THROUGH-CIRCULATION DRYING OF VEGETABLE MATERIALS

by

CHARLES S. POTTS, B.Sc.

Royal College of Science and Technology,
September, 1957.

Summary.

Comparison has been made of the drying properties of five different vegetable materials although variation in piece size and initial moisture content made this difficult. The effect of the following variables on the drying rates of the materials has been discussed: the nature of the material; the method of preparation and size reduction: the loadings, temperatures, humidities and air velocities practised; the practicability of agitation of the bed and recirculation of the air; the resistance of the bed to the passage of air.

The accuracy of various methods of predicting drying times and rates has been examined. A graphical method for the design of continuous multi-stage through circulation driers is presented.

Seaweed.

The drying characteristics of freshly harvested Ascophyllum nodosum, Fucus vesiculosus and F. serratus have been investigated in a through-circulation dryer. All tests were carried out with minced seaweed. Variables studied were bed depth (0.5-6 in. approx.), air temperature (100-220°F.), air wet-bulb depression (30-115°F), air mass velocity (5-11 lb./sq.ft. min., and static pressure drops of air through beds of wet and dry weed. Bed-depth experiments have given equations relating drying times, constant drying rates and outputs to loading. The output versus loading curve shows a well-defined optimum value for each species of seaweed. Empirical equations have been derived, relating drying times (between definite/

definite water content limits) and initial constant drying rates to air mass flow. It has been shown that the drying rates, at average water contents of 3.0 to 0.2, 2.7 to 0.2, and 3.5 to 0.15 lb./lb. of bone-dry solids (for A.nodosum, F. vesiculosus and F.serratus respectively), are directly proportional and the drying times inversely proportional to the wet-bulb depression of the air. A study of the water content of various layers in a seaweed bed has been made. A typical drying rate versus water content curve is shown, and a mechanism of drying of deep beds has been postulated. A section is included dealing with the prediction of approximate drying times and rates.

Brewers' spent grain.

Brewers' spent grain has been dried by through circulation of hot air in single layers and in beds up to 8 inches in depth.

The effect of air temperature (100 to 220°F.), and air velocity (6.63 to 22.2 lb./(sq.ft.) (min.)) on the drying rates of single layers has been studied. It has been found that the drying rate is proportional to the total moisture ratio of the layer, and that both temperature and velocity have a marked effect on the proportionality constant.

A method of predicting drying times in deep beds, based on the results of the single layer tests, is proposed and discussed. The accuracy of this method has been checked against actual drying times in deep beds and found to be within ± 11.5%.

The resistance of deep beds to the passage of air has been investigated briefly.

Sugar/

Sugar beet.

The rate of drying of single layers of sugar beet cossettes has been studied, and has been found to vary markedly with temperature of the drying air (140 to 220°F) and to increase slightly with a fourfold increase of air velocity, while humidity changes have little effect. The rate of drying has been found to be proportional to the total moisture content of the cossettes.

A method of predicting the rate of drying of cossettes in beds up to 9 inches deep is given, for velocities in the range 6 to 21 lb./sq.ft.)(min.), for temperatures of 140 to 220°F, and humidities up to 40% R.H. The accuracy of the method is shown to be within ± 15%.

Observations have also been made on the variation of internal temperature with change of moisture content and air temperature, and on the evidence of caramelisation.

Carrots.

The drying of carrots has been investigated in single layer tests. The effect of particle size (slices, cubes, and strips), temperature (110°F to 160°F), humidity (up to 45% R.H.), and air velocity (8 to 15.5 lb./(sq.ft.)(min.)) on the drying rates of single layers has been studied. The drying rate is proportional to the total moisture content of the layer. Calculated times of drying of deep beds, based on single layer experimental results, are within ± 10% of the actual times.

Peas.

The drying rates of peas, in single layers and in deep beds, have been studied at different air temperatures (110 to 150°F), humidities (6% and 40% R.H.) and/

and air velocities (8 to 25 lb.d.a./(sq.ft.)(min.)).

Observations have been made on the evidence of case hardening and and the influence of humidity upon it.

An approximate prediction method, based on single-layer results, is proposed for the drying times of deep beds.

Acknowledgments.

The author wishes to express his thanks to Professor P.D. Ritchie for the provision of facilities for this research. The author is also indebted to Dr. T. J. Mitchell under whose guidance this work was carried out.

Thanks are also due to the staff of the departmental workshop for erection of apparatus and the photographing and printing of graphs and diagrams.

To the D.S.I.R. goes the author's gratitude for the provision of a maintenance award for the research period.

PUBLICATIONS

The following paper has been published:-

"Through circulation drying of seaweed"

T.J. MITCHELL & C.S. POTTS, J.Sci. Fd. Agric., 1953, 3, 113.

The following papers have been accepted for publication in the Journal of the Science of Food and Agriculture:-

"Through circulation drying of vegetable materials"

Part I	Brewers' spent grain.
Part II	Sugar beet.
Part III	Carrots.
Part IV	Peas.

INDEX

SECTION I.

1. Introduction.
2. Mass Transfer theory.
3. Diffusion theory.
4. Capillary flow theory.
5. Drying of vegetable material.
6. Through circulation drying.

1. INTRODUCTION.

The process of drying involves the removal of a liquid from a solid by thermal means, as distinct from mechanical methods of draining by filtration or centrifuging. Drying and evaporation can be distinguished from one another on the basis of the types of equipment involved and by the fact that evaporation processes generally remove much larger quantities of water per unit time than do drying processes. Dehydration is a term used to describe drying, but its use is largely restricted to the drying of foods, fruits and vegetables.

The reasons for drying are many and may be classified as :-

1. To ease handling in future processing.
2. To permit satisfactory use of the final product.
3. To reduce weight and volume with consequent reduction in freight charges.
4. To increase the capacity of other equipment in the process.
5. To prevent decomposition during storage.
6. To enhance the value and usefulness of waste or by-products.

Drying normally has a fixed position in relation to the other unit operations of a particular process. Thus it frequently follows filtration or centrifuging and precedes a grinding or packaging operation. Sometimes it takes place before extraction in order that more concentrated liquors result/

result, but it is usually regarded as a finishing operation before preparation of the product for transport and sale.

There are many different methods of drying, and any one method must be chosen with the view of giving both highest efficiency and the most suitable final product. Considerations which must be made when choosing a drier are:-

1. Temperature which the material can stand and its deterioration properties.
2. Size, shape and surface characteristics of the material.
3. Initial moisture content and final moisture content required.
4. Type of operation (batch or continuous) and approximate time.
5. Condition of final product.
6. Capacity of drier and space available.
7. Heat and power supply available.
8. Capital and running costs.

Sometimes the cost and efficiency of a drying process may not matter since the value of the material may be so great that it is of primary importance that the product should be of good quality and unaffected by the conditions in the drier. Within these limitations it is usually possible to design a drier for a given material to operate efficiently both from the handling and operational cost viewpoints, provided that the characteristic properties of the substance are known. Some knowledge/

knowledge of drying behaviour of the material is generally essential for the efficient design of such a drier and indeed extensive tests undertaken before the design stage are often more than compensated for by the final result.

Many workers have tried to predict the drying times or rates for various solids for a given set of air conditions. These workers have succeeded to some extent but drying is such a complex process that no universal theory or prediction method has yet been put forward. Water may be bound with solids in a wide variety of ways, e.g. as free water on an exposed surface; between granules or fibres; inside living cells enclosed by a permeable or impermeable membrane; absorbed on walls; as water of hydration. Considering these combinations and the varying extents to which they may occur in different materials it is not surprising that drying rates vary so widely. It is fortunate that many materials can be classified in groups which dry in the same manner although at slightly different rates. As a result of the complexity of many drying problems, it is frequently simpler and more accurate to conduct laboratory or pilot plant drying tests on the material, to supply the information necessary.

Many factors are involved in these tests, and the provision/

provision of data which is complete and yet simple to use is a task of some difficulty.

The work here reported describes experiments intended to assess the effect of the most important factors in drying vegetable materials and information has been obtained whereby reasonably accurate solutions can be worked out for similar materials.

2. MASS TRANSFER.

(a) The Boundary Layer.

When air flows over a solid surface a velocity gradient is set up at right angles to the direction of flow, because of the viscous forces acting within the air stream. The drag force resulting from the retardation of the air at the surface is transmitted throughout the whole of the air stream and therefore the velocity gradient also extends through the whole of the air. At progressively greater distances from the surface, however, the effect of the drag becomes smaller and, for all practical purposes, can be regarded as being confined to the surface and known as the boundary layer.

In any plane at right angles to the direction of flow, the velocity within the layer will vary from zero at the surface to U_s, the velocity of the undisturbed stream at its outer edge. Where the boundary layer thickness is small, the flow is streamline and the velocity at any distance from the surface is a simple function of that distance.

A knowledge of conditions in the boundary layer is necessary to calculate the resultant drag force of the surface on the air stream and in the calculation of heat and mass transfer coefficients. Such expressions as are required to derive the thickness and velocity of flow at any point have been summarised by Coulson and Richardson[1].

(b) Mass Transfer through the Boundary Layer.

If mass transfer takes place as a result of a

concentration/

concentration gradient between the flowing air and the surface the whole of the resistance to transfer can be considered as lying within the boundary layer. If the concentration, and hence the rate of mass transfer, are small it can be shown that the velocity and thermal boundary layers are unaffected and that the basic equation for mass transfer is

$$\frac{\partial}{\partial x}\int_0^{l}(P_A - P)\,u_y.\,dy \quad = D\left(\frac{\partial P_A}{\partial y}\right)_{y=0}$$

Where

P_A = Partial pressure of A at a distance y from the surface.

P = Partial pressure of A outside the mass transfer boundary layer.

l = Distance in the Y direction, greater than the thickness of any of the three boundary layers.

It is not possible to obtain a simple relation connecting P_A and y, so that integration is not possible. It has been shown, however, that an extension of Reynolds Analogy can give relations for heat and mass transfer between a surface and a turbulent stream of air.

(c) <u>Mass Transfer Theory</u>.

The process of mass transfer occurs when, if there is a concentration gradient between two substances, there is a tendency for each constituent to flow in such a direction as to reduce the concentration gradient. The transfer, if between a solid and fluid flowing in streamline conditions in a direction at right angles to the concentration gradient, is effected/

effected as a result of the random motion of the molecules. In a turbulent fluid, this mechanism is supplemented by transference of material by eddy currents.

The rate of transfer of A in a mixture of two components, A and B, will be determined not only by the rate of diffusion of A, but by the behaviour of B. The molar rate of transfer of A, per unit area, due to molecular diffusion is given by Fick's law[2],

$$N_A = -D_{AB} \cdot \frac{\partial C_A}{\partial y}$$

Where

N_A = Molar rate of diffusion per unit area.

D_{AB} = Diffusivity of A in B, a physical property of the two components.

C_A = Molar concentration of A.

y = Distance in the direction of diffusion.

When the fluid is turbulent, eddy diffusion takes place in addition to molecular diffusion resulting in an increase thus:

$$N_A = \left[D_{AB} + E_D\right] \frac{\partial C_A}{\partial y}$$

Where

E_D = Eddy diffusivity.

Chilton and Colburn[3] have deduced a mass transfer factor which is expressed in the form

$$j_D = \frac{h_D . P_{Bm}}{u . P} \cdot \left[\frac{\mu}{\rho D}\right]^{0.67}$$

Where/

Where

P_{Bm} = Logarithmic mean of the partial pressure of the inert component B.

P = Total pressure.

h_D = Mass Transfer coefficient.

μ = Viscosity of fluid.

ρ = Density of fluid.

D = Gas phase diffusivity.

u = Mean velocity of fluid.

This is analogous to the expression obtained for heat transfer and is a suitable method of correlating mass transfer data. Various workers have applied this method to the solution of problems, generally plotting against a modified Reynolds number. Gilliland and Sherwood[4] studied the evaporation of a number of liquids into an air stream flowing up a tube and by introducing the Schmidt number, were able to bring the points of all the liquids to the same line, the equation of which was: $\frac{h_D}{u} \cdot \frac{P_{Bm}}{P} \cdot \left(\frac{\mu}{\rho . D}\right)^{0.56} = 0.023\, Re^{-0.17}$

(d) Mass Transfer from Plane Surfaces.

Early work by Hinchley and Himus[5] on the evaporation rate of water into a tangential stream of air showed that this rate was proportional to the pressure difference ($P_s - P_w$) where P_s is the vapour pressure of the water and P_w the partial pressure of the water vapour in the air. Powell and Griffiths[6] studied the vaporisation rate with more systematic work in better equipment, as also have Wade[7] and Pasquill[8]. The relationships/

relationships between the evaporation rate and the partial pressure difference and air flow rate were the same, and on the basis of those findings, Sherwood[9] has plotted the results of Powell and Griffiths in terms of the Reynolds group Re. The influence of the Schmidt group was ascertained by Linton and Sherwood[10] for the rates of solution of benzoic acid, cinnamic acid, and B - naphthol, all relatively insoluble materials, in water.

Maisel and Sherwood[11] have shown that turbulence in an air stream in contact with spheres is characterised by its scale and intensity. The scale (the size of the eddies) had little effect on the mass transfer whereas the intensity, which is the local fluctuation of velocity, increased the mass transfer markedly.

(e) Mass Transfer in Beds of Solids.

In the above work it was found reasonable to assume that both j_D and j_H were approximately equal to the friction term $\frac{R}{\rho \cdot u^2}$ These cases all refer to considerations of the viscous drag as entirely in the form of skin friction. When attempts are made to apply the relations to cases where additional drag, caused by eddies as a result of fluid obstruction, is set up, the j - factor and friction term are no longer equal. Thus it is with beds of granular solids, or evaporation from cylinders or spheres.

Gamson, Thodos and Haugen[12] have investigated the constant drying rates of beds of catalyst pellets and have correlated/

correlated the data by a plot of j_D and j_H versus modified Reynolds number Re. This work was extended to low Reynolds numbers by Wilke and Hougen[13]. The work on spherical and cylindrical shapes, was carried further by Taecker and Hougen[14] for Raschig rings, partition rings, and Berl saddles, giving the same type of relation but displaced slightly from the graphs obtained with the former shapes.

Hobson and Thodos[15] investigated the transfer rates of organic liquids which had been absorbed on spherical pellets and extracted by a stream of water flowing up through the bed. For the two systems studied, methyl ethyl ketone/water and isobutyl alcohol/water, the j factor correlation lay on the general line of Gamson et al., although the variation in the Schmidt group was of the order of 2,000. A further system, beta-naphthol/water, was tested by M'Cune and Wilhelm[16] with similar results.

Different Reynolds numbers had been used in some of the tests and Gamson[17] introduced a modified Reynolds number in an attempt to consolidate all the existing data. Data for other commercial packings were made to fall on the plot for spheres by inserting a shape factor in the Reynolds number.

3. **MOVEMENT OF WATER IN A SOLID BY DIFFUSION DURING DRYING.**

Evaporation from a surface cannot proceed far before the surface layers of the piece become drier than those beneath them. If there are communicating pore spaces in the piece, the surface may be supplied by capillarity with moisture from the interior. When capillary transfer ceases, the rest of the internal moisture must reach the surface by diffusion, and this process must continue during the remainder of the drying. It is a complex phenomenon, as yet not fully understood, although the rate of moisture diffusion controls the drying rate down to low moisture contents, more than any other single factor, and as such has received extensive treatment. Diffusion can be defined as the spontaneous intermixing of molecules caused by the random thermal motion of the particles concerned and tending to take place from high concentration areas to regions of low concentration.

The general differential equation for diffusion in one direction has been defined as:

$$\frac{\partial T}{\partial \theta} = D\left[\frac{\partial^2 T}{\partial x^2}\right]$$

Where

T = Water content θ = Time

D = Diffusivity of the liquid through the solid.

x = Distance from middle of the solid in the direction of diffusion.

Sherwood[18] adopted the diffusion equations to the falling rate period for the case where the surface is dry or at its equilibrium moisture content and the solid has a uniform initial/

initial moisture distribution,

Thus
$$\frac{W - W_e}{W_0 - W_e} = \frac{8}{\pi^2}\left[e^{-D\theta\left(\frac{\pi}{2L}\right)^2} + \frac{1}{9} e^{-9D\theta\left(\frac{\pi}{2L}\right)^2} + \cdots \right]$$

Where

W, W_0, W_e = Average moisture contents at any time θ, at the start of the diffusional flow period, and at equilibrium with the atmosphere.

D = Liquid diffusivity, sq.ft./hr.

L = One half of the thickness of the total diffusional layer, ft.

This assumes that evaporation is occurring at two opposite faces of the solid, and when only one face is free for evaporation. L is the total thickness of the solid layer.

The above equation assumes that D is constant. This is rarely true and D has been found to vary with moisture content, temperature and humidity. Both Bateman, and Stamm[19] and Hougen, McAuley and Marshall[20] have referred to this variation and the latter workers have summarised the limitations of diffusion equations in drying and their restrictions to certain classes of materials and certain times in the drying cycle. Hougen et al suggested further that for materials where the water is contained in cell cavities and inter sticesor is present on the surface, that gravity and capillarity controlled the liquid movement.

Van Arsdel[21] has developed a graphical method for taking into account the variation of diffusivity with moisture content/

content in drying hydrophilic solids to low moisture contents. He assumed that shrinkage and the presence of temperature gradients may be neglected without undue error since drying in the low moisture region was being dealt with. In the study of diffusion, if the driving force is vapour pressure then the rate of moisture movement is referred to as permeability, and diffusivity when the potential is water content.

The relation between D, the diffusivity, and P, the permeability is:

$$D = \frac{P}{S} \cdot \frac{dp}{dT} \qquad \text{where } \frac{dp}{dT} = \text{Slope of vapour pressure isotherm.}$$

Van Arsdel then wrote the diffusion equation for permeability:-

$$\frac{\partial T}{\partial \theta} = \frac{1}{S} \cdot \frac{\partial}{\partial x}\left[P \cdot \frac{\partial p}{\partial x}\right]$$

Where S = Mass of dry solids per unit volume.

He then evaluated approximate numerical solutions of the general diffusional equation for the infinite slab, long cylinder and sphere. The shapes of the drying rate curves were found to bear no simple relation to the quantitative change of permeability, and no procedure for deducing the latter is known.

The work of Peck, Griffith and Rao[22] took into account the resistance offered by the air film at the surface of the specimen being dried. Due consideration was also given to the change in diffusivity and the temperature of the slab, the/

the effective area available for diffusion and heat transfer, and how these factors affect the drying schedules. An attempt was made to separate the effect of these resistances due to the air film from that of the solid itself. The results made it possible to predict the effect of velocity by drying several thicknesses or the effect of thickness by drying at a few velocities.

The work of Sherwood[18] for special shapes was continued by Newman[23] for other shapes and it was maintained that the falling rate could be frequently expressed with fair accuracy by a simple equation:

$$\left(\frac{dW}{d\theta}\right)_f = -K(W - W_e)$$

Where K is a function of the constant rate.

$$K = -\frac{\left(\frac{dW}{d\theta}\right)_c}{W_c - W_e}$$

The falling rate may also be expressed in terms of heat transfer equations and

$$\left(\frac{dW}{d\theta}\right)_f = \frac{h_f(t_a - t_s)(W - W_e)}{\rho_s L \lambda (W_c - W_e)}$$

For materials obeying this equation the drying time varied directly as the square of the thickness.

By diffusional law

$$\theta_f = \frac{4L^2}{D\pi^2}\log_e\left(\frac{W_c - W_e}{W - W_e}\right)$$

Again this only refers to pieces where the length is large compared with the thickness, and where the drying time is large.

4. MOVEMENT OF WATER BY CAPILLARITY DURING DRYING.

Movement of water may be governed by other mechanisms besides diffusional movement. Moisture held in the interstices of solids as liquid covering the surface and as free moisture in cell cavities is subject to movement by gravity and capillarity, provided that passageways for continuous flow are present. In drying, liquid flow due to capillarity applies to liquids not held in solution and to all moisture above the fibre saturation point, as in textiles, paper, leather, and to all moisture above the equilibrium moisture content at atmospheric saturation, as in fine powders and granular solids, such as paint pigments, minerals, clays, soil, and sand.

Water may thus flow from regions of low concentration to those of high concentration if the pore sizes are suitable, and for this and other reasons Ceaglske and Hougen [24] suggested the capillary theory. The importance of the pore space between granular particles was first pointed out by Slichter[25] in connection with the moisture movement in soils, and this work was modified and increased by Haines[26], who showed the various configurations possible in beds of spheres.

When evaporation takes place from a bed of spheres, the water in the waists recedes between the top layer of particles/

particles, and an increasing suction potential is developed in the liquid. When the menisci of these cubical waists have receded to the narrowest section, the suction potential at the surface equals :

$$\frac{4.82\,\sigma}{r\rho g}$$

Where

σ = Surface tension.

r = Radius of sphere.

ρ = Density of liquid.

g = Acceleration due to gravity.

Further evaporation results in h_s increasing so that the menisci on the surface cubical waists will collapse, and the larger pores will open. As steadily increases, the entry suction of progressively finer surface waists will be reached, so that the menisci collapse into the adjacent pores which are thereby opened.

When the bed is composed of granular material with particles of mixed sizes, the suction potential cannot be calculated but must be measured by methods such as those given by Haines and Newitt et al[27]

As drying proceeds, progressively finer waists collapse, and the resulting opening of pores and waists also takes place. There is also collapse of further full waists within the bed adjoining open pores, and the consequent opening of adjacent pores.

5. **DRYING OF VEGETABLE MATERIAL.**

Vegetables cannot be satisfactorily sun dried since decomposition occurs. They were dried on a large scale in the second world war and the most important in this country were potatoes, cabbages and carrots. Drying was carried out under controlled conditions, employing a forced draught of heated air resulting in much work being done on all aspects of the subject, in particular at the Western Regional Research Laboratory of the U.S. Department of Agriculture. A comprehensive account[28] has been published of a systematic investigation of the drying rates of different vegetables.

A vegetable piece, when exposed to an air stream, behaves as a water surface and may be compared to a fine grained sponge full of water[29]. The moisture in the surface layers evaporates very rapidly and thereafter the surface may be fed for a time with water by capillarity. This flow of water is replaced by diffusional flow over most of the drying time and may be accompanied by diffusion of soluble sugars and salts to the interior owing to a concentration gradient being set up. It has already been stated that the drying of vegetables is difficult to explain by diffusion equations due to the shrinkage effect which changes the diffusivity greatly throughout drying. The presence of temperature effects and the fact that water is present as solutions further complicates the application of diffusion theory.

Quantitative/

Quantitative measurements of the actual diffusion of moisture within a piece of vegetable during drying are extremely difficult to make during drying owing to distortion of the pieces by shrinkage. The only published results are those of Ede and Hales[30] who dissected thick slices of potato during drying, and determined the moisture content in successive layers. Generally similar pictures of the internal distribution of moisture have been found during the drying of soap [31] and for wood by Bateman, Hoff and Stamm[19]. The latter concluded that capillarity, liquid diffusion and vapour diffusion were controlling influences in the drying of wood. Capillary control is evident above the fibre saturation point and diffusion control below, while vapour may occur at both levels and diffuse to the surface under vapour pressure gradients.

Van Arsdel[21] arrived by calculation at moisture distribution curves in the low moisture range of the same type as the above workers. Thus it is that the form of these curves is consistent with the laws of diffusion and the change in diffusivity at low moisture levels.

