of infrared radiant energy were first made during the 1930's, with the Ford Motor Company being given the credit as the first to apply this type of heat energy on a large scale. The Ford engineers adopted infrared radiant energy to replace steam heated ovens for baking enamel at $250^{O}F$ on the finished automobile bodies. Out of this conversion grew the widely publicized Ford infrared "tunnels" now used for the complete automobile body baking operation. The carbon-filament infrared lamp was used widely in the early industrial applications, and it still is used in some industrial applications.

Although artificially produced infrared radiant energy was used prior to World War II, it was not until the increased demand of war time production necessitated it that infrared radiant heating was really applied on a large scale industrially. Greatly accelerated experience was gained in this field during these years, and infrared heating was applied with almost miraculous drying speeds.

Different types of industrial heating requirements, and previous rapid and satisfactory applications of artificially produced infrared energy to numerous heating and drying industrial processes brought about different designs in infrared elements. Some of these were the ceramic gas-fired infrared generators, quartz tube infrared lamps, tungsten filament infrared lamps, and calrod units. These infrared

producing elements differ essentially only in design and spectral energy distribution with each producing its own characteristic peak energy emission at a specific wavelength depending primarily on the temperature and emission properties of the emitter.

Industrial applications of infrared radiant energy have been numerous though problems did and still exist. Its applications are primarily where quick spot heating and drying are necessary. Some of the applications are drying in paper manufacturing, skin drying of foundry molds, softening of plastic sheets for cutting, stamping and molding, injection mold drying, paint drying, drying of freshly molded porcelain bathtubs prior to being placed into high temperature kilns, baking enamel on traffic signs, preheating of metal products prior to high temperature welding operations, fusing special labels on glass bottles, curing bakelite varnish on small coils of wire, drying dye-printed pattern cloth, and numerous others (Hall, 1947).

Application of infrared energy in the food processing industry has been applied with limited success. Such large scale applications as the baking of cookies, drying cookie icing, dehydrating noodles for packaging, cooking meat balls for spaghetti, drying dog biscuits, and so forth have been reported (Food Engineering, 1958).

Research for applying infrared radiant energy in other areas of food processing have also been reported, such as peeling of apples (Food Technology, 1956), controlling bacteria and fungi in grain, blanching of celery and apples, curing of onions, drying rough rice, and other cereal grains. In any event applications of infrared radiant energy have been successful primarily when heating or drying of only a single or thin layer of product. Attempts to use product layers of one inch depth and larger particularly in the area of agricultural products have resulted in failure denoted by uneven drying and surface scorching of the product, thus a basis for further research in the field of infrared drying agricultural products.

Agricultural Applications of Infrared Energy

Schroeder and Rosberg (1959) indicated favorable results with gas-fired infrared drying of stationary layers of rough rice. The most efficient moisture removal was achieved by intermittently exposing the rice to increased infrared intensities until a surface temperature of 122°F was reached followed by cooling in atmospheric air.

Bilowicka (1960) showed the rate of temperature increase of rapeseed during heating and drying as being greater for the larger infrared intensities. A seed temperature increase of 81°F in ten minutes at a lamp height of 170 mm was obtained as compared to an increase of 68°F at a lamp height of 340 mm.

Person and Sorenson (1961) increased the capacity of infrared drying of hay by increasing the depth of the layer. Increasing the depth of the hay layer exposed to the infrared radiant energy resulted in wide variations of moisture distribution in the hay. The 1.15 micron (wavelength at peak intensity) infrared energy source produced the lowest drying capacity, while the 3 micron infrared source at same intensity gave the highest. Energy utilization showed the 1.15 micron source as yielding an efficiency of only 13 per cent as compared to 38.1 per cent for the 5 micron infrared source.

Hall (1960) presented the theory of infrared radiant energy in relation to the drying of agricultural and food products. It was illustrated that infrared radiant energy has only superficial penetration at the surface of hay or grain. White and whole wheat flour, exposed to an infrared radiant energy source emitting in the wavelength range of 0.7 micron to 3.5 microns showed only 0.14 per cent of the energy as being transmitted to a depth of 1/32 inch and beyond thus leaving 99.86 per cent of the absorbed energy concentrated in the thin surface layer of 1/32 inch or less.

Aselburgs et al. (1960) studied the effectiveness of infrared sources such as quartz lamps, quartz tubes, and calrod units in the blanching of apple tissue. The results indicated the depth of heat penetration as being influenced by wavelength characteristics, voltage input, and energy output. A quartz lamp with a maximum peak wavelength of 1.16 microns resulted in a 4.1 millimeter heat penetration into the apple tissue after a five minute exposure. Calrod units operating at the same voltage with a wavelength at peak intensity of 2.65 microns yielded a penetration of 5.9 millimeters in the same length of time.

Vorobev (1961) studied the application of infrared radiant energy for grain drying. A laboratory model was constructed which consisted of an insulated steel cylinder with a weighing mechanism and infrared lamps at the top and an electric heater at the bottom. The grain descended over a series of revolving transverse cylinders to a convection dryer. The infrared radiation was applied to the grain when on the top of the cylinders, thus allowing intervals for evaporation of moisture. Three experiments were carried out with supplementary convectional drying temperatures of 20°C and 140°C, and without infrared heating, using 709, 1,114 and 1,320 calories per kilogram of moisture reduction.

Picket and co-workers (1962) studied high energy intensities (heated air temperatures up to 900°F) for drying shelled corn. Heated air and high moisture shelled corn were passed countercurrently through a small rotary drum dryer. The results indicated a definite effect of temperature level upon moisture removal. Using air temperatures of

$500^{o}F$ reduced 18 per cent moisture shelled corn to 16 per cent; at $700^{o}F$ air temperatures, 18 per cent moisture shelled was reduced to 12.5 per cent; and at $900^{o}F$ air temperatures 18 per cent moisture shelled corn was reduced to 8 per cent in two and two-tenths minutes. Some visible damage to the grain was observed at these exposure times and temperatures.

Headley and Hall (1963) reported the drying rates of shelled corn using high temperature convection heating with air temperatures up to $800^{o}F$. High moisture shelled corn was exposed to elevated air temperatures and curves were established denoting time, temperature and percentage of moisture removal at the point of maximum allowable exposure time to visible kernel damage. Grain movement during drying when exposed to elevated heated air temperatures at $700^{o}F$ increased the allowable exposure time to visible grain damage (surface scorching) from approximately ten seconds to eighteen seconds while in the same manner at $500^{o}F$ air temperatures the allowable exposure time was increased from thirty seconds to approximately fifty-two seconds through grain movement.

Works (1963) used infrared irradiation as an effective treatment to increase the percentage of germination of seeds such as clover, alfalfa and white pine. The structure surrounding the seed embryo of some seeds blocks germination, and one of the most complete blocks is the impermeable seed coat. Seeds possessing these characteristics fail to or are slow in germinating. Exposing seeds of this nature to infrared radiation for short periods of time improved the percentage of germination. Red clover seed samples untreated, exposed for 1.41 seconds to infrared radiant energy with wavelength at peak intensity of 1.2 μ (quartz tubes), and exposed for 1.01 seconds to infrared radiant energy with wavelength at peak intensity of 1.14 μ, showed germination percentages of 82.7, 98.7 and 97.9 respectively.

Nelson and co-workers (1963) compared the effect of infrared radiant energy, radiofrequency and gas-plasma treatments on alfalfa seed for hard seed reduction. All three types of energy sources were about equally effective in increasing the germination of alfalfa seed by reducing the so-called hard seed percentages in seedlots. For infrared radiant energy treatments the best germination results occurred when using a 1.36 second exposure time in an infrared field emitting its peak energy intensity at 1.18 microns. For radiofrequency treatments, a frequency of 39 megacycles for 14 seconds, produced the best germination, and using gas plasma, an exposure time of 3 minutes gave the best germination for alfalfa seeds, thus lowering the amounts of hard seed.

Food Engineering (1963) reported satisfactory results in drying a heat-sensitive cheese with infrared radiant energy. Gas-fired infrared was used in conjunction with a continuous belt system in drying heat-sensitive cheese at a one inch depth. Moving a one inch layer of cheese pellets, at a speed of six feet per minute on a continuous belt sixteen feet long through a gas-fired infrared field with the source maintained five inches above the product, resulted in satisfactory drying of 1,500 lbs/hr of the cheese pellets with an absorption of 68 per cent of the heat energy input.

Vibration or Fluidization of the Product and Its Effect on Infrared Drying

Reed and Fenske (1955) studied the effects of agitation on gas fluidization and the convection heat transfer coefficient. The convection heat transfer coefficient between the vibrating plate and bed of carbon particles, assisted in fluidization by an air flow of 0.2 ft/sec, increased from 40 Btu/hr.ft^2F to 72 Btu/hr.ft^2F when the vibration stroke was increased from 0.0625 inches to 0.313 inches at a vibration frequency of 1,000 cycles per minute. In the same manner holding the vibration stroke constant at 0.313 inches, while varying the frequency from 1,000 cycles per minute to 2,000 cycles per minute increased the convection heat transfer coefficient between the vibration plate and carbon particles from 72 Btu/hr.ft^2F to approximately 100 Btu/hr.ft^2F respectively.

It was further illustrated that as the product of the frequency (cycles per minute) times stroke (inches) was increased a point was reached in which the forced air flow, aiding in fluidization of the particles, could be eliminated as a factor in attaining a higher convection heat transfer coefficient. For aerated nickel powder when comparing air flows of 12 ft/min and 60 ft/min while using a vibration stroke of 0.313 inches (amplitude of 5/32 inch), a maximum convection heat transfer coefficient of 135 Btu/hr.ft^{2}F was obtained at a frequency of 1,200 cycles per minute or a frequency-times-stroke product of 375 in/min. At this point the convection heat transfer coefficients for both forced air velocities of 12 and 60 ft/min were essentially identical, indicating that forced air could be eliminated as a factor for attaining higher heat transfer rates.

Leva (1959) has presented the theory of fluidized beds pertaining primarily to air-solid relationships in relation to heat and mass transfer. Also it has been illustrated that with increasing air flow and particle diameter the heat transfer coefficient also increases. Equations have been given indicating the relationship between heat transfer, air flow and mass transfer in fixed, expanded, and fluidized beds.

Baader (1961) studied the behavior of loose material on oscillating sieves. It was shown that the separation of the lowest layer of material during oscillation takes place only when the sum of all forces, operating between the material and the sieve and normal to the sieve surface, have reached zero. It was also concluded that the movement of the material in so far as the sieve was concerned was determined by the frequency, amplitude, and angle of inclination of the sieve. For optimum sieve performance the duration of the material projection must coincide with the oscillation period of the sieve.

Schertz and Hazen (1963) made a study predicting the movement of shelled corn on an oscillating conveyer. Mass rate and flow measurements were made to determine the rate of material movement. It was shown that the mean velocity of the conveyed material was not always constant with respect to the depth of the layer. Predicted results were within 10 per cent of the observed values.

Stephenson and McKee (1963) showed favorable drying results and capacities when using a small multistage infrared dryer with three vibrating trays oscillating at intervals. Solenoids were used to produce vibration range of from 20 to 60 cycles per minute. The absorptivities of corn, oats, and wheat, part of which were blackened, were compared to those of natural surface color. It was assumed that most grains for all practical purposes could be treated as gray bodies. Shelled corn at 28 per cent initial moisture content, exposed for two minutes in an infrared field generated by a 250 watt industrial drying lamp and located one foot above the source, indicated corn kernals coated with black ink and natural surface as having temperatures of 85^{o}F and 80^{o}F respectively. This gave a temperature ratio, $(\frac{t_n}{t_b})$, of 0.93. Since a corn kernel covered with the dull black ink could be considered essentially as a black body, thus the temperature ratio could also be considered as a measure of the degree of absorptivity.

Headley and Hall (1963) illustrated that vibration of shelled corn in an infrared field provided a means of satisfactorily utilizing increased infrared intensities for drying without visible damage (surface scorching) occurring in the grain. A two inch layer of high moisture shelled corn, vibrated at a frequency of 1,200 cycles per minute at an amplitude of 1/4 inch, was satisfactorily dried from 35 per cent moisture (dry basis) to 15 per cent in forty-four minutes when exposed to an effective intensity of 1,620 Btu/hr.ft^{2}. A constant rate of change in moisture content with respect to time was observed as seen from the linearity of the drying curve in the range of drying from 35 per cent moisture (dry basis) to 15 per cent moisture.

Effects of Rapid Drying and Cooling on Product Structure

Thompson and Foster (1963) found that shelled corn dried in heated air with temperatures ranging from 140^{o}F to 240^{o}F was two to three times more susceptible to breakage than when dried with unheated air. Most of the stress cracks (endosperm fissures) occurred during the drying period in passing through the moisture content range of 19 to 14 per cent. Rapid cooling of the grain also increased the number of stress cracks, a damage undesirable for corn milling. Reduction in the number of stress cracks appearing in the corn kernal were obtained by lowering the drying speeds, especially through the moisture range of 19 to 14 per cent, and delaying the cooling of shelled corn immediately following the drying period, thus allowing time for grain tempering prior to rapid cooling.

Theory of Infrared Radiant Energy Transfer

The largest radiant energy source available is the sun. The sun emits radiant energy nearly as a black body at a temperature of $10,800^{o}R$. Of the radiation received by earth from the sun about 50 per cent lies in the infrared range. Almost all of the remaining 50 per cent received lies in the visible range, except for a minute portion as ultraviolet.

Of the solar radiation directed toward earth from the sun, a portion is absorbed by the gaseous media surrounding earth. The remainder is transmitted to earth, where again part is absorbed ($\epsilon_{earth} = 0.83$) and the remainder reflected back to outer space. Theoretically the earth receives infrared radiant energy from the sun at the outer fringes of its atmosphere at the rate of 442 Btu/hr.ft^2, a value commonly referred to as the "solar constant."

Infrared radiant energy rays are electromagnetic waves similar in nature to x-rays, radio, gamma, and visible rays varying only in frequency and wave length and traveling at a constant speed of 3×10^{10} cm/sec in a vacuum. In other media the velocity of infrared rays may be somewhat less and can be calculated by equation, $\eta = \frac{C_v}{C}$, more commonly called the refraction index. The letter C_v denotes the velocity of the rays in a vacuum where maximum transfer occurs, and C is the velocity of the rays in any media under observation. However, for most practical purposes the velocity of all infrared rays are considered constant or that C_v equals C for air. Thus the speed of radiant energy is described by equation, $f \lambda = C$, where f denotes frequency of wave oscillation, λ the wavelength, and C the constant speed for light travel, 3.0×10^{10} cm/sec. All electromagnetic waves travel at this speed.

As seen from Figure 1, thermal radiation occupies only a small portion of the electromagnetic spectrum as far as wavelength is concerned, but in terms of quantity of energy infrared energy contributes practically one-half of all energy received on earth from the sun.

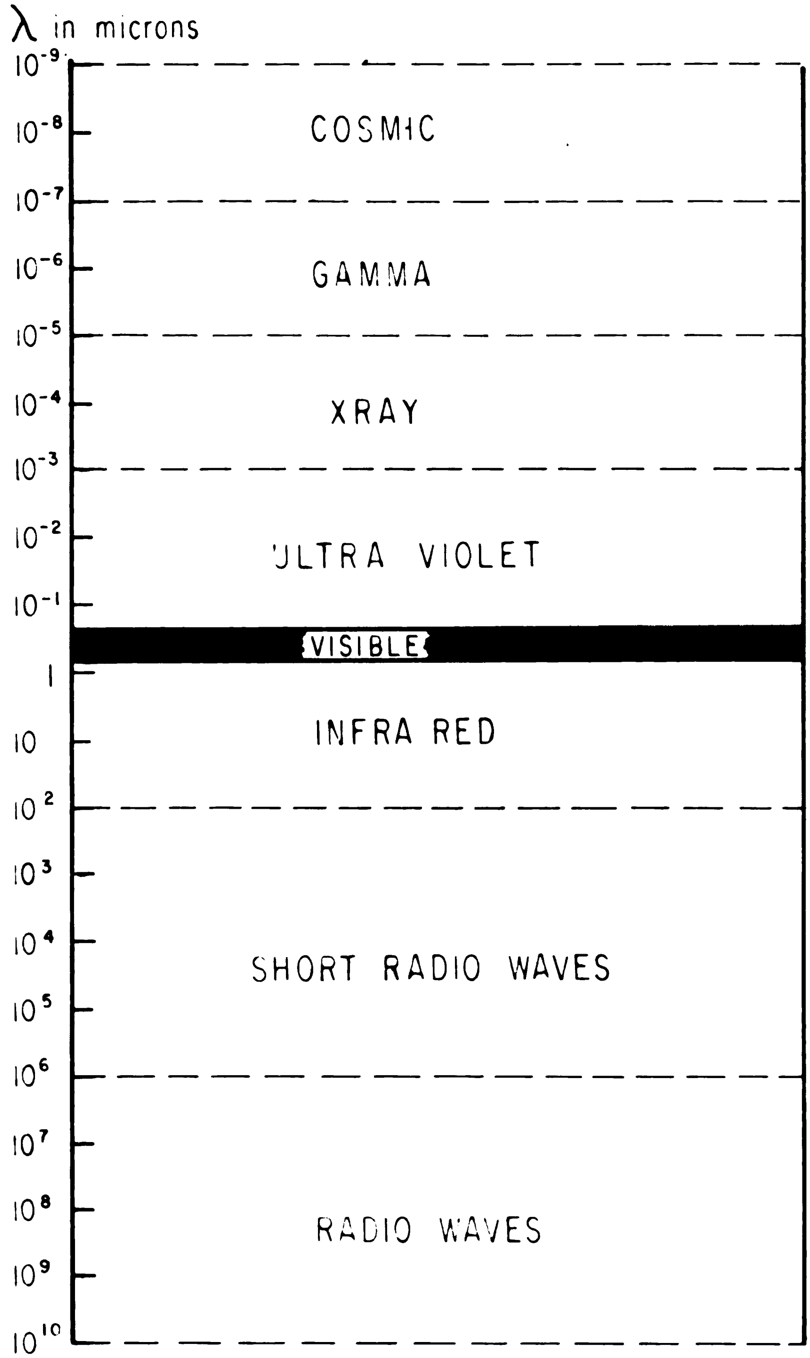


Figure 1 Wavelength of various electromagnetic waves

The sun emits radiant energy at a temperature estimated to be 10,800°R, and is considered to be an ideal emitter or more commonly referred to a "black body" emitter. An energy source emitting radiant energy as a black body represents the limit of performance, and no material can emit greater amounts than this. Thus a perfect or nearly perfect emitter of this type is said to have an emissivity equal to one (ϵ = 1).

In 1900, a German physicist Max Planck developed an equation which describes the energy distribution as a function of wavelength for a black body emitting at any temperature. Planck's radiation formula has thus far stood up under all tests satisfactorily, including many refined systematic measurements. Planck's law can be expressed as

$$E_{b\lambda} = \frac{C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} ,$$

where E_b is the monochromatic emissive power of a black body; λ , wavelength of radiation; T, absolute temperature of the emitter; C_1 and C_2, constants, the values of which depend upon the units used to describe the wavelength and temperature of emitter. Planck's equation illustrates how at various temperatures, a black body emits infrared radiant energy over a wide range of wave lengths. Each Planckian curve indicates infrared radiation intensity as a function of the wavelength for a black body emitting at a specific temperature as shown in Figure 2.

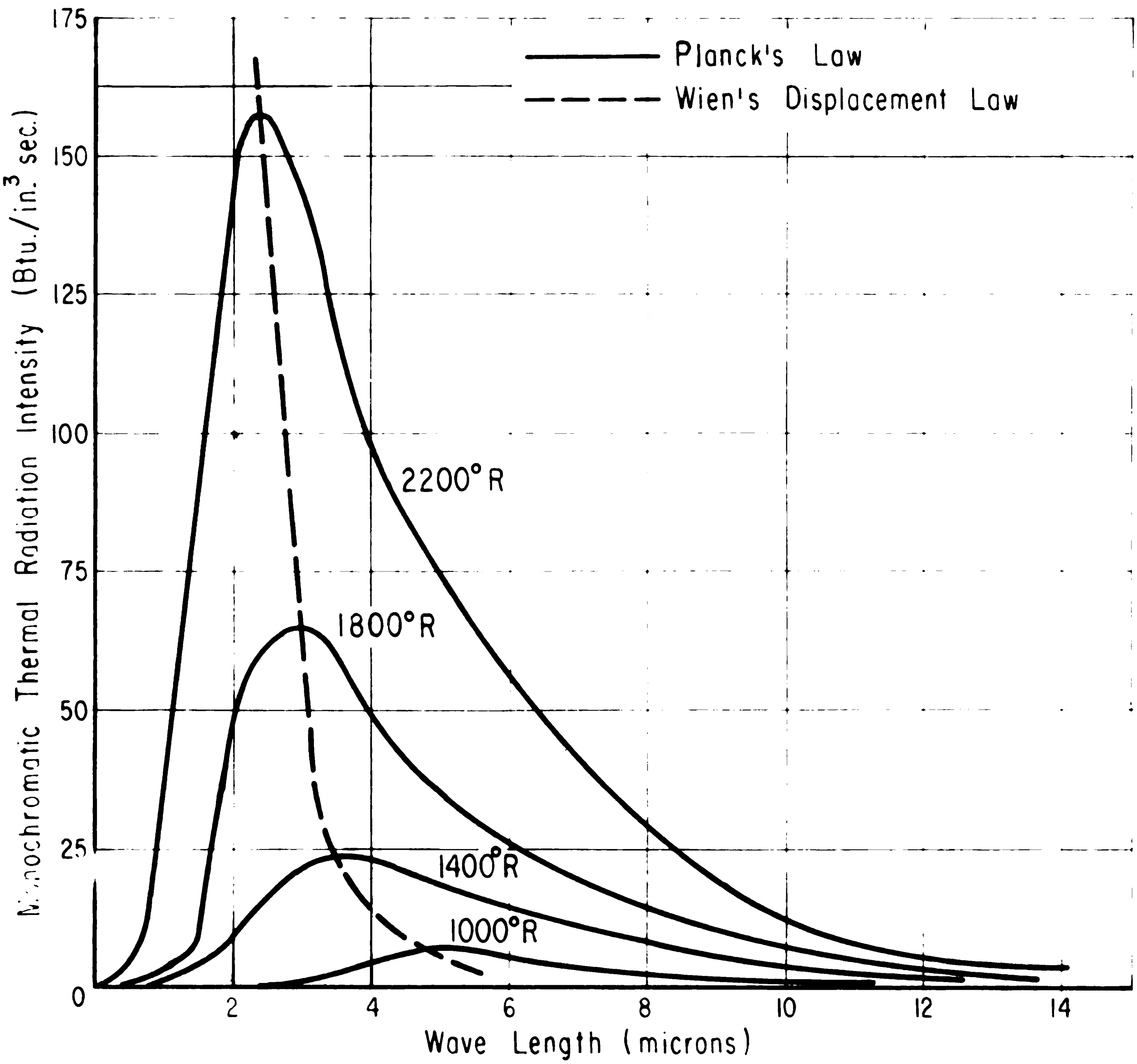


Figure 2 Energy distribution for black body emitters as a function of wavelength for different temperatures (Eckert and Drake, 1959)

By differentiating Planck's equation and setting the first derivative equal to zero, the wavelength at which the slope of the tangent to each energy distribution curve is equal to zero is obtained. This also indicates the wavelength, (λ_{max}), at which the peak energy emittance for a black body radiating at a specific temperature occurs. Differentiation of Planck's equation with respect to the wavelength yields

$$d\,E_{b\lambda} = \frac{0 - C_1[5\,\lambda^4(e^{C_2/\lambda T}-1) + \lambda^5(e^{C_2/\lambda T}-1)(\frac{-C_2 T}{\lambda^2 T^2})]\,d\lambda}{\lambda^{10}(e^{C_2/\lambda T}-1)^2}$$

Setting the first derivative equal to zero, $\frac{dE_{b\lambda}}{d\lambda} = 0$, thus the equation becomes

$$-5C_1\,\lambda^4(e^{C_2/\lambda T}-1) + \lambda^5 C_1(e^{C_2/\lambda T}-1)(\frac{C_2}{\lambda^2 T}) = 0.$$

Further simplification is obtained by dividing through by $5C_1\,\lambda^4(e^{C_2/\lambda T}-1)$. The equation reduces to $\lambda_{max}T = \frac{C_2}{5} = C_3$, where λ_{max} is the wavelength at peak intensity, T the absolute temperature of the emitter, and C_3 a constant, the value of which depends upon the units in which λ_{max} and T are expressed. When the wavelength of radiant energy at peak intensity is expressed in microns and the temperature of the black body radiator in Kelvin degrees, then the value of constant C_2 is 14,387 $\mu^{o}K$. Thus the first derivative reduces to $\lambda_{max}\ T_{^oK} = 2{,}877.4\ \mu\ ^oK$ and is usually expressed as $\lambda_{max}\ T_{^oK} = 2{,}900\ \mu\ ^oK$. This equation is a form of Wien's displacement law. From this relation it is seen that as the infrared emissive power of a black body increases with increasing black body temperature the wavelength at peak emission shifts to shorter wavelengths.