The rates of drying of some common vegetables have been determined by Ede and Hales. A wet bulb depression method of correlating the drying data for use in prediction of drying rates and times has been proposed. This was based on the fact that the drying time was proportional to the wet bulb depression. The same type of relation was found by Culpepper and Moon[32] and Smith[33] for the drying of Keiffer pears/

pears. The drying times of different segments of these pears were found to be approximately proportional to the specific surface.

Guillou[34] found that the drying time of prunes could be expressed by a logarithmic relation

$$\theta_{12} = \frac{1}{K} \cdot \log . \frac{W_1}{W_2}$$

$$K = 0.2\left(\frac{t}{165}\right)^4\left(\frac{V}{600}\right)^{0.2}\left(\frac{100-H}{60}\right)$$

Where t = Air temperature °F.

v = Air velocity

H = Relative humidity

This work was continued by Perry[35] who calculated the thermal conductivity of the prune surface using measurements of internal temperatures during drying. He found that the surface temperature did not remain at the wet bulb temperature for any appreciable time, but rose steadily owing to the high internal resistance as compared with the surface permeability. Drying rates were found to be unaffected by changes of humidity below 40%, since below this value the equilibrium moisture content showed no great change.

Cashmore[36] has surveyed the drying of agricultural products while the treatment and conditions of drying for common vegetables have been summarised in manuals on food dehydration by Von Loesecke[37] and Morris[38] Marshall[39] has published a comprehensive account of the drying rates of dehydrated/

delydrated foods, presenting a summary of temperatures, loadings, air velocities most suitable for each type.

Gardner and Mitchell[40] have given data for the drying of sub-littoral seaveed and have postulated a prediction method for times and rates based on the proportionality to wet bulb depression findings as reported by Ede and Hales[30]. This basis for drier design has been stated by Hendry and Scott[4] to be as accurate as other methods with the additional advantage of simplicity.

The drying of grass has been studied with regard to the effect of grass structure on drying rate[42]. The danger of heat damage was emphasised and in a later report by Bailey and Hamblin[43] the development of a procedure for testing grass driers was outlined.

The drying of grain has been reviewed by Oxley[44], but recent work by McEwen, Simmonds, Ward and O'Callaghan[45], has applied more fundamental principles of chemical engineering to the problem of drying of wheatgrain.

Microscopic examination of the cell structure changes has been made by Reeve[47] for carrots and potatoes. He noted that when potatoes are blanched or scalded before drying, the starch in the tissues is gelled and cell shrinkage is limited. When carrots are dried, the outer cells initially form a hard shell which opposed the shrinkage of the interior cells and caused rupture of some intermediate cells. It was found that if carrots were dried at temperatures exceeding 100°C there was some internal vaporisation of water which could generate enough pressure to rupture the internal tissues.

6. THROUGH CIRCULATION DRYING.

The oast houses in which hops are dried, are natural through-circulation drying chambers. Burgess[48] has discussed the subject at length and found that θ, the drying time from 80 to 2% at a constant air temperature is given by:-

$$\theta = \frac{1}{P-p}\left[\frac{716.5\,L}{V^{1.047}} + \frac{6250}{V^{0.39}}\right]$$

Where : P = Vapour pressure of water at temperature of the drying air, ins.Hg.

p = Partial pressure of vapour in atmosphere, ins.Hg.

L = Loss in weight during drying, oz/sq.ft. floor surface.

θ = Drying time, min.

V = Exit air velocity, ft/min.

The desiccation of sugar beet has been studied by Owen[49]. Such factors as resistance to air flow, effect of temperature, air velocity on drying times of cossettes on the laboratory and plant scale, and degree of inversion and caramelication during drying, were investigated.

Scott[50] used a through draught of air to find the effect of temperature on grass drying, and concluded that the maximum temperature was 300 - 350°F, above which blowholes of scorched grass were evident.

Marshall and Hougen[51] showed that, for the through circulation drying of a wide variety of materials, the constant drying/

drying rate could be given by the expression :

$$\frac{dW}{d\theta} = k\,G^{0.81}(H_S - H_A)$$

Where G = Air Velocity,

Hs,Ha = Saturation and air humidities

k varied from 3 to 6 for clays and pigments, 25 to 100 for granular solids and 110 to 220 for fibres. Using the same methods, Gamson, Thedos and Hougen[12] found, that for the drying of wetted catalyst pellets, in the turbulent air flow region:

$$\frac{dW}{d\theta} = \frac{0.42\,a.\,G^{0.59}\,\Delta H_m}{\rho.\,D_p^{0.41}}$$

Where a = Drying area. Sq.ft./cu.ft. of bed volume

ρ = Bulk density of dry granular bed, lb/cu. ft.

D_p = Average particle diameter, ft.

ΔH_m = Log mean of inlet and outlet humidity driving forces.

Wilke and Hougen[13] gave expressions for the constant drying rate when the flow was streamline.

The drying of vegetables has already been summarised, and although most of this work was done by cross flow air circulation, some through circulation work is reported.

Brown, Kilpatrick and Van Arsdel[28] have presented nomographic data for the drying of white potato strips ($5/_{32}$" square cross section) A uniform air distribution was obtained with a perforated sheet which gave a substantial pressure drop. Marshall[39] has given, an account of times of drying at certain loadings, air temperatures and velocities, for a/

a range of foods, fruits and vegetables. He suggested that drying data in the constant rate period were more reliably correlated by means of a heat transfer coefficient rather than a mass transfer coefficient:-

$$\lambda . \frac{dW}{d\theta} = h . A (t_a - t_s)$$

Where: λ = Latent heat of vaporisation of water.

h = Heat transfer coefficient; btu per hr.per sq. ft.

A = Area of evaporation.

t_a = Air temperature, ^{o}F.

t_s = Temperature of drying surface.

Ede and Hales[30] have described tests on vegetable and fruit delydration with through draught driers. Fruit was found to be more suitable for drying by this method than vegetables which shrunk and matted, resulting in uneven air flow with consequent difficulty of maintaining steady test conditions.

Gardner and Mitchell[40] predicted rates of drying of common sub-littoral seaweeds. Frond and stipe were found to be adequately dealt with by through drying, although shrinkage and end effects were once more evident.

Kraybill[52] investigated a process for delydrating meat in a two stage through circulation drier using fresh minced meat, and Coles[58] carried out laboratory and plant tests on the through drying of viscose staple fibre.

Allerton, Brownell and Katz[54] studied the basic mechanism/

mechanism and measuredthe experimental rates of drying of rotary vacuum filter cakes. Tests were performed on porous beds composed of glass bulbs, crushed quarty and a binary mixture of glass balls. They have postulated a drying mechanism whereby a narrow zone of vaporisation moved down through the bed, leaving a dry bed above. Since the air was at low temperature (85 - 95°F) and large surface area was exposed, the air left the bed virtually saturated with water at the adiabatic saturation temperature.

The correlation was based on the following relationship:-

$$E = \frac{r}{R} = \frac{r}{\frac{G'}{60}(H_{AS} - H_1)} = 1 - e^{-yW'}$$

Where: E = Vaporisation efficiency.

r = Rate of drying lb/(sq.ft.)(min).

R = Maximum rate of drying lb/(sq.ft.)(min).

G' = Mass velocity of air, lb/(sq.ft.)(hr).

H_{AS} = Humidity at adiabatic saturation temperature, lb/lb.

H_1 = Humidity of entering air lb/lb.

y = Drying factor, sq. ft./hr.

W' = Mass of liquid per unit area, lb/sq.Ft.

and $y = 2.72\,(Re)^{0.215}(D\quad)^{-0.350}(W^1)^{-0.36}$

Results of many tests established the likelihood of a "proportionality to thickness" drying law as stated by Marshall and Friedman[55], which may be stated:-

stated:-

$$\theta_f = \frac{e_s L \lambda (W_c - W_e)}{h_t (t_a - t_s)} \cdot \log_e \left(\frac{W_c - W_e}{W - W_e} \right)$$

Where θ_f = Time in falling rate period, hr.

L = One half thickness, ft.

λ = Latent heat of vaporisation of water BThU/lb.

h_t = Heat transfer coefficient, BThU/(sq.ft.)(hr)(^{o}F).

Mounfield[56] investigated the drying of wheat in a batch through circulation drier, and recent work of more complete nature by McEwen, Simmonds and Ward[45] on the drying of wheatgrain has been carried out. These workers have developed both a mathematical and graphical method for predicting the drying times of deep beds. The methods are based on the work done on single layer tests for different temperatures, humidities and air flows.

Thus for constant rate drying:

$$\theta_1 = \frac{M(W_1 - W_c)}{AG(H_s - H_1)}$$

Falling rate drying

$$\theta_2 = \frac{1}{m} \cdot \log_e \left(\frac{W_c - W_e}{W_f - W_e} \right)$$

And the value of We can be found from

$$(W_c - W_e) = \frac{AG(H_s - H_1)}{2.3\, m.M}$$

Where M = Weight of dry grain in bed, lb.

W = Average moisture content in bed, lb/lb.

A = Area of bed, sq. ft.

G = Mass air rate, lb.d.a./(sq.ft.)(hr).

H_s, H_1 = Humidity at saturation; humidity of entering/

entering air, lb/lb.

M = Rate constant, $hr.^{-1}$.

A new type of through circulation drier has been described by Lowe et al.[57], with a conveyor which moves longtitudinally and laterally, thus causing the material to flow along the drier in a spiral motion. The obvious advantage is bed mixing and these workers consider that such a drier will have wide application in industry.

Broughton and Mickley[58] have proposed a design method by simulating the continuous variation of stock and gas properties in a drying test in a batch drier. This only works on the basis that a drier has been designed and that the time of drying of a certain material must be found for the conditions of drying expected in the drier.

S E C T I O N   II.

1. Apparatus.
2. Experimental procedure.
3. Preliminary tests.

1. APPARATUS.

Three through-circulation driers of varying sizes were used in the tests.

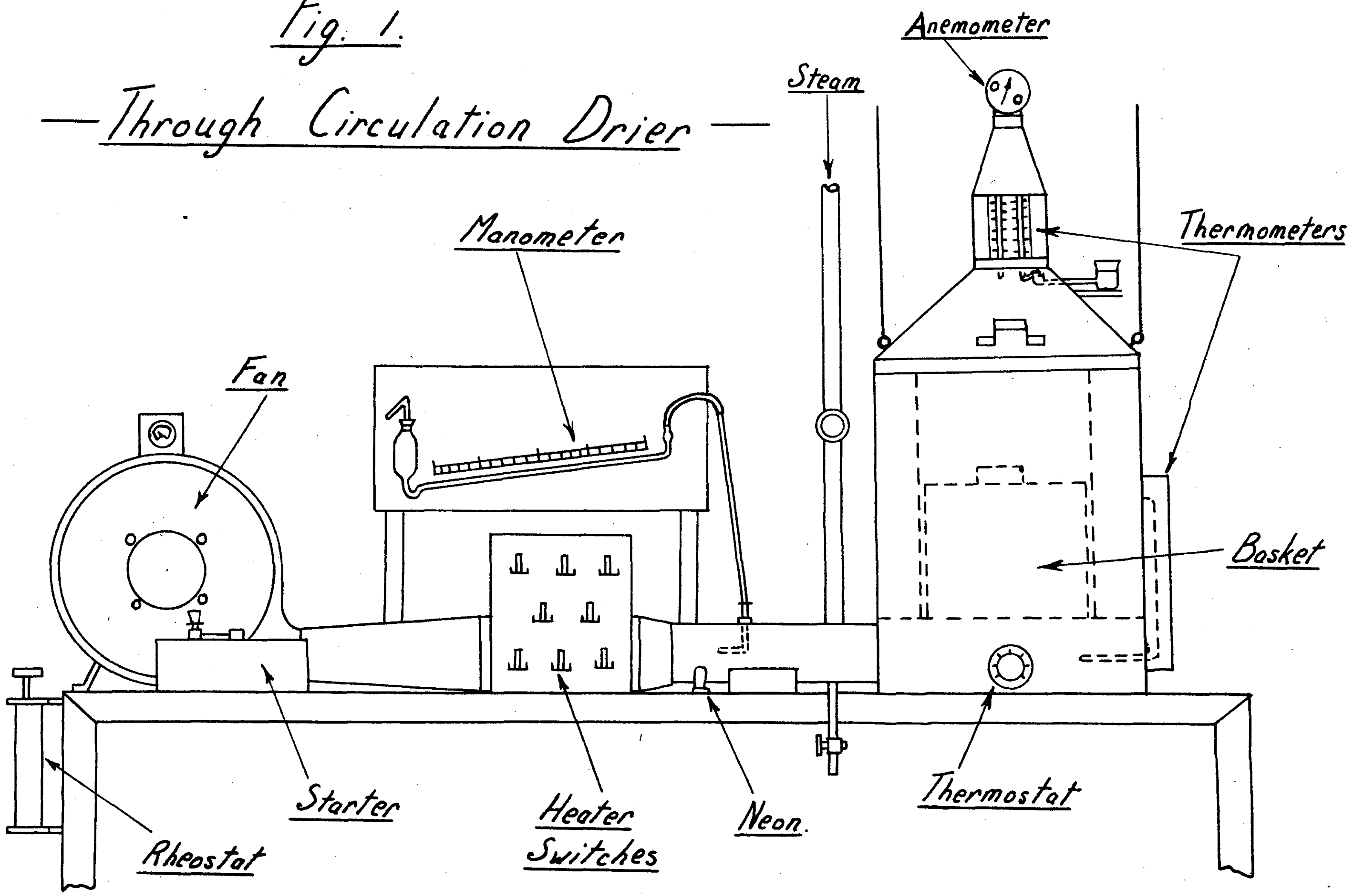
(a) The first drier (Fig.1) consisted of a centrifugal fan, directly coupled to a d.c. motor, which blew the air over eight 1-kw bar elements into a pleaum chamber and thence upwards through a vertical duct (12in. square) in which the basket of wet material rested on stout wire gauge. The lid for the drying chamber had a 6 in. diameter Perspex outlet surmounted by an aluminium cone, and was counterpoised for rapid opening. The drier was lagged with $\frac{1}{4}$ in. asbestos millboard. Wet and dry bulb thermometers were fitted at the air inlet below the basket and in the Perspex cylinder outlet. Water was supplied to the wicks from external reservoirs, through glass tubes. The inlet dry bulb temperature was regulated by a Sunvic thermostat and relay which controlled one of the heaters. A supplementary 3-kW heating element situated in the inlet fan duct permitted preheating of the air.

The air velocity was varied by a nine-point starter with fine control by a separate rheostat. The air flow was measured by an anemometer which was a push fit in the top of the aluminium cone. The humidity of the inlet air could be increased by a steam injector which could be adjusted manually by a steam valve.

The static pressure before the basket was measured by a pressure tube connected to an inclined manometer, reading up/

Fig. 1.

— Through Circulation Drier —



up to 2 in. water gauge. The basket for the wet material 9 in deep approximately 11 in. square was constructed of sheet aluminium with a floor of 1/16 in. copper gauge strengthened by a stouter ¼ in. gauge. A gasket of asbestos cord prevented air leakage round the basket.

(b) The second drier (Fig.2) was on the same principle as the first, except for the following details.

(1) The drying chamber was much smaller (0.471 sq. ft.)

(2) The fan and heaters (4xx - 1 kW) were situated directly below the test section.

(3) The exit air could be recirculated to the inlet line to the drier, the degree of recirculation being controlled by a series of baffles.

This drier was used only for recirculation tests, since the temperature control was relatively poor compared with the first drier, because of the small size of basket and since the air velocity varied over the test section.

(c) Certain disadvantages had been evident with the former two driers and in an effort to improve drying test variations and the range of operating conditions a new through-circulation drier was designed. (Fig. 3).

Formerly the air was measured at the outlet by anemometer, which had several disadvantages:

(1) The air left the bed at widely varying temperatures and humidities and correction had to be made for this before adjustment could be made to the fan speed in order to keep the inlet air flow constant.

(2)/

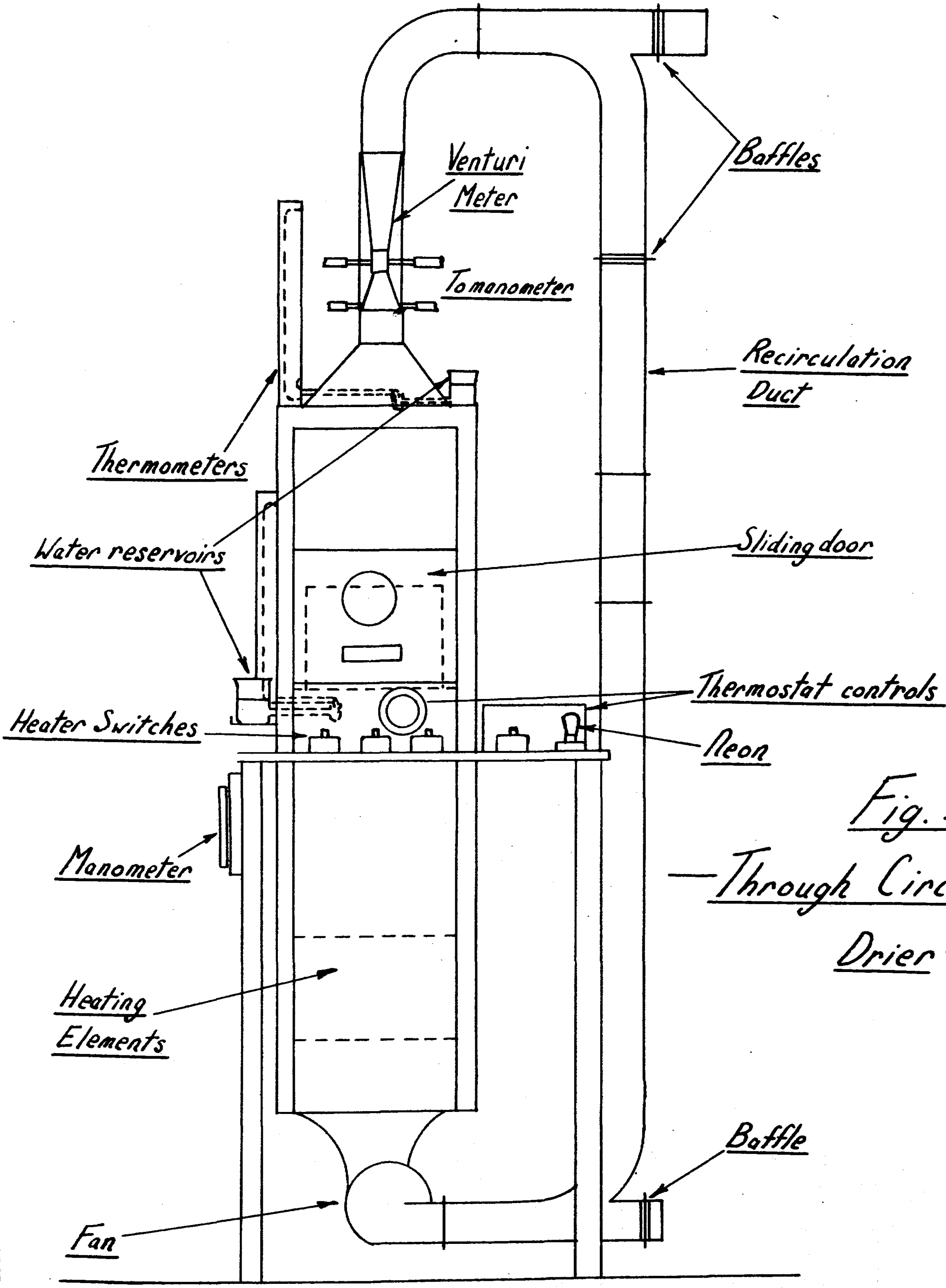


Fig. 2

—Through Circulation Drier—

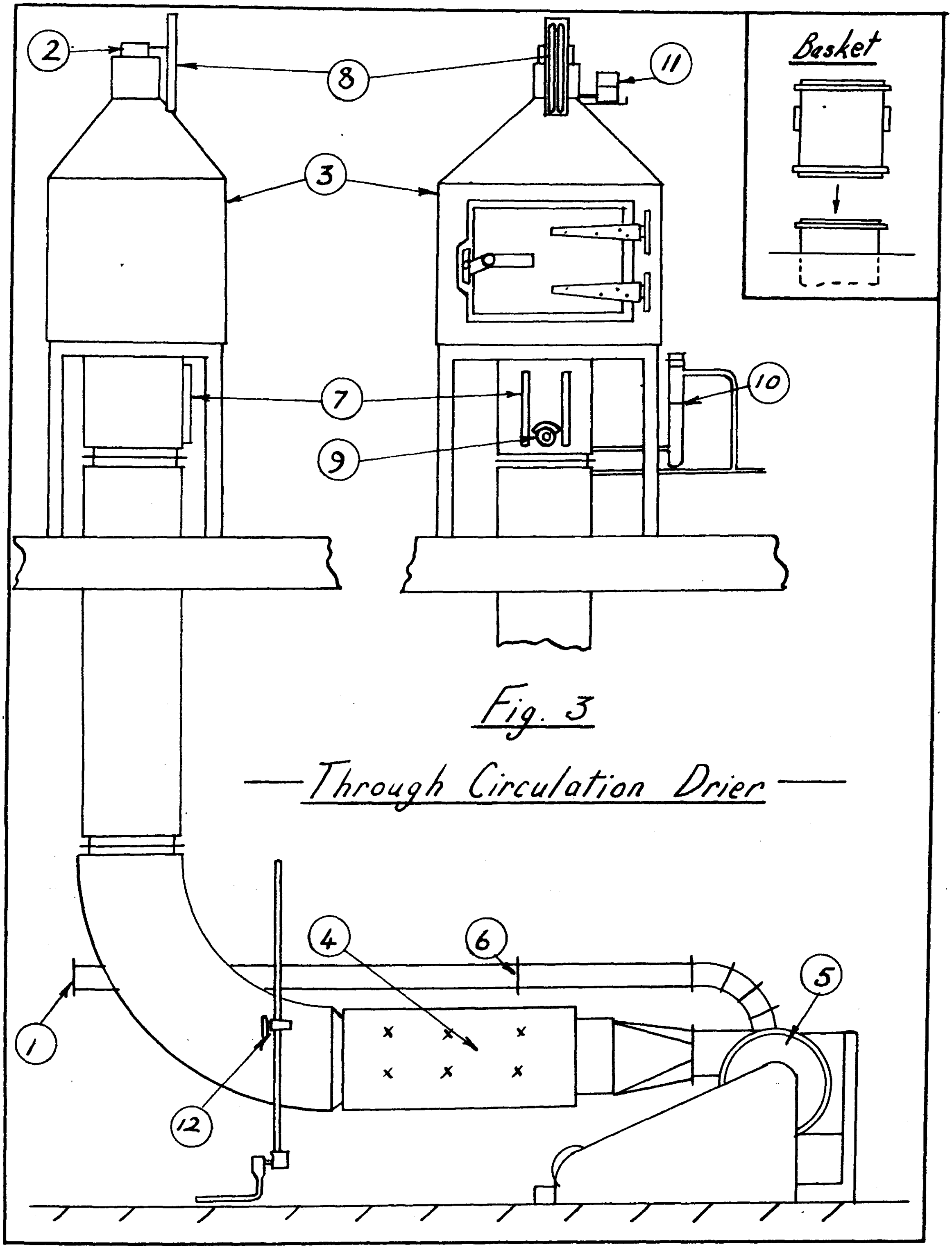


Fig. 3

—Through Circulation Drier—

1. Air intake.
2. Air outlet.
3. Drying chamber.
4. Heating section.
5. Fan.
6. Orifice plate.
7. Inlet thermometers.
8. Outlet thermometers.
9. Thermostat.
10. Reservoir.
11. Reservoir.
12. Steam supply.

(2) The reading was not instantaneous.

(3) Insertion of the anemometer caused a slight increase in back pressure with consequent decrease of air flow over the period of measurement.

It was therefore decided to measure the air flow by pressure drop measurements over a 3 in. diameter orifice in a 5 in. diameter inlet pipe, in which the air was at atmospheric temperature and humidity. The pressure tappings were connected to an inclined manometer so that any variation in manometer reading was rapidly noted and adjustment of the fan speed made.

Non-uniform flow of air over the drier cross section had been previously noted and therefore instead of a sharp change in direction of air flow, a smooth bend was incorporated between the horizontal heating section and the vertical drying chamber. The cross-sectional area of the drier was constant at 1 ft. square.

In order to increase the air capacity a larger fan was inserted and increase in drying temperature was obtained by having 18-1 kW bar heaters in the lagged heating section.

An attempt was made to decrease bypassing of air round the drying basket by fitting the basket into a U-section aluminium joint in which was an asbestos gasket.

In order to cut down loss of heat, the drier body was lagged with 1 in. thick magnesia lagging, the heating section being constructed of 3/8in. Sindanyo board and lagged with asbestos pads.

This/

This drier gave greatly improved air flow characteristics; a wider range of operating conditions; less heat loss; more rapid and accurate control of air flow.

2. DISCUSSION OF EXPERIMENTAL PROCEDURE.

Loading

The depth of bed is a most important variable in drying by through circulation. Linear measurement of the bed is inaccurate for large particle sizes while a basis of wet loading in lb. wet material/sq.ft. does not consider changes in initial moisture ratio. Loadings have therefore been measured in lb. dry material/sq.ft. This system would be inconvenient for industrial use unless the water ratio was known, and therefore one of the former two methods would have to be used.

Weighings.

The progress of each experiment was followed by weighing the sample at regular intervals.

Ideally this should be done instantaneously without removal of the sample from the drying chamber. This necessitates a variable correction for the upthrust of the air, errors in air measurement being reflected in errors in weighing. The accuracy demanded by the experiments, and in particular in single layer tests, required the sample to be withdrawn and weighed on a balance. This resulted in a slight heat loss from the basket for the period of weighing.

In/

In the present work, the basket was removed and weighed on a balance of 30 lb. capacity, calibrated by 0.005 lb. Weighings were estimated to 0.001 lb. with a good degree of accuracy.

Moisture Content and Sampling.

After completion of the drying tests, samples were taken at the sides and corners of the bed. The composite sample was thoroughly mixed and ground in a Christy and Norris 8 in. laboratory mill to pass a 1 m.m. screen. This powder (Approx. 10 g.) was weighed into aluminium dishes (2½ in. in diameter x 7/8 in. deep) provided with tightly fitting lids, and exposed for 6 hrs. (Temp. 60-100°C depending on material) in a vacuum oven. The dishes were cooled and reweighed, the loss in weight being attributed to water. The mean of duplicate determination was used as a basis for calculations.

Experimental Procedure.

The fan was started, adjusted to give the correct anemometer or orifice plate reading, the heaters switched on and conditions allowed to stabilize at the desired temperature. (15-45 minutes).

The empty basket was counterpoised on the balance and the desired quantity of material weighed into it from a fixed height with random packing. Prior to the test, the inlet and outlet temperatures were recorded and the atmospheric humidity taken with a whirling hygrometer. The static pressure was noted with the drier closed and the empty basket in position

The/

The basket was inserted in the drier, the timer started, and the drier closed. The initial static pressure was noted and the exit temperatures checked each minute. The basket was removed, weighed, and replaced at regular intervals, normally 5 minutes for the first hour of drying, 10 minutes for the second hour of drying, and 15 minutes thereafter. Before closing the lid the timer was returned to zero so that the measured time interval (5,10 or15 minutes) represented the actual time the material was in the drier.

Anemometer readings were taken 2 minutes before each weighing to allow the exhaust temperature to steady after the interruptions caused by the removal of the basket for weighing. Anemometer readings for air flow were taken several times between each weighing so that immediate control of air flow was possible.

The experiment was generally concluded when the loss in weight was less than 0.005 lb. over a weighing period, although this figure depended to large extent on the loading used. Insingle layer tests the figure was 0.002 lb. or less.

Temperature and humidity measurements.

With the original drier, uneven air flow at the bottom of the plenum chamber caused the inlet dry-bulb thermometer to read a few degrees too high. Radiation from the heaters was also thought to have an effect on this temperature. The out let temperature which was accurate, was therefore measured before starting the test, and the inlet value used throughout the test to measure temperature fluctuation. From this/

this, it was evident that the thermostat controlled the temperature to within ± 1°F. although temperature distribution was less even. Sometimes the wet-bulb temperatures were too high because of low air velocity past the wicks. When this occurred, a check was made from the humidity values obtained from a sling psychrometer.

A similar procedure was carried out for the small drier, where air variation over the cross section and radiation from the heaters also affected the inlet thermometers.

With the redesigned drier no such fluctuations occurred, and therefore the only check carried out was one of humidity comparison between drier temperatures and external whirling hygrometer temperatures.

Air velocity measurement

For the first two driers, the exit air velocity was obtained by measuring the time taken for 1000 feet of air to be recorded on an anemometer in the outlet duct, and the value obtained corrected by the calibration factor for the instrument The mass flow was calculated from the area of the outlet duct and the air density. Leakage of air took place round the lid or door and mass balances on trial runs were necessary in order to get an accurate value for the inlet air velocity.

With the new drier the air flow was readily measured on the inlet line by pressure drop readings over a 3 in. diameter orifice plate in a 5 in. diameter line.

Calculation of results/

Calculation of results

The bone-dry weight of the seaweed was calculated from the final weight of the product and its moisture content. The water content of the sample (lb.water/lb.B.D.S.) was then found at each time of weighing. The curves of water content vs. time of drying, were then plotted for each run, and the drying times of required moisture contents interpolated.

In deep bed tests, the constant drying rate was measured as the slope of the straight line section of the drying plot. Instantaneous values of drying rate at other points were measured with a tangentimeter.

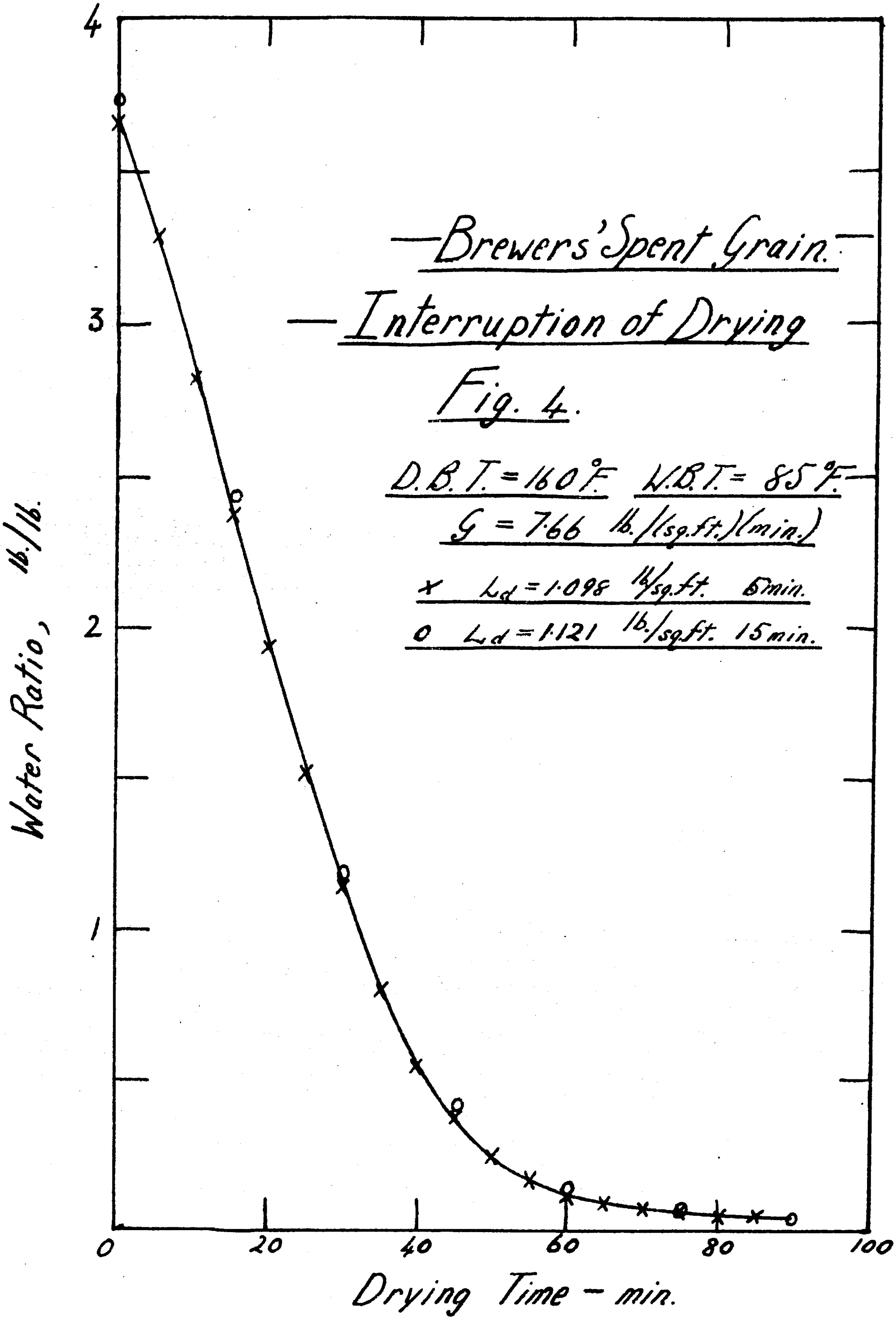
The curves of water content vs. time were normally plotted as obtained, showing the variation in initial moisture contents, but for ease of comparison, others were plotted starting from a constant water content by subtracting a constan time from each time of weighing.

3. PRELIMINARY TESTS.

Interuption of Drying.

The rate of drying of catalyst pellets[12] and of L. cloustoni stipe[40] has been shown to be little affected by the time lost when the sample was removed from the drier for weighing. This was confirmed by tests on the various materials used in the present work (Fig. 4).

The result of the interruptions was that, although the material temperature fell during the 15 seconds when weighing/


Brewers' Spent Grain.
Interruption of Drying
Fig. 4.
D.B.T. = 160°F. W.B.T. = 85°F.
G = 7.66 lb./(sq.ft.)(min.)
x Ld = 1.098 lb./sq.ft. 5 min.
o Ld = 1.121 lb./sq.ft. 15 min.
Water Ratio, lb./lb.
Drying Time - min.
0
1
2
3
4
20
40
60
80
100

weighing, drying did continue during this time and also slight agitation occurred owing to disturbance. The first factor would tend to increase the drying time and the last two would decrease it.

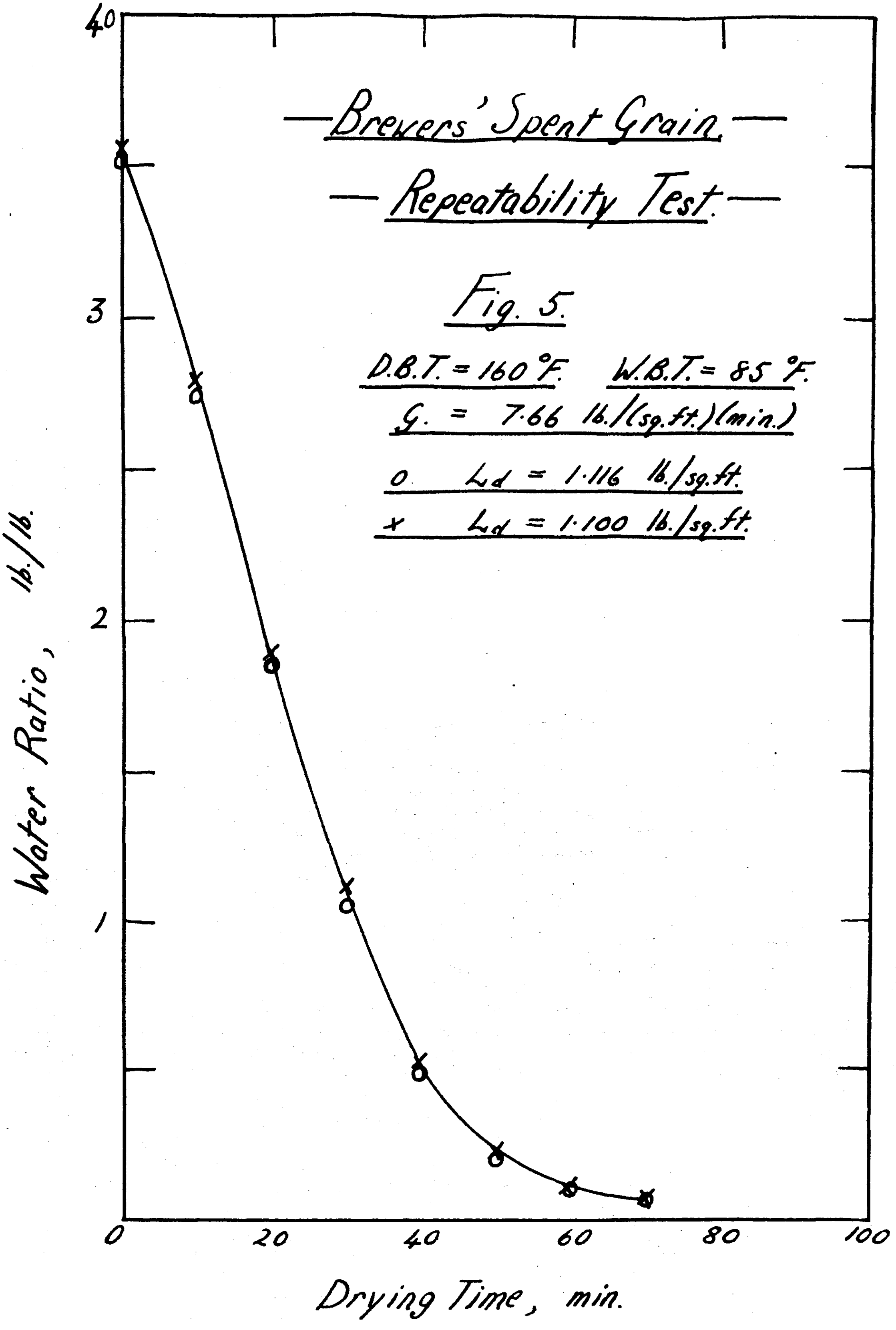
Repeatability test.

This test was conducted to find how closely tests could be duplicated under identical conditions of loading, air velocity and humidity. The result of such a test on brewers' spent grain can be seen in Fig.5. The curves are almost coincident, corroborating the findings of Gardner and Mitchell[40] for L. cloustoni stipe.

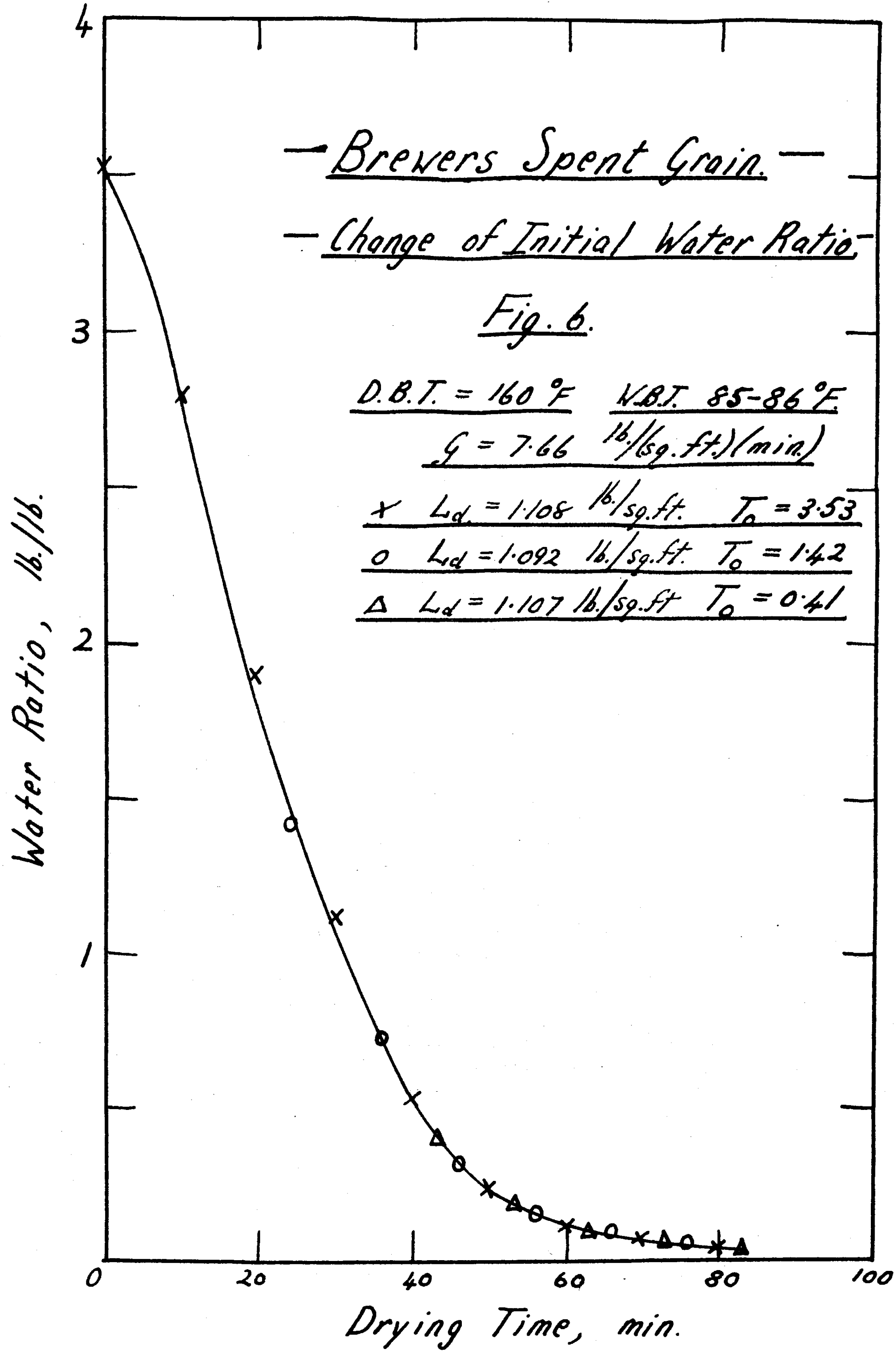
Initial water ratio change.

Initial moisture ratio has been found to vary in vegetable materials, making comparison of drying tests difficult. Brown and Kilpatrick[28] and Gardner and Mitchell have encountered this and have made small time corrections in order to base each test on a common initial water ratio.

Thus three tests were carried at different initial water ratios for brewers' spent grain at almost the same loading, air velocity and humidity. Fig. 6 shows that the curves of water content vs time are coincident, a time correction being added to the last two to allow for their lower water content. It is evident, therefore, that the amount of previous air drying does not affect the drying rates in the later stages



Brewers' Spent Grain.
Repeatability Test.
Fig. 5.
D.B.T. = 160 °F. W.B.T. = 85 °F.
G. = 7.66 lb./(sq.ft.)(min.)
o Ld = 1.116 lb./sq.ft.
x Ld = 1.100 lb./sq.ft.
Water Ratio, lb./lb.
Drying Time, min.
0
1
2
3
4.0
20
40
60
80
100



— Brewers Spent Grain. —
— Change of Initial Water Ratio —
Fig. 6.
D.B.T. = 160 °F W.B.T. 85-86 °F
G = 7·66 lb./(sq.ft.)(min.)
× Ld = 1·108 lb./sq.ft. To = 3·53
o Ld = 1·092 lb./sq.ft. To = 1·42
Δ Ld = 1·107 lb./sq.ft To = 0·41
Water Ratio, lb./lb.
Drying Time, min.
0
20
40
60
80
100
1
2
3
4

SECTION III.

EXPERIMENTAL WORK.

Through-circulation drying of seaweed.

(a) Ascophyllum Nodosum.

(b) Fucus serratus.

(c) Fucus vesiculosus.

INTRODUCTION

The main reasons for drying seaweed are to reduce transport costs, to enable the material to be stored without bacterial decomposition, and to allow it to be compounded more easily with other products (e.g. animal feeding-stuffs). The extraction of the constituents of seaweed is usually preceded by drying and grinding. Search for a cheap and efficient method of drying has revealed that a through circulation conveyor dryer is probably best for seaweed.

Previous work in this laboratory has been concerned primarily with the sub-littoral weeds Laminaria cloustoni, L. digitata and L. saccharina. Preliminary studies on the drying of these weeds have been carried out by Black & Duthie[59] and McLean & White[60]. Gardner & Mitchell[40] have investigated the through-circulation drying characteristics of the above seaweeds and have suggested a graphical method for predicting the drying times and rates of seaweed beds. Hyndman, McEwen & Mitchell[61] have conducted tests on a mixture of L. cloustoni stipe and frond and have also carried out initial investigations into the drying of the littoral weeds Ascophyllum nodosum, Fucus vesiculosus and F. serratus at different bed loadings. The effect of agitation of the bed has been studied by Rankin[62] for the above rock seaweeds.

The use of rotary dryers for the drying of seaweeds has met with limited success, owing to the excessive mucilage con-

tent/

content of the weed. Gardner, Mitchell & Scott[63], using a radioactive-tracer technique, have shown that Laminaria cloustoni frond did not receive uniform treatment in a pilot plant rotary louvre dryer, since frond particles stuck to the inside of the drum. L. saccharina frond at an initial moisture content of 50% has been successfully dried in such a dryer. A rotary dryer has been described by Clark et al[65] for drying Macrocystis pyrifera, a seaweed found off the Californian coast, from a moisture content of 87% to 40-65%. Drying to lower moisture content (5-15%) was effected on a conveyor dryer with a seaweed bed-depth of 2-3in. Gardner[12] has described a test on a large-scale grass drier (Pehrson Dual Process) using L. cloustoni as feed. This dryer had a pneumatic drying tower followed by two rotary drying sections. A description of some of the industrial uses of red and brown seaweeds and a comparison of the methods of drying seaweed with those used for grass and vegetables, has been made by Mitchell[13].

<u>RAW MATERIAL</u>

Most of the seaweed used was harvested in the Firth of Forth area with a few samples from the Oban area. A two-day supply of weed was harvested one day and despatched that day, arriving at the laboratory the following day. Tests on the weed were thus completed within 48 hours of harvesting.

A. nodosum, F. vesiculosus and F. serratus belong to the Fucaceae family of the Phaeophyceae group which covers a

large/

large area of the tidal rocks of Great Britain, and all attach themselves to rocks by a discoid holdfast or hapteron.