An equation describing the total emissive power of a black body radiator may be obtained by multiplying both sides of Planck's equation by $d\lambda$ and integrating from zero to infinity. This quantitative relationship is read as $E_b = \int_0^\infty E_{b_\lambda}\ d\lambda$, or the total relationship reads

$$E_b = \int_0^\infty \frac{C_1\ \lambda^{-5} d\lambda}{(e^{C_2/\lambda T}-1)} \ .$$

The integration yields an equation which represents the total infrared energy radiated by a black body emitter at any specific temperature. This equation is $E_b = \sigma T^4$ and is known as the Stefan-Boltzmann equation or law, where E_b represents the total emissive power (Btu/hr.ft^2), σ the Stefan-Boltzmann constant (1.714×10^{-9} Btu/hr.ft^{2}R^4), and T the absolute temperature of the emitter (^{o}R).

Of the electromagnetic waves (infrared rays) impinging on the surface of an object, all must be absorbed, transmitted, or reflected. From the law of conservation of energy it follows that $\rho + \alpha + \tau = 1$ (Kirchoff's Law).

ρ indicates the ratio of the reflected energy to the incident energy and is called the reflectivity, α the ratio of the absorbed radiant energy to the incident energy and is called the absorptivity, and τ the ratio the radiant energy transmitted to the incident energy, and is called the transmissivity. Solid and liquid bodies absorb practically all the infrared radiation penetrating through their surfaces within a very thin layer. For most agricultural products it has been reported that the depth of penetration of infrared radiant energy rays is no greater than from one to two millimeters below the surface.

Since the thickness of most solids is greater than these values, then Kirchoff's law can be written as $\rho + \alpha = 1$, thus transmissivity is essentially zero. Likewise the reflectivity for most gaseous media between the infrared energy source and the product can usually be neglected, thus Kirchoff's law reduces to $\alpha + \tau = 1$. In the same manner where the gaseous media between source and product is kept relatively free of water vapor and carbon dioxide by proper air movement then the absorptivity of the gaseous media can be neglected, thus Kirchoff's law for air can essentially be written as $\tau = 1$.

The total emissivity of an infrared radiating surface at some specific temperature is defined as the ratio of the emissive power, E, of the surface to that of the emissive power, E_b, of a black body radiating at the same temperature, The total emissivity of a black body emitter is equal to one ($\epsilon = 1$). Thus for a black body the absorptivity and emissivity are equal, thus $\alpha_\lambda = \epsilon_\lambda = 1$.

The monochromatic emissivity of a radiating non-black body is defined as $\epsilon_\lambda = \frac{E_\lambda}{E_{b_\lambda}}$. Integrating over the entire wavelength range, the total emissivity of a non-black emitter can be expressed as $\epsilon = \frac{E}{E_b} = \frac{1}{E_b(T_s)} \int_0^\infty \epsilon_\lambda (T_s) E_b(T_s)\, d\lambda$. In the same manner the absorptivity $\alpha = \int_0^\infty \frac{\alpha_\lambda (T_s) E_b (T_i) d\lambda}{E_b(T_i)}$.

These relations show that the emissivity (ϵ) and absorptivity (α) are a function of the wavelength at a specific temperature of the emitter.

For a surface which is considered to exist as a gray body, both the absorptivity and emissivity are independent of the wavelength. Thus one can write for gray bodies $\alpha = \alpha_\lambda (T_s) = \epsilon_\lambda (T_s) = \epsilon (T_s)$. The monochromatic absorptivity values and emissivity values are rarely available for many products for all wavelengths. Unfortunately not too many surfaces exist in nature which can be considered as truly gray bodies either. However, agricultural products, grain for example, are assumed to act as gray bodies and designate a relatively high absorption of infrared radiant energy. Shelled corn at about 20 per cent moisture (wet basis) was estimated to have an absorptivity of approximately 0.93, determined by Stephenson and McKee (1963).

During the drying period for agricultural products, initially relatively high in moisture, the absorption properties undoubtedly change. Thus, the wavelength at peak infrared absorption by the product also changes. Ideally, for efficient absorption of infrared radiant energy during drying of agricultural products, it would be desirable to have an energy source whose maximum intensity could be varied to wavelengths corresponding to the wavelengths of maximum absorption by the product throughout the entire drying period.

The production of infrared radiant energy artificially by electrical resistance elements or gas-fired infrared sources provide a relatively efficient production of infrared radiant energy in relation to the energy input. From 75 to 85 per cent of the wattage input to the tungsten filament lamp is dissipated as heat energy through infrared radiation. The greater portion of the radiant energy emitted by this source is primarily in the near infrared range of 0.76 μ to 5 μ, with the wavelength at peak intensity lying usually between 1 μ and 2 μ. Any energy waves emitted at wavelengths longer than 5 μ are absorbed by the glass bulb of the infrared lamp. This energy may be transferred away from the glass by conduction, convection, or reradiation at the temperature of the glass (Weitz, 1956).

Gas-fired infrared is generally produced by the combustion of natural or propane gases. However, only 10 to 20 per cent of the flame energy is in the form of infrared energy, therefore the hot flame energy is usually used to heat some radiating refractory material. Such surfaces offer the advantage of controlling the wavelength range over which radiation is distributed by controlling the temperature of the radiating refractory material. With small Schwank gas-fired infrared heaters (10,000 to 11,000 Btu/hr. range) about 55 per cent of the energy liberated from combustion is converted to infrared radiation and the remainder is primarily in the combustion gases and transferred essentially by convection (Heidlkamp, 1957).

The manner in which energy is transferred from the source to the product differs considerably between convection heating and infrared heating. In convection heating the air is at a higher temperature than the product, thus energy is transferred from the air to the product. Increasing the velocity of heated air (within limits) over the product in convection heating increases the rate of energy transfer from the air to the product thus increasing the temperature of the product.

Infrared radiant energy, on the other hand, is transferred directly from the source to the product. The transfer is essentially independent of the media through which the electromagnetic waves pass, with exception of water vapor or carbon dioxide which when present between the source absorb infrared energy at specific wavelengths as shown in Figure 3 (Eckert, 1959). Otherwise the infrared rays are transferred directly from source to product without loss in intensity to the gaseous surroundings and are absorbed by the product depending upon its absorption characteristics (Figure 4).

The transfer of infrared radiant energy to the product is primarily surface phenomenon. Radiant energy impinges upon the surface of the product with only superficial penetration. This results in a high concentration of energy at the surface resulting in increased product surface temperatures greater than that of the surrounding media. Thus increasing air velocities over a product receiving infrared radiant energy will result in energy being transferred from the product to the air and surface cooling will occur, a factor undesirable as shown in Figure 5.

Using low air velocities (20 ft/min) countercurrent to the direction of radiant energy transfer to a product being dried decreases its effectiveness, while air movement concurrent to the direction of infrared radiant energy transfer to the product increases the effectiveness of energy utilization when drying high moisture shelled corn with gas-fired infrared as seen in Figure 6.

Application of the principles of infrared radiant energy transfer, along with a product movement sufficient to produce thorough mixing have permitted increased product depths to be dried satisfactorily. Increased infrared

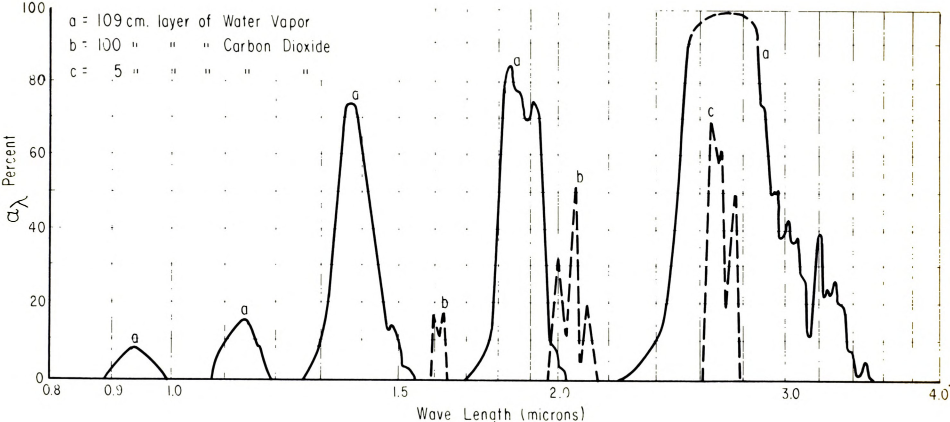


Figure 3 Absorption bands of water vapor and carbon dioxide (Eckert and Drake, 1959)

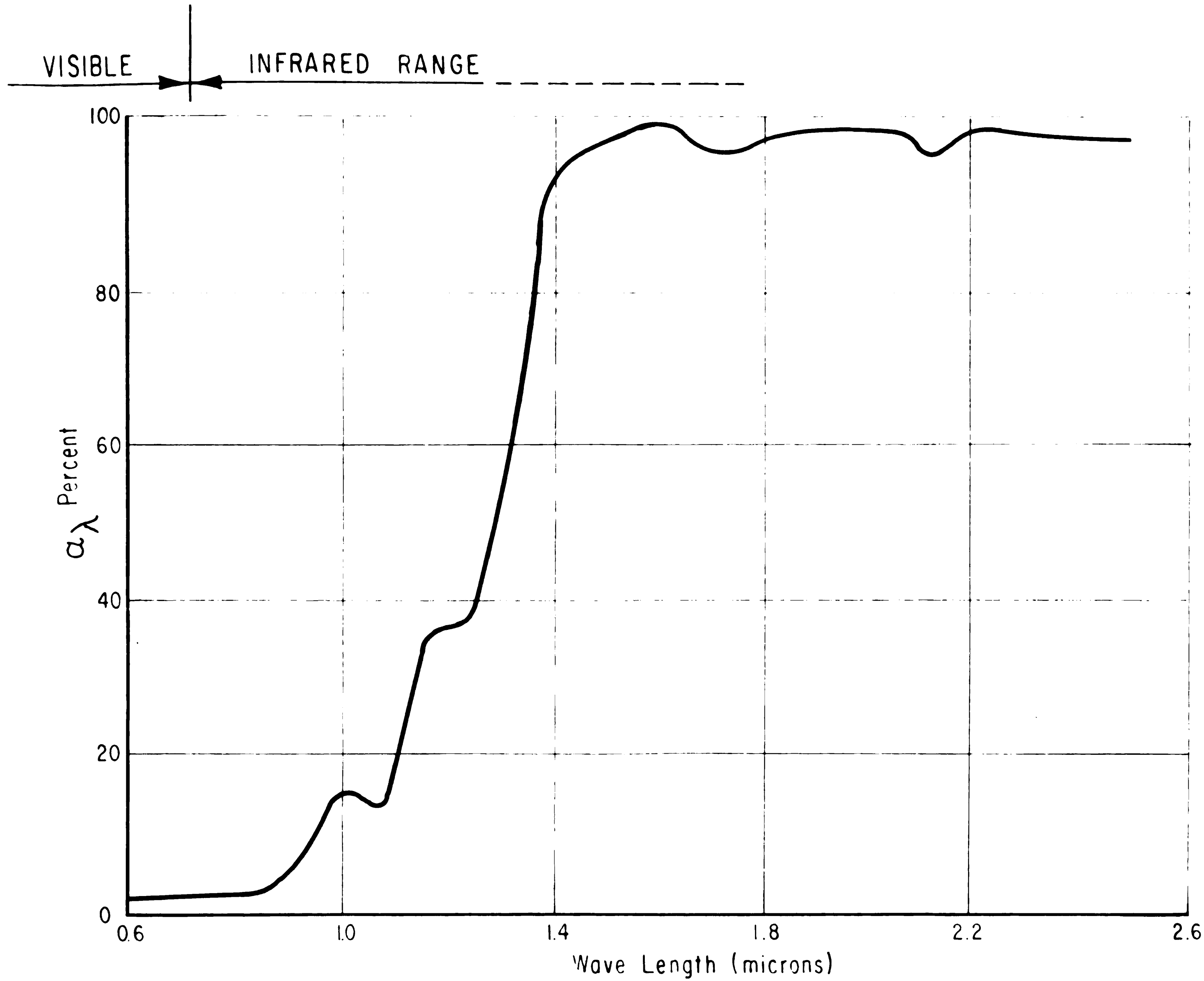


Figure 4 Absorption characteristics of a film of water three millimeters thick (Shuman and Staley, 1950)

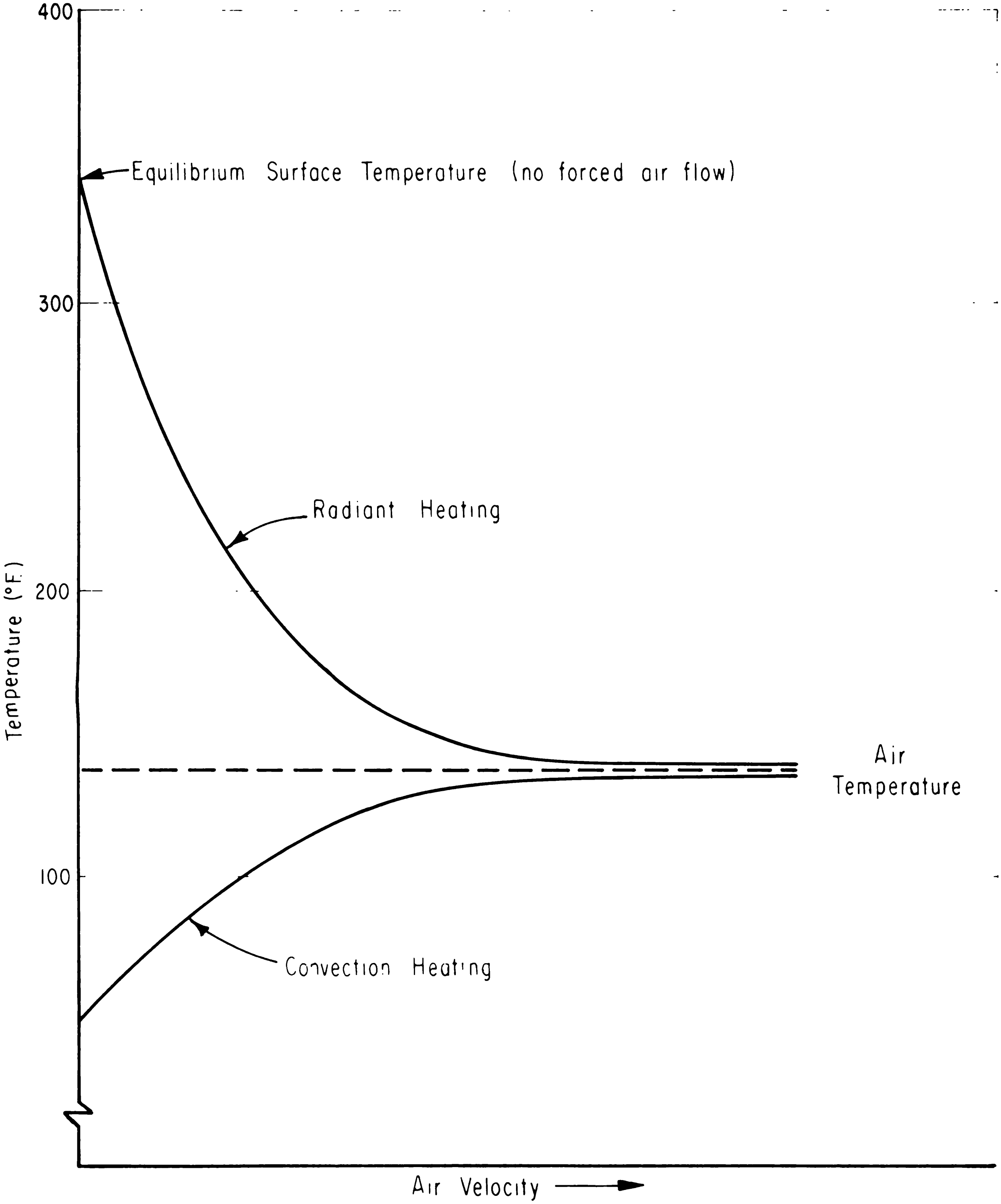
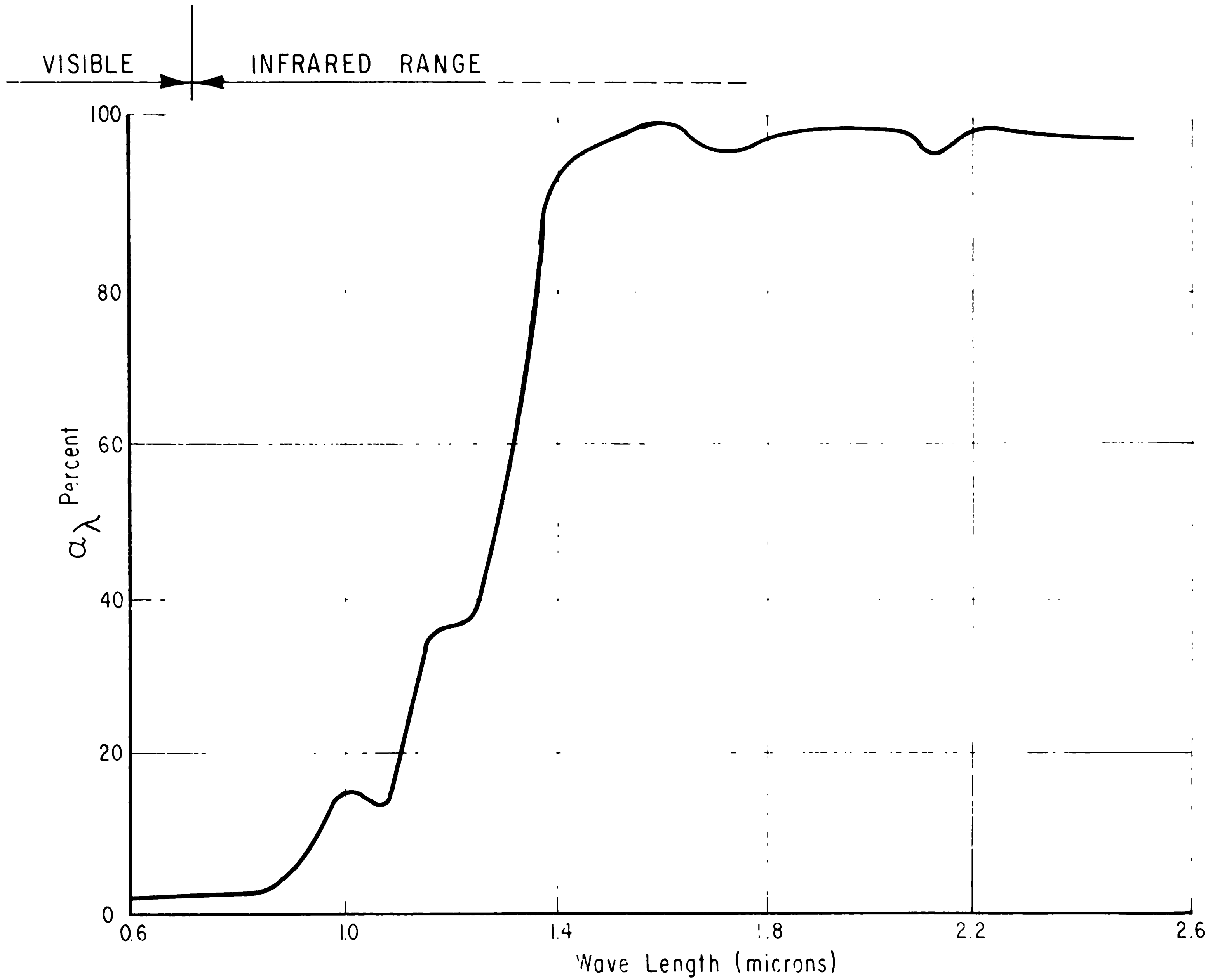


Figure 5 Effect of air velocity on surface temperature of product in relation to convection and radiation heating (Hall, 1960)



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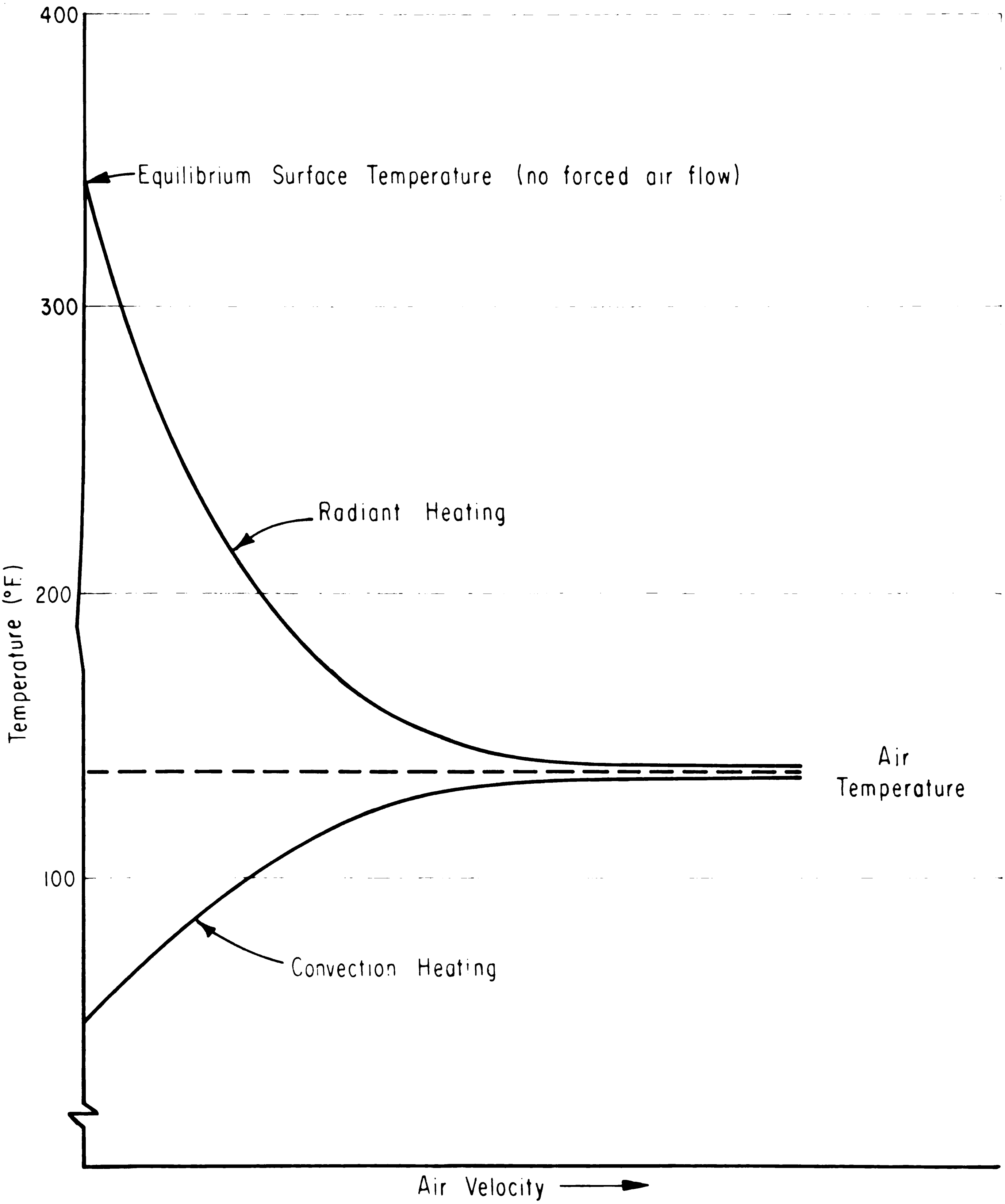

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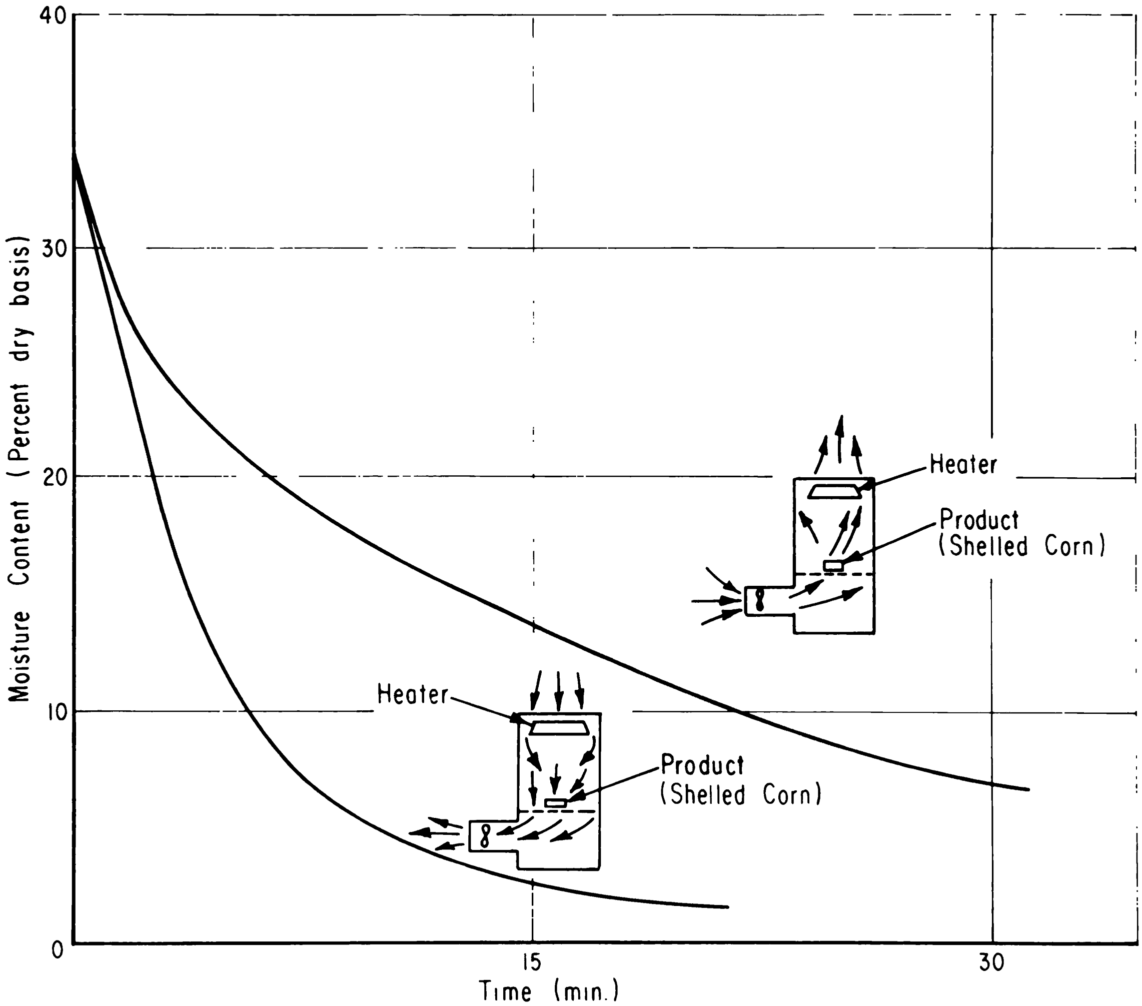

Figure 6 Effect of air flow direction on the rate of infrared radiation drying of a single stationary layer of shelled corn (Headley and Hall, 1963).

energy intensities have also been permitted, which reduced drying time along with increased drying capacities.