A. nodosum occurs on rocks and boulders from high-water mark to half-tide level and is abundant on rocky shores. It is distinguished by air vesicles or bladders formed at intervals on the whole plant, the fronds of which grow from 12 to 60 in. in length, and are tough and leathery.

F. vesiculosus is a rock-weed growing up to 3 ft. in length with the fronds ½-1 in. in width. It has a flat thallus with a distinct midrib and branches out in one plane, with air bladders formed at intervals on eigher side of the midrib. The weed grows freely on rocks and stones between high and low-tide marks.

F. serratus is of similar form to F. vesiculosus with the distinction that the air bladders are absent and that the margin of the frond is serrated. It grows to a maximum length of 6 ft. and is very common on rocks from half-tide level to low-water mark.

The size of the weeds harvested was about 1 ft. in length for F. serratus and F. vesiculosus, and approximately 2 ft. in the case of A. nodosum, i.e. considerably smaller than the largest plants.

EXPERIMENTAL PROCEDURE

The dryer used has been described in Section II (Fig.1 it operates by means of a centrifugal fan blowing air over electric/

electric heating elements and thence vertically through the static seaweed bed contained in a removable basket.

The experimental procedure was similar to that described in the above paper, with one major exception. In previous tests a mean air mass flow was taken throughout the whole test period. This was not completely satisfactory since any change in flow made comparison of tests more difficult. Hyndman, McEwan & Mitchell[7] have therefore constructed a triangular chart which can be used to maintain the air mass flow at a steady value throughout a test. The chart relates the exit dry and wet-bulb temperatures to air velocity. By measuring the two temperatures, the true air velocity at the desired mass flow can be read from the chart, and then any adjustment in fan speed required can be made.

The prepared weed was weighed into the basket with random packing, and the bed levelled off without any unnecessary pressure being applied. No great change in colour during drying was noted, but when steam injection was used to humidify the inlet air, the colour of the weed changed initially to bright green which gradually became darker as the test proceeded.

Identical shrinkage and matting effects to those described by Gardner & Mitchell[5] were noted in all tests, causing part of the air to short-circuit the bed.

Tests on the effect of one variable were performed consecutively/

consecutively so as to reduce to a minimum the seasonal variation in the biological nature of the material.

Effect of operating variables.

(1) Bed-depth - The obvious advantage of through-circulation drying is that the drying air is much more economically used than in tray drying, i.e. cross-circulation drying, since more intimate contact is made between the air and the particles of the bed. Thus in contrast to cross-circulation drying, much heavier loading is possible.

The minced weed was dried by air at 160°F at an air mass flow of 7.5 lb./sq.ft.min., using thermostatic control on one of the heating elements.

(a) Ascophyllum nodosum

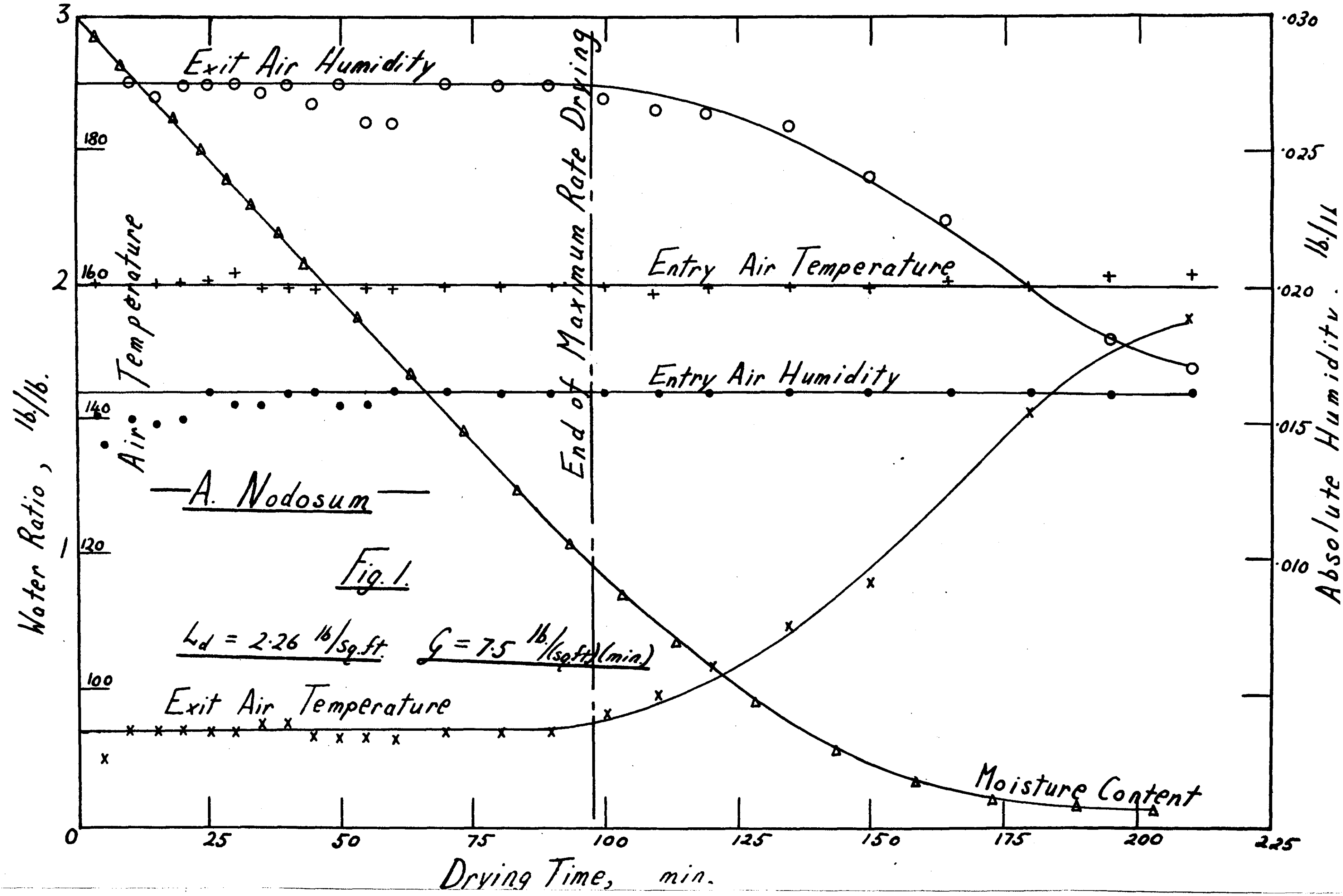
Fig.1 indicates the values of temperature and humidity for inlet and exit air and of water content versus drying time for a typical drying run on A. nodosum. The time required to dry the minced weed between a water ratio of 3.2 and 0.15 was plotted against the dry loading L_d. The curve, in which drying time rapidly increases above a dry loading of 2.0 lb./sq.ft., has the empirical equation:

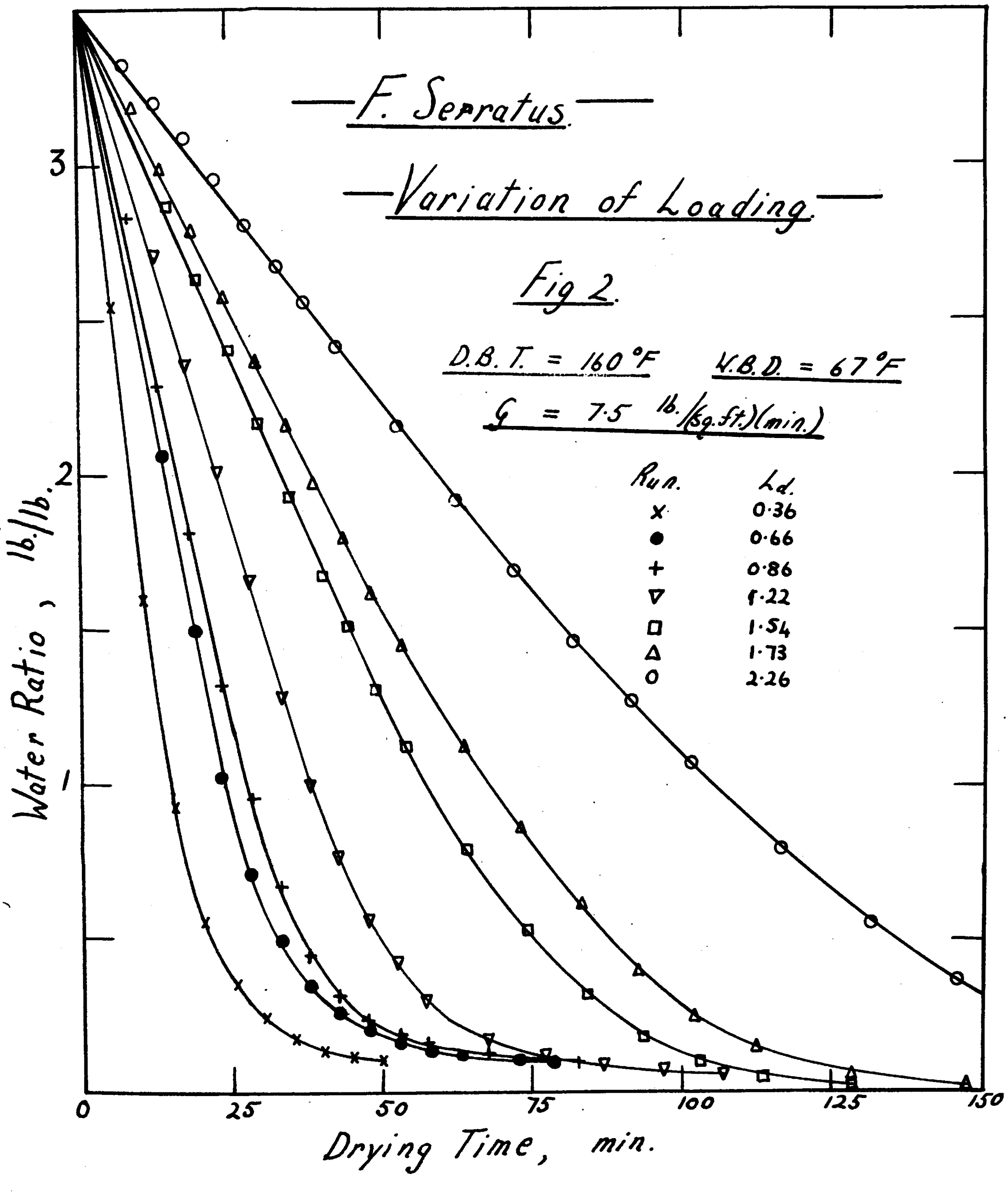
$$\theta = 77.5 - 27.9 \log_e (2.62 - L_d) \text{ for } L_d < 20 \quad \text{(Fig. 3)}$$

The constant drying rate plotted against the dry loading gives a curve represented by the equation:

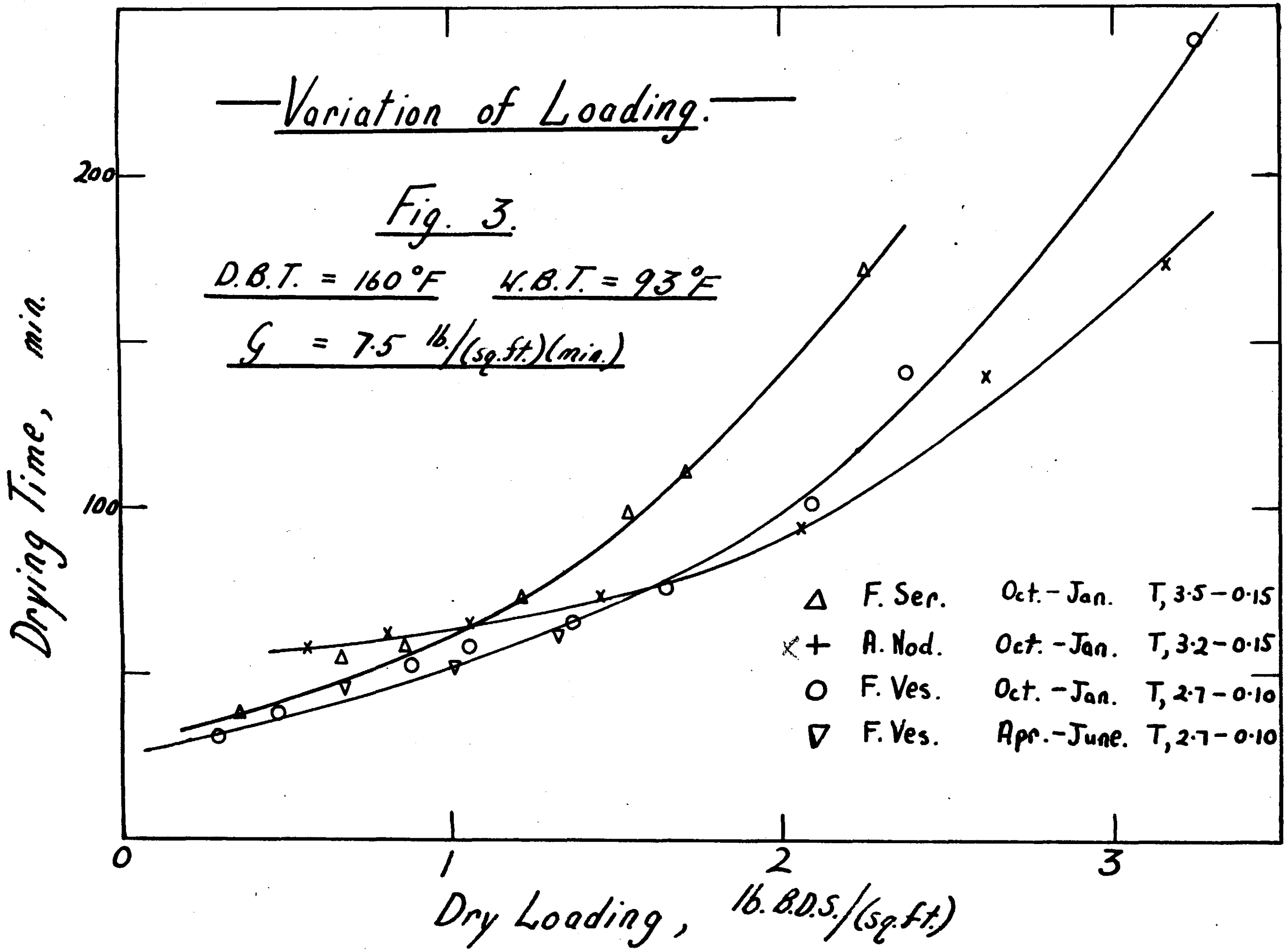
$$\left(\frac{\partial T}{\partial \theta}\right)_c = 5.4 \; Ld^{-1} \qquad \text{(Fig. 4)}$$

The output of commercial dry seaweed (0.15 lb./lb.B.D.S.)

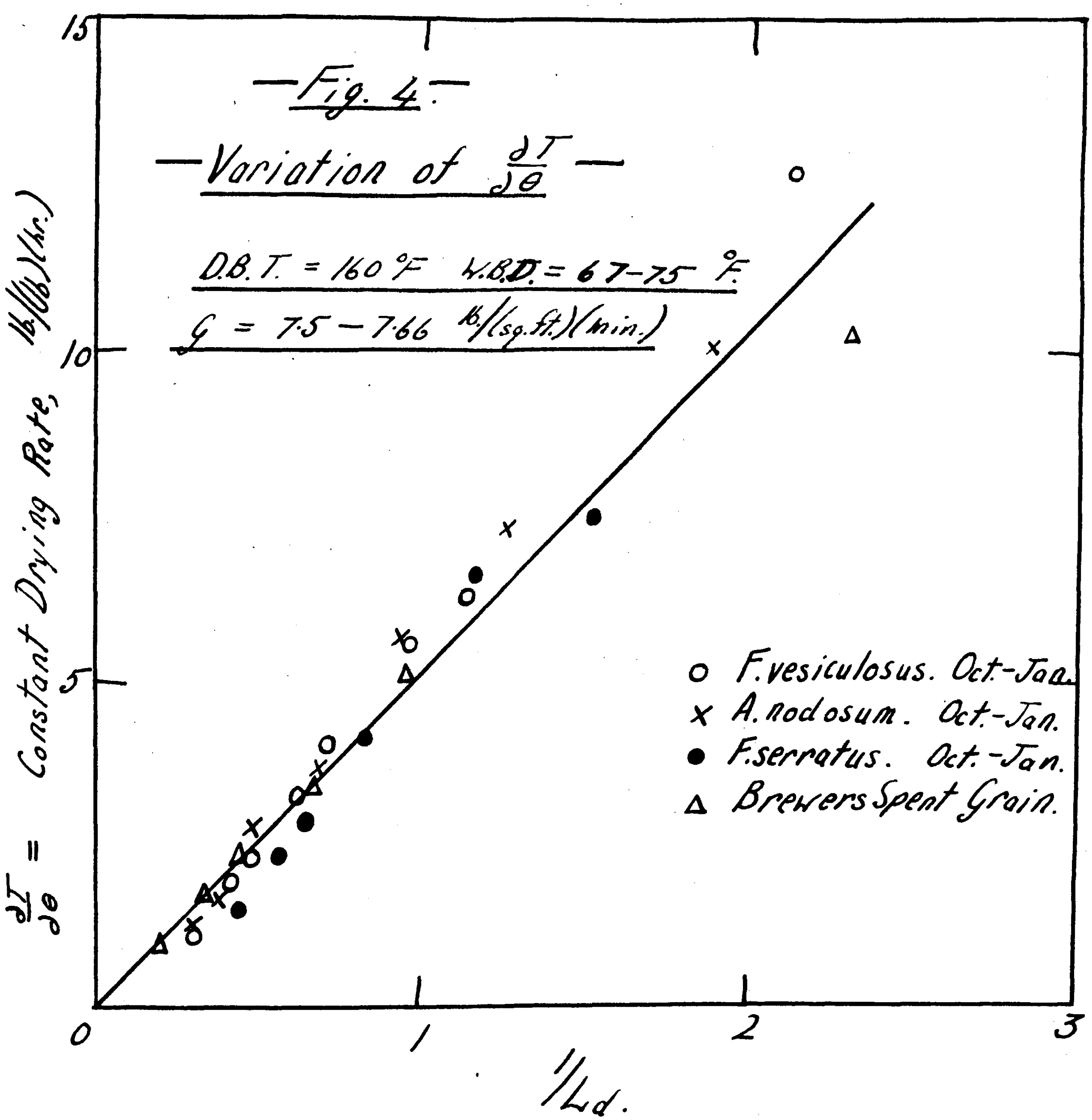

Exit Air Humidity
Entry Air Temperature
Entry Air Humidity
Exit Air Temperature
Moisture Content
End of Maximum Rate Drying
Air Temperature
A. Nodosum
Fig. 1.
L_d = 2·26 lb/sq.ft.
G = 7·5 lb/(sq.ft)(min)
Water Ratio, lb/lb.
Absolute Humidity, lb/lb
Drying Time, min.
0
25
50
75
100
125
150
175
200
225
3
2
1
180
160
140
120
100
·030
·025
·020
·015
·010



F. Serratus
Variation of Loading
Fig 2.
D.B.T. = 160°F
W.B.D. = 67°F
G = 7.5 lb./(sq.ft.)(min.)
Run.
Ld.
0·36
0·66
0·86
1·22
1·54
1·73
2·26
Water Ratio, lb./lb.
3
2
1
0
25
50
75
100
125
150
Drying Time, min.



—Variation of Loading.—
Fig. 3.
D.B.T. = 160°F W.B.T. = 93°F
G = 7.5 lb./(sq.ft.)(min.)
200
100
Drying Time, min.
0
1
2
3
Dry Loading, lb. B.D.S./(sq.ft.)
Δ F. Ser. Oct.-Jan. T, 3·5-0·15
x + A. Nod. Oct.-Jan. T, 3·2-0·15
○ F. Ves. Oct.-Jan. T, 2·7-0·10
∇ F. Ves. Apr.-June. T, 2·7-0·10



-Fig. 4.-
-Variation of ∂T/∂θ -
D.B.T. = 160°F W.B.T. = 67-75 °F.
G = 7.5 - 7.66 lb./(sq.ft.)(min.)
∂T/∂θ = Constant Drying Rate, lb./(lb.)(hr.)
1/Ld.
0
1
2
3
5
10
15
○ F. vesiculosus. Oct.-Jan.
× A. nodosum. Oct.-Jan.
● F. serratus. Oct.-Jan.
△ Brewers Spent Grain.

from seaweed of initial moisture 3.2 is expressed as:

$$R = (L_d/\theta) \times 69 \quad \text{(Fig. 5)}$$

A plot of output versus dry loading shows a well defined optimum value for output at L_d = 2.0 lb./ sq.ft. (3½ in. bed-depth), above which the output decreases markedly. All further tests on the influence of other drying variables were carried out at slightly below this loading.

(b) Fuscus vesiculosus

The drying time (T = 2.7 - 0.10) versus dry loading can be represented by the equation:

$$\theta = \exp 0.67L_d + 3.28 \quad \text{(Fig.3)}$$

The constant drying rate versus L_d can be expressed as:

$$\left(\frac{\partial T}{\partial \theta}\right)_C = 5.4\ Ld^{-1} \quad \text{(Fig.4)}$$

The output of commercial dry seaweed (C.D.S.)(0.10 lb./lb./lb. B.D.S.) from minced weed of initial water ratio 2.7, has an optimu value at L_d = 1.6, the equation of the curve being:

$$R = 66\ L_d/\theta \quad \text{(Fig. 5)}$$

(c) Fucus serratus

Fig. 2 shows typical curves for water content versus drying time for bed-depth tests on F. serratus. The equation for drying (T = 3.5 - 0.15) versus dry loading is of similar form to that for F. vesiculosus:

$$\theta = \exp 0.78L_d + 3.37 \quad \text{(Fig.3)}$$

The constant drying rate versus L_d has the equation:

$$\left(\frac{\partial T}{\partial \theta}\right)_C = 5.4\ Ld^{-1} \quad \text{(Fig. 4)}$$

The/

The output of C.D.S. (0.15 lb/lb.B.D.S.) from seaweed of initial water ratio 3.5, has an optimum value at L_d = 1.25, and is related to L_d by:

$$R = 66L_d/\theta \qquad \text{(Fig. 5)}$$

(2) <u>Air Velocity</u> - In this series of tests, the air dry-bulb temperature was maintained constant at 160°F and the air mass velocity was varied from 5 - 11 lb.d.a./sq.ft.min., each flow-rate being kept steady at the predetermined value as in the loading tests. This method of control was independent of any variation in inlet air humidity, but did not include a correction factor for any 'edge effects' taking place in the tests, or channelling of the air-stream.

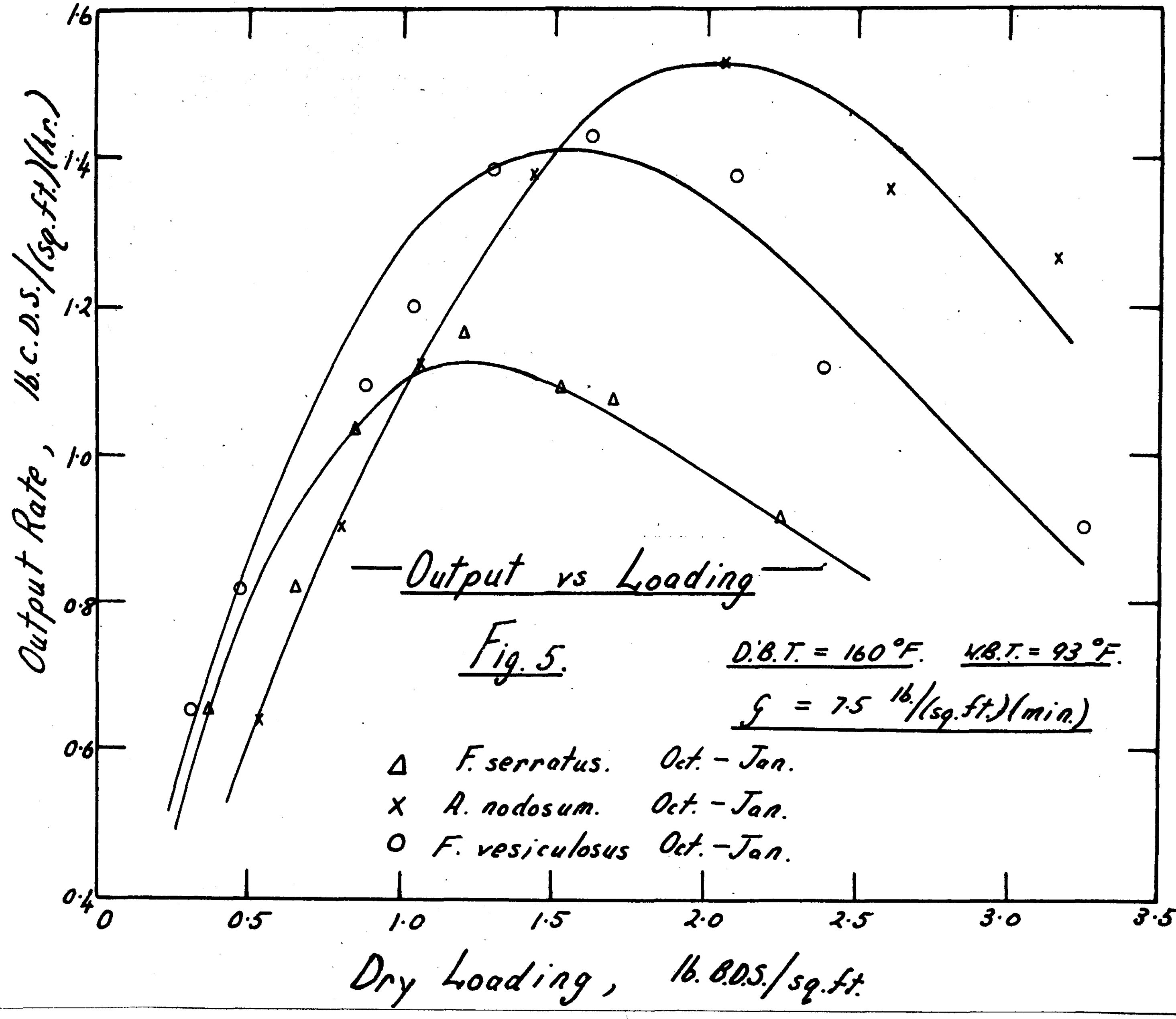
Fig. 6 shows the results of three series of tests for A. nodosum, F. vesiculosus and F. serratus respectively. The curves may be represented by the equations:

$$\theta = 479G^{-0.79} \quad \text{(A. nodosum } T = 3.2 - 0.15)$$

$$\theta = 385G^{-0.864} \quad \text{(F. vesiculosus } T = 2.7 - 0.1)$$

$$\theta = 531G^{-1.038} \quad \text{(F. serratus } T = 3.5 - 0.15)$$

These equations are of the same form as those obtained by Gardner and Mitchell[40] for L. digitata and L. cloustoni fronds in which case the drying times were proportional to the - 1.17 and 1.40 powers of the air-velocity respectively, for the approximate range G = 4 - 9.5 lb/sq.ft.min. These figures are confirmed by those of other workers. The 'minimum time' of drying for hops was found by Burgess[48] to be related to the - 0.39/



—Output vs Loading—
Fig. 5.
D.B.T. = 160 °F.   W.B.T. = 93 °F.
G = 7.5 lb./(sq.ft.)(min.)
Δ F. serratus. Oct. - Jan.
X A. nodosum. Oct. - Jan.
O F. vesiculosus Oct. - Jan.
Output Rate, lb. C.D.S./(sq.ft.)(hr.)
Dry Loading, lb. B.D.S./sq.ft.
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

0.39 power of the air-flow, while Brown & Van Arsdel[28] found that the velocity index for the drying time was - 0.4 for potato strips. Coles[53] obtained an index of - 1.25 for the time required to dry viscose staple fibre.

From Fig. 6 it can be seen that no great decrease in drying time can be effected by increasing the air-flow above 10 lb/sq.ft.min.

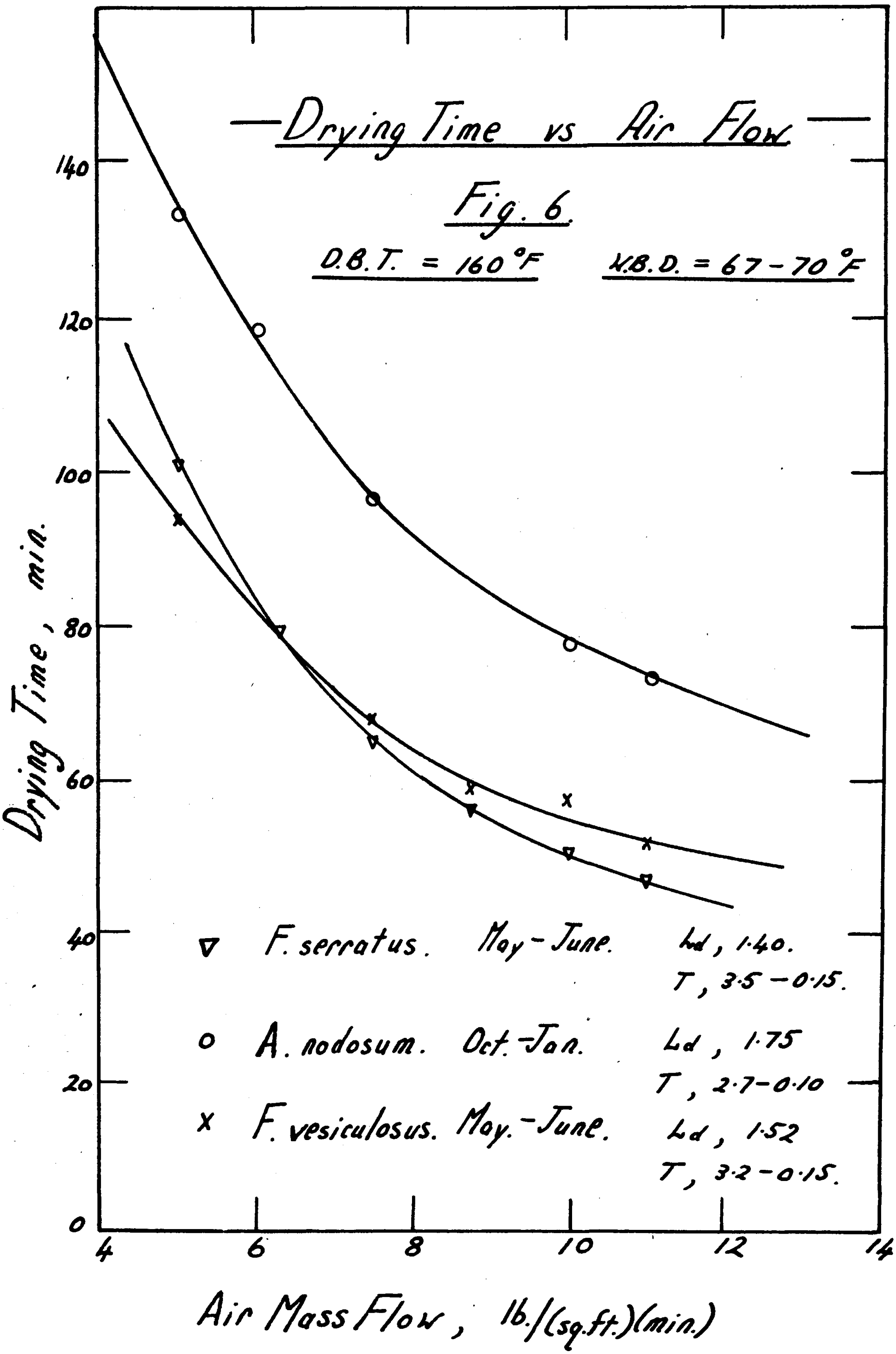
The data for constant drying rate versus air-flow is represented by a straight-line plot (Fig.7) for each seaweed, giving the equations:

$$\left(\frac{\partial T}{\partial \theta}\right)_c = 0.41G$$

$$\left(\frac{\partial T}{\partial \theta}\right)_c = 0.45G$$

$$\left(\frac{\partial T}{\partial \theta}\right)_c = 0.52G$$

Allowing for the change in loading, the value of the constant drying rate for L.cloustoni stipe[1] is higher than for fronds or rock-weeds. This is due to the soft flexible particles being compressed, preventing free access of air through the bed. Obviously, the deeper the bed, the more compressed are the lower layers and the more resistance is made to the drying air. This compressibility factor largely controls the drying rate. The smaller the particle size then the more compressible is the bed. Thus, while small particles are the basis of spray-drying and air suspension techniques, they are probably not suitable for through-circulation work. Conversely, it is seldom economic to dry whole plants or vegetables/

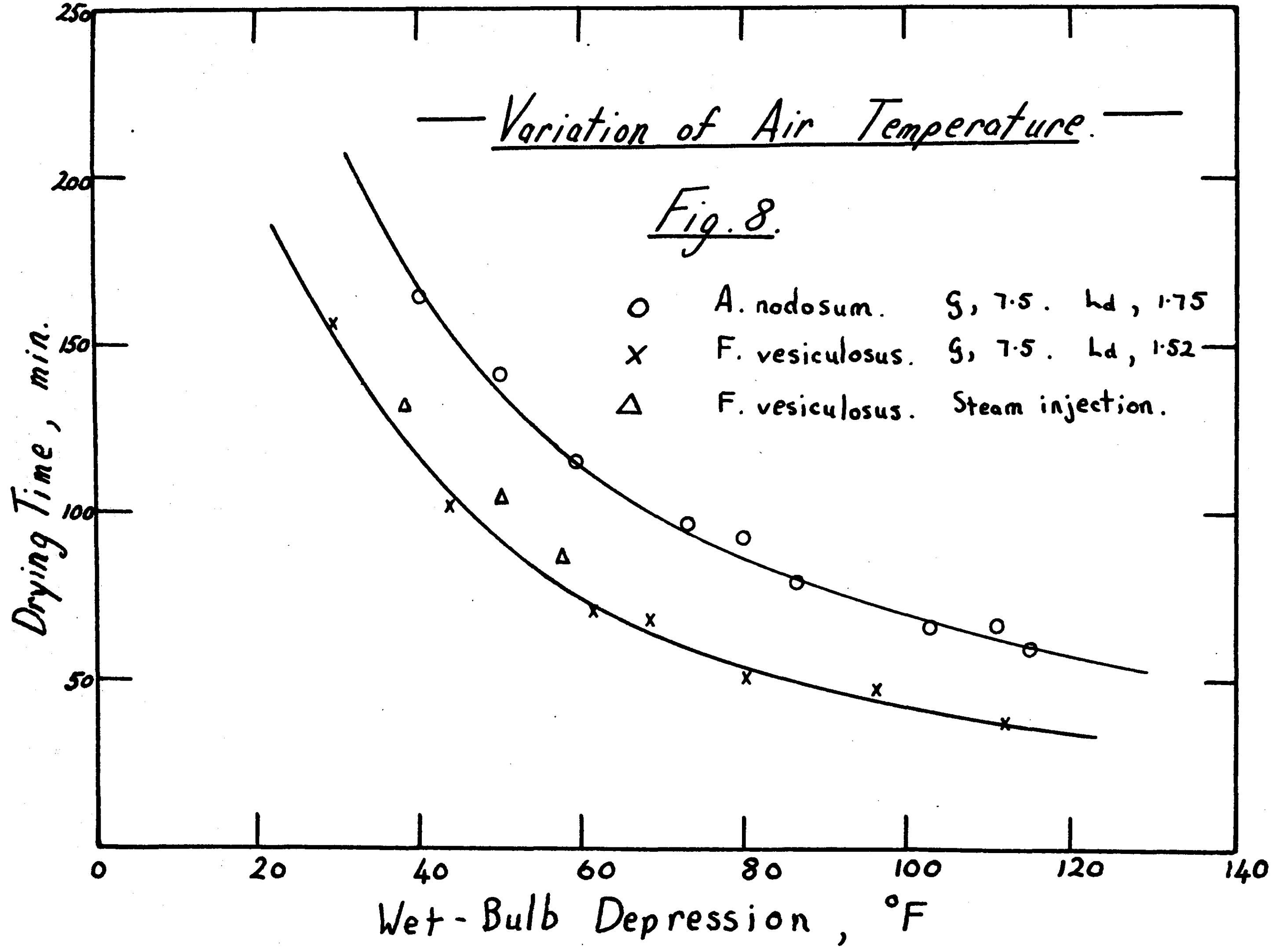

Drying Time vs Air Flow
Fig. 6
D.B.T. = 160 °F
W.B.D. = 67 – 70 °F
F. serratus. May – June. Ld, 1·40. T, 3·5 – 0·15.
A. nodosum. Oct. – Jan. Ld, 1·75 T, 2·7 – 0·10
F. vesiculosus. May. – June. Ld, 1·52 T, 3·2 – 0·15.
Drying Time, min.
Air Mass Flow, lb./(sq.ft.)(min.)
0
20
40
60
80
100
120
140
4
6
8
10
12
14

vegetables (e.g. seaweed stipe, carrots), due to the excessively long drying times required. In industrial drying a compromise is made between the size of the product required by the consumer and the economy needed in drying time. Consequently in seaweed drying, stipes have been sliced at an optimum thickness, whereas fronds and rock-weeds have been minced to give suitable particle sizes of approximately $\frac{3}{8}$ in. x $\frac{1}{2}$ in., x $^{1}/32$ in.

(3) Temperature and humidity - Investigations of the effect of temperature and humidity have been made by measuring the time of drying, for a fixed loading and air velocity, against the wet-bulb depression of the drying air.

For the three seaweeds under test, it was found that $\theta \propto 1/(t_d - t_w)$, i.e. the drying time was inversely proportional to the W.B.D. A series of tests was carried out for each seaweed, the dry-bulb temperature alone being varied, thus giving different values of W.B.D. (Fig.8), although the absolute humidity of the drying air was that of the atmosphere.

An attempt was made to vary the wet-bulb depression, while maintaining the D.B.T. constant, by steam injection into the air stream. Van Arsdel[39] found in the drying of potato half-dice that a rise in air-temperature at constant wet-bulb depression increases the rate of drying. This was attributed to the fact that in the low moisture end of the run, when internal diffusion controls the rate of moisture removal, the higher internal temperature of the material increased the rate of internal/


— Variation of Air Temperature. —
Fig. 8.
○ A. nodosum. G, 7·5. Ld, 1·75
× F. vesiculosus. G, 7·5. Ld, 1·52
△ F. vesiculosus. Steam injection.
250
200
150
100
50
Drying Time, min.
0
20
40
60
80
100
120
140
Wet-Bulb Depression, °F

internal diffusion of moisture. This theory should also apply to the drying of seaweed, but in fact did not appear to when steam was injected to raise the wet-bulb temperature of the air. This anomaly was apparently due to considerable matting of the bed taking place in the steam injection tests, and to areas of the basket mesh being clogged with mucilage, both resulting in an increase in drying time. When tests using very low wet-bulb depressions were attempted by steam injection it was found that the weight of the seaweed bed increased initially due to condensation of water-vapour on the lower layers. This condensation ceased as the bed temperature rose, and gradually the weight decreased as drying commenced.

No great reliance could therefore be placed on the findings of the tests in which this happened and variation of W.B.D. by altering the D.B.T. was alone found to give accurate results.

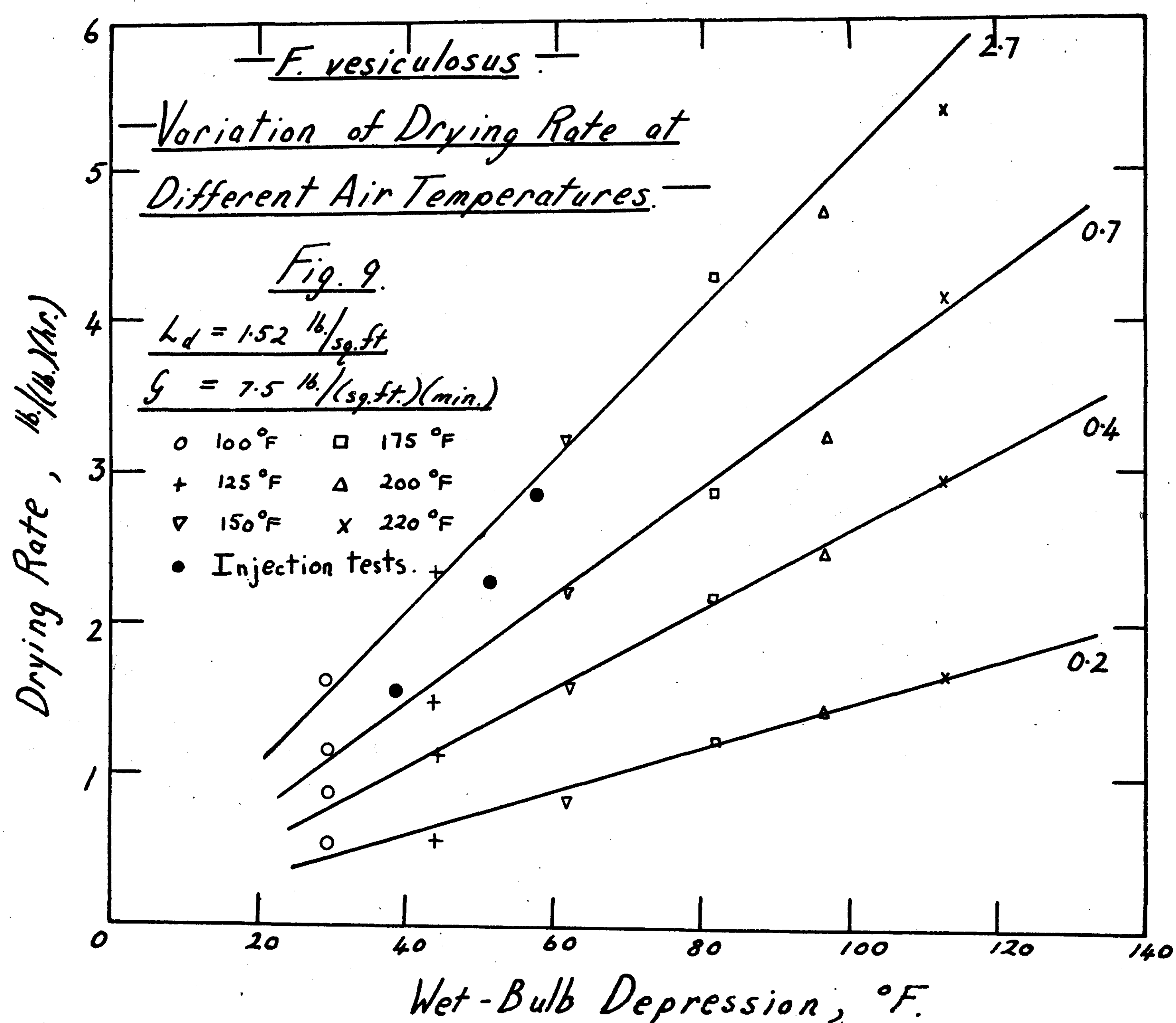
The drying rates versus W.B.D. for F. vesiculosus at average water contents of 2.7 to 0.2 lb./lb., gave a straight-line relationship passing through the origin.

i.e. $dW/d\theta = K(t_d - t_w)$ where K = constant.

Similar results have been found for A.nodosum and F.serratus (See Table 1).

<u>Table I.</u>

Seaweed	T.lb/lb.	L_d lb/sq.ft.	K in equation (for constant drying).
A.nodosum	3.0	1.715	0.04
F. vesiculosus	2.7	1.52	0.05
F.serratus	3.5	1.30	0.066

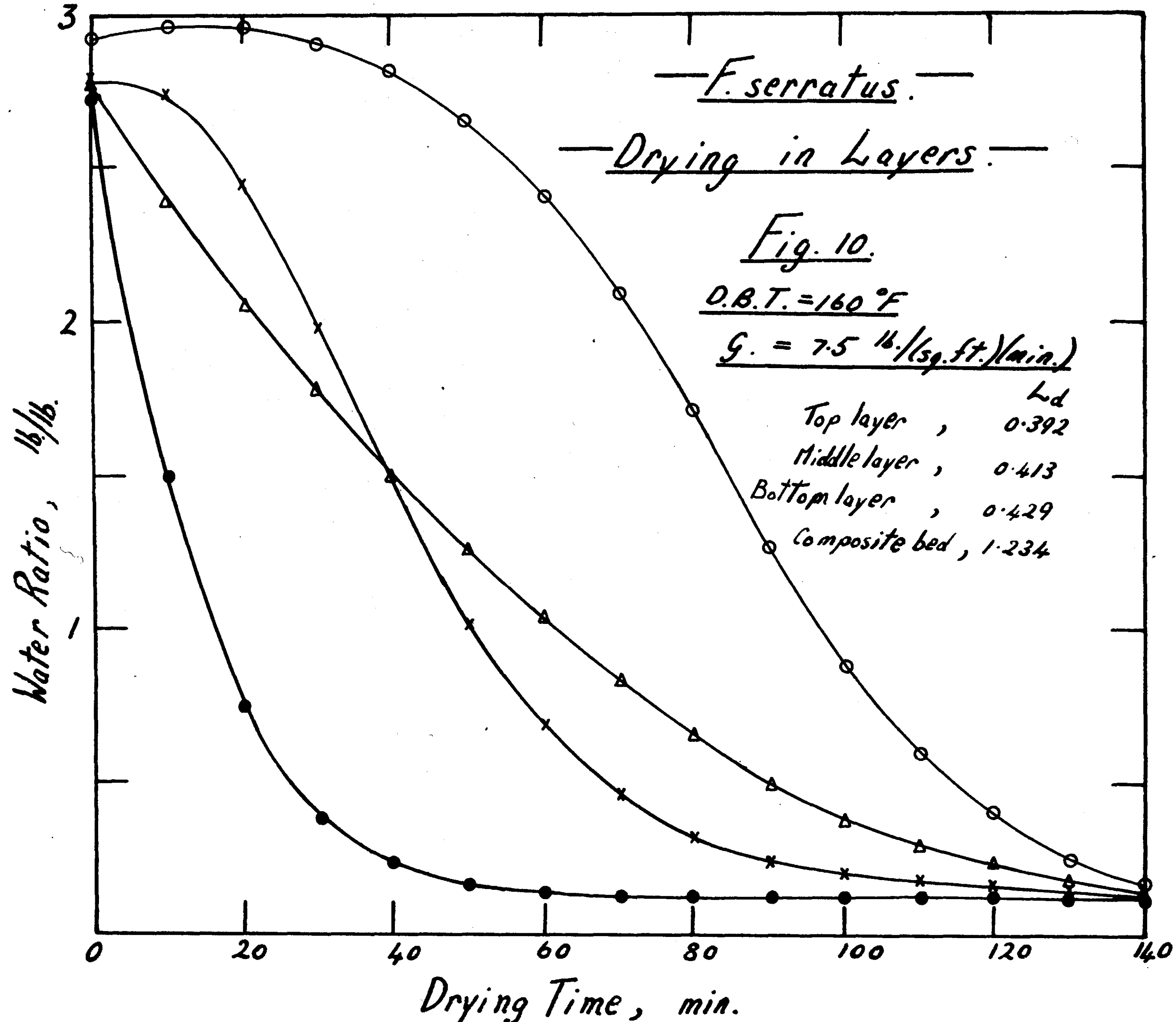

F. vesiculosus
Variation of Drying Rate at
Different Air Temperatures.
Fig. 9.
Ld = 1.52 lb./sq.ft
G = 7.5 lb./(sq.ft.)(min.)
o 100°F
□ 175°F
+ 125°F
Δ 200°F
▽ 150°F
x 220°F
● Injection tests.
2.7
0.7
0.4
0.2
Drying Rate, lb./(lb.)(hr.)
Wet-Bulb Depression, °F.
0
1
2
3
4
5
6
20
40
60
80
100
120
140

Below this range of water contents (0.2 lb/lb.B.D.S.) the D.B.T. becomes increasingly important, as has already been stated, and the W.B.D. will therefore not be directly proportional to the drying rate.