Infrared vibration drying involves both heat and mass transfer. When an electron is deflected from an atom it suffers a decrease in energy. The quantum of energy lost is emitted as radiation, and is called a photon. In the infrared range the photon energy is low, thus the primary effect on a biological product is heating. Infrared radiant energy is transferred directly from the source to the product and is essentially independent of the medium (air) through which it passes. The heating effect is a superficial phenomenon with a high concentration of energy on the surface of the product.

Drying of biological products in relation to the internal variables involves primarily thermal and moisture diffusion. These values are not known for most biological products. With infrared drying the rate of vapor diffusion from the surface may effect the drying rate, but at increased forced air velocities over the product convection controls and vapor diffusion effects are negligible.

With infrared vibration drying of biological products, transient conditions exist throughout the products in relation to temperature, moisture diffusion, and other physical characteristics both internal and external. In this study the drying constant, k, of the exponential drying equation was related to the external variables involved in infrared vibration drying.

EXPERIMENTAL APPARATUS AND CALIBRATION PROCEDURES

Vibration Apparatus

Since the absorption of infrared radiant energy by a product is primarily a surface phenomenon, increased product depths in infrared drying required some sort of grain movement sufficient to produce thorough mixing or cycling product surface exposure. Grain vibration was produced by remodeling a small orbital sander with circular type motions. The vibrator was altered to hold the mounts for a circular six inch diameter drying tray, and was mounted to a reinforced steel framework. Construction of the vibrator was such that the drying tray could be clamped into place and vibrated while being exposed to an overhead radiating infrared field. The drying tray was circular, metal, six inches in diameter, four and one-half inches in height, and constructed with a wire mesh base containing eight openings per inch. This allowed the fine particles to be excluded and collected below during vibration (Figure 7).

Frequency Calibration

The frequency of vibration was varied by placing a

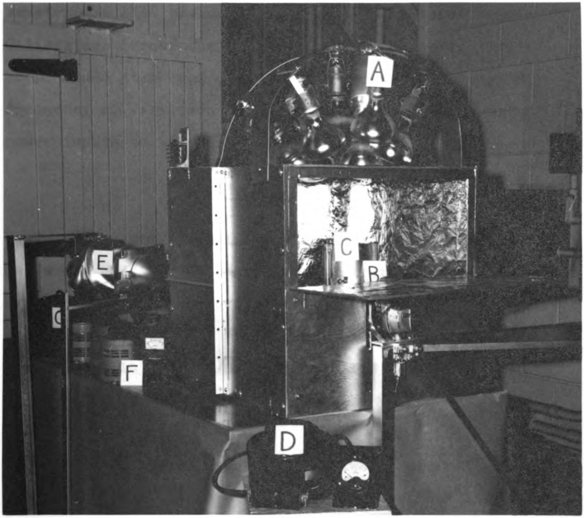

Figure 7. Overall infrared vibration drying apparatus. A. Hemispherical installation of seven 375 watt infrared heat lamps; B. Grain vibrator with variable amplitude attachments; C. Detachable circular grain tray with wire mesh base; D. Apparatus for vibration frequency variation and input voltage-current measurement; E. Forced air flow apparatus with flexible tube attached to vibrating grain tray for drawing air through grain layer concurrent to the direction of infrared energy transfer; F. Apparatus for forced air flow variation and input voltage-current measurement; G. Variacs used to alter wavelength of infrared radiation at peak intensity by limiting input voltage to infrared lamps.

calibrated Variac in series with the series wound vibrator motor, thus limiting the voltage applied to the motor. An ammeter was also placed in a circuit to measure the current. Calibration frequencies were determined by using a stroboscope aimed at a spot on the vibrating drying tray. The frequency of vibration was determined in relation to various power inputs to vibrate grain depths as shown in Figure 8.

Amplitude Calibration

The amplitude of vibration was varied by constructing a cam which could be attached directly over the existing drive cam, but carrying a different eccentricity. Amplitude variations, determined with a dial indicator, were established as 1/16 inch, 3/32 inch, and 1/8 inch.

Drying Chamber

The infrared drying chamber was a cubical box with dimensions two feet on a side. The chamber was lined with heavy weight aluminum foil to reflect infrared rays. On the top of the drying chamber was mounted the hemispherical metal frame to which were mounted seven 375 watt infrared lamps directed downward at a distance of one foot from the center of the drying tray.

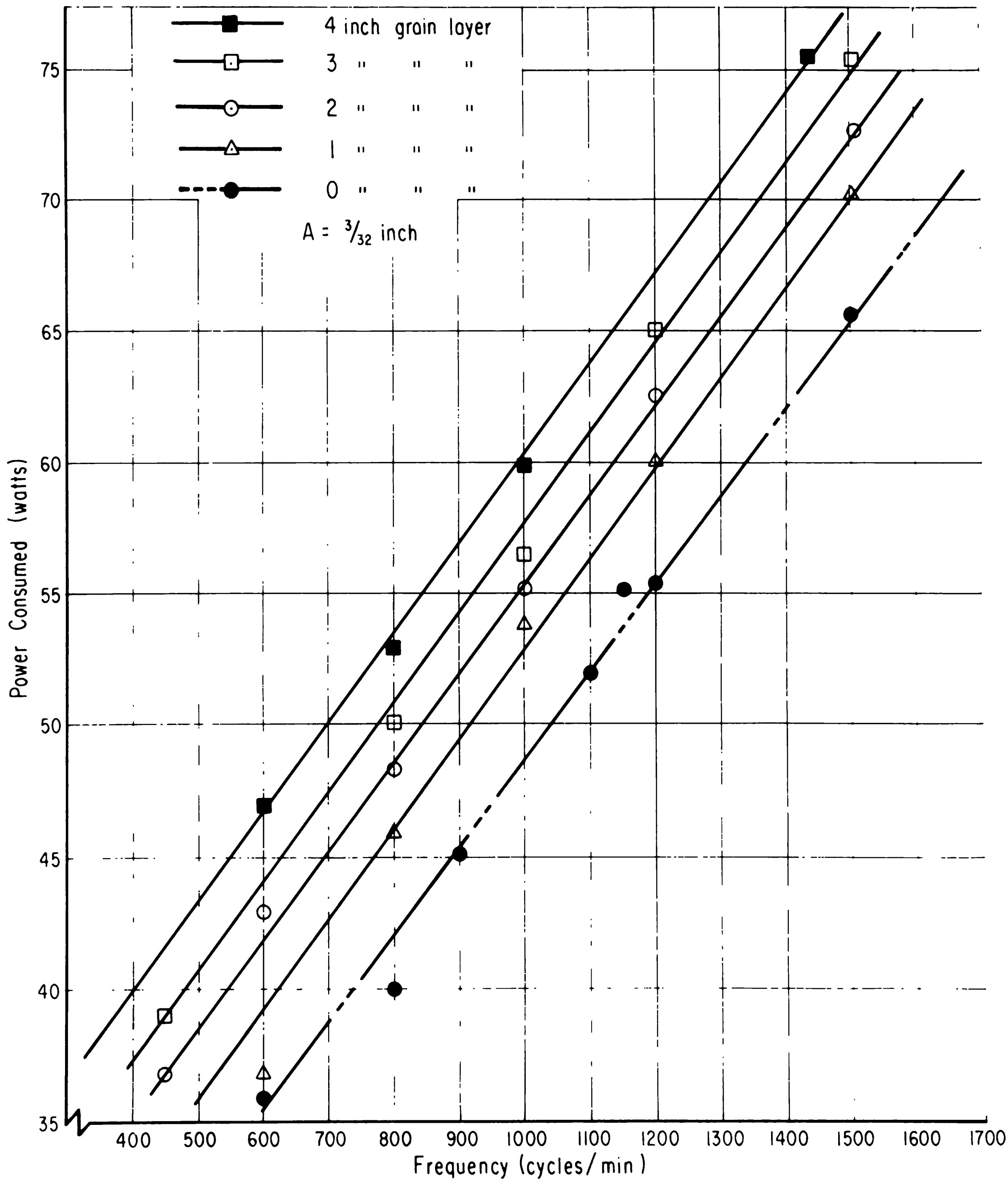

Figure 8 Plot of power consumed versus frequency of vibration at optimum amplitude for various depths of grain layers.

Forced Air Flow System and Calibration

The forced air flow apparatus consisted of a blower mounted outside the drying chamber to which was attached several feet of five inch aluminum pipe. A flexible, fabricated, sealed connection was attached from the end of the five inch air duct to the bottom of the vibrating grain tray. Air was drawn through a stationary two inch grain layer and the air velocities measured in the five inch tube by use of a hot wire anemometer. An average velocity for each forced air flow setting was determined by averaging measurements taken both vertically and horizontally across the cross section of the five inch circular duct. To correct the air velocity to that of the velocity through the vibrating grain layer, it was necessary first to correct the measured average air velocity in the five inch diameter duct to that passing through the six inch diameter empty drying tray. The next step was to determine the percentage voids in a two inch grain layer when vibrating at various frequencies. This was accomplished by attaching a graduated probe in the center of the drying tray. A two inch layer of shelled corn was vibrated at various frequencies, and the increase in height of the grain layer determined with the stroboscope. Using these grain heights the percentage of voidage of the vibrating or mechanically-fluidized bed was determined as shown in Figure 9. With the percentage voids as the basis

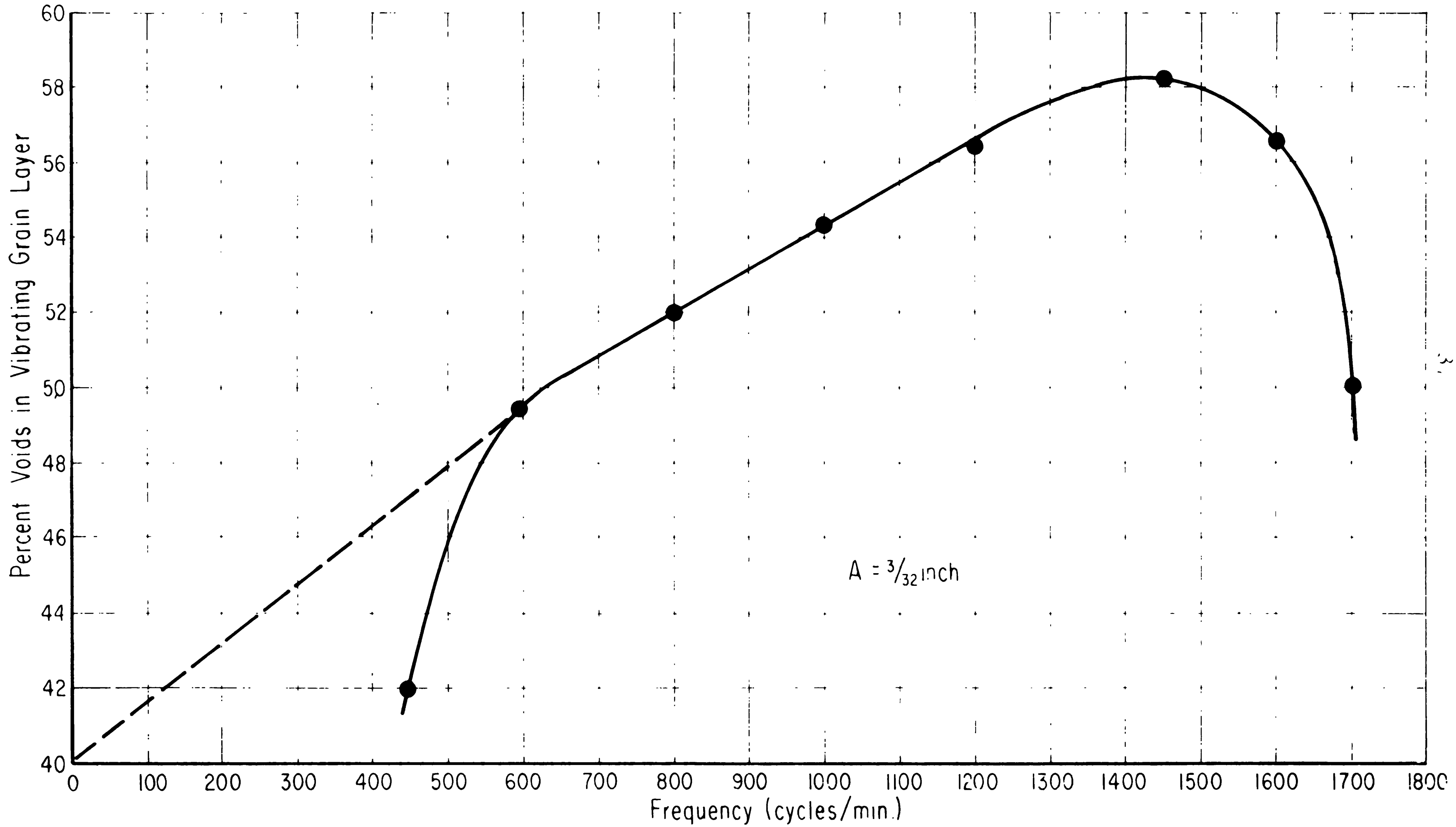

Figure 9 Percent voids in [illegible] grain layer versus frequency of vibration

for calculation of the mean cross sectional area of the grain bed, the air velocities through the drying tray were corrected to those through the vibrating grain layer.

Grain Movement Calibration

At increased depths of the grain layer, a grain movement sufficient to produce thorough mixing was required for satisfactory application of infrared radiant energy for drying. Determination as to whether or not the vibration apparatus constructed produced thorough mixing or cycling of the corn kernels was made first by placing five dyed kernels on the bottom of a two inch layer of shelled corn. Vibration at a frequency of 1,000 cycles per minute and amplitude of 3/32 inch was used. The average rate of cycling ranged from five to six cycles per minute per kernal. Thus it could be concluded that on the average each kernel was cycling at this rate from the bottom of a two inch grain layer to the surface, where it was exposed to infrared radiation for a short period of time before cycling again.

Further confirmation to determine whether or not the frequency and circular type vibratory motion traced by the eccentricity of the cam (amplitude) were sufficient to produce thorough mixing of the grain layer was made by a temperature distribution study. To do this a two point thermocouple probe was constructed and attached to the base of the drying tray which was filled with a two inch layer of high moisture shelled corn. The leads from the thermocouples were connected to an automatic recording potentiometer. The temperature distribution was recorded for forty-five minutes during the drying period for both stationary and vibrating two inch grain layers being vibrated at 1,000 cycles per minute, amplitude of 3/32 inch, while receiving infrared radiant energy at the rate of 3,250 Btu/hr.ft^2. The results of these tests are shown in Figure 10. From these graphical results it was confirmed that the vibrated or mechanically-fluidized grain layer was being thoroughly mixed since the temperature distribution in the vibrating grain layer was essentially the same at the center of the mass as it was just below the exposed surface, much in contrast to the temperature distribution in the stationary layer.

Calibration for Equivalent Effect Between Vibration and Forced Air Flow in Relation to Moisture Removal

Conventional drying (heated air) uses forced air flow not only to aid in the rate of heat transfer but to carry away moisture as well. Tests were run to determine the equivalent effect of vibration in the relation to moisture removal by comparison to forced air through a stationary layer of high moisture grain.

Stationary grain layer tests were made by placing a two inch layer of high moisture shelled corn in the drying tray, then forced air at 70°F was drawn through the grain

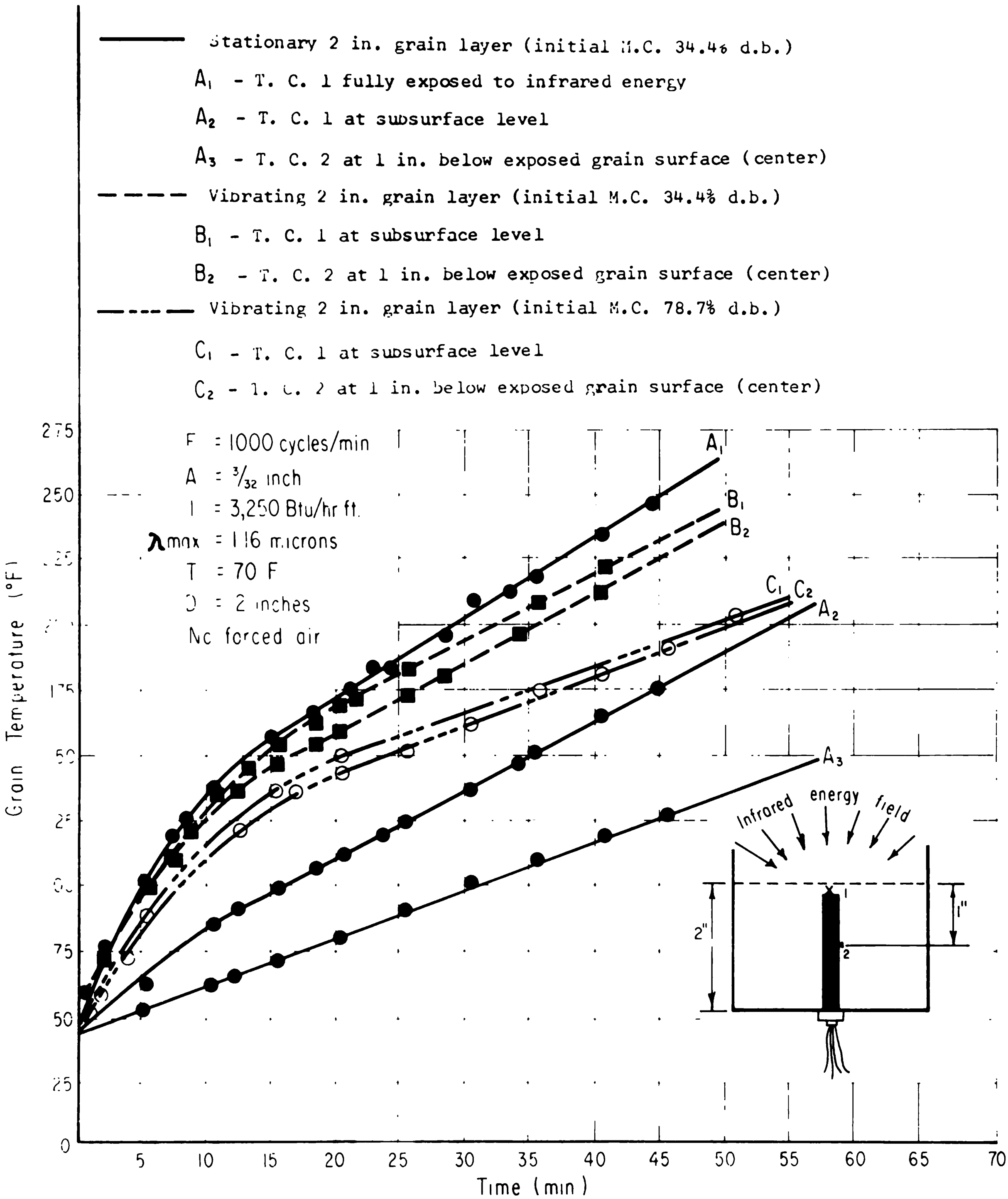

Figure 10 Temperature distribution in two inch stationary and vibrating grain layers of shelled corn versus time.

layer at a previously determined velocity. The test was run for a two hour period at which time the grain sample was reweighed and the moisture removal determined. Similar two hour drying tests were run at various forced air velocities through two inch grain layers and the moisture removal determined.

In comparison two inch grain layers were vibrated for two hours at room temperature (70°F), no forced air, using an amplitude of 3/32 inch and at various frequencies. In the same manner the amounts of moisture removed at the end of the two hour vibration drying periods at various frequencies were determined.

A comparison was then made to determine the equivalent effect of vibrating the grain layer in relation to forced air through the grain layer in terms of moisture removal. The results of these data are shown in Figure 11. From these results it can be concluded that vibrating the grain in relation to the moisture removed is equivalent to a forced air velocity in the range of from 25 to 36 feet per minute or an average of approximately 30 feet per minute.

Infrared Radiant Energy Source and Calibration

The infrared radiant energy was produced by 375 watt, electrical resistance, tungsten filament, industrial type heat lamps. These lamps were mounted to the hemispherical shaped metal frame with the tip of the bulb being maintained

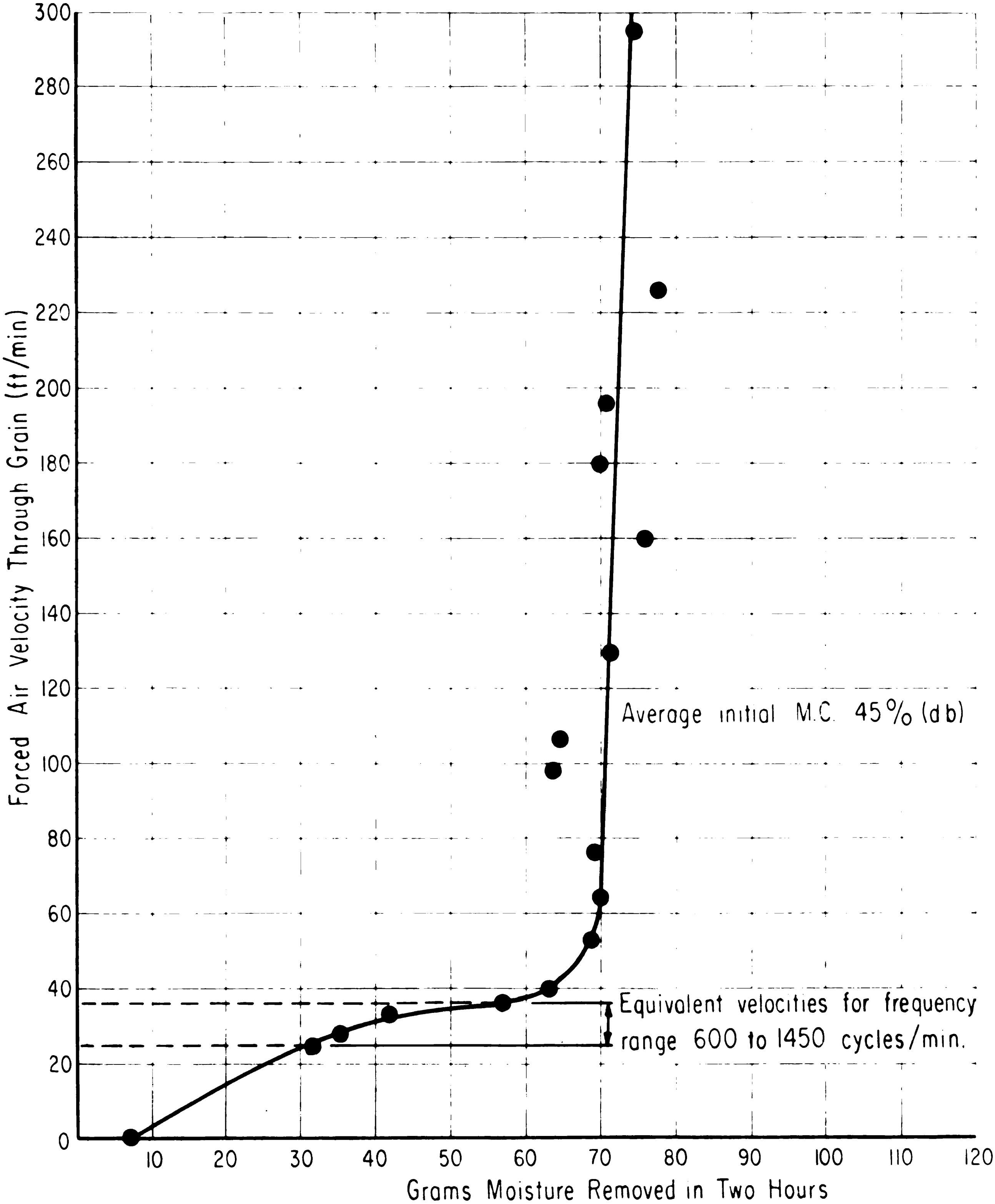

Figure 11 Forced air velocity versus moisture removal from two inch layer of shelled corn and equivalent velocity of vibration only

at a distance of one foot from the vibrating grain tray. The size of the apparatus was such that a maximum of seven of these infrared bulbs could be mounted at once to the hemispherical frame.