<u>Drying mechanism.</u>

A constant drying-rate period was observed for the bed-depths of above 1 in. This rate is largely governed by the amount of water which the drying air can take up, and this 'water capacity' depends on the degree of saturation of the air. Allerton, Brownell & Katz[54] found that in the drying of filter-cakes, drying took place in a narrow zone of vaporization which gradually moved up through the wet-bed, while Simmonds, Ward & McEwen[2] found that for wheat-grain drying, this zone extended throughout the bed of material. An examination of the layer drying of minced F.serratus (Fig.10) suggests that the zone is deeper than in the case of filter-cake drying, the depth being controlled by the water capacity of the air and its velocity. Fig.10 shows that the water contents varied widely throughout three layers during drying and that maximum deviation occurred at an average of 1.5 (lb/lb) with condensation taking place initially in the upper layer.

Thus it cannot be said that there is a true constant drying rate (Fig.10); rather is there an average maximum rate of evaporation. This rate is maintained constant for the period known as the constant-rate period, by combination of high rates/


—F. serratus.—
—Drying in Layers.—
Fig. 10.
D.B.T. = 160 °F
G. = 7.5 lb./(sq.ft.)(min.)
Ld
Top layer , 0·392
Middle layer , 0·413
Bottom layer , 0·429
Composite bed , 1·234
3
2
1
Water Ratio, lb./lb.
0
20
40
60
80
100
120
140
Drying Time, min.

rates of drying in the lower layers and low rates in the upper layers initially, this being reversed in the latter stages of the period. The falling-rate period commences when the depth of the drying zone begins to decrease on reaching the top of the bed. The drying air is therefore used to a less efficient degree, its exit temperature increasing and its outlet humidity decreasing. Drying is then largely controlled by the rate of internal movement of the moisture to the surface of the material The drying rate of the composite seaweed bed is mainly dependent upon the air dry-bulb temperature and therefore the particle surface temperature. Particle size also controls this rate, and obviously the larger the particles, the longer will the moisture take to move to the surface and the longer will the falling-rate period last.

It must be added that the mucilage content of rock-seaweeds has a great effect on the drying period. It has been found that the weed, on drying, sticks together and prevents ready access of air in certain parts of the bed. This indicates that the agitation of the bed at intervals would be very beneficial to drying, tending to expose fresh surfaces to the air, with consequent shortening of the drying time.

It is evident that the lower layers are dry and are being subjected to the full heat of the incoming air in the latter stages of drying. This is undesirable and in many dryers the flow of air is reversed about midway through the drying process.

Fig II shows a plot of drying rate versus water content characteristic of three seaweeds under investigation. The curve, although for a deep bed of material, is of similar form to typical curves for unit layers, showing the marked change from 'constant-rate' drying to falling-rate drying at a critical value of water content.

In conclusion, it seems that high air-velocities and air temperatures may be used in the initial stages of drying, while the surface of the particles is covered with moisture, and in the falling-rate period lower air-velocities and higher air-temperatures are suitable. Economy of the drying air may be made by agitation of the bed, reversal of the air-flow and recirculation of the air especially in the latter stages of drying when the air has not reached its maximum 'water capacity', on passing through the bed.

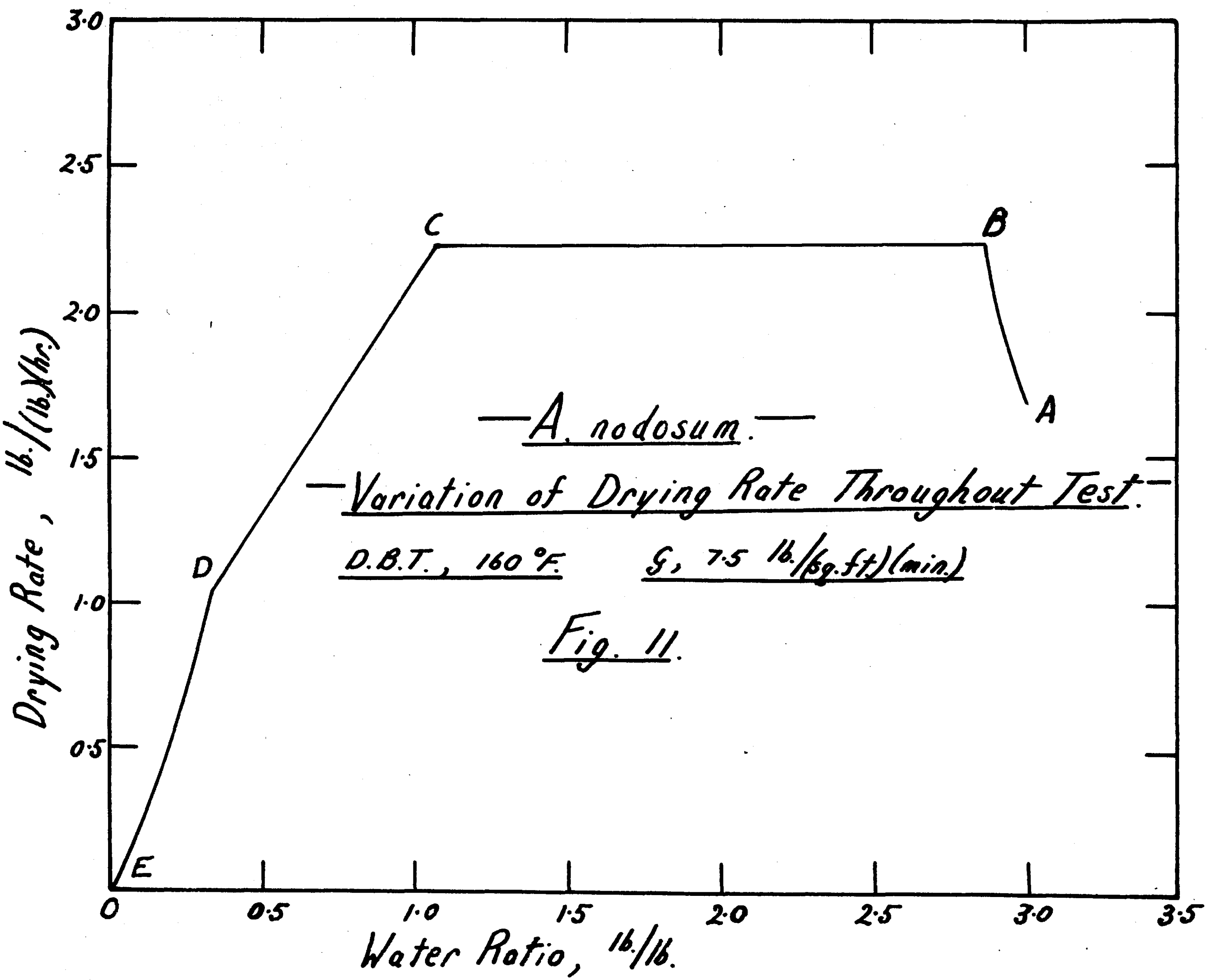
Static pressure tests.

Static pressure-drops across beds of wet and dry seaweed have been measured by Gardner & Mitchell[40].

Similar measurements have been made for A.nodosum, F.serratus and F.vesiculosus. Examples of the linear relationship found by a logarithmic plot of static pressure-drop versus air-flow are shown in Figs.12 and 13. The family of straight lines all have equations of the form:

$$Q = a.G^n$$

where a and n are experimental constants, and Q = pressure-drop in in. of water/ft. of bed-depth.

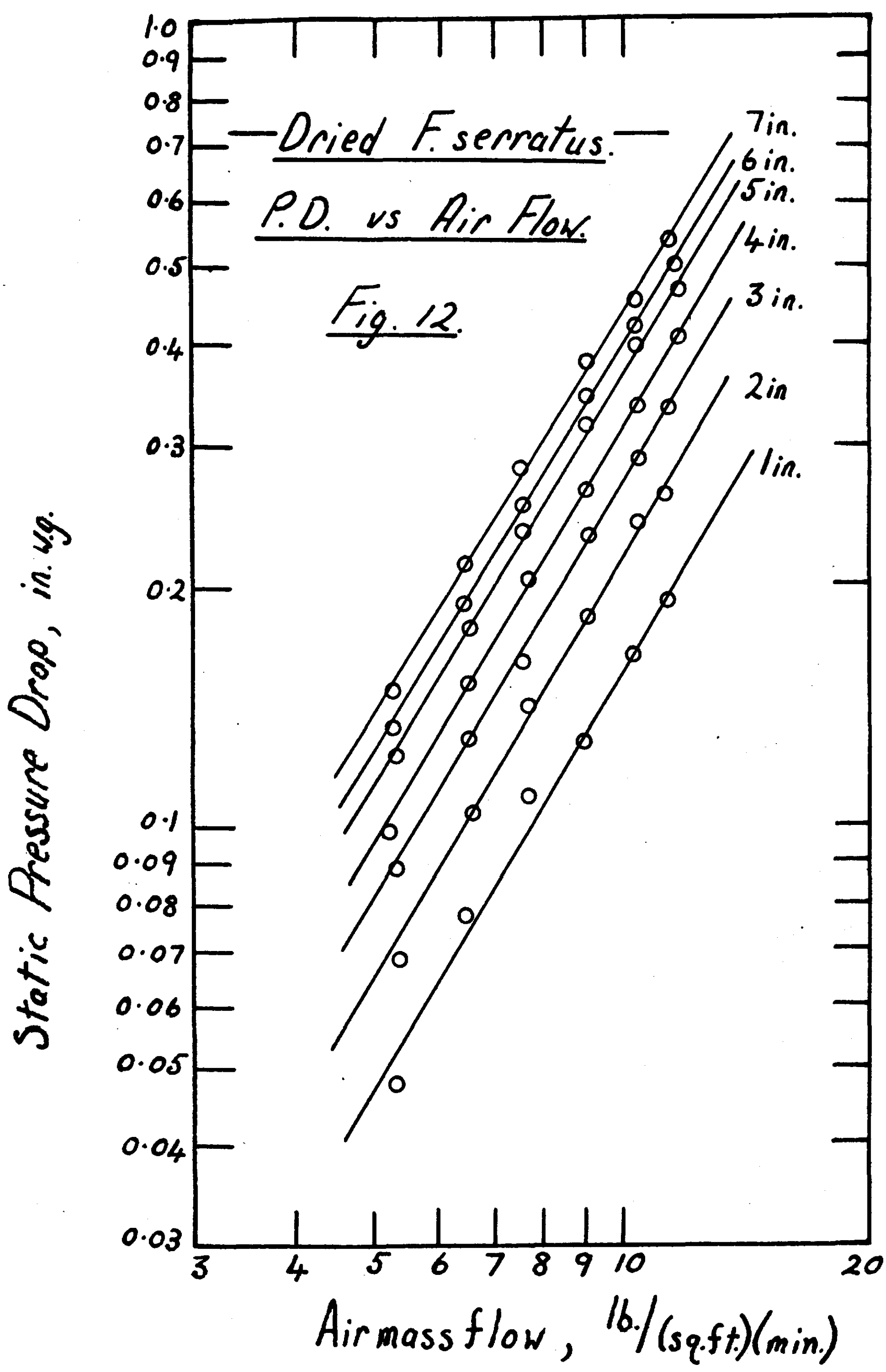


—*A. nodosum.*—

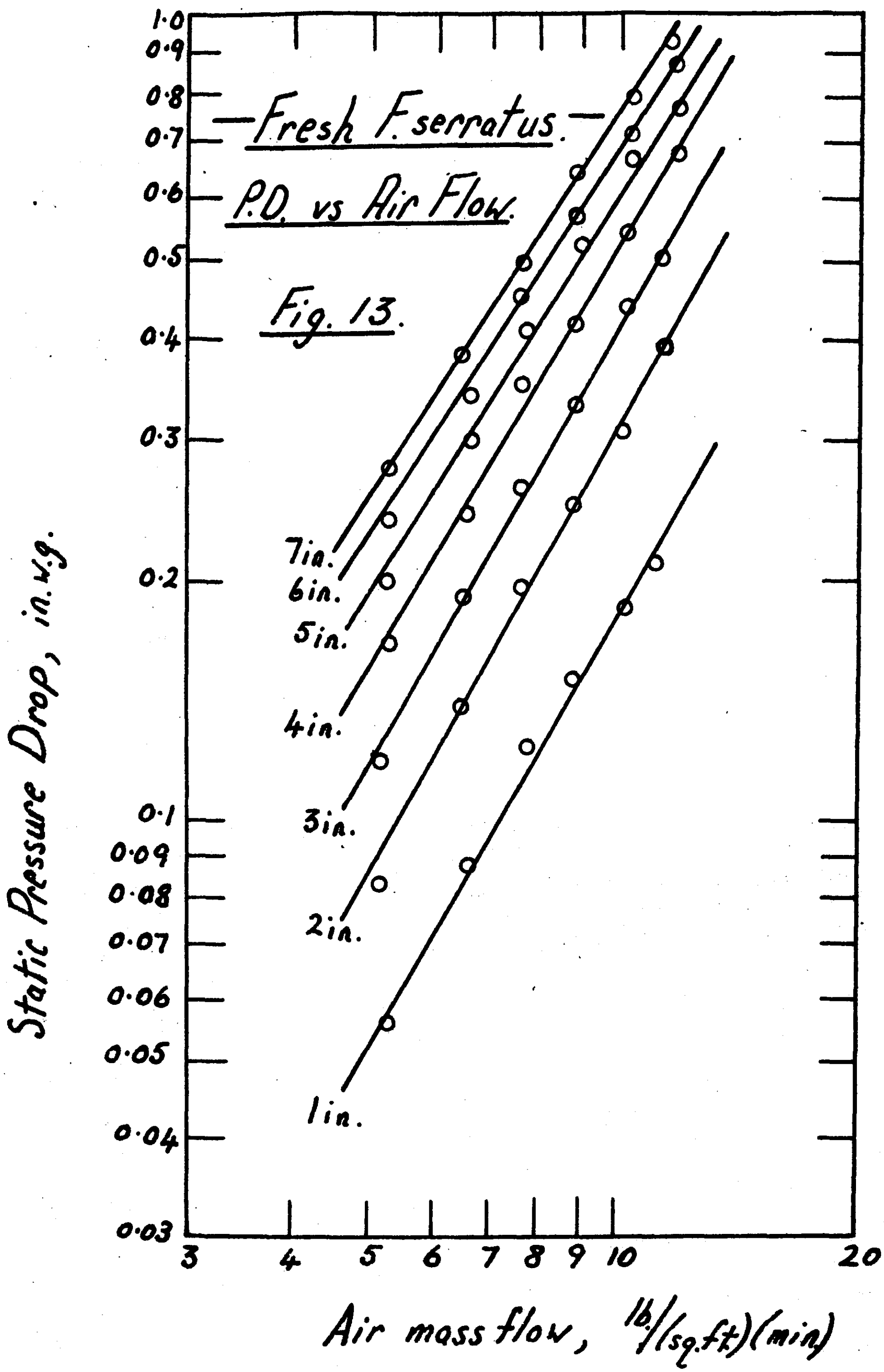
—*Variation of Drying Rate Throughout Test.*—

D.B.T., 160°F. G, 7·5 lb./(sq.ft.)(min.)

Fig. 11.



Dried F. serratus.
P.D. vs Air Flow.
Fig. 12.
7in.
6in.
5in.
4in.
3in.
2in
1in.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
3
4
5
6
7
8
9
10
20
Static Pressure Drop, in. w.g.
Airmass flow, lb./(sq.ft.)(min.)



—Fresh F. serratus.—
P.D. vs Air Flow.
Fig. 13.
Static Pressure Drop, in. w.g.
Air mass flow, lb./(sq.ft.)(min)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
3
4
5
6
7
8
9
10
20
7in.
6in.
5in.
4in.
3in.
2in.
1in.

The velocity index (n) tends to a constant value (approximately 1.8 for both wet and dry minced F.serratus) at the deepest loadings (7 in.), as does the static pressure-drop per unit of bed-depth. The results of these tests can be used in the selection of fans and design of finishing bins.

Equations for pressure-drops for the deepest beds are derived from the average value of the exponents and are:

$$Q = 0.015G^{1.82}, \text{ for dried F.serratus.}$$

and $$Q = 0.030G^{1.81}, \text{ for wet F.serratus.}$$

Prediction of drying times.

The graphical method proposed by Gardner & Mitchell[40] is fairly reliable for rock seaweeds. This method is based on the unit wet-bulb depression curves (Figs.14 and 15) for drying times and rates versus water contents.

Certain optimum values for variables have been found by bed-depth and air-velocity experiments (Table II).

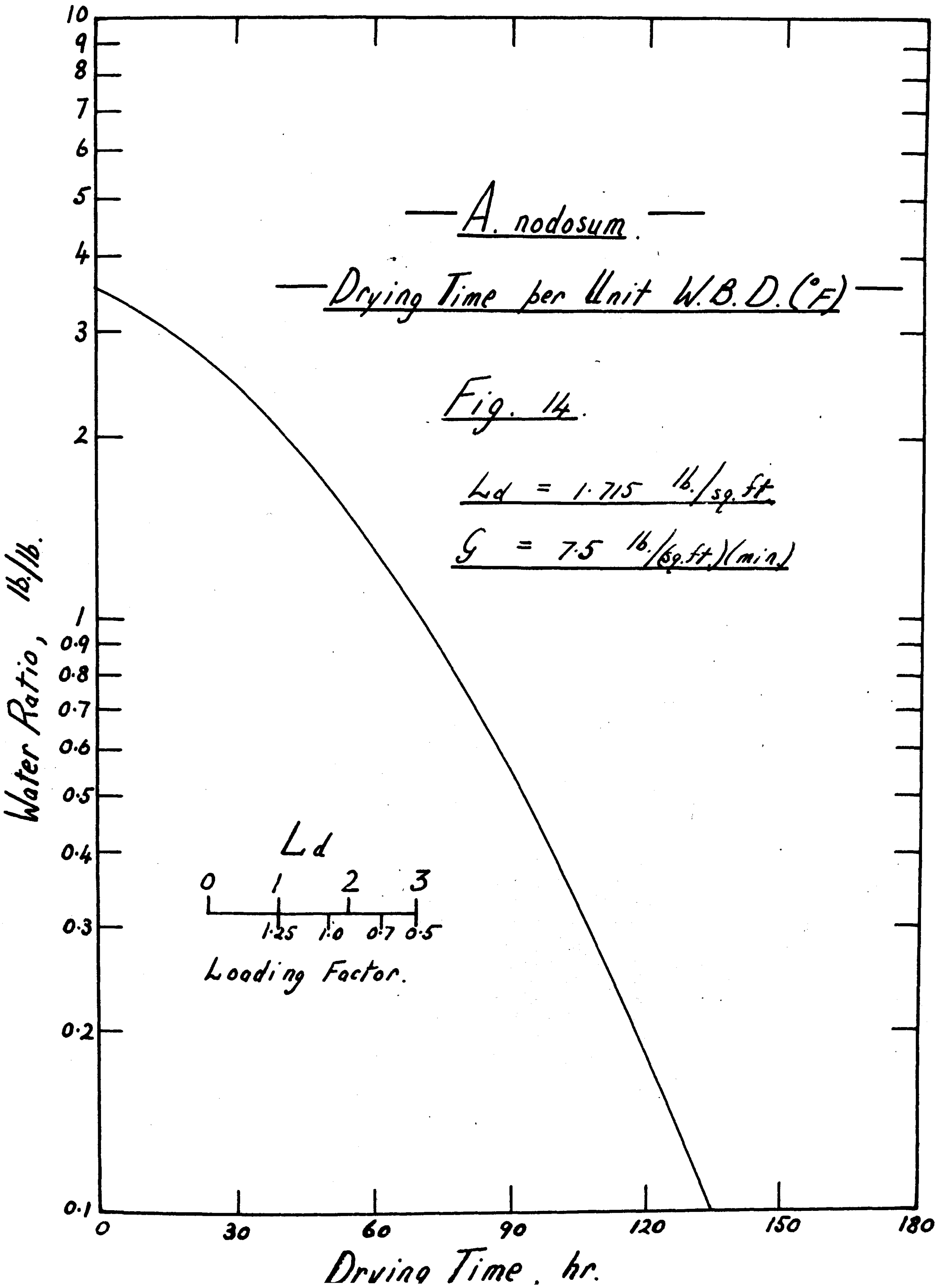
Table II.