Calibration tests for determining the intensity at which infrared radiant energy was being received at surface of the grain layer were made by use of a thermopile (Figure 16). The Eppley thermopile was used in conjunction with a Leeds and Northrup millivolt potentiometer. The infrared lamps were given several minutes to obtain maximum operating temperatures before calibrating. By exposing the thermopile in the infrared energy field, the maximum millivolt reading was determined by the manual millivolt potentiometer in approximately thirty seconds exposure time. From this maximum millivolt reading one need only to multiply by the calibrated conversion factor of 117.4 Btu/hr.ft^2mv, (value furnished by the manufacturer) to obtain the rate at which radiant energy was being received at the surface of the grain in terms of Btu/hr.ft^2. Values were obtained for a series of from one through seven 375 watt infrared heat lamps centered over the drying tray at a distance of one foot from it. These maximum intensity values, shown in Figure 12, obtained at an input voltage of 115 volts, and measured at the center of the drying tray, were used in all calculations. However, the average energy distribution measured over the surface of the drying tray was approximately 10 per cent less.

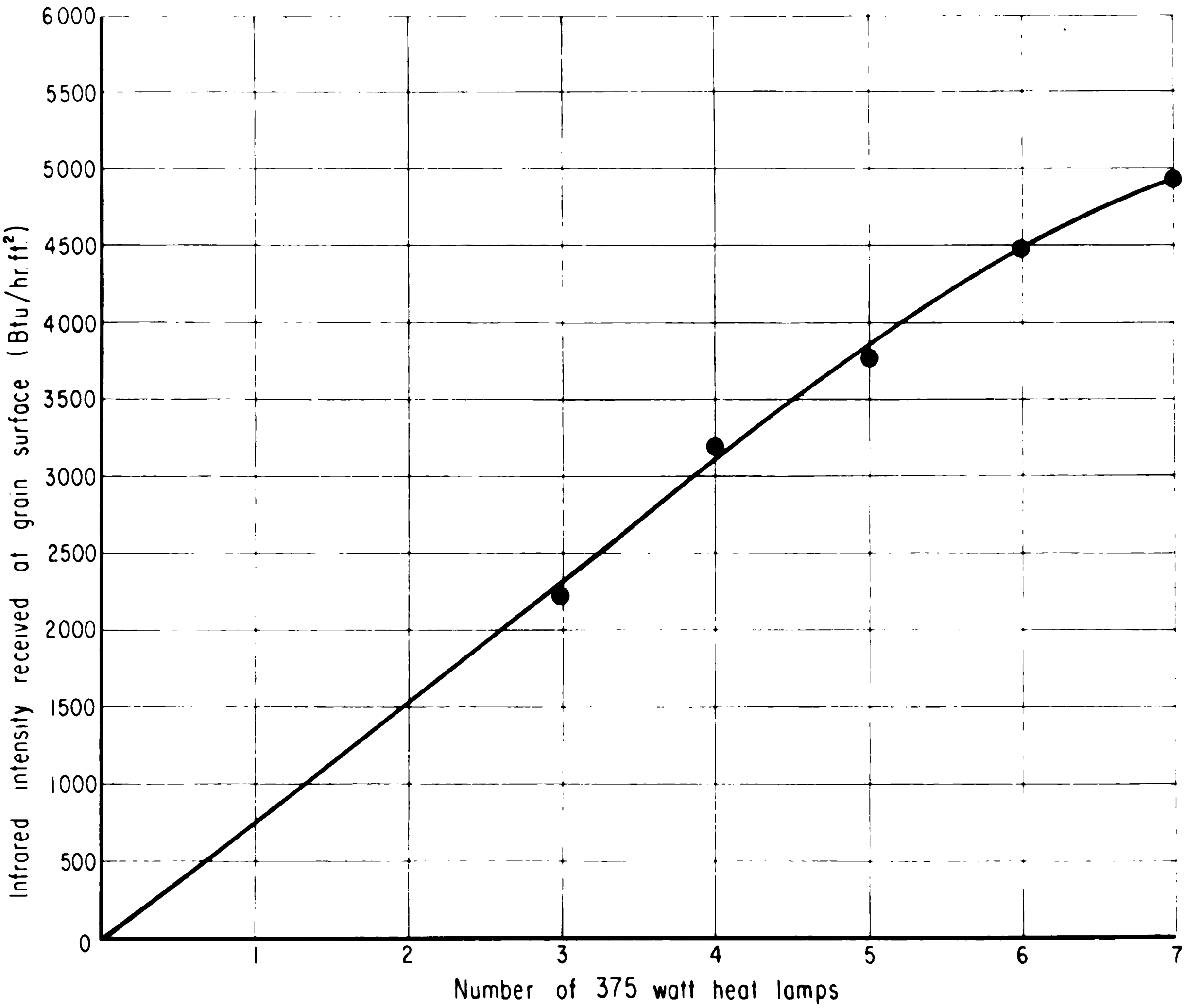

Figure 12 Energy received at surface of grain laver versus number of infrared lamps centered at one foot above drying tray.

Calibration for Varying Wavelength at Peak Infrared Intensity

The wavelength at peak intensity of the infrared emitter, in this case 375 watt industrial type heat lamps, was varied by varying the input voltage. The intensity of infrared radiant energy received at the surface of the grain layer was held constant, while the input voltage was varied. This increased or decreased the temperature of the tungsten filament which in the same manner shortened or lengthened the wavelength at peak intensity of the emitter. Longer wavelengths required that more heat lamps be used to maintain the same intensity, while in the same manner for a shorter wavelength with increased input voltage the number of heat lamps could be reduced. A Variac was used in series to vary the input voltage, while the Eppley thermopile and Leeds and Northrup millivolt potentiometer were used to determine when the infrared intensity being received at the surface of the grain layer had reached the previously calibrated constant intensity value.

Using the input voltage reading from the calibrated Variac, the percentage of the rated voltage of the lamp was calculated. From a log-log plot of the percentage input wattage and percentage color temperature versus the percentage of rated voltage, shown in Figure 13, the output color temperature was calculated. Using these color temperature values and applying Wein's law, $\lambda_{max}\ To_K = 2,900$, on the

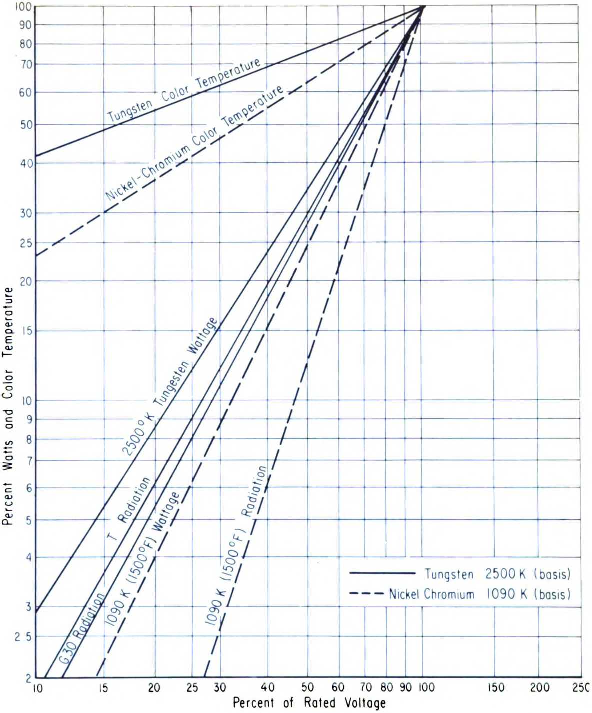

Figure 13 Comparative performance of various infrared sources as percent volts versus percent input, output and temperature (Fostoria Pressed Steel Corporation, Fostoria, Ohio).

assumption that the infrared lamps emit radiant energy approximately as a black body, the wavelengths at peak intensity for various color temperatures were calculated.

Method of Determining Total Heat Transfer Coefficient

The total heat transfer coefficient, h_t, included both the convection value, h_c, and the equivalent radiation coefficient, h_r. The total heat transfer coefficient, h_t, was predicted through application of an empirical fluidized bed particle-to-fluid convection equation (Leva, 1959), $h_c = 2.2 \times 10^{-3} (G)^{1.7}(D_p)^{0.5}$ and the radiation equation for the equivalent radiation coefficient, $h_r = \dfrac{\epsilon_c \sigma T_c^4}{(t_c - t_\infty)}$.

The equivalent particle diameter of a kernel of corn, D_p, was determined on the basis of an equivalent sphere with the same volume. A mercury displacement apparatus was used and an average equivalent diameter of a kernel of corn was found to be 0.33 inches. In the same manner the air mass flow rate, G, was determined from experimentally established air velocities through the grain layer and inlet air temperature conditions.

The equation for equivalent radiation coefficient was calculated by applying the radiation equation, using an established emissivity, ϵ_c, for shelled corn of 0.93. The absolute temperatures of the grain were determined both by temperature distribution data and exhaust air temperatures after thirty minutes drying time. Similarly the denominator was composed of the temperature difference between the grain, t_c, and surrounding air temperature, t_∞, expressed in degrees Fahrenheit.

APPLICATION OF DIMENSIONAL ANALYSIS FOR DESCRIBING INFRARED VIBRATION DRYING

Selection of Variables

The Buckingham Pi Theorem was applied to establish dimensionless ratios containing what was believed to be all the pertinent variables involved in infrared vibration drying of cereal grain. These variables were frequency, amplitude, depth, wavelength, infrared intensity, air velocity, initial grain temperature, heat capacity of grain, thermal conductivity of the grain, heat transfer coefficient, and drying time.

The following symbols were used to denote these variables.

F - frequency of vibration, cycle/min.

A - amplitude of vibration, inches.

D - depth of grain layer, inches.

λ_{max} - wavelength at peak intensity of infrared radiant energy emitter, microns.

I - infrared radiant energy intensity being received by product; Btu/hr.ft^2,

V - air velocity through grain layer, ft/min.

T_i - initial grain temperature, ^oF.

C_p - heat capacity of grain, Btu/lb.^oF.

k - thermal conductivity of grain, Btu/hr.ft^oF.

h_t - heat transfer coefficient at surface of grain from convection and reradiation, where h_t = $(h_c + h_r)$, Btu/hr.ft^{2o}F.

θ - drying time, min.

W - moisture content ratio of grain, $\frac{M}{M_o}$.

These variables or secondary quantities carry the following dimensions:

Variable Symbol	Variable Name	Dimension
F	frequency	$1/\theta$
A	amplitude	L
D	grain depth	L
λ_{max}	wavelength	L
I	radiant intensity	$H/\theta L^2$
V	air velocity	L/θ
T_i	initial grain temperature	T
C_p	grain heat capacity	H/MT
k	grain thermal conductivity	$H/\theta LT$
h_t	total heat transfer coefficient	$H/\theta L^2 T$
θ	drying time	θ
W	moisture content ratio	M/M_o

The symbols for the dimensions of the variables denote the following primary quantities:

H - heat

M - mass

L - length

T - temperature

θ - time

From this listing, it was seen that the number of variables which was believed to be sufficient to describe infrared vibration drying was twelve, and the number of dimensions contained in these variables was five. Therefore, the number of dimensionless groups involved would be $m = (n-b)$, or the number of variables minus the number of dimensions. Thus the number of P_i ratios (π ratios) would equal seven, $m = (12-5) = 7$.

Combining Infrared Vibration Drying Variables

In applying the Buckingham P_i theorem for combining the infrared vibration drying parameters, five of the twelve variables were selected which together included all of the dimensions involving heat, mass, length, time and temperature. These five variables were the grain depth, frequency of vibration, grain thermal heat capacity, grain thermal conductivity, and initial grain temperature. This left the amplitude of vibration, wavelength at peak intensity of the emitter, infrared intensity, air velocity, heat transfer coefficient, time, and moisture content ratio to be introduced one at a time into the analysis. Thus solving one may write the equation for π_1 as follows:

$$(D)^v(F)^w(C_p)^x(k)^y(T_i)^z A = H^o M^o L^o T^o \theta^o$$

Introducing the dimensions for each of the variables into the equation, the analysis for determining the π_1 dimensionless ratio was as follows:

$$(L)^v(\frac{1}{\theta})^w(\frac{H}{MT})^x(\frac{H}{\theta LT})^y(T)^z L = H^o M^o L^o T^o \theta^o$$

Solution for powers pertaining to each of the variables by dimensional analysis was:

(a) Heat, H	$x + y = 0$
(b) Mass, M	$-x = 0$
(c) Length, L	$v - y + 1 = 0$
(d) Temperature, T	$-x - y + z = 0$
(e) Time, θ	$-w - y = 0$

Solving the equations simultaneously the powers were found to be $v = -1$, $w = 0$, $x = 0$, $y = 0$, $z = 0$. This yielded the value of the first dimensionless ratio, $\pi_1 = A/D$.

Similarly introduction of wavelength, infrared intensity, forced air velocity, total heat transfer coefficient, time, and moisture content ratio into the analyses one at a time as in previous analysis for π_1, the following seven dimensionless π ratios were determined:

$$\pi_1 = A/D, \quad \pi_2 = \lambda_{max}/D, \quad \pi_3 = ID/kT_i, \quad \pi_4 = V/FD,$$

$$\pi_5 = h_t D/k, \quad \pi_6 = F\theta \text{ and } \pi_7 = W.$$

These seven dimensionless π ratios were combined as $\pi_7 = f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6)$ or $M/M_o = f(A/D, \lambda_{max}/D, ID/kT_i, V/FD, h_tD/k, F\theta)$. A number of similar analyses were performed with each analysis obtaining a set of dimensionless ratios slightly different from the previous.

Each of the dimensionless ratios contained part of the twelve variables related to the infrared vibration drying of shelled corn. Therefore, it was necessary to establish experimentally which of the variables affect the drying rate of shelled corn most.

Of the twelve variables involved in infrared vibration drying, essentially two of them vary continually during every drying period. These are the moisture content ratio, M/M_o, and the drying time, θ. Of the remaining ten variables, it was decided to study the effect of eight of these on the drying rate of high moisture shelled corn. These variables were frequency of vibration, F; amplitude of vibration, A; wavelength at peak intensity of the emitter, λ_{max}; intensity of infrared radiant energy received by the product, I; depth of the grain layer, D; initial grain temperature, T_i; the effect of concurrent forced air velocity, V; and the total heat transfer coefficient, h_t; where h_t includes both the convection value, h_c; and an equivalent radiation value, h_r. The grain thermal conductivity, k_c, and thermal heat capacity, C_p, were assumed to be relatively constant throughout the drying period (Kazarian, 1962).

To study the effect of each of the variables on the drying rate of shelled corn it was necessary to vary one at a time while holding the others constant. Thus experiments were performed with this objective in mind. In each case the drying constant, k, was determined on the basis that the equation, $M/M_o = e^{-k\theta}$, was valid for describing the entire period, since the equilibrium moisture content, M_e, was essentially zero. Thus the k-values were used as criteria for comparing the effect of each variable on the drying rate of shelled corn.

DRYING PROCEDURE

High moisture shelled corn used in this study had been harvested with a picker sheller. It was then placed in plastic lined bags, sealed and stored in a $0^{o}F$ freezer until which time the grain was needed for drying tests. At this time a quantity of the frozen grain was removed from the $0^{o}F$ freezer, placed in a small plastic bag or sealed jar and allowed to thaw and warm to room temperature.

Drying tests were run by weighing the proper amount of shelled corn, for example enough for a two inch layer in the six inch diameter drying tray, on a Mettler balance to the nearest 0.1 gram. The sample was placed in the drying tray and vibrated in the infrared field. Sample weights were taken every fifteen minutes, with the total drying time ranging from forty-five to sixty minutes depending upon the variable under study. All samples were then placed in an oven maintained at $212^{o}F$ for forty-eight hours at which time samples were removed, the dry matter weighed and moisture contents calculated as percentage dry basis.

When studying the effect of one of the variables, for example frequency variation, then the amplitude was held constant at 3/32 inch, intensity constant at 3,250 Btu/hr. ft^2, λ_{max} constant at 1.16 microns, grain depth constant at two inches, initial grain temperature constant at 70°F, air velocity equivalent by vibration only, while the frequency was varied in the range of from 600 cycles per minute to 1,450 cycles per minute and its effect on the drying rate determined.

Similarly when studying the effect of the variable intensity of infrared radiation on the drying rate, the frequency was held constant at 1,000 cycles per minute, and all the other variables were maintained at the same previously mentioned values except the intensity which was varied in the range of from 1,500 to 4,600 Btu/hr.ft^2.

The same procedure was carried out until all the variables had been studied. The drying constant, k, was calculated as a criterion for determining the effect of each variable on the drying rate.

RESULTS OF INFRARED VARIABLE STUDY

Calculation of k Values

The drying constant was determined by the relation, $k = 2.303 \frac{[\log (M_2) - \log (M_1)]}{\theta_2 - \theta_1}$, which is the slope of a straight line of a semilogarithmic plot of log M versus θ. The tabulation of these values are listed in Table 1.

Frequency Variation Effect

The effect of varying the frequency of vibration (within range) of the grain layer during drying was shown to have essentially no effect upon the drying rate of high moisture shelled corn. A frequency of at least 600 cycles per minute (amplitude 3/32 inch) was required to bring about a reasonable amount of mechanical fluidization of the grain layer or kernel cycling. Also a vibration frequency of 1,000 cycles per minute yielded the smoothest operation of the equipment and grain movements. This value was recommended as the frequency to be used throughout. Figure 14 denotes that varying the frequency of vibration has essentially no effect upon the drying rate of high moisture corn. Similarly Figure 15 shows the relationship of moisture content of the shelled corn versus time and further confirms

Table 1. Drying constants for shelled corn determined by varying infrared vibration drying parameters one at a time

	k (1/min)	F (cycles/ min)	A (in.)	λ_{max} (microns)	I (Btu/hr. ft^2)	V (ft/ min)	T_i (^oF)	D (in.)	h_t (Btu/hr. ft^2 ^oF)	M_o (dry basis)
Frequency Variation	2.34×10^{-2}	600	3/32	1.16	3,250	25	70	2	6.5	48.0
	2.26×10^{-2}	930	3/32	1.16	3,250	29	70	2	7.7	48.8
	2.37×10^{-2}	930	3/32	1.16	3,250	29	70	2	7.7	50.8
	2.3×10^{-2}	1,000	3/32	1.16	3,250	30	70	2	8.0	49.1
	2.17×10^{-2}	1,100	3/32	1.16	3,250	32	70	2	8.5	51.9
	2.28×10^{-2}	1,200	3/32	1.16	3,250	33	70	2	9.0	48.0
	2.11×10^{-2}	1,290	3/32	1.16	3,250	34	70	2	9.5	49.6
	2.23×10^{-2}	1,450	3/32	1.16	3,250	36	70	2	10.0	49.7
	2.32×10^{-2}	1,450	3/32	1.16	3,250	36	70	2	10.0	48.8
Amplitude Variation	1.54×10^{-2}	800	1/8	1.16	3,250	32	70	2	8.5	48.1
	1.53×10^{-2}	800	1/8	1.16	3,250	32	70	2	8.5	46.8
	1.75×10^{-2}	800	1/8	1.16	3,250	32	70	2	8.5	48.0
	1.76×10^{-2}	1,000	1/16	1.16	3,250	20	70	2	5.3	47.9
	1.75×10^{-2}	1,200	1/16	1.16	3,250	24	70	2	6.3	47.6
	1.82×10^{-2}	1,450	1/16	1.16	3,250	29	70	2	7.7	47.6

Table 1--Continued

	k (1/min)	F (cycles/ min	A (in.)	λ_{max} (microns	I (Btu/hr. ft^2)	V (ft/ min)	T_i (^oF)	D (in.)	h_t (Btu/hr. ft^2 ^oF	M_o (dry basis)
Wavelength Variation	2.28×10^{-2}	600	3/32	1.08	3,250	25	70	2	6.5	46.2
	2.47×10^{-2}	1,000	3/32	1.08	3,250	30	70	2	8.0	45.9
	2.29×10^{-2}	1,200	3/32	1.08	3,250	33	70	2	9.0	45.5
	2.32×10^{-2}	600	3/32	1.32	3,250	25	70	2	6.5	46.7
	2.35×10^{-2}	1,000	3/32	1.32	3,250	30	70	2	8.0	46.5
	2.47×10^{-2}	1,200	3/32	1.32	3,250	33	70	2	9.0	46.2
Intensity Variation	1.18×10^{-2}	1,000	3/32	1.16	1,500	30	70	2	8.0	34.0
	1.28×10^{-2}	1,000	3/32	1.16	1,500	30	70	2	8.0	39.2
	1.36×10^{-2}	1,000	3/32	1.16	1,500	30	70	2	8.0	40.0
	1.37×10^{-2}	1,000	3/32	1.16	1,500	30	70	2	8.0	40.0
	1.25×10^{-2}	1,000	3/32	1.16	1,500	30	70	2	8.0	37.0
	1.24×10^{-2}	1,000	3/32	1.16	1,500	30	70	2	8.0	34.7
	1.30×10^{-2}	1,000	3/32	1.16	1,500	30	70	2	8.0	32.7
	2.01×10^{-2}	600	3/32	1.16	2,230	25	70	2	6.5	34.0
	1.99×10^{-2}	600	3/32	1.16	2,230	25	70	2	6.5	32.7

Table 1--Continued

	k (1/min)	F (cycles/min)	A (in.)	λ_{max} (microns)	I (Btu/hr. ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr. ft^2 ^oF)	M_o (dry basis
Intensity Variation	$1.20x10^{-2}$	1,000	3/32	1.16	2,230	30	70	2	8.0	32.1
	$1.19x10^{-2}$	1,000	3/32	1.16	2,230	30	70	2	8.0	31.2
	$1.93x10^{-2}$	1,000	3/32	1.16	2,230	30	70	2	8.0	35.3
	$1.81x10^{-2}$	1,200	3/32	1.16	2,230	30	70	2	9.0	31.9
	$1.94x10^{-2}$	1,200	3/32	1.16	2,230	33	70	2	9.0	36.5
	$1.70x10^{-2}$	1,000	3/32	1.16	2,600	30	70	2	8.0	37.0
	$1.55x10^{-2}$	1,000	3/32	1.16	2,600	30	70	2	8.0	36.6
	$1.80x10^{-2}$	1,000	3/32	1.16	2,600	30	70	2	8.0	50.0
	$1.84x10^{-2}$	1,000	3/32	1.16	2,600	30	70	2	8.0	50.6
	$1.78x10^{-2}$	1,000	3/32	1.16	2,600	30	70	2	8.0	50.6
	$3.06x10^{-2}$	600	3/32	1.16	3,760	25	70	2	6.5	48.4
	$3.09x10^{-2}$	1,000	3/32	1.16	3,760	30	70	2	8.0	46.8
	$3.25x10^{-2}$	1,200	3/32	1.16	3,760	33	70	2	9.0	47.3
	$3.04x10^{-2}$	1,450	3/32	1.16	3,760	36	70	2	10.0	47.5
	$2.87x10^{-2}$	1,000	3/32	1.16	4,000	30	70	2	8.0	37.8
	$2.67x10^{-2}$	1,000	3/32	1.16	4,000	30	70	2	8.0	37.8
	$2.57x10^{-2}$	1,000	3/32	1.16	4,000	30	70	2	8.0	35.7