Seaweed	Bed-depth in.	Air-flow G.lb/sq.ft./min.
A.nodosum	3.5 (L_d = 2.0)	10
F.vesiculosus	3 (L_d = 1.6)	10
F.serratus	3 (L_d = 1.25)	10

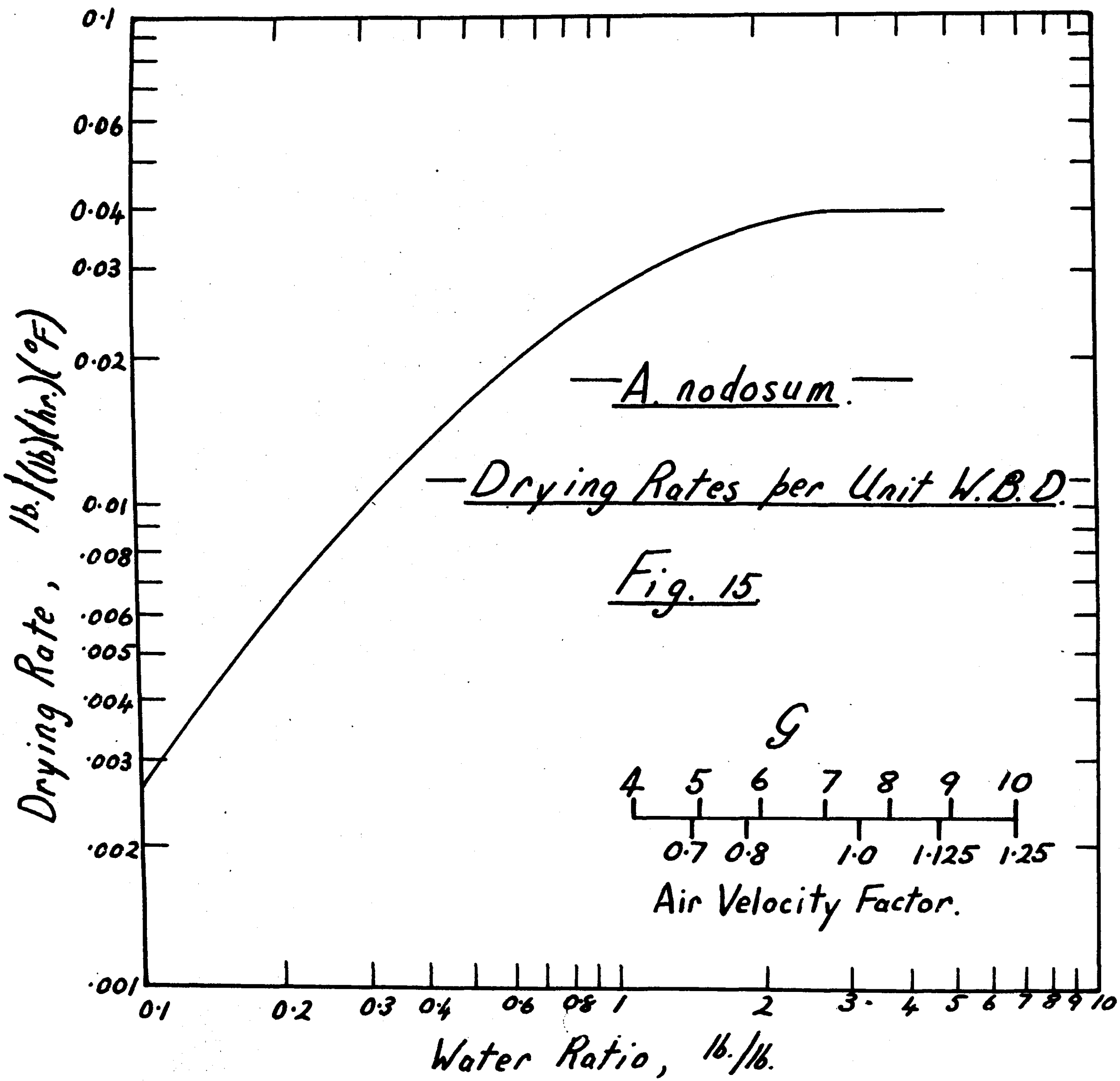
Above a dry-bulb temperature of 225°F, static beds of rock seaweeds are scorched, and temperatures should never exceed this value.

Design of multi-stage through-circulation dryers

for/



— A. nodosum —
— Drying Time per Unit W.B.D. (°F) —
Fig. 14.
Ld = 1.715 lb./sq.ft.
G = 7.5 lb./(sq.ft.)(min.)
Ld
0 1 2 3
1.25 1.0 0.7 0.5
Loading Factor.
Water Ratio, lb./lb.
10 9 8 7 6 5 4 3 2 1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1
0 30 60 90 120 150 180
Drying Time, hr.


-A. nodosum.-
-Drying Rates per Unit W.B.D.-
Fig. 15.
0·1
0·06
0·04
0·03
0·02
0·01
·008
·006
·005
·004
·003
·002
·001
Drying Rate, lb./(lb.)(hr.)(°F)
0·1
0·2
0·3
0·4
0·6
0·8
1
2
3
4
5
6
7
8
9
10
Water Ratio, lb./lb.
G
4
5
6
7
8
9
10
0·7
0·8
1·0
1·125
1·25
Air Velocity Factor.

for A.nodosum, F.vesiculosus and F.serratus can therefore be made on the principles laid down by Gardner & Mitchell. Shrinkage and edge effects are thought to be negligible, where wide conveyor belts are in use, while deepening of the beds on completion of shrinkage (at approx. T = 1.5) should be economic, since better use is made of the drying air.

S E C T I O N IV.

EXPERIMENTAL WORK.

Through-circulation drying of brewers' spent grain.

Introduction:

Brewers' spent grain is the waste material remaining from the brewing process. It contains 75 to 80% water as received from the brewery, and has a percentage composition, on a dry basis of :- oil 4.7; protein 18.6; fibre 20; carbohydrate 52.2; ash 4.5. The material is widely used as cattle fodder, because of its fairly high protein content. The disadvantages are two-fold: (1) The seasonal demand, (2) the instability of the wet material, with subsequent decay.

Several methods of preservation are available[68], including the exclusion of air, the addition of common salt, pH control by treatment with HCl, or drying. Of these four method drying appears to offer the most positive protection, besides the advantage of aiding transport. The removal of about 30% of the water by centrifuging is possible, but would increase capital charges.

Summary of Previous Work on Grain Drying.

Although there has been recent work on the drying of grain[56,69,70], there is little published work on the drying of brewers' spent grain. Simmonds, Ward and McEwen[45] have investigated the drying of wheatgrain and have postulated a method for approximate prediction of drying times, besides giving comprehensive data on the effect of a wide range of variables on drying rates.

Test Procedure.

The/

The fan was started, adjusted to give the correct air flow, the heaters switched on and conditions allowed to stabilise at the desired temperature. The correct amount of mixed and cooled spent grain was weighed into the basket, which was then inserted in the drier. The initial static pressure was noted and the inlet and exit temperatures checked. Uniform air flow was maintained by regular adjustment of the fan speed, since bed resistance decreased giving greater air flow as drying proceeded. The basket was weighed every 5 min. until the loss of weight in consecutive time intervals was less than 0.005 lb. The dried material was sampled at the centre and corners of the bed, finely ground, and the loss in weight taken after 6 hours of drying at 60°C under 29.5 in. vacuum.

Shallow Bed Tests.

In through circulation work on the drying of deep beds of material, the behaviour of the individual pieces is not apparent owing to the variation of temperature and humidity at different points throughout the bed. The difficulties of drying an individual piece, because of its small size, are:-

(1) Accurate measurement of moisture removal, especially at low moisutre ratios.

(2) Choice of an individual piece as representative of the whole bulk.

If/

If, however, a shallow layer is dried, the drying characteristics of the individual pieces can be observed and the above difficulties are eliminated. Hence, tests were conducted on brewers' spent grain on beds one-quarter of an inch in depth, in order to study the behaviour of the separate particles during drying.

Effect of Varying Velocity Temperature = 160°F. G = 6.63 to 22.2.

The effect of varying the velocity of the drying air through a shallow layer is not generally great, and the effect must be contrasted sharply with its influence in deep beds. In the initial stages and in particular where there is much surface moisture, the rate of drying in deep beds depends largely on the drying capacity of the air. Obviously, if the velocity and hence the volume of the air is increased, then the rate of drying will increase. In the drying of shallow layers the effect of increasing the air velocity is to increase the drying rate for an initial short period by removing any surface moisture more rapidly. The increase of air velocity also aids the transfer of sensible heat to the material. In materials where most of the moisture is internally bound, the effect of air velocity is not great (Wheatgrain; peas) but with brewers' grain, where there is a large percentage of surface moisture and the remaining moisture diffuses readily, a distinct difference in drying rate should take place with variation in air flow. For the four air velocities studied/

Zonal Drying.

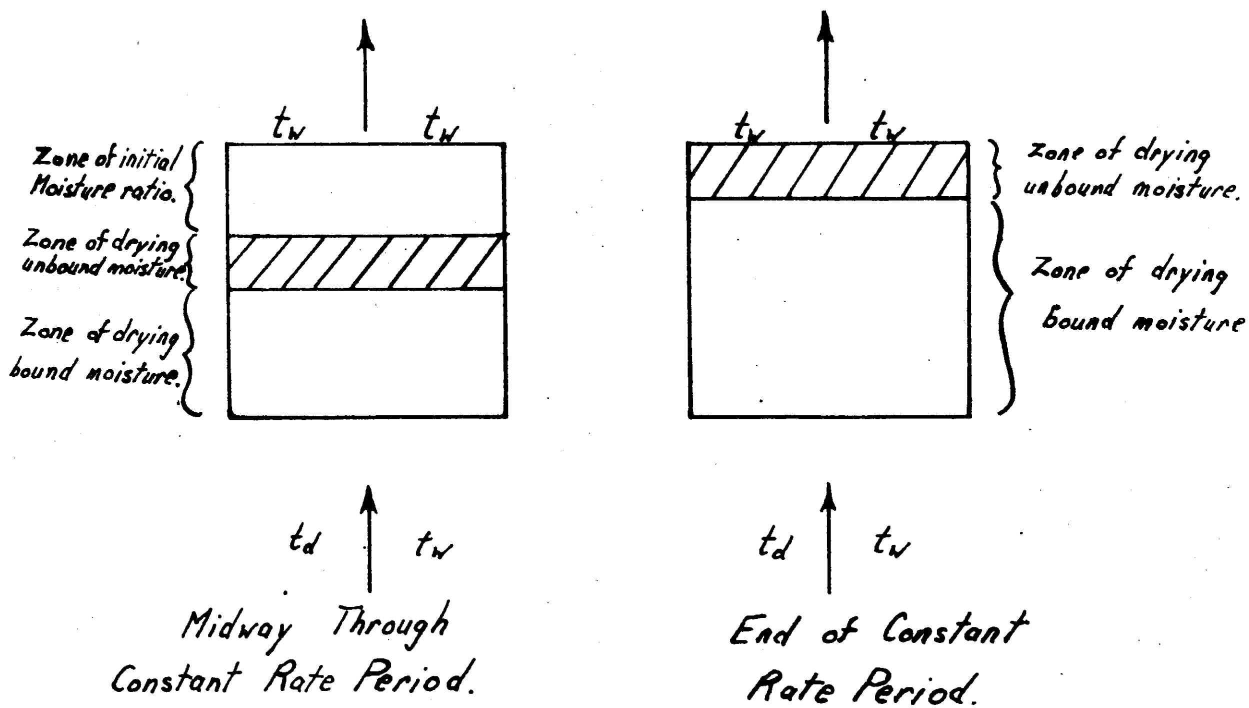


Fig. 1.

studied, variation in the time of drying was considerable between 86 and 288 ft./min. However, an increase of air flow from 218 to 288 ft./min. resulted in only a very small decrease in drying time, suggesting that some limiting velocity is being approached above which no significant decrease in drying time will be obtained by a positive change of air flow. Also, at the highest air velocity, "spouting" of parts of the bed took place, resulting in blowholes which allowed some of the air to short circuit the bed resulting in slight increase of drying time

A semi-logarithmic plot of water ratio (T) VS time of drying resulted in a straight line over almost the whole test, apart from a short building-up period and a tailing-off period. The value of the gradient of the straight line (-m) increased with increase of air flow (Fig.11).

<u>Effect of Varying Temperature.</u>

A series of runs was made at constant air flow and varying drying temperatures. (G = 11.4 lb.d.c./(sq.ft.)(min) and Temp. = 100 - 220°F). The tests were completed when the ambient air humidity remained almost constant. Straight line plots were obtained from log T vs. Time in drier, and the slope of these lines varied significantly with temperature. (Figs. 111 and 1V).

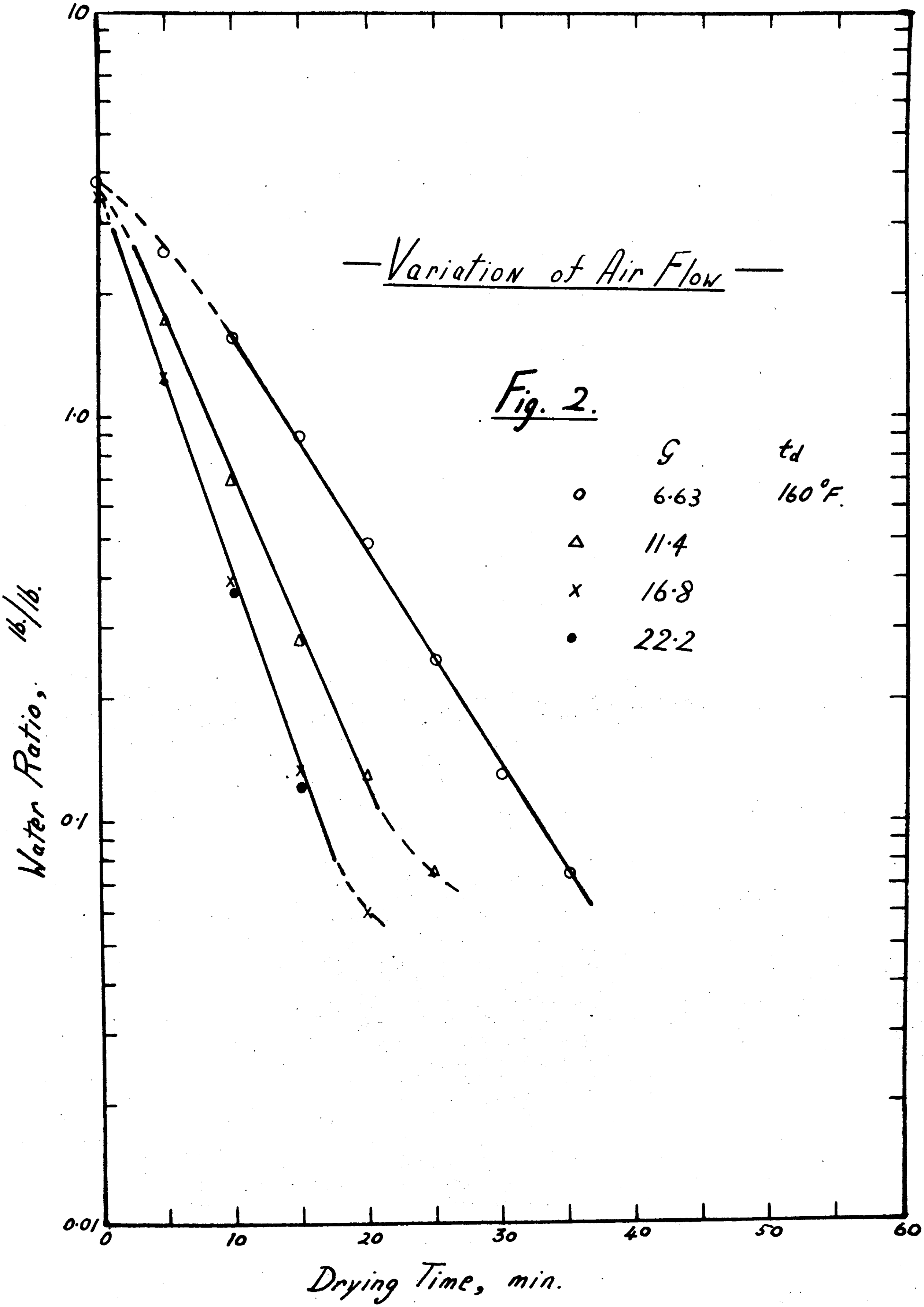
<u>Prediction of Drying Times.</u>

From a plot of log T vs. θ,

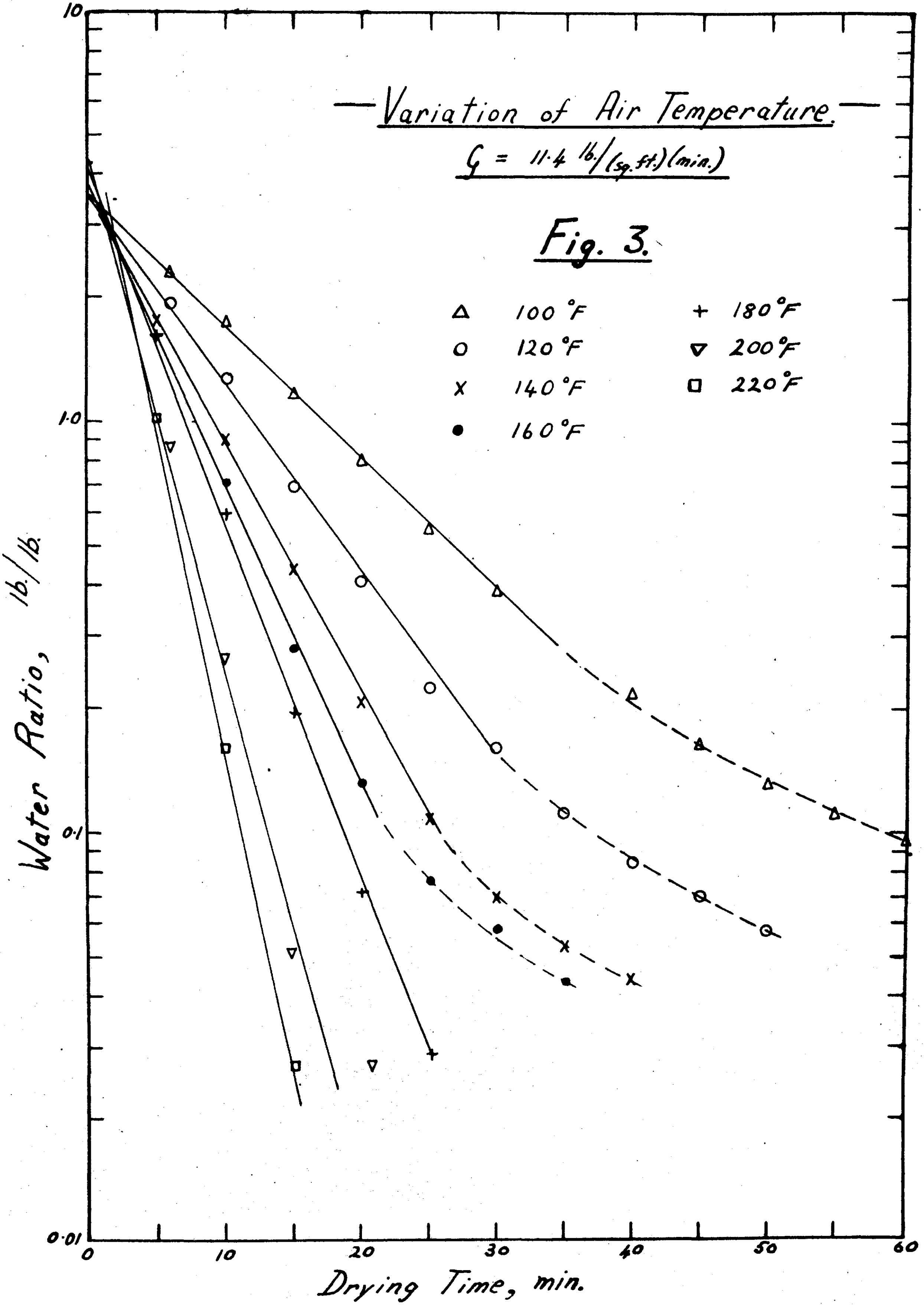
$$\log_e T = -m\theta + k$$

$$(\text{A t}, \theta = 0, T = T_e) \quad \log_e \frac{T}{T_o} = -m\theta$$

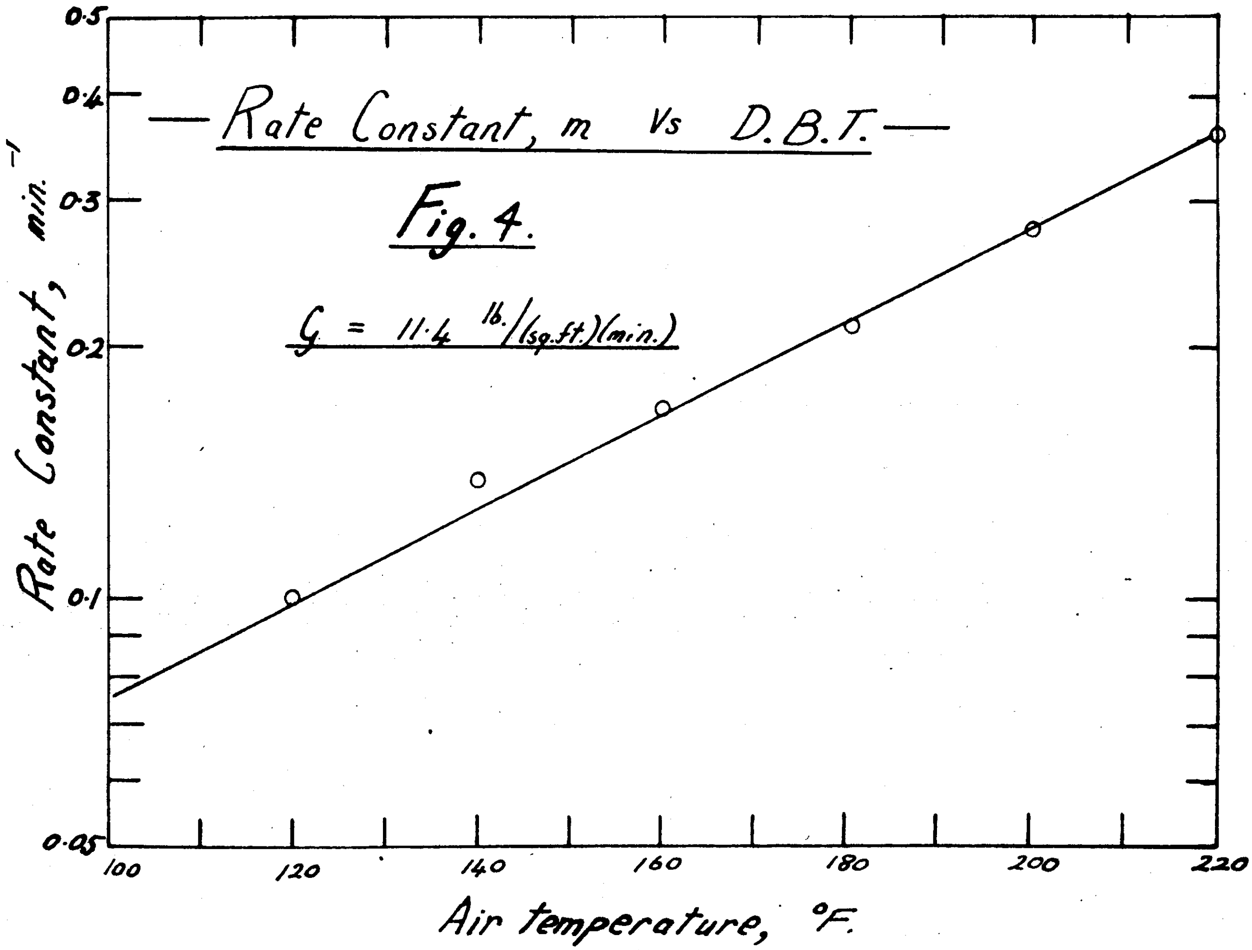
$$\text{or } \theta = \frac{1}{m} \log_e \frac{T_o}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

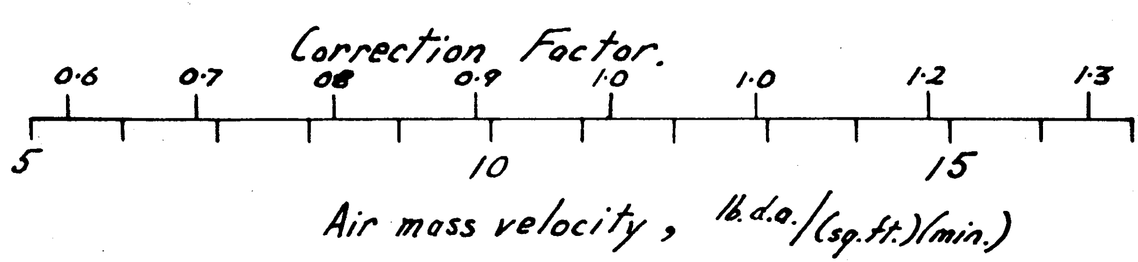


—Variation of Air Flow—
Fig. 2.
G
td
o 6·63 160°F.
Δ 11·4
x 16·8
• 22·2
10
1·0
0·1
0·01
Water Ratio, lb./lb.
0
10
20
30
40
50
60
Drying Time, min.