Table 1--Continued

	k (1/min)	F (cycles/min)	A (in.)	λ_{max} (microns)	I (Btu/hr. ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr. ft^{2o}F)	M_o (dry basis
Intensity Variation	3.45×10^{-2}	1,000	3/32	1.16	4,600	30	70	2	8.0	51.2
	3.58×10^{-2}	1,000	3/32	1.16	4,600	30	70	2	8.0	50.7
	3.18×10^{-2}	1,000	3/32	1.16	4,600	30	70	2	8.0	50.1
	3.57×10^{-2}	1,000	3/32	1.16	4,600	30	70	2	8.0	49.0
Air Velocity Variation	1.53×10^{-2}	600	3/32	1.16	3,250	145	70	2	80.0	48.9
	1.65×10^{-2}	1,000	3/32	1.16	3,250	147	70	2	80.0	49.7
	1.80×10^{-2}	1,450	3/32	1.16	3,250	147	70	2	80.0	49.9
	1.54×10^{-2}	1,000	3/32	1.16	3,250	220	70	2	160.0	50.7
	1.65×10^{-2}	1,450	3/32	1.16	3,250	225	70	2	160.0	49.9
	1.44×10^{-2}	600	3/32	1.16	3,250	228	70	2	160.0	50.7
	1.42×10^{-2}	1,000	3/32	1.16	3,250	285	70	2	230.0	50.5
	1.42×10^{-2}	1,450	3/32	1.16	3,250	293	70	2	230.0	48.1
	1.38×10^{-2}	600	3/32	1.16	3,250	297	70	2	230.0	49.6
	1.29×10^{-2}	1,450	3/32	1.16	3,250	355	70	2	360.0	49.9
	1.31×10^{-2}	1,000	3/32	1.16	3,250	259	70	2	360.0	50.8

Table 1--Continued

	k (1/min)	F (cycles/min)	A (in.)	λ_{max} (microns)	I (Btu/hr. ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr. ft^2 ^oF)	M_o (dry basis)
Air Vel. Var.	1.29×10^{-2}	600	3/32	1.16	3,250	366	70	2	360.0	48.0
Initial Grain Temperature Variation	1.99×10^{-2}	1,000	3/32	1.16	3,250	30	32	2	8.0	47.9
	2.16×10^{-2}	1,000	3/32	1.16	3,250	30	50	2	8.0	48.7
	2.28×10^{-2}	1,000	3/32	1.16	3,250	30	70	2	8.0	47.5
	2.34×10^{-2}	1,000	3/32	1.16	3,250	30	100	2	8.0	47.9
	2.33×10^{-2}	1,000	3/32	1.16	3,250	30	120	2	8.0	47.3
Grain Depth and Intensity Variation	1.92×10^{-2}	1,000	3/32	1.16	1,500	30	70	1	8.0	33.3
	2.28×10^{-2}	1,000	3/32	1.16	1,500	30	70	1	8.0	33.5
	1.98×10^{-2}	1,000	3/32	1.16	1,500	30	70	1	8.0	35.3
	2.80×10^{-2}	1,000	3/32	1.16	1,500	30	70	1	8.0	34.3
	2.16×10^{-2}	1,000	3/32	1.16	1,500	30	70	1	8.0	34.5
	2.00×10^{-2}	1,000	3/32	1.16	3,250	30	70	1	8.0	35.4
	2.44×10^{-2}	1,000	3/32	1.16	3,250	30	70	1	8.0	35.7
	2.25×10^{-2}	1,000	3/32	1.16	3,250	30	70	1	8.0	35.7

Table 1--Continued

	k (1/min)	F (cycles/min)	A (in.)	λ max (microns)	I (Btu/hr. ft^2)	V (ft/min)	Ti (^oF)	D (in.)	h_t (Btu/hr. ft^2 ^oF)	M_o (dry basis)
Grain Depth and Intensity Variation	$2.33x10^{-2}$	1,000	3/32	1.16	3,250	30	70	1	8.0	35.9
	$2.44x10^{-2}$	1,000	3/32	1.16	3,250	30	70	1	8.0	35.1
	$2.36x10^{-2}$	1,000	3/32	1.16	3,250	30	70	1	8.0	40.7
	$2.34x10^{-2}$	1,000	3/32	1.16	3,250	30	70	1	8.0	40.0
	$2.53x10^{-2}$	1,000	3/32	1.16	3,250	30	70	1	8.0	40.9
	$2.92x10^{-2}$	1,000	3/32	1.16	3,250	30	70	1	8.0	38.4
	$2.60x10^{-2}$	1,000	3/32	1.16	3,250	30	70	1	8.0	38.4
	$1.62x10^{-2}$	1,000	3/32	1.16	1,500	30	70	1-1/2	8.0	34.2
	$1.62x10^{-2}$	1,000	3/32	1.16	1,500	30	70	1-1/2	8.0	32.9
	$2.25x10^{-2}$	1,000	3/32	1.16	2,230	30	70	1-1/2	8.0	33.8
	$1.87x10^{-2}$	1,000	3/32	1.16	2,230	30	70	1-1/2	8.0	36.5
	$2.39x10^{-2}$	1,000	3/32	1.16	2,230	30	70	1-1/2	8.0	34.5
	$1.20x10^{-2}$	1,000	3/32	1.16	3,250	30	70	3	8.0	34.7
	$1.22x10^{-2}$	1,000	3/32	1.16	3,250	30	70	3	8.0	33.6
	$1.10x10^{-2}$	1,000	3/32	1.16	3,250	30	70	3	8.0	34.1

Table 1--Continued

	k (1/min)	F (cycles/min)	A (in.)	λ_{max} (microns)	I (Btu/hr. ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr. $ft^{2o}F$)	M_o (dry basis)
Grain Depth and Intensity Variation	$1.38x10^{-2}$	1,000	3/32	1.16	3,250	30	70	3	8.0	37.8
	$1.41x10^{-2}$	1,000	3/32	1.16	3,250	30	70	3	8.0	39.8
	$1.48x10^{-2}$	1,000	3/32	1.16	3,250	30	70	3	8.0	38.1
	$1.14x10^{-2}$	1,000	3/32	1.16	3,250	30	70	4	8.0	34.1
	$1.02x10^{-2}$	1,000	3/32	1.16	3,250	30	70	4	8.0	34.7
	$1.02x10^{-2}$	1,000	3/32	1.16	3,250	30	70	4	8.0	34.4
	$0.93x10^{-2}$	1,000	3/32	1.16	3,250	30	70	4	8.0	43.7
	$1.00x10^{-2}$	1,000	3/32	1.16	3,250	30	70	4	8.0	40.0
	$1.15x10^{-2}$	1,000	3/32	1.16	3,250	30	70	4	8.0	41.2

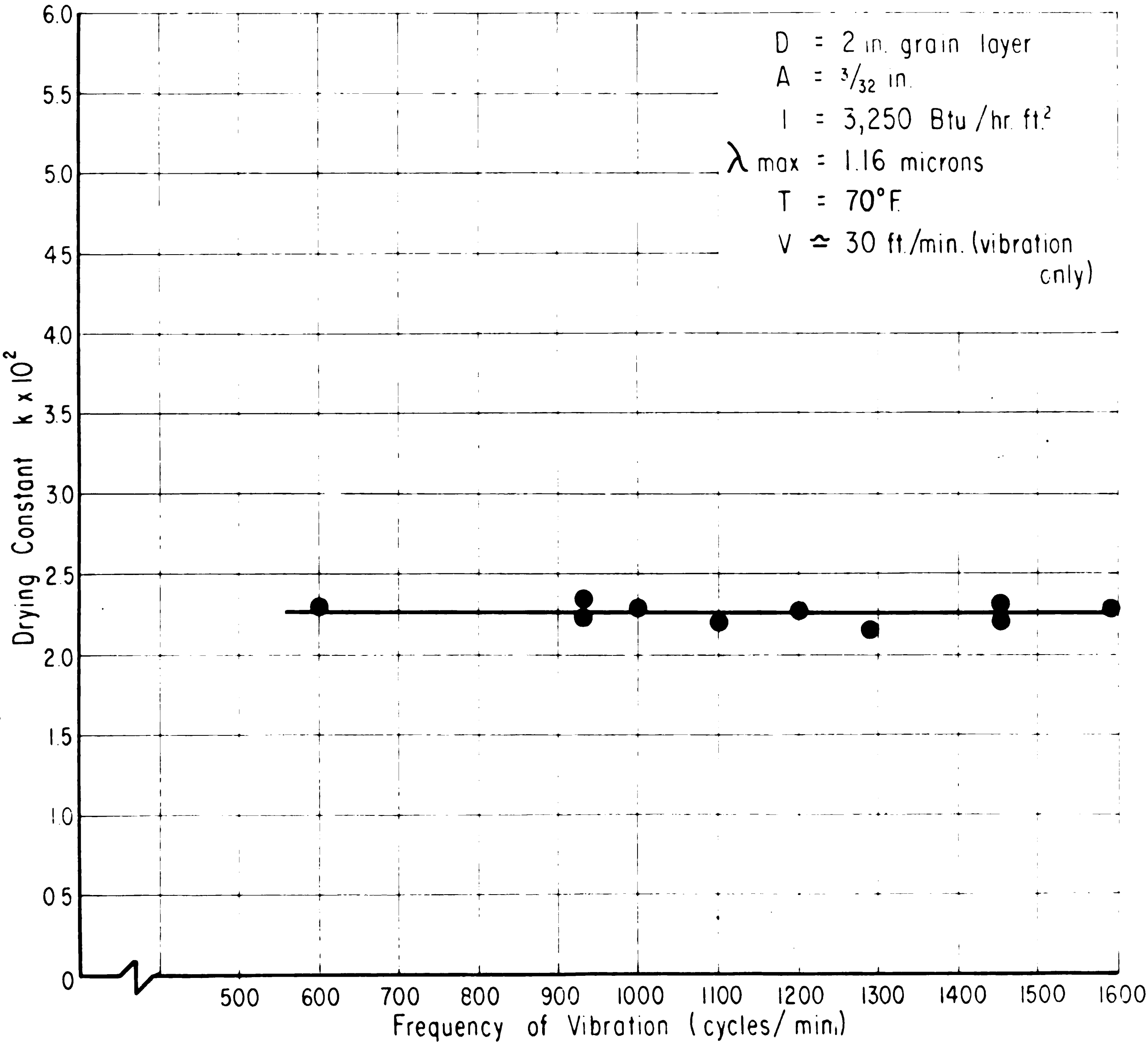

Figure 14 Effect of frequency of vibration on drying constant for shelled corn

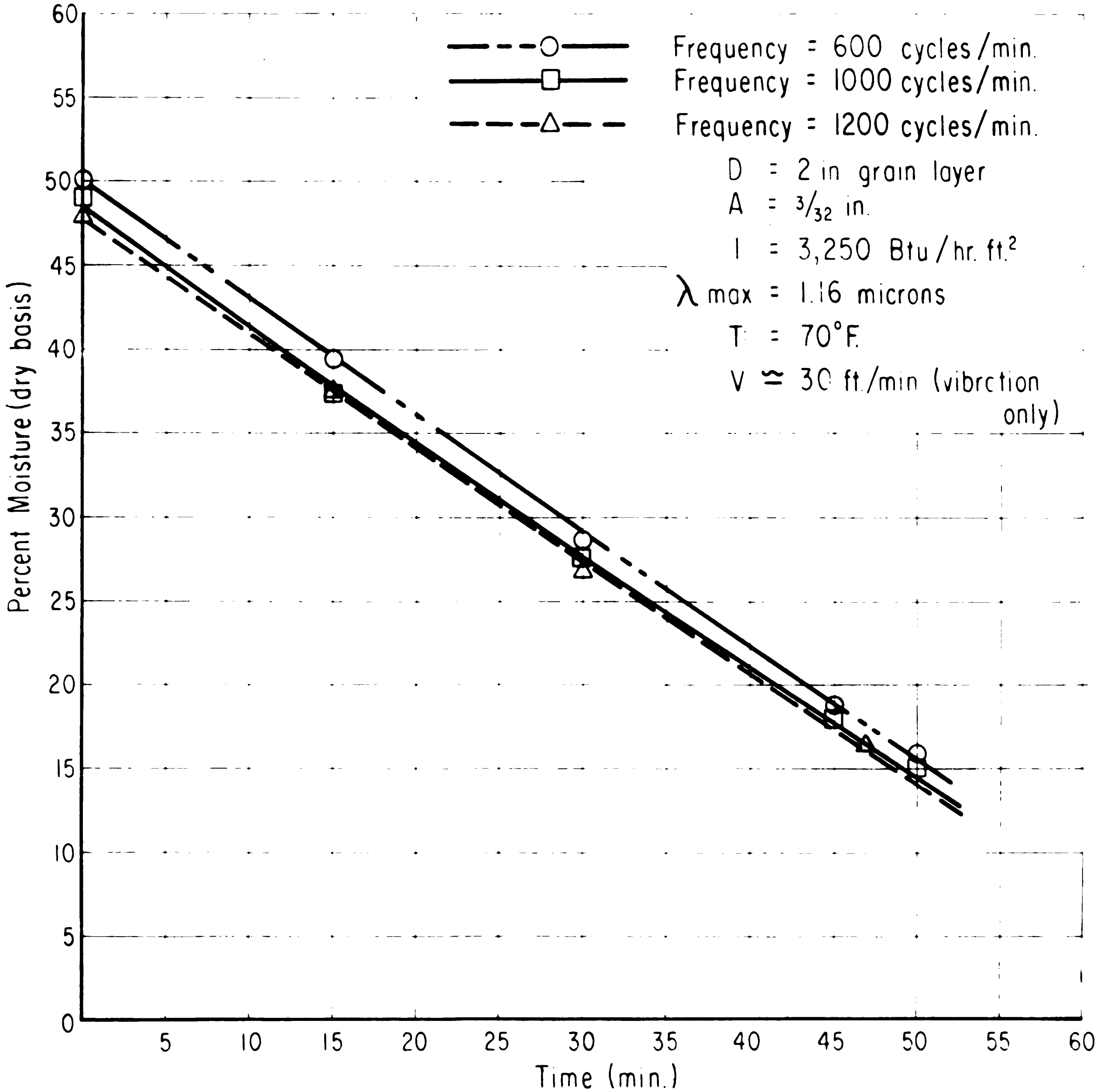

Figure 15 Moisture content of shelled corn versus time in relation to vibration frequency variation

that frequency variation has essentially no effect on the drying rate of shelled corn.

Amplitude Variation Effect

The effect of varying the amplitude of vibration on the drying rate of high moisture shelled corn yielded one value which contributed most to optimum drying results. Of the three amplitudes studied, 1/16 inch, 3/32 inch, and 1/8 inch, optimum drying resulted when the 3/32 inch value was used. All replicate drying tests indicated that the drying constant, k, declined for both 1/16 inch and 1/8 inch amplitudes. These results are illustrated in Figure 16. Further verification of these results are shown in Figure 17, which illustrates the relationship of moisture content of the shelled corn versus time at the three amplitudes under study.

Infrared Intensity Variation Effect

Varying the infrared radiant energy intensity produced a definite effect on the drying rate of high moisture shelled corn. The infrared intensities studied, ranging from 1,500 to 4,600 Btu/hr.ft^2, showed increased drying rates with increased infrared intensities. The relation was not linear over the range studied but appeared sinusoidal within limits as shown in Figure 18. The plot of moisture content of the grain versus time of infrared vibration drying as shown in Figure 19 also indicated increased drying

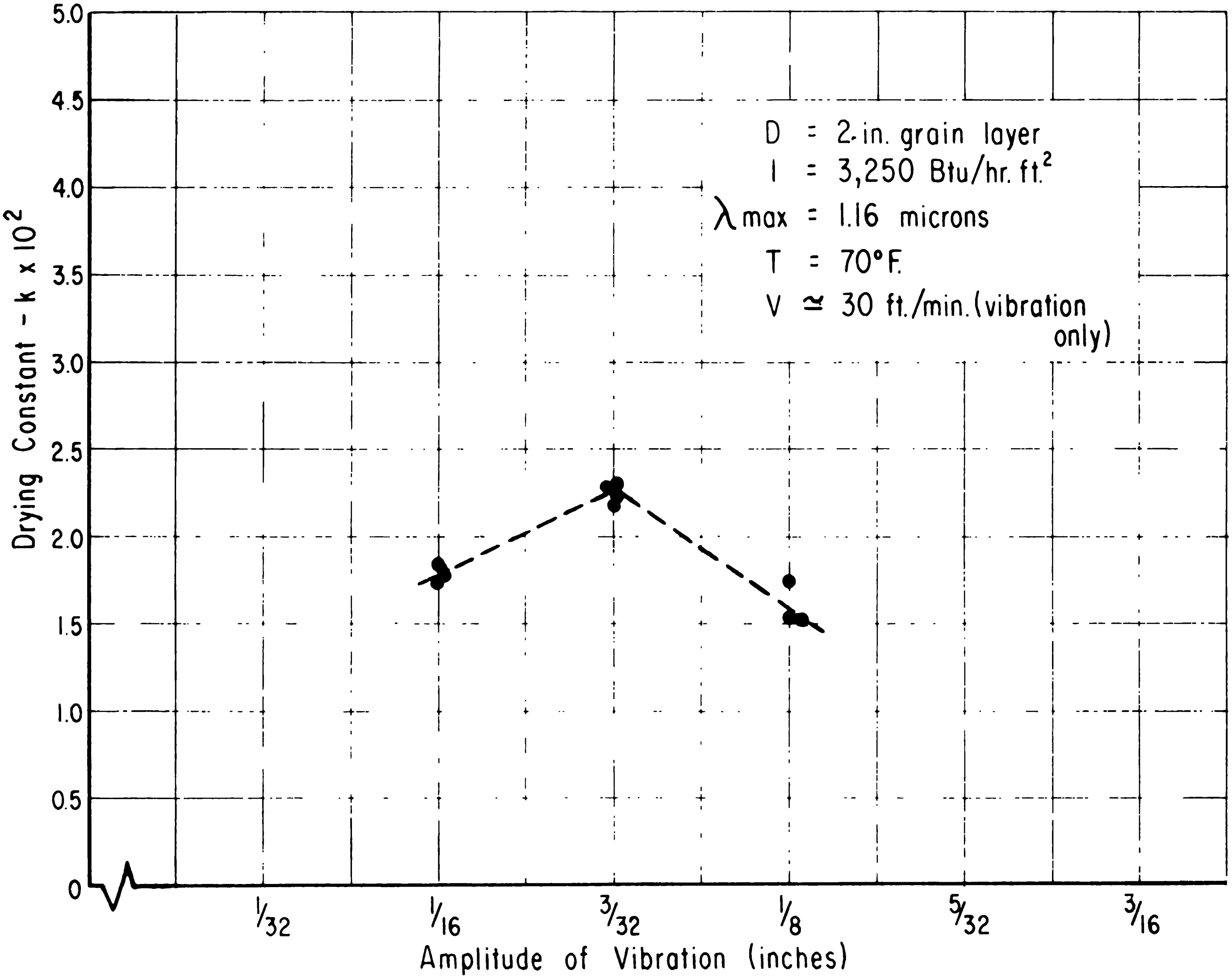

Figure 16 Effect of amplitude variation on the drying constant for shelled corn

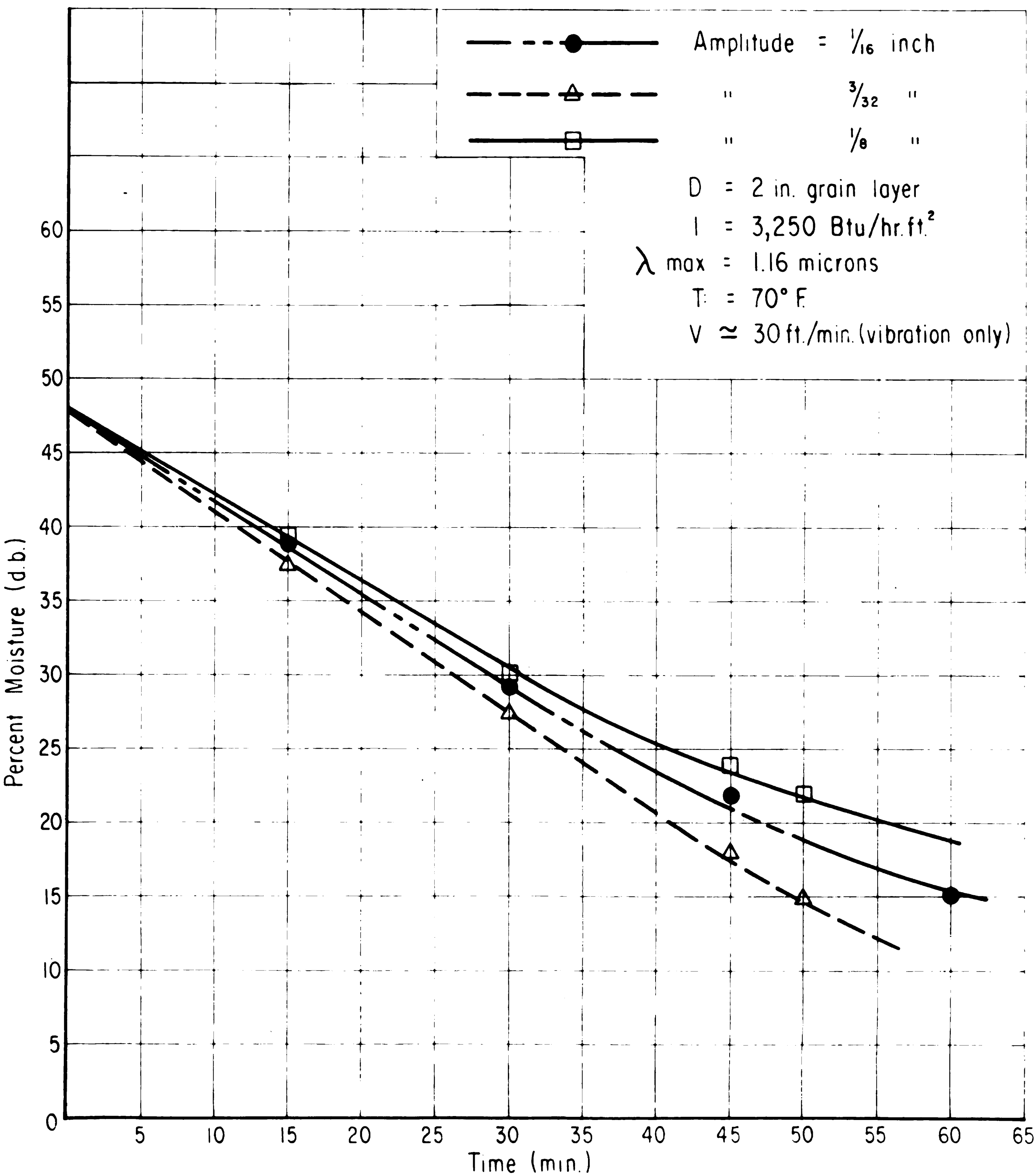

Figure 17 Moisture content of shelled corn versus time in relation to amplitude variation

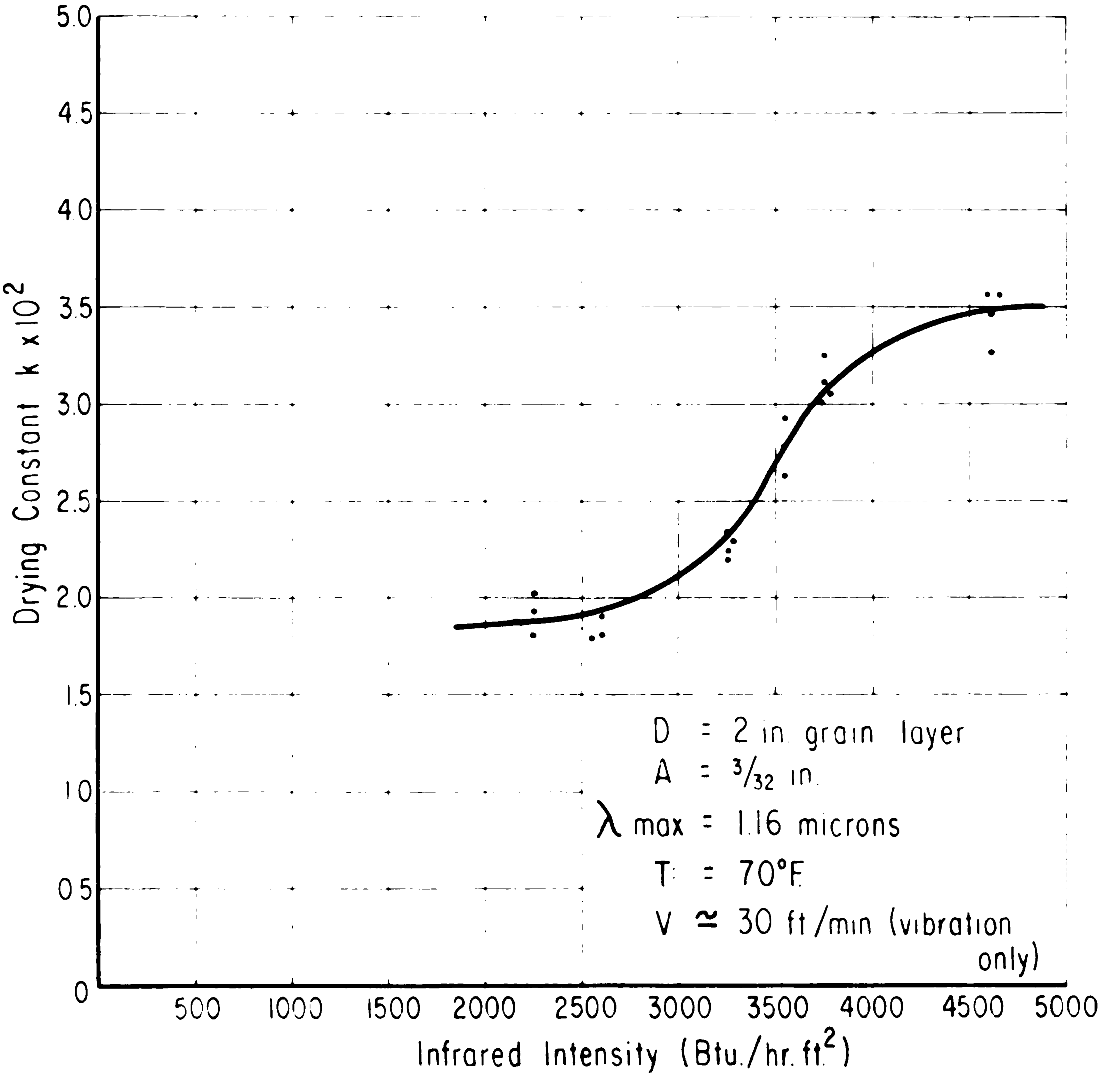

Figure 18 Effect of infrared intensity variation on the drying constant for shelled corn

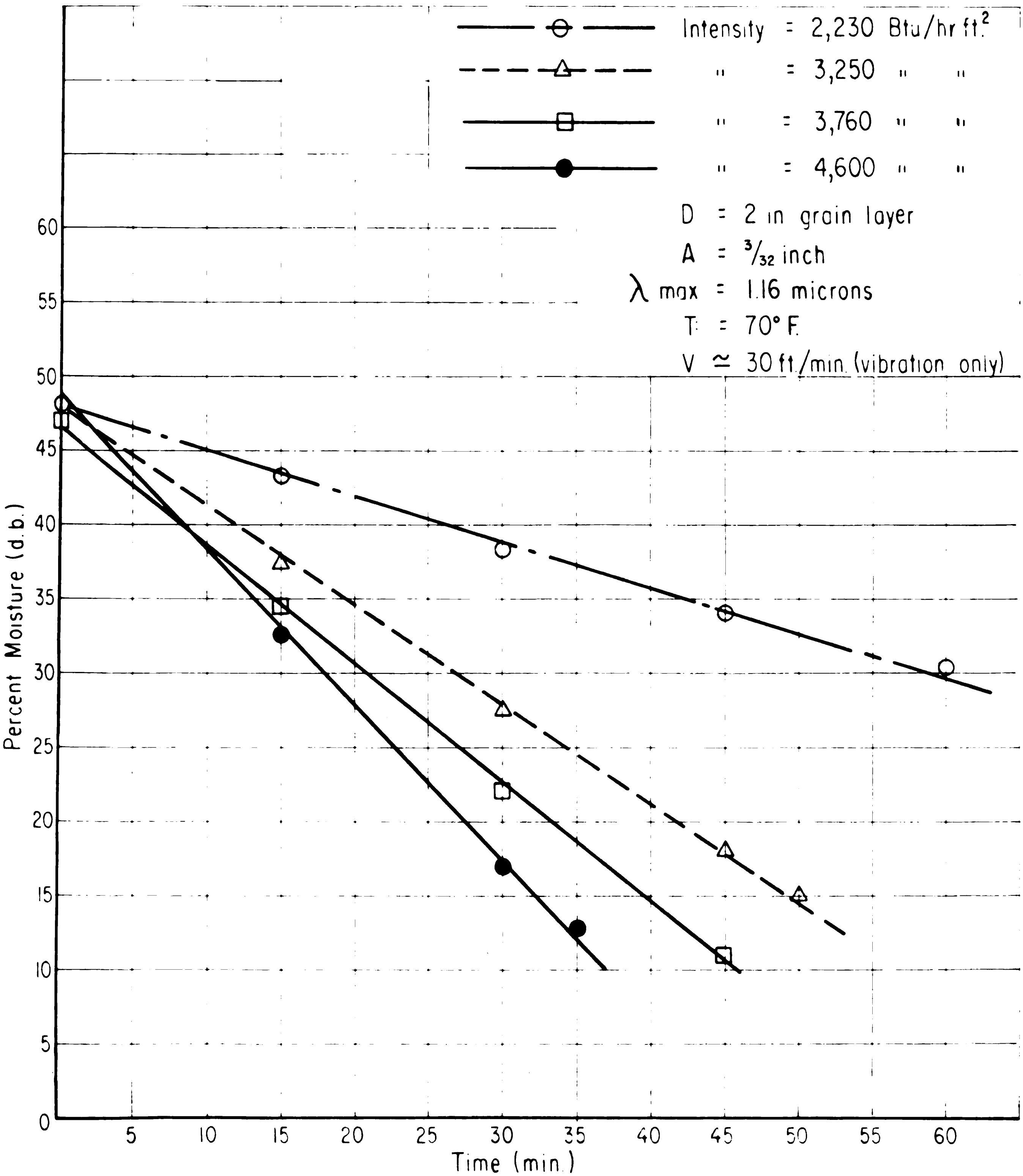

Figure 19 Moisture content of shelled corn versus time in relation to infrared intensity variation

rates with increased infrared radiant energy intensities.

Wavelength Variation Effect

Wavelength variation at the peak intensity of the infrared emitter, using the assumption that the infrared lamps were emitting as black bodies, produced a definite effect on the drying rate of high moisture shelled corn. Increasing the wavelength at peak intensity also increased the drying rate of shelled corn. Wavelengths at peak intensities of 1.08 μ, 1.16 μ, 1.32 μ and 2.50 μ were studied. Essentially a linear relationship resulted as shown in Figure 20. Similarly Figure 21 illustrates a more rapid reduction in moisture of high moisture shelled corn when infrared vibration drying is conducted with an infrared source emitting a longer wavelength at peak intensity.

Initial Grain Temperature Effect

Varying the initial temperature of the grain prior to drying with infrared radiant energy showed only a slight but positive effect on the drying rate. An increase in the value of the drying constant of a little over 12 per cent was observed when the initial grain temperature was varied from 32^{o}F to 120^{o}F. The results of these data are shown in Figure 22. In the same manner Figure 23 illustrates the change in moisture content as a function of time in relation to the initial temperature of the grain.

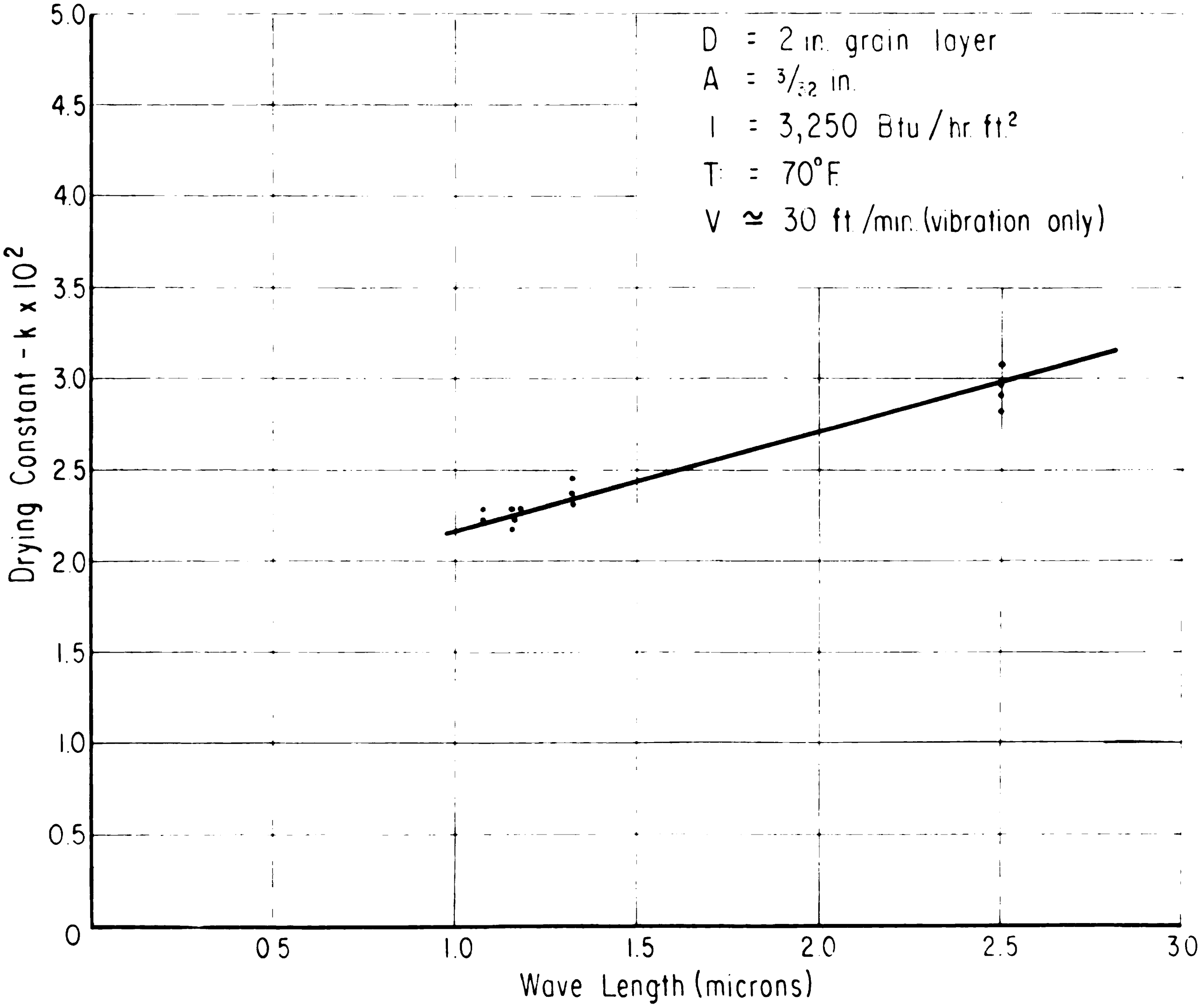

Figure 20 Effect of wavelength at peak intensity variation on the drying constant for shelled corn

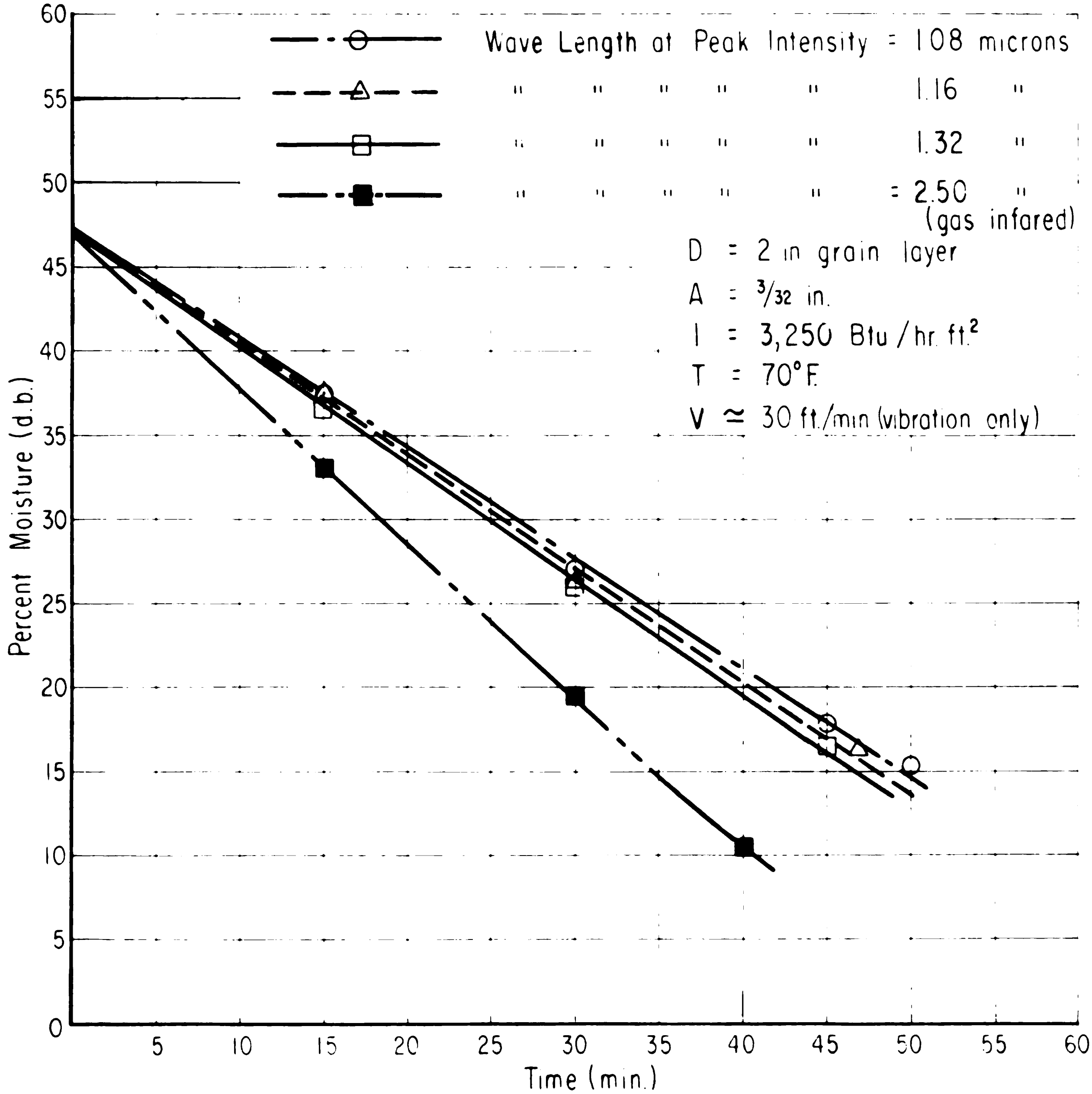

Figure 21 Moisture content of shelled corn versus time in relation to wavelength of infrared energy at peak intensity

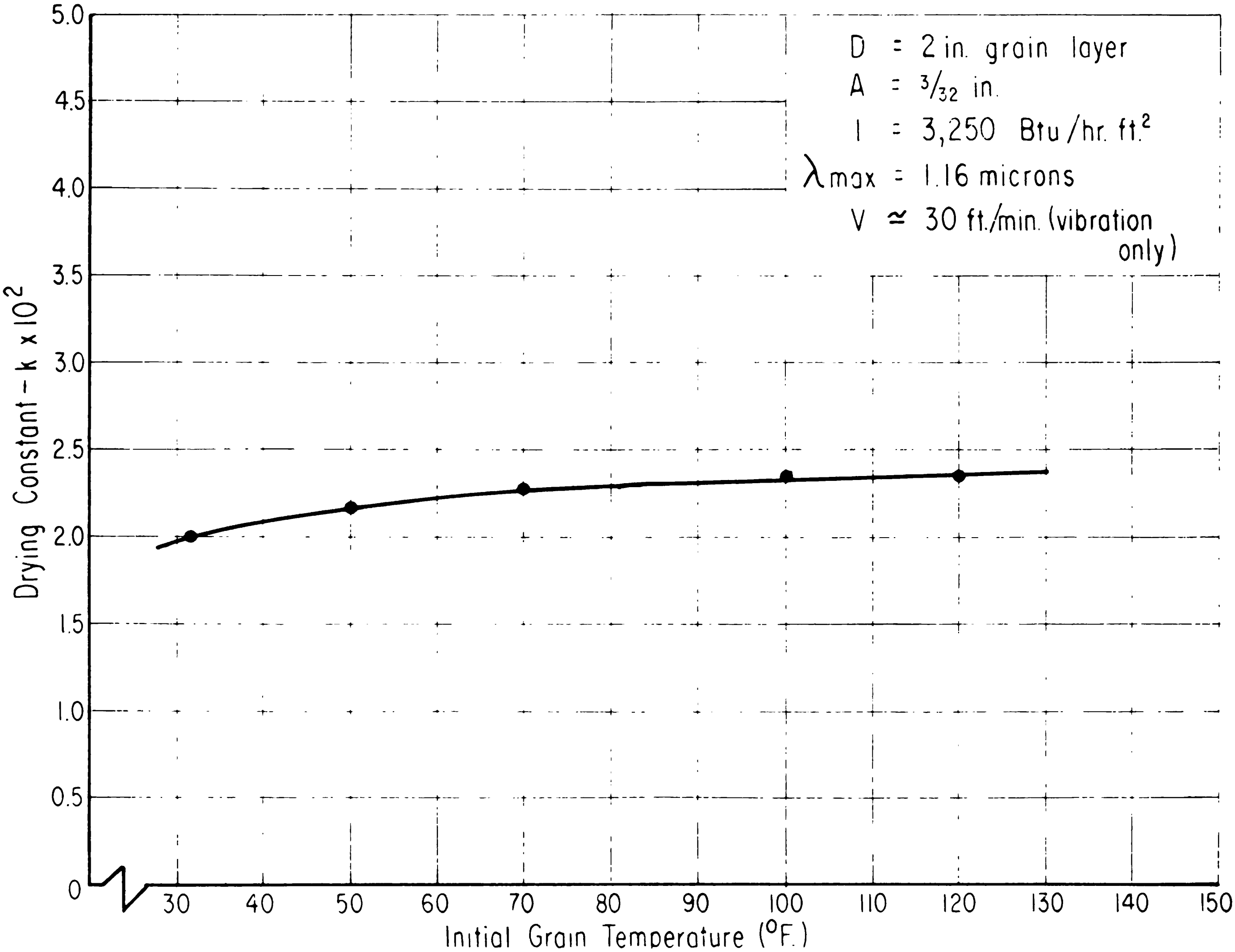

Figure 22 Effect of initial grain temperature on the drying constant for shelled corn

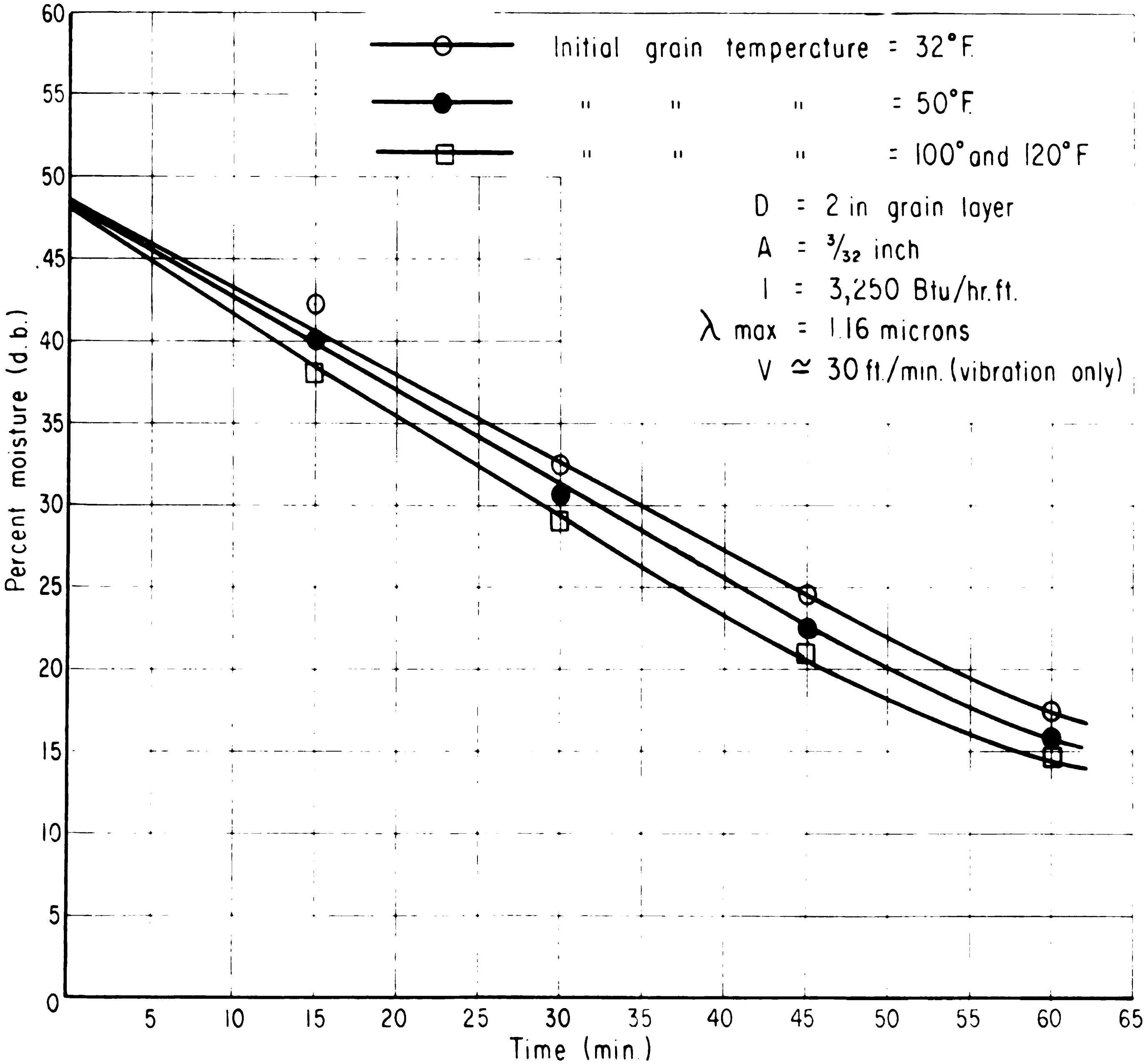

Figure 23 Moisture content of shelled corn versus time in relation to the initial grain temperature

Forced Air Flow Effect

Vibration of the grain layer (no forced air) was shown to have an equivalent forced air flow effect in relation to drying of approximately thirty to thirty-one feet per minute. Using forced air flows concurrent to the direction of infrared energy transfer throughout the entire drying period reduced the drying rate of high moisture shelled corn, which indicated a cooling effect on the surface of the grain.

Figure 24 illustrates the effect of forced air velocities (values include equivalent vibration effect). Forced air flow decreased the drying rate and in a linear fashion. Using the vibration equivalent (30 ft/min) a larger drying rate was obtained. Further verification was seen in Figure 30 illustrating moisture content as a function of time for the various forced air velocities through the grain. The most efficient use of forced air flow used in conjunction with infrared vibration drying was obtained when intermittent air flows were used. A forced air flow of approximately 115 feet per minute for the first fifteen minutes only of the infrared vibration drying period and then continuing with the vibration frequency of 1,000 cycles per minute (velocity equivalent 30 ft/min) for the remainder of the drying period produced superior drying results over the use of forced air flow during the entire drying period as shown in Figure 25.

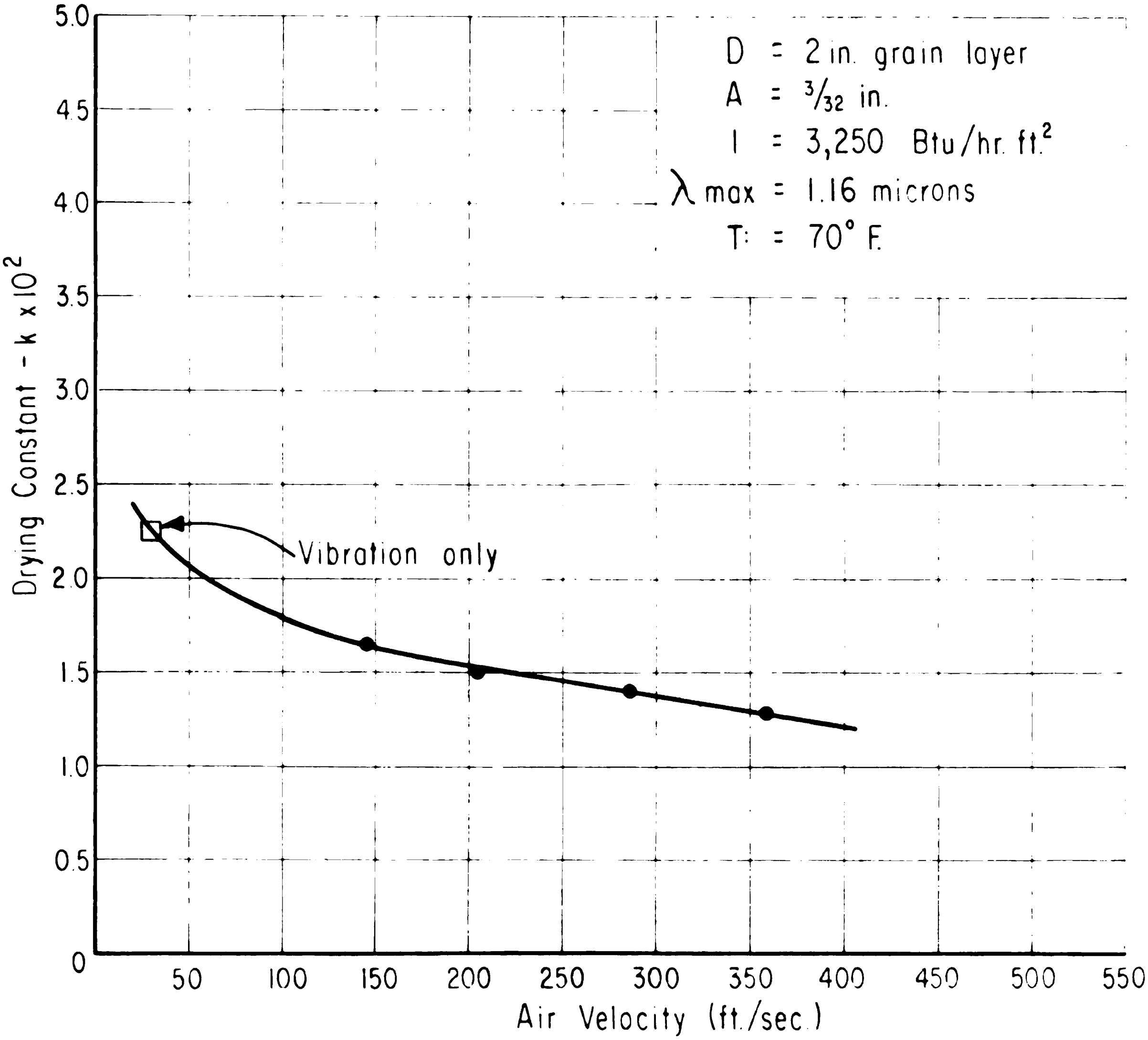

Figure 24 Effect of forced air velocity (vibration effect plus forced air) on the drying constant for shelled corn

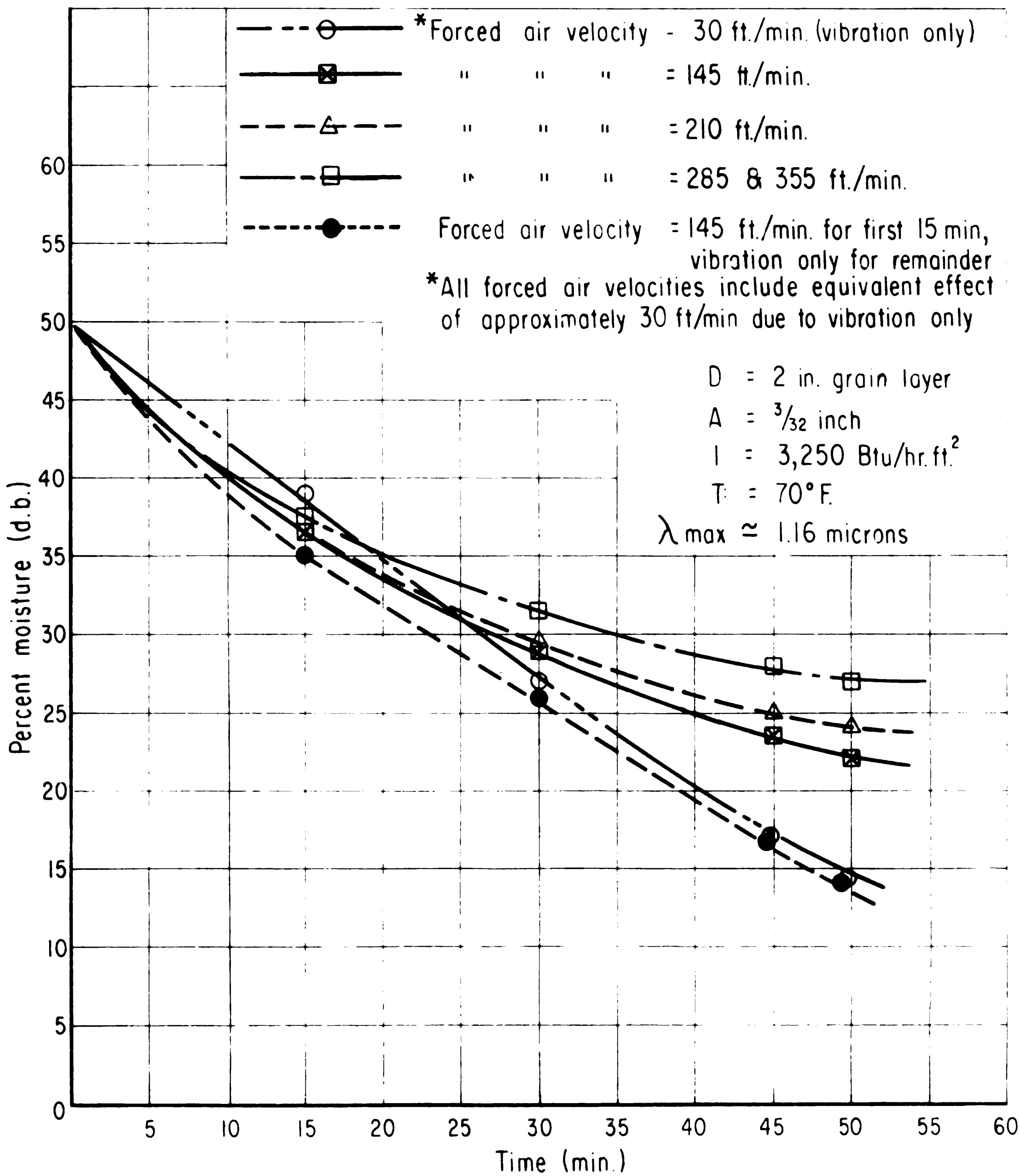

Figure 25 Moisture content of shelled corn in relation to rate of forced air flow through grain layer

Grain Depth Variation Effect

Vibration of the grain layer, sufficient to produce thorough mixing, permitted satisfactory drying of high moisture grain at increased depths. Increasing the depth of the grain layer resulted in a decrease in the drying rate (holding intensity constant) as shown in Figure 26. Considering the drying rate within the range of depths from one to four inches, the drying constant, k, appeared to follow a sinusoidal relationship. In the same manner Figure 27 showed a decrease in the drying rate as the depth of the grain layer was increased.

Effect of Total Heat Transfer Coefficient Variation

The total heat transfer coefficient, h_t, established from the sum of the convection and equivalent radiation coefficient values, $h_t = 2.2\text{x}10^{-3}(G)^{1.7}(D_p)^{0.5} + \dfrac{\epsilon_c \sigma T_c^{\ 4}}{(t_c - t_\infty)}$, increased sharply with increasing forced air velocities as shown in Figure 28. It was also seen that the equivalent radiation coefficient, h_r, contributed relatively little to the value of the total heat transfer coefficient. Vibration equivalent (30 ft/min) at a frequency of 1,000 cycles per minute yielded a total heat transfer coefficient, h_t = 8 Btu/hr.ft^{2}F. Thus increased air velocities produced increased total heat transfer coefficients and reduced drying rates in infrared vibration drying.

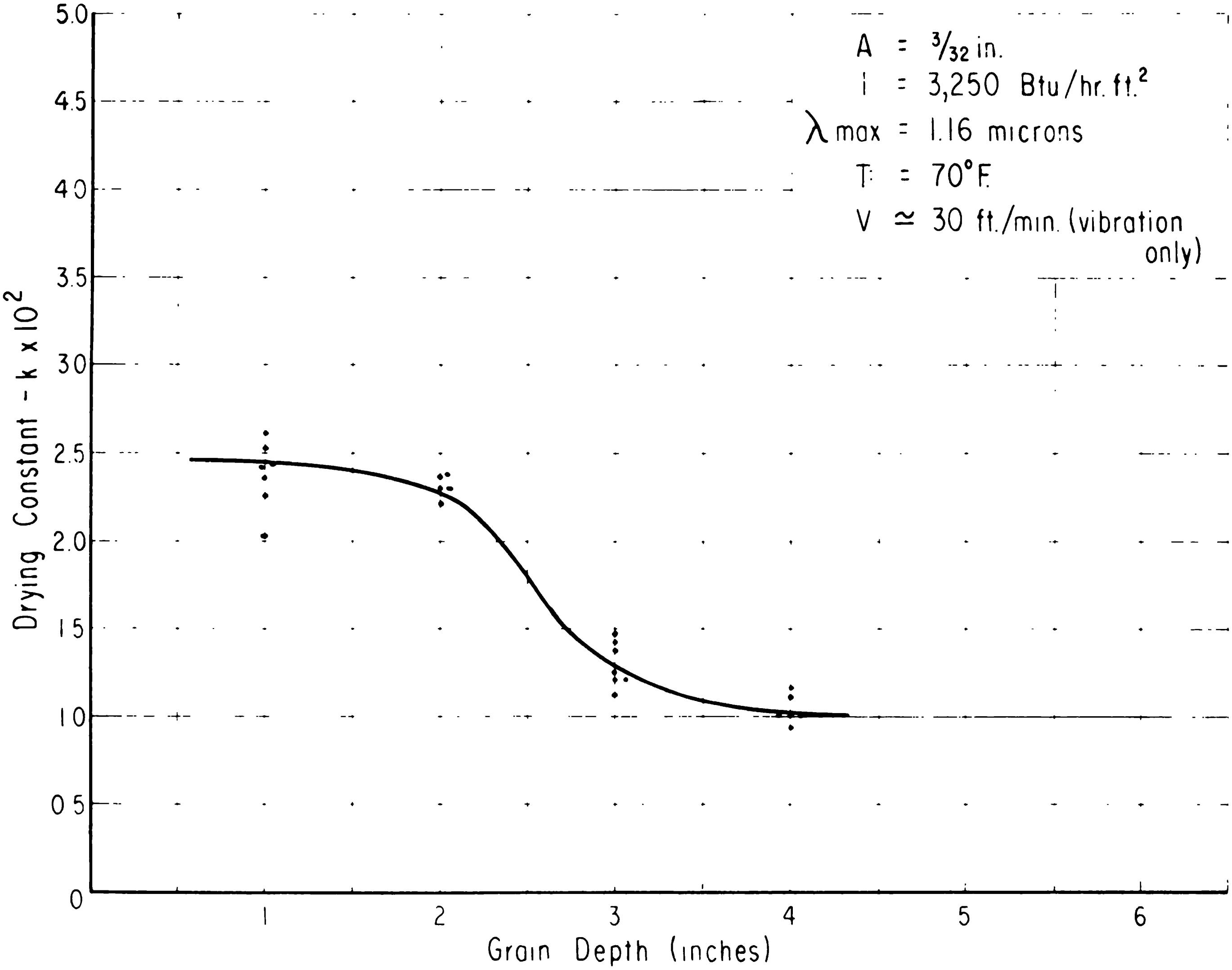

Figure 26 Effect of grain depth on the drying constant for shelled corn

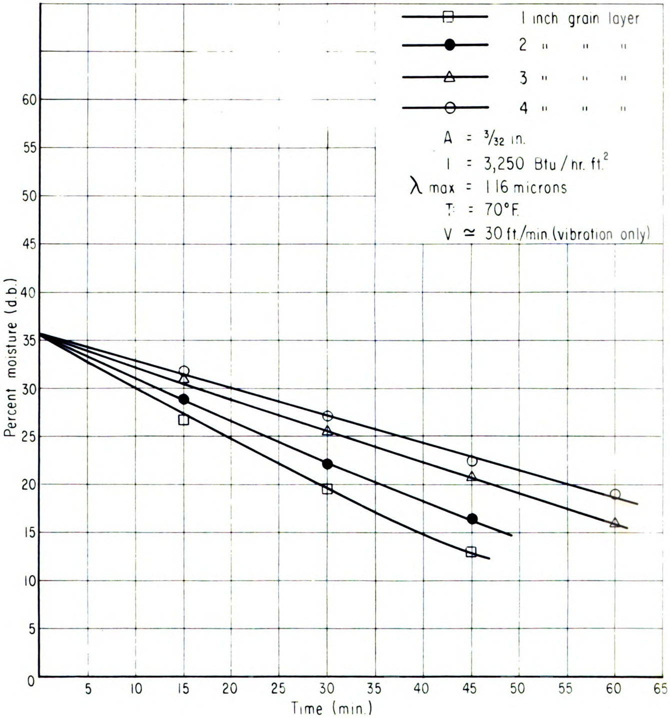

Figure 27 Moisture content of shelled corn versus time in relation to variation in grain depth

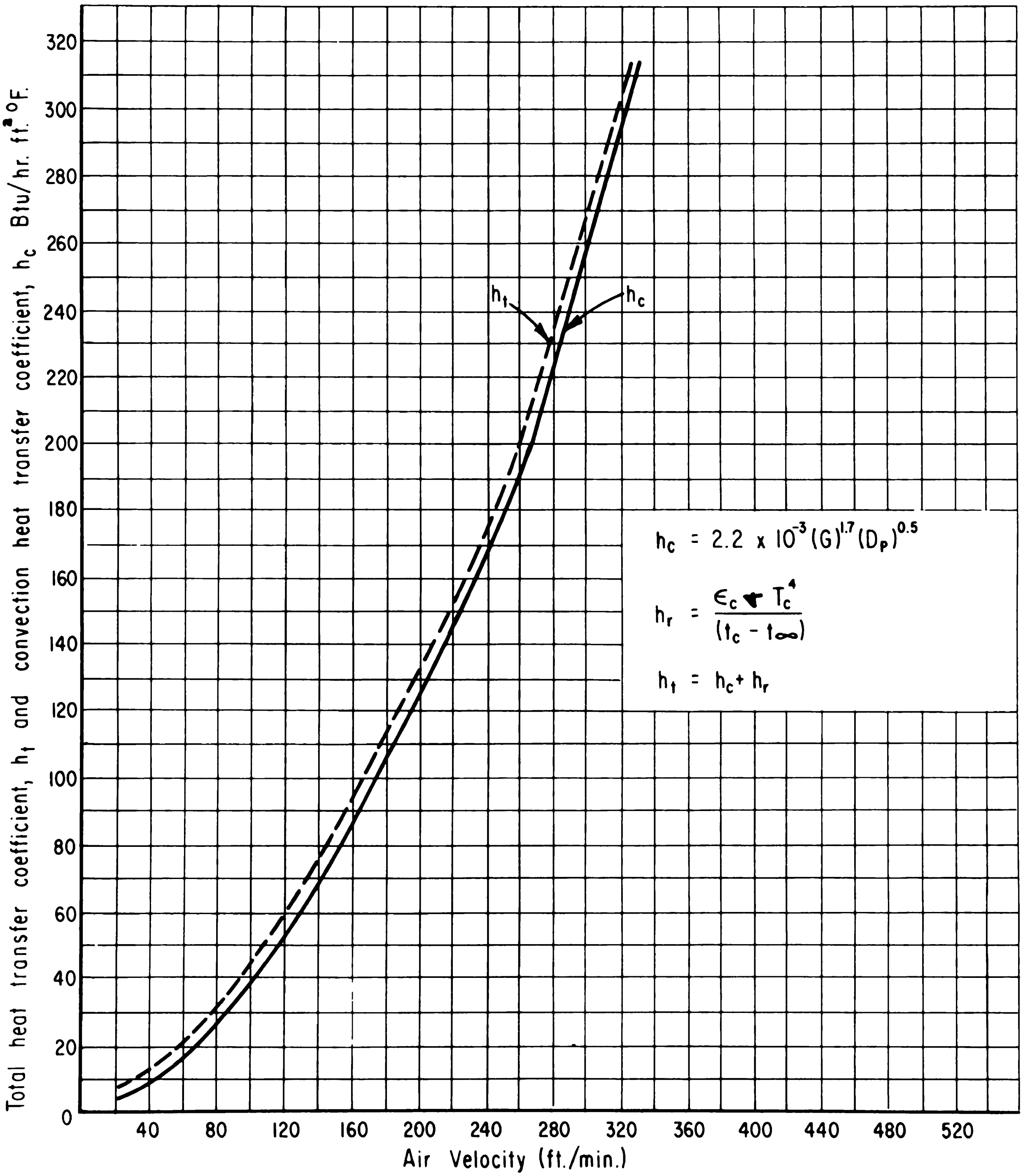

Figure 28 A plot of total heat transfer coefficient and convection heat transfer coefficient versus air velocity through grain layer.

Efficiency of Infrared Energy Utilization

The efficiency of infrared radiant energy utilization was improved by vibrating the grain layer as well as using forced air flows for both the proper time interval and concurrent to the direction of infrared radiant energy transfer. A forced air flow of 115 feet per minute for only the first fifteen minutes of infrared vibration drying period improved the efficiency of utilization of infrared energy being received at the rate of 3,250 Btu/hr.ft^2 at the surface of a two inch vibrating grain layer from 76 per cent when vibration only was used (vibration equivalent to an air velocity of thirty to thirty-one feet per minute) to 83.5 per cent. The overall efficiency, including electrical energy to vibrate and for forced air flow was 60.4 per cent as compared to an overall efficiency of 59 per cent when vibration only was used. The results of these calculations are listed in Table 2.

Figure 25, a plot of moisture content versus time, illustrates further the effect on efficiency of infrared energy utilization. The efficiencies of infrared vibration drying of high moisture shelled corn were compared when vibration only was used, forced air velocity of 145 ft/min (value includes vibration effect) for the first fifteen minutes only of the infrared vibration drying period, and for various forced air velocities used throughout the entire infrared vibration drying period.

Table 2. Comparison of efficiencies of radiant energy utilization in vibration drying of shelled corn receiving infrared radiant energy at the rate of 3,250 Btu/hr.ft^2

Depth of grain layer (inches)	Drying range (moisture content) per cent dry basis	Drying time (min)	Efficiency of infrared utilization based on heat energy received (%)	Efficiency of infrared energy utilization based on infrared energy received plus energy to vibrate (%)	Efficiency of infrared energy utilization based on infrared energy received plus energy required to vibrate grain layer plus energy required for forced air flow (%)
2 (vibration only)	49.2-15.6	50	76	59	--
2 (vibration plus forced air flow of 115 ft/min for first 15 min.)	47.0-13.8	45	83.5	64.3	60.4
3 (vibration plus forced air flow of 115 ft/min for the first 15 min.)	50.0-14.1	60	84	65	61
4 (vibration plus forced air flow of 115 ft/min for the first 15 min.)	46.7-16.8	60	91.3	69.7	67.8

COMBINING INFRARED VARIABLES AS THE RESULT OF VARIATION STUDY

By experimentation the determination of the significance of the variables involved in infrared vibration drying was established by varying one at a time while holding the others constant. The trend as to whether or not an increase in a specific variable had an increasing, decreasing, or negligible effect on the drying rate could thus be seen.

From these results it was desired to manipulate several of the seven π ratios so as to have three of the ratios containing the major variables under study and in dimensionless form. To accomplish this a combination of the original series of the seven dimensionless ratios was made. The first manipulation was for a new π_8 dimensionless ratio, where $\pi_8 = \pi_1/\pi_4 = (A/D)(FD/V) = FA/V$. Similarly $\pi_9 = \pi_2\ \pi_3/\ \pi_5 = (\lambda_{max}/D)(ID/k\ T_i)(k/h_tD) = \frac{I\lambda_{max}}{h_tD\ T_i}$. Thus it was stated that of the seven original π ratios there were now three π ratios which contained nine of the twelve infrared vibration variables. These dimensionless ratios were $\pi_7 = W = M/M_o$, $\pi_8 = FA/V$ and $\pi_9 = \frac{I\lambda_{max}}{h_t\ DT_i}$ and were considered to contain the most important. Thus it could be

stated that essentially $\pi_7 = f(\pi_8, \pi_9)$, and that this function was sufficient to describe infrared vibration drying.

Infrared vibration drying tests made under various conditions and with no forced air flow indicated nearly linear drying rates could be obtained when drying high moisture shelled corn (initially in the range of 35 to 50 per cent moisture dry basis) to a moisture content of approximately 15 per cent. Drying beyond this point linearity ceased. Thus the overall drying curve was assumed to take form of the exponential drying equation.

From indications of data collected and with a little manipulation it was shown that the value of π_8 was essentially unity, when no forced air was used through the vibrating grain layer. Since the amplitude of vibration was the maximum vertical distance traveled by the vibrating cam away from its zero reference point, then in the same manner the total vertical distance traveled in one cycle could be written as $4\ A = C_d$.

Rewriting the dimensionless ratio as $\pi_8 = \frac{FC_d}{V}$, it can now be shown that the value of this dimensionless ratio was unity when no forced air was used. Optimum amplitude in relation to drying was found to be 3/32 inch, thus the optimum cycle distance was 3/8 inch or 3.125×10^{-2} feet. From previous data, as shown in Figure 11, the equivalent air velocity in relation to vibration of the grain layer ranged between twenty-five to thirty-six feet per minute. The higher equivalent velocity occurred at the higher frequency and similarly the lower equivalent velocity at the lower vibration frequency, though in either case the difference in equivalent velocities was quite small.

For the frequency of vibration range of 600 to 1,450 cycles per minute and the range of equivalent vibration velocity of twenty-five to thirty-six feet per minute, the value of $\pi_8 = \frac{F\ C_d}{V}$ was essentially equal to unity. Illustrating, the average frequency within range was 1,000 cycles per minute and the average equivalent velocity was thirty-one feet per minute, therefore $\pi_8 = \frac{F\ C_d}{V} =$

$\frac{1{,}000\ \cancel{\text{cycles}}}{\cancel{\text{min}}} \Big| \frac{3.125\text{x}10^{-2}\ \cancel{\text{ft}}}{\cancel{\text{cycles}}} \Big| \frac{\cancel{\text{min}}}{31\ \cancel{\text{ft}}} = 1.$ With these results and taking into consideration forced air velocities as well, it could be stated that the value of the dimensionless ratio, $\pi_8 = \frac{F\ C_d}{V}$, would essentially always have a value less than or equal to one.

Taking into consideration the entire period of infrared vibration drying it has been shown that non-linearity exists, particularly when forced air velocities were used. To describe all variable situations it was assumed that infrared vibration drying took the form of the usual exponential drying equation, $\frac{M-M_e}{M_o-M_e} = e^{-k\theta}$. The equilibrium moisture content for a vibrating grain layer exposed to an infrared source was essentially zero, thus the drying equation became $M/M_o = e^{-k\theta}$.

The previously established dimensionless parameters for infrared vibration drying were

$$M/M_o = f\left[\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \ T_{i_R}}\right)\right] .$$

Thus, it was assumed that since the moisture content ratio, M/M_o, was equal to some function of the other two dimensionless ratios, then it was proposed to show that the drying constant, k, for infrared vibration drying was also a function of π_8 and π_9. This was written in the form of

$$k = f\left[\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \ T_{i_R}}\right)\right] .$$

Therefore, the task was to establish an equation describing infrared vibration drying over the entire drying period for all variable situations and to place it into the form

$$M/M_o = e^{-f\left[\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \ T_{i_R}}\right)\right] \theta} .$$

It was proposed to make the prediction equation for the drying constant dimensionless by introducing the drying constant ratio. This relation was introduced as

$$k' = k/k_o = f\left[\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \ T_{i_R}}\right)\right] ,$$

where k_o was the drying constant for high moisture shelled corn for vibration drying without applying infrared energy. The k_o value was determined as being approximately 2×10^{-3} min^{-1}, and it was used throughout all calculations in the moisture content range studied. This yielded a dimensionless relationship with the drying constant ratio as a function of the infrared vibration drying dimensionless ratios, from which the prediction drying constant for shelled corn could be determined.

RESULTS OF DATA ANALYSIS FOR ESTIMATING DRYING CONSTANT AS A FUNCTION OF DIMENSIONLESS RATIOS BY USE OF REGRESSION EQUATION

To establish the relationship between the drying constant, k, for high moisture shelled corn and the dimensionless ratios, $\left(\frac{FC_d}{V}\right)\left(\frac{I\ \lambda_{max}}{h_t D\ T_{i_R}}\right)$, the methods of linear regression and correlation were used. To the experimentally determined values of drying constant ratio, k', versus the values of the dimensionless ratios determined by the infrared variables under study, the linear regression analysis was applied.

The regression analysis yielded an equation for a straight line, which gave an estimated value of the drying constant ratio, $\widetilde{k'}$, from the known values of the dimensionless ratios containing the infrared vibration drying variables. The linear regression equation was given by the relationship $\widetilde{k'} = \overline{k'} + b_{k',(\pi_8 \pi_9)} [(\pi_8 \pi_9) - (\overline{\pi_8 \pi_9})]$.

The slope of the regression equation or regression coefficient was calculated by the equation,

$$b_{k',(\pi_8 \pi_9)} = \frac{N\sum(\pi_8 \pi_9)(k') - (\sum(\pi_8 \pi_9))(\sum k')}{N\sum(\pi_8 \pi_9)^2 - (\sum(\pi_8 \pi_9))^2}$$

Similarly the correlation coefficient was determined by the relationship,

$$r_{(\pi_8\pi_9),k'} = \frac{N\sum(\pi_8\pi_9)(k') - (\sum(\pi_8\pi_9)(\sum k')}{\sqrt{[N\sum(\pi_8\pi_9)^2 - (\sum(\pi_8\pi_9))^2]\ [N\sum k'^2 - (\sum k')^2}}$$

where: $\tilde{k}'$ = estimated or predicted value of the drying constant ratio, k_a/k_o .

$\bar{k}'$ = mean value of experimental drying constant ratios.

$b_{k',(\pi_8\pi_9)}$ = slope of regression equation or regression coefficient.

$(\pi_8\pi_9)$ = value of product of dimensionless ratios.

$(\overline{\pi_8\pi_9})$ = mean value of products of dimensionless ratios from experimental data.

N = number of observations.

$r_{(\pi_8\pi_9),k'}$ = coefficient of linear correlation.

The calculations for the linear regression equation for estimating the drying constant ratio, $\tilde{k}'$, from the known values of the dimensionless ratios,

$$\left(\frac{FC_d}{V}\right)\left(\frac{I\ \lambda_{max}}{h_t D\ T_{i_R}}\right),$$

yielded a value for $b_{k',(\pi_8\pi_9)}$, the slope of regression equation, of 2.22×10^5. The linear correlation coefficient illustrating the precision of the estimated drying constant ratio, k', from a known value of dimensionless ratios,

$\left(\frac{FC_d}{V}\right)\left(\frac{I\ \lambda_{max}}{h_t D\ T_{i_R}}\right)$, calculated to be 0.66. From these results the prediction linear regression equation for the prediction drying constant, k_a, from a known value of the dimensionless ratios, $\left(\frac{FC_d}{V}\right)\left(\frac{I\,\lambda_{max}}{h_t D\,T_{i_R}}\right)$, produced the dimensionless prediction equation

$$\widetilde{k'} = \frac{k_a}{k_o} = 2.22 \times 10^{5} \left[\left(\frac{FC_d}{V}\right)\left(\frac{I\,\lambda_{max}}{h_t D\,T_{i_R}}\right)\right] + 6.42.$$

The graphical results of this analysis are shown in Figure 29.

The 95 per cent confidence interval was determined for the linear regression dimensionless prediction equation. The statistical relationship applied was of the form

$$\widetilde{k'} + t_{1/2\alpha}\, S_{(k'\,\pi_8\,\pi_9)} \sqrt{1 + \frac{1}{N} + \frac{(\pi_8\pi_9 - \overline{\pi_8\pi_9})^2}{(N-1)\; S^2_{(\pi_8\,\pi_9)}}} < k'$$

$$< \widetilde{k'} + t_{1-1/2\alpha}\, S_{(k',\,\pi_8\,\pi_9)} \sqrt{1 + \frac{1}{N} + \frac{(\pi_8\pi_9 - \overline{\pi_8\pi_9})^2}{(N-1)\; S^2_{(\pi_8\,\pi_9)}}}$$

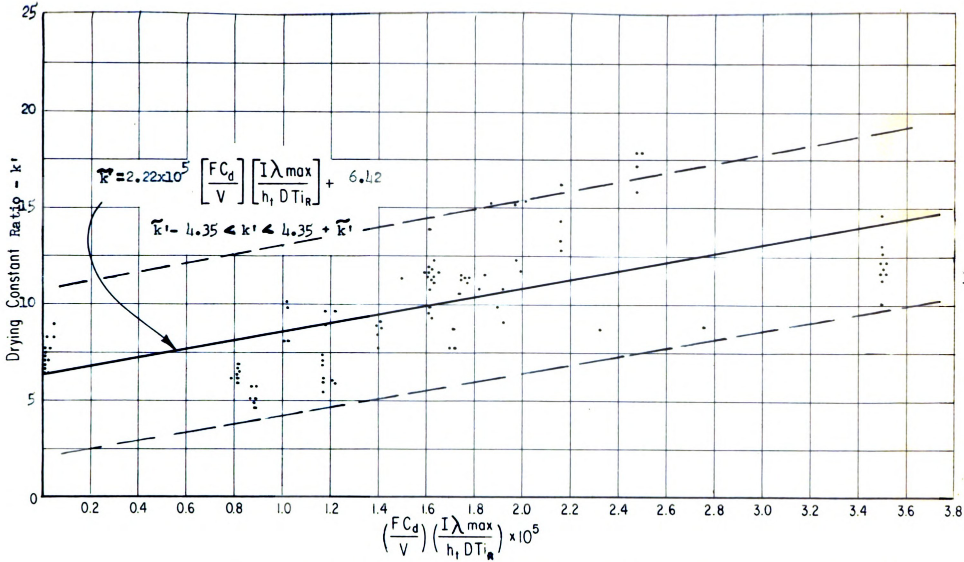

Figure 29 Plot of drying constant ratio for shelled corn versus dimensionless ratios for infrared vibration drying and regression equation for estimating the drying constant from a known value of the dimensionless ratios

From this relationship the 95 per cent confidence interval for the drying constant ratio pertaining to the linear regression line was calculated and was found to be

$$\widetilde{k'} - 4.35 < k' < 4.35 + \widetilde{k'}$$

VERIFICATION OF PREDICTED EQUATIONS

Verification of the prediction equation was made by running laboratory tests under variable conditions of the vibration drying variables. From these drying tests the experimental drying constant values, k, for shelled corn were obtained as shown in Table 3. In the same manner the experimental and predicted values of the drying constant ratio, k' and $\tilde{k}'$, were calculated.

An analysis of variance was run between the experimental k' values and prediction $\tilde{k}'$ values. From the analysis it could be determined whether the drying constant prediction equation for $\tilde{k}'$ would closely predict the actual value of the drying constant ratio , k'. The results of this analysis is shown in Table 4. Further confirmation was made by placing the predicted k_a values into the exponential drying equation, $\frac{M}{M_o} = e^{-k\theta}$, for describing infrared vibration drying and comparing this relationship to the curves obtained from laboratory tests (Figure 30).

Table 3. Drying constants for shelled corn determined by varying infrared vibration drying parameters simultaneously to establish validity of prediction equations for drying constants

k (1/min)	F (cycles/min)	A (in.)	λ_{max} (microns)	I (Btu/hr.ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr. ft^{2o}F)	M_o (dry basis)
$2.76x10^{-2}$	1,000	3/32	1.32	2,700	85	40	1	34	41.4
$3.46x10^{-2}$	1,000	3/32	1.32	2,700	85	40	1	34	42.6
$2.76x10^{-2}$	1,000	3/32	1.32	2,700	85	90	1	34	41.2
$3.56x10^{-2}$	1,000	3/32	1.32	2,700	55	90	1	18	41.3
$3.41x10^{-2}$	1,000	3/32	1.32	2,700	30	90	1	8	42.5
$3.35x10^{-2}$	1,000	3/32	1.32	2,700	30	40	1	8	42.3
$2.75x10^{-2}$	1,000	3/32	1.32	2,700	30	70	1	8	44.4
$2.75x10^{-2}$	1,000	3/32	1.08	3,450	85	40	1	34	47.8
$3.24x10^{-2}$	1,000	3/32	1.08	3,450	55	90	1	18	48.5
$3.22x10^{-2}$	1,000	3/32	1.08	3,450	30	90	1	8	48.1
$4.50x10^{-2}$	1,000	3/32	1.08	4,220	30	40	1	8	47.2
$1.82x10^{-2}$	1,000	3/32	1.32	2,700	90	40	2	38	42.2
$1.76x10^{-2}$	1,000	3/32	1.32	2,700	130	40	2	66	42.7

Table 3--Continued

k (1/min)	F (cycles/min)	A (in.)	λ_{max} (microns)	I (Btu/hr.ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr.ft^2 ^oF)	M_o (dry basis)
$1.80x10^{-2}$	1,000	3/32	1.32	2,700	55	40	2	20	42.7
$2.08x10^{-2}$	1,000	3/32	1.32	2,700	90	90	2	38	41.2
$1.89x10^{-2}$	1,000	3/32	1.32	2,700	130	90	2	66	40.9
$2.16x10^{-2}$	1,000	3/32	1.32	2,700	55	90	2	20	41.7
$2.05x10^{-2}$	1,000	3/32	1.32	2,700	30	40	2	8	42.7
$2.03x10^{-2}$	1,000	3/32	1.32	2,700	30	70	2	8	41.9
$1.83x10^{-2}$	1,000	3/32	1.08	3,450	130	90	2	66	47.3
$1.94x10^{-2}$	1,000	3/32	1.08	3,450	90	40	2	38	45.6
$2.54x10^{-2}$	1,000	3/32	1.08	3,450	30	70	2	8	44.2
$2.50x10^{-2}$	1,000	3/32	1.08	4,220	30	40	2	8	45.8
$1.48x10^{-2}$	1,000	3/32	1.32	2,700	60	40	3	22	45.1
$1.48x10^{-2}$	1,000	3/32	1.32	2,700	60	40	3	22	45.7
$1.51x10^{-2}$	1,000	3/32	1.32	2,700	100	40	3	44	46.0
$1.68x10^{-2}$	1,000	3/32	1.32	2,700	100	40	3	44	45.5

Table 3--Continued

k (1/min)	F (cycles/ min)	A (in.)	λ max (microns)	I (Btu/hr.ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr. ft^2 ^oF)	M_o (dry basis)
1.41×10^{-2}	1,000	3/32	1.32	2,700	150	40	3	84	44.4
1.43×10^{-2}	1,000	3/32	1.32	2,700	150	90	3	84	48.5
1.60×10^{-2}	1,000	3/32	1.32	2,700	60	90	3	22	47.3
1.48×10^{-2}	1,000	3/32	1.32	2,700	100	80	3	44	47.0
2.00×10^{-2}	1,000	3/32	1.16	4,000	100	40	3	44	49.3
1.83×10^{-2}	1,000	3/32	1.16	4,000	100	40	3	44	48.0
2.26×10^{-2}	1,000	3/32	1.16	4,000	60	90	3	22	50.0
2.40×10^{-2}	1,000	3/32	1.16	4,000	60	90	3	22	45.6
2.25×10^{-2}	1,000	3/32	1.16	4,000	60	90	3	22	45.0
1.55×10^{-2}	1,000	3/32	1.32	2,700	30	40	3	8	43.5
1.80×10^{-2}	1,000	3/32	1.32	2,700	30	90	3	8	44.4
1.67×10^{-2}	1,000	3/32	1.08	3,450	150	90	3	84	45.1
1.79×10^{-2}	1,000	3/32	1.08	3,450	100	40	3	44	43.2
1.47×10^{-2}	1,000	3/32	1.08	3,450	100	40	3	44	46.5
1.75×10^{-2}	1,000	3/32	1.08	3,450	30	90	3	8	44.7

Table 3--Continued

k (1/min)	F (cycles/min)	A (in.)	λ_{max} (microns)	I (Btu/hr.ft^2)	V (ft/min)	T_i (^oF)	D (in.)	h_t (Btu/hr.ft^2 ^oF)	M_o (dry basis)
2.40×10^{-2}	1,000	3/32	1.08	4,220	30	40	3	8	44.2
2.16×10^{-2}	1,000	3/32	1.16	4,600	30	40	4	8	46.2
2.22×10^{-2}	1,000	3/32	1.16	4,600	30	40	4	8	46.0
2.41×10^{-2}	1,000	3/32	1.16	4,600	30	40	4	8	46.6
1.57×10^{-2}	1,000	3/32	1.16	3,360	30	90	4	8	45.8
1.45×10^{-2}	1,000	3/32	1.16	3,360	30	90	4	8	45.5
1.51×10^{-2}	1,000	3/32	1.16	3,360	30	90	4	8	46.1
1.46×10^{-2}	1,000	3/32	1.32	2,700	100	40	4	44	45.0
1.43×10^{-2}	1,000	3/32	1.32	2,700	60	40	4	32	43.8
1.40×10^{-2}	1,000	3/32	1.32	2,700	150	40	4	84	46.7
1.44×10^{-2}	1,000	3/32	1.32	2,700	100	90	4	44	42.6
1.44×10^{-2}	1,000	3/32	1.32	2,700	150	90	4	84	43.0
1.39×10^{-2}	1,000	3/32	1.32	2,700	60	90	4	32	43.0
1.45×10^{-2}	1,000	3/32	1.32	2,700	30	90	4	8	45.5

Table 3--Continued

k ($1/min$)	F (cycles/min)	A (in.)	λ_{max} (microns)	I ($Btu/hr.ft^2$)	V (ft/min)	T_i (^oF)	D (in.)	h_t ($Btu/hr.ft^{2o}F$)	M_o (dry basis)
$1.42x10^{-2}$	1,000	3/32	1.32	2,700	30	40	4	8	44.3
$1.47x10^{-2}$	1,000	3/32	1.08	3,450	150	90	4	84	46.8
$1.38x10^{-2}$	1,000	3/32	1.08	3,450	150	40	4	84	46.0
$1.60x10^{-2}$	1,000	3/32	1.08	3,450	30	90	4	8	46.4

Table 4. Analysis of Variance Results in Relation to the Experimental Drying Constant Ratios for Shelled Corn and Those Calculated by the Prediction Equation[1]

Results for Grain Depths Up To and Including 4 Inch Layers When Vibrations Only Was Used				
Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	$F_{0.95}$-Ratio
Total	459.63	43	10.69	
Between	9.63	1	9.63	$F_{(1,42)}=0.90$
Within	450.00	42	10.71	$r = 0.93$

[1]Analysis of variance results showed significant difference for 1 through 4 inch vibrating grain layers when forced air was used, thus indicating that the prediction equation was not valid when forced air was used.

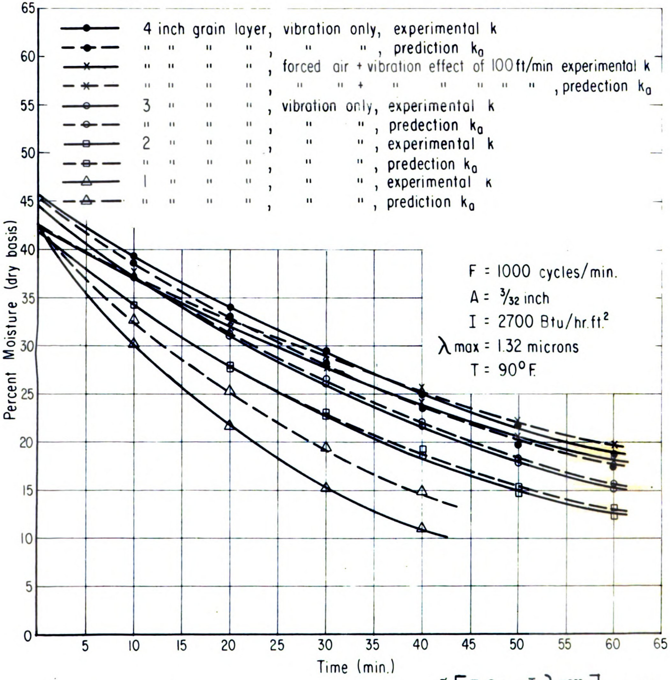

Figure 30 Verification of equation $\widetilde{k}' = 2.22 \times 10^5 \left[\left(\frac{F\ C_d}{V}\right)\left(\frac{I\ \lambda_{max}}{h_t\ D\ T_{IR}}\right)\right] + 6.42$ predicting the infrared vibration drying constant for shelled corn with an initial moisture content in the range of 35 to 50 percent (dry basis) as compared to the experimental k value when applied to the exponential drying equation

SUMMARY

Infrared vibration drying studies were made with high moisture shelled corn ranging in initial moisture content from 30 to 50 per cent dry basis. Mechanical fluidization of the grain layer was obtained by use of a remodeled orbital sander which permitted grain vibration at various frequencies and amplitudes. Grain movement of increased depths of shelled corn vibrated in the infrared field and sufficient to produce thorough mixing of the grain layer was verified by cycling of dyed kernels and uniform temperature distribution throughout the grain layer as measured with thermocouples installed in the grain bed used in conjunction with an automatic recording potentiometer. Drying tests were run by studying one variable at a time while holding the remaining variables constant at established reference values.

Frequency variation in the range of from 600 to 1,450 cycles per minute showed no effect upon the drying rate of high moisture shelled corn. Amplitude variations of 1/16 inch, 3/32 inch and 1/8 inch gave optimum drying results at the value of 3/32 inch, while the other two amplitudes indicated a sharp decline in the drying rates.

Intensity variation in the range of 1,500 to 4,600 Btu/hr.ft^2 gave increased drying rates with increasing infrared radiant energy intensities received at the grain surface. In the same manner longer wavelengths at the peak intensity of the infrared source also gave more rapid drying than shorter wavelength source, with the wavelength range studied varying from 1.08 μ to 2.50 μ.

The initial grain temperature affects the drying rate of shelled corn but only slightly. The initial grain temperature range studied was from 32^{o}F to 120^{o}F. The results showed essentially a linear increase in the drying constant between initial grain temperatures of 32^{o}F to 100^{o}F, although the percentage of increase in the drying constant was only 12 per cent. There was no difference in the drying rates when the initial grain temperature was increased from 100^{o}F to 120^{o}F.

Forced air velocities concurrent to the direction of infrared radiant energy transfer had a decreasing effect upon the drying rate with increasing air velocities. Forced air velocities (including the equivalent effect of vibration) were studied in the range of from 30 to 360 ft/min. The decline in the drying rate was linear particularly for forced air velocities of 100 ft/min and above. The most rapid rate of drying from 50 to 15 per cent moisture (dry basis) was obtained when vibration only was used, vibration of the grain layer being equivalent to an average air velocity of from 30 to 31 feet per minute in relation to moisture removal. Intermittent forced air flow of 145 ft/min (value includes equivalent effect of vibration) for the first fifteen minutes of only the drying period proved superior to other combinations.

The total heat transfer coefficient, h_t, increased with increasing forced air velocities, a factor undesirable for efficient radiant energy heat transfer. Vibration of the grain layer produces a total heat transfer coefficient of between eight and ten Btu/hr.ft^{2}F. The equivalent radiation heat transfer coefficient, h_r, was negligible compared to the convection coefficient at larger forced air velocities, but usually carried a value of between two and three Btu/hr.ft^{2}F, which was not negligible at low velocities or when vibration only was used.

Increasing the depth of the vibrating grain layer showed a decrease in the drying rate. Grain depths ranging from one to four inches were studied. Satisfactory drying results were obtained at all depths by vibrating the grain layer at an amplitude of 3/32 inch, while receiving infrared radiant energy intensities up to 4,600 Btu/hr.ft^2.

The efficiency of infrared energy utilization can be increased by vibration of increased depths of the grain layer sufficiently to produce thorough mixing as well as proper use of forced air velocities. An efficiency of energy utilization of 76 per cent of the infrared energy received at the rate of 3,250 Btu/hr.ft^2 at the grain surface was obtained with two inch vibrating high moisture shelled corn layers. This efficiency was increased to 83.5 per cent when an intermittent forced air velocity of 115 ft/min was used in conjunction with vibration. An overall efficiency of 59 per cent was obtained when vibration only (vibration equivalent to a forced air velocity of thirty to thirty-one ft/min) was used as compared to an overall efficiency of 60.4 per cent when the energy to vibrate and energy for forced air flow of 115 ft/min for the first fifteen minutes of the drying period were included. In the same manner the drying time was also reduced. These values compare well to efficiencies reported with infrared drying of other food products.

Drying tests indicated the variables effecting most the drying rates of infrared vibration drying of shelled corn. Knowing this the seven dimensionless ratios were manipulated so that three of the ratios contained nine of the original twelve variables. These dimensionless ratios were

$$\pi_7 = f(\pi_8, \pi_9) \text{ or } W = \frac{M}{M_o} = f\left[\left(\frac{FC_d}{V}\right)\left(\frac{I\ \lambda_{max}}{h_t D\ T_{iR}}\right)\right] .$$

With the moisture content ratio equal to some function of the other two dimensionless ratios. Thus, for the drying equation $\frac{M}{M_o} = e^{-k\theta}$, the drying constant ratio, k', for infrared vibration was expressed as a function of these two ratios or

$$k' = \frac{k}{k_o} = f\left[\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \; T_{i_R}}\right)\right] .$$

Linear regression and correlation analysis yielded a prediction equation whereby a drying constant ratio could be predicted from a known value of the dimensionless ratios, $\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \; T_{i_R}}\right)$. The analysis yielded the linear regression equation

$$\tilde{k}' = \frac{k_a}{k_o} = 2.22 \times 10^5 \left[\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \; T_{i_R}}\right)\right] + 6.42$$

The linear correlation coefficient, indicating the precision of the estimate of an unknown drying constant from a known value of $\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \; T_{i_R}}\right)$, was determined as 0.66. The 95 per cent confidence interval for the dimensionless linear regression prediction equation was calculated and found to be

$$\widetilde{k'} - 4.35 < k' < 4.35 + \widetilde{k'}$$

Analysis of variance performed from verification test data between the experimental drying constant ratios,

k', and the predicted values, $\tilde{k}'$, indicated that the prediction equation was reasonably accurate when vibration only was used ($r = 0.93$), but validity was limited when forced air was applied.

Conclusions

As the result of this infrared vibration drying study, the following conclusions were made:

1. The capacity of an infrared dryer for drying high moisture shelled corn can be sharply increased by vibrating larger grain layers in such a manner so as to produce thorough mixing of the product, while exposing the grain surface to increased infrared intensities.

2. When grain vibration at the amplitude of 3/32 inch for optimum drying results is used, then varying frequency of vibration sufficient to produce mechanical fluidization (range 600 to 1,450 cycles per minute) has no effect upon the drying rate of high moisture shelled corn. An amplitude of 3/32 inch and frequency of vibration at 1,000 cycles per minute give the best operational results.

3. Mechanical fluidization or agitation of the grain layer permits satisfactory exposure to larger infrared intensities. An infrared radiant energy intensity of 5,000 Btu/hr.ft^2 received at the grain surface appeared to be the maximum allowable intensity which would allow continuous

vibration drying from 50 to 15 per cent moisture (dry basis) without surface scorching of the product occurring. This also appeared to be the optimum intensity as illustrated by the leveling off of the drying constant.

4. More efficient absorption of infrared radiant energy by high moisture shelled corn is obtained when the wavelength at peak intensity of the emitter lies preferably in the range of 1.5 to 3 microns. More rapid drying rates are obtained for longer wavelengths at the peak intensity of the emitter than for the shorter wavelengths. This is explained by the fact that high moisture shelled corn at initial moisture contents of 50 per cent dry basis contains therefore 0.5 pound of water in liquid form per pound of dry matter. Water absorbs almost 100 per cent of the infrared radiant energy received in the wavelength range of 1.4 to 3 microns, while in the same manner it absorbs only 35 to 40 per cent at the wavelength of 1.16 microns, which is the wavelength at peak intensity of the standard tungsten filament heat lamp.

5. Initial grain temperature affects the drying rates of shelled corn slightly. A 12 per cent increase in the drying constant is obtained between grain with a 32^{o}F initial temperature and grain initially at 100^{o}F.

6. Forced air velocities used over the entire infrared vibration drying period decrease the drying rate of shelled corn because of the surface cooling effect particularly at reduced moisture contents. Intermittent use of

forced air velocities (preferably 100 ft/min or less) for the first fifteen minutes of the vibration drying period and then vibration only throughout the remainder of the infrared vibration drying period will produce more rapid drying than forced air velocities used throughout the entire drying period and a slightly faster drying rate than when vibration only was used.

7. The total heat transfer coefficient increases sharply with increasing forced air velocities, a factor undesirable for effective infrared radiant energy utilization by the product. The total heat transfer coefficient, h_t, should be maintained at a minimum, which means that vibration of the grain layer and a low concurrent forced air velocity would be preferable. Just enough forced air flow is needed to remove vapors from between source and product.

8. Vibration of the grain layer at an amplitude of 3/32 inch and an average frequency of 1,000 cycles per minute produces an equivalent effect in relation to moisture removal as an average forced air velocity of thirty to thirty-one feet per minute. In the same manner when vibration only is used, then the dimensionless ratio, $\frac{FC_d}{V}$, is equal to unity. Thus it is concluded when taking into consideration forced air velocities as well that the value of the dimensionless ratio, $\frac{FC_d}{V}$, is for all practical purposes less than or equal to one.

8. Infrared vibration drying allows grain layers up to and including four inches in depth to be continuously dried from a moisture content of 50 to 15 per cent when exposed to infrared intensities up to 5,000 Btu/hr.ft^2.

9. Infrared vibration drying used in combination with intermittent low forced air velocities can improve the efficiency of infrared radiant energy utilization by the product. An overall efficiency of 60 per cent, based on energy received at grain surface, energy to vibrate, and energy for forced air flow, is obtainable when drying two inch layers of shelled corn from 47 to 14 per cent moisture (dry basis) in 45 minutes.

10. The prediction equation,

$$\widetilde{k'} = \frac{k_a}{k_o} = 2.22 \times 10^5 \left[\left(\frac{FC_d}{V}\right)\left(\frac{I \quad \lambda_{max}}{h_t D \quad T_{i_R}}\right)\right] + 6.42,$$

$$\widetilde{k'} - 4.35 < k' < 4.35 + \widetilde{k'}$$

involving the dimensionless ratios is valid for all grain depths up to and including four inch grain layers when vibration only (no forced air flow) is used, but it is not valid for forced air velocities through the vibrating grain layer during drying.

SUGGESTIONS FOR FURTHER STUDY

1. Determine the wavelength at peak emitter intensity at which shelled corn has maximum absorption of infrared energy and the optimum wavelength-moisture content infrared absorption relationships for various grain moisture contents.

2. Study infrared vibration drying of deeper grain layers primarily four inches and larger, and the efficiency of infrared energy utilization in relation to the depth of the grain layer.

3. Study infrared vibration drying rates of other cereal grains such as oats, wheat and rice; compare these to the drying rates for shelled corn and adapt the drying constant prediction equations of these cereal grains to the one established for shelled corn.

4. Establish the forced air velocity-vibration combination for optimum infrared vibration drying results.

5. Determine the effect of infrared vibration drying on seed germination.

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