Variation of Air Temperature.
G = 11.4 lb./(sq. ft.)(min.)
Fig. 3.
100 °F
120 °F
140 °F
160 °F
180 °F
200 °F
220 °F
10
1.0
0.1
0.01
Water Ratio, lb./lb.
0
10
20
30
40
50
60
Drying Time, min.


Rate Constant, m Vs D.B.T.
Fig. 4.
G = 11·4 lb./(sq.ft.)(min.)
Rate Constant, min.⁻¹
0·5
0·4
0·3
0·2
0·1
0·05
100
120
140
160
180
200
220
Air temperature, °F.


Correction Factor.
0·6
0·7
0·8
0·9
1·0
1·0
1·2
1·3
5
10
15
Air mass velocity, lb.d.a./(sq.ft.)(min.)

Hence, as found by Simmonds et al.[45], the drying time of a single layer is given by a simple expression relating time (θ) to the moisture content limits (T_e and T) and a rate constant (m) which can be correlated with temperature, with a slight adjustment for the effect of air flow. This correlation differs from that of Simmonds et al. only in that it is based on total moisture content instead of free moisture content (i.e., total minus terminal moisture content). The marked similarity in the equation is interesting in face of the very different characteristics of the materials (cf. wheat grain and brewers' spent grain). The work on wheat grain is the only strictly comparable work to be found in the literature although such types of relationship are cited[39] for the drying of deep beds in the falling-rate periods. Treybal[71] developed a simple equation for the drying time in the falling rate period, assuming that drying rate was proportional to moisture content throughout the constant rate period. Attempts to relate rate of drying in the falling rate period in terms of heat and mass transfer coefficients have met with limited success, owing to the change of internal resistances during drying. For the same reason studies involving the use of a diffusivity or concentration term have resulted in unwieldy mathematical solutions, too complex for use in the drying of small pieces of material where three directional diffusion takes place.

The/

The more empirical approach to the present problem presents a brief, practical solution, with a good degree of accuracy. The value of m can be read at the desired temperature (Fig.IV) and adjusted for the different air flow value. This value may then be substituted in the equn. (I) and the drying time calculated between the desired moisture ratios.

Deep Bed Tests.

These tests were carried out mainly with spent grain produced from the brewing of Ale or Beer. Four variables were studied, namely, loading, air velocity, temperature, and the degree of agitation of the composite bed. Any complete investigation would involve an extremely large number of tests and it is therefore usual to choose carefully the tests to be carried out and to set them at an optimum. It is customary to assume that if a variation in drying rate takes place at a certain loading and temperature with two different air velocities, then an almost proportional variation will result with the same air velocities but at a different loading and temperature. Without such assumptions as this many more investigations would be necessary with resultant complications and perhaps little less increase in the accuracy of the final solution. With this in mind, "standard" values of each of the variables were chosen:-Loading,(Ld) = 4 in. Bed depth = 2.17 lb.B.D.S./sq.ft.

Temperature/

Temperature, (td) = 160°F.

Air velocity, (g) = 0.5 in.w.g. = 7.66 lb.d.a./(sq.ft.)(min.)

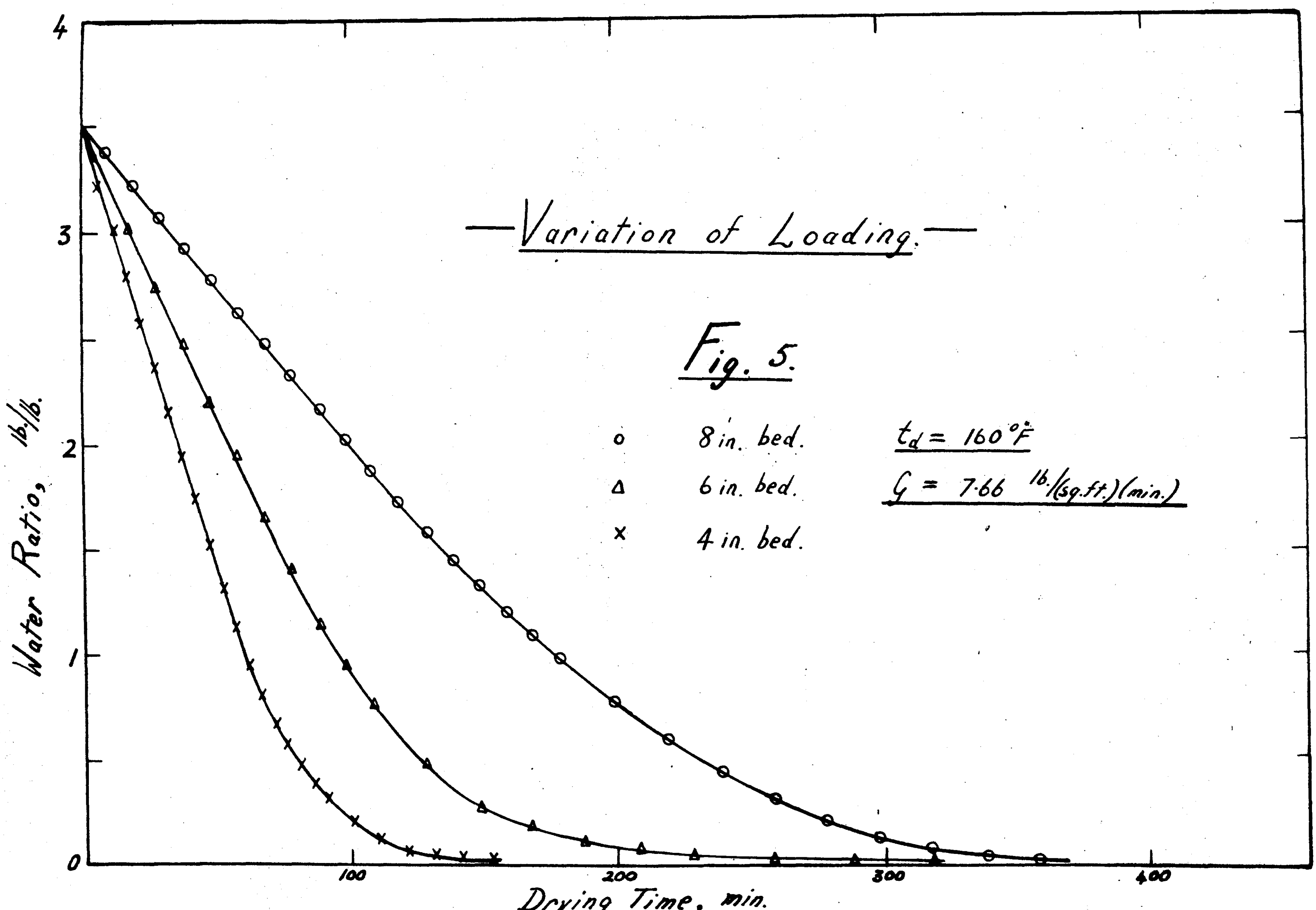
Normally agitation was not used, and tests were carried out by maintaining two of the variables at the above values and varying the third.

Effect of Varying Loading. (Fig. 5 and Fig. 6)

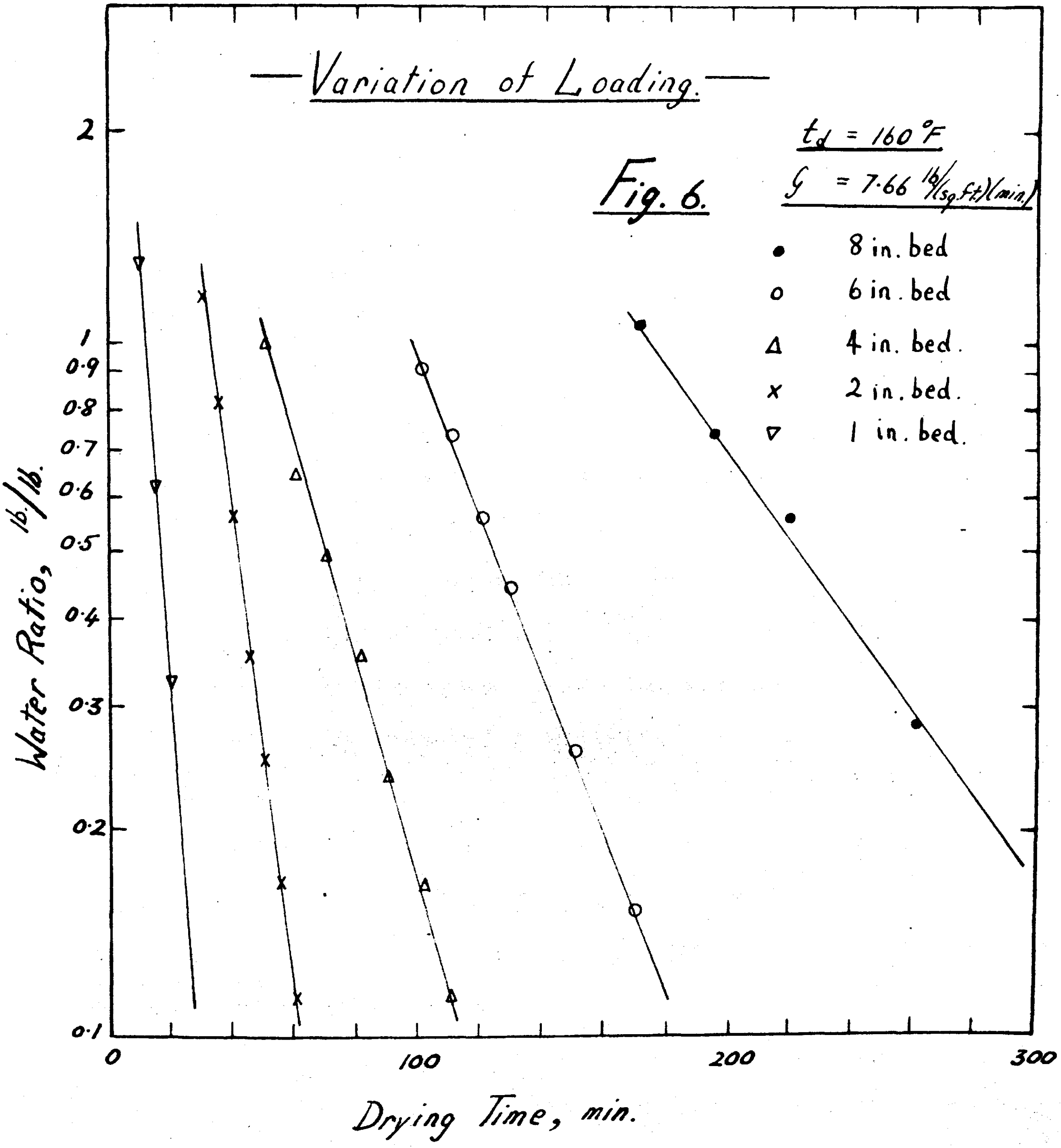
Temperature = 160°F G = 7.66 lb.d.a./(Sq.ft.)(min).

Bed Depths = 1 in., 2 in., 3 in., 4 in., 6 in., 8 in.

Two bases, dry loading (lb.B.D.S./sq.ft.) or bed depth (in.) were available in the loading trials. Both were used to some extent, and although the former is the more precise term, it was found that with any variation in initial moisture content it was difficult to obtain constant dry loadings by maintaining the initial wet loading constant. It was found, however, that a reasonably good relationship held between bed depth and dry loading, and that 1 in. bed depth = 1.95 lb.B.D.S./sq.ft. The bed dried out and normally shrunk from the basket sides to form a composite structure, up to a bed depth of six inches. Above this value there is evidence of ready collapse of the bed, and of course in the agitation tests the bed structure is completely broken down. Plots of moisture content versus time of drying are shown in graphs and these graphs have been related to an initial moisture content of 3.5 for clearer illustration of drying rate variations. The normal constant and falling rate drying portions are/



—Variation of Loading.—
Fig. 5.
o 8 in. bed.
Δ 6 in. bed.
x 4 in. bed.
t_d = 160°F
G = 7·66 lb./(sq.ft.)(min.)
Water Ratio, lb./lb.
Drying Time, min.
0
1
2
3
4
100
200
300
400



—Variation of Loading.—
t_d = 160 °F
G = 7.66 lb/(sq.ft)(min)
Fig. 6.
8 in. bed
6 in. bed
4 in. bed.
2 in. bed.
1 in. bed.
Water Ratio, lb./lb.
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
Drying Time, min.

are evident on examination of the curves. The constant drying rate varied with loading according to the equation

Fig. 8: $$\left(\frac{\partial T}{\partial \theta}\right) = 5.41 \; Ld^{-1} \quad \ldots\ldots\ldots\ldots \quad (2)$$

A straight line relationship was found for the falling rate period of the type:- $\log_e T = -m\theta + C$, in the region of moisture content 1.6 to 1.0 down to 1.6 to 0.08. The values of the constan m have been plotted against Ld, and are indicated in Fig.7 by:-

$$-m = 0.0303 \; Ld^{-1} \quad \ldots\ldots\ldots\ldots \quad (3)$$

this equation is only relevant to a temperature (td) of 160°F and an air mass flow (G) of 7.65 lb. d.a./(sq.ft.)(min.).

Now, having found a relation for the constant drying rate and the falling rate with variation of loading, if correctio for temperature, air velocity and agitation can be made then a possible method of prediction of drying rates and times can be obtained, for a given set of drying conditions. The tests on these other variables were therefore conducted for this purpose.

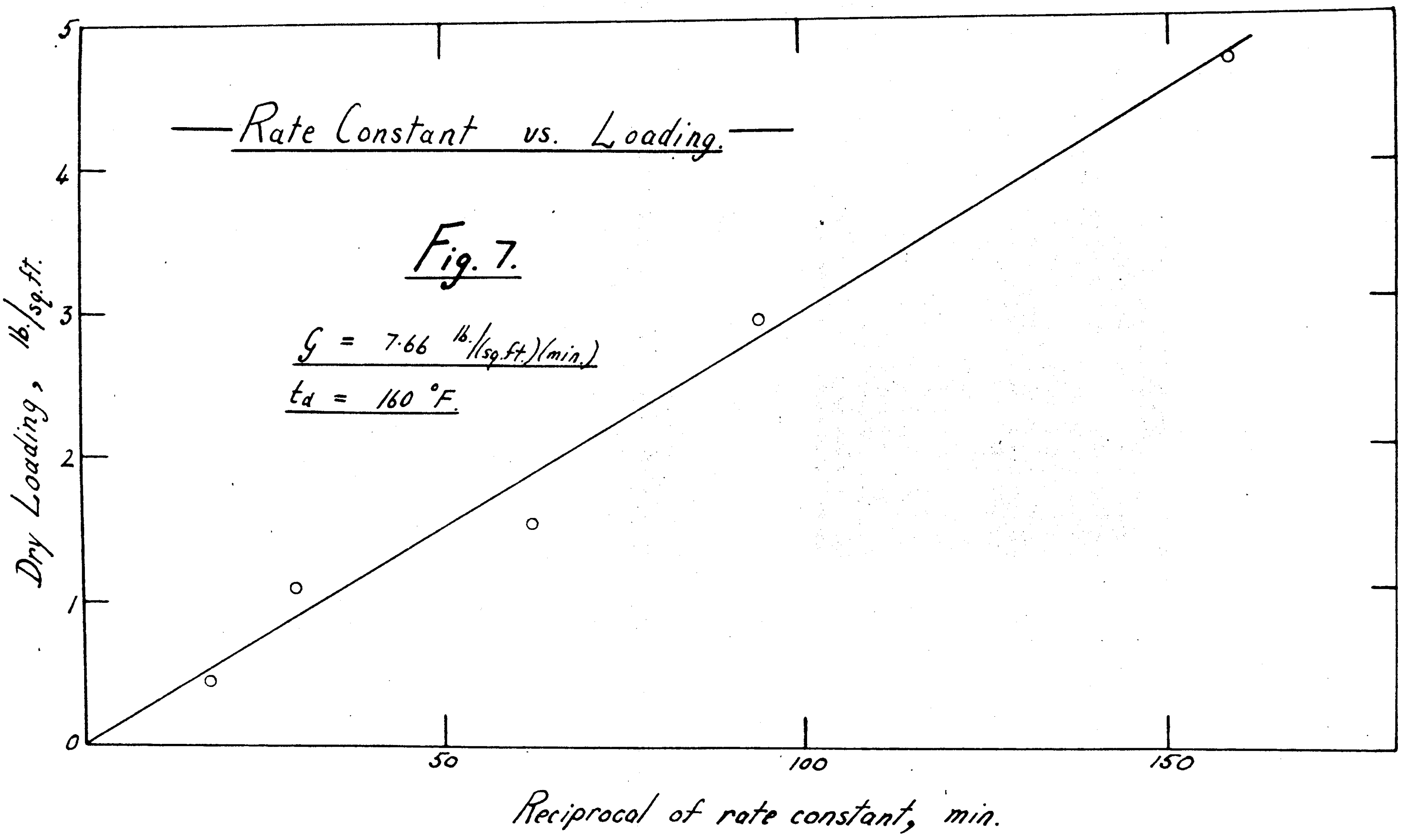
<u>Effect of Varying Temperature</u>.

Bed Depth = 4 in. G = 7.66 lb.d.a./(sq.ft.)(min.)

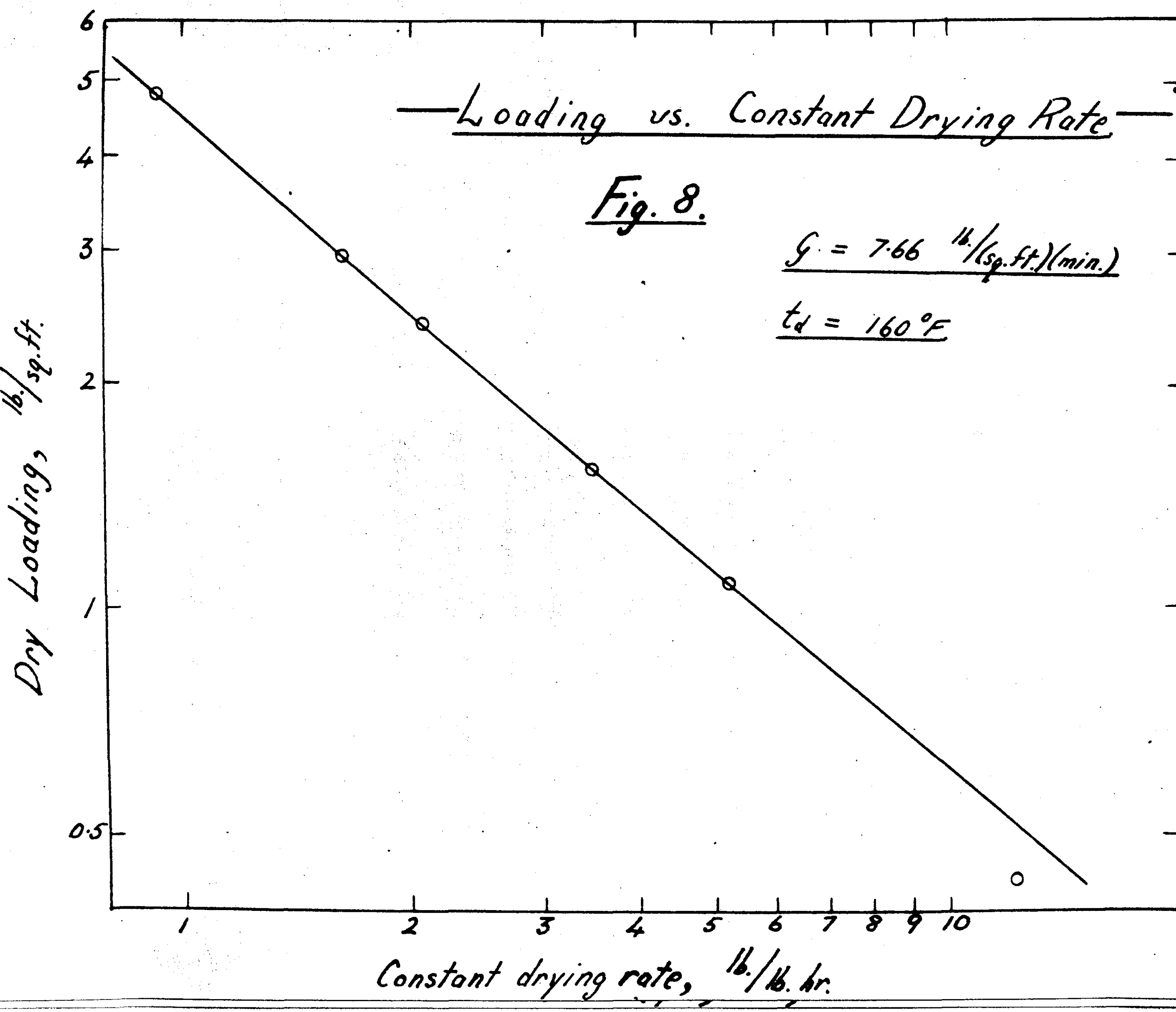
Temperatures (td) = 120, 140, 160, 180, 200, 220°F.

The upper limit of temperature (220°F) was set by the tendency of the grain to char above this, the lower limit by the prolonged drying time.

Plots of moisture content versus time were of similar form to those of the loading tests, exhibiting the same type of relationship/



Rate Constant vs. Loading.
Fig. 7.
G = 7.66 lb./(sq.ft.)(min.)
td = 160 °F.
Dry Loading, lb./sq.ft.
Reciprocal of rate constant, min.
0
1
2
3
4
5
50
100
150


—Loading vs. Constant Drying Rate—
Fig. 8.
G = 7·66 lb./(sq.ft.)(min.)
td = 160°F
6
5
4
3
2
1
0·5
1
2
3
4
5
6
7
8
9
10
Dry Loading, lb./sq.ft.
Constant drying rate, lb./lb. hr.

relationship.

Constant drying rate varied with temperature as in Fig.9, and

$$(\frac{\partial T}{\partial \theta}) = 0.028\,td - 1.97 \quad \ldots\ldots(4)$$

In the calculation of the constant drying rate values from the experimental readings, it was assumed that the relation $(\frac{\partial T}{\partial \theta})_c$ Ld = Constant, held at all test temperatures. The corrections for slight variations in loadings thus took the form:-

$$(\frac{\partial T}{\partial \theta})_s = \frac{(\frac{\partial T}{\partial \theta})_e \cdot Ld_e}{Ld_s} \quad \ldots\ldots(5)$$

Plots of the drying time in the falling rate period versus logarithm of the moisture content showed linear relationships, the variation in $\bar{m}$ being related to temperature as follows:-

(Fig.10) $$\log_{10}(\bar{m}) = (0.00664\,td + 0.560) \quad \ldots\ldots(6)$$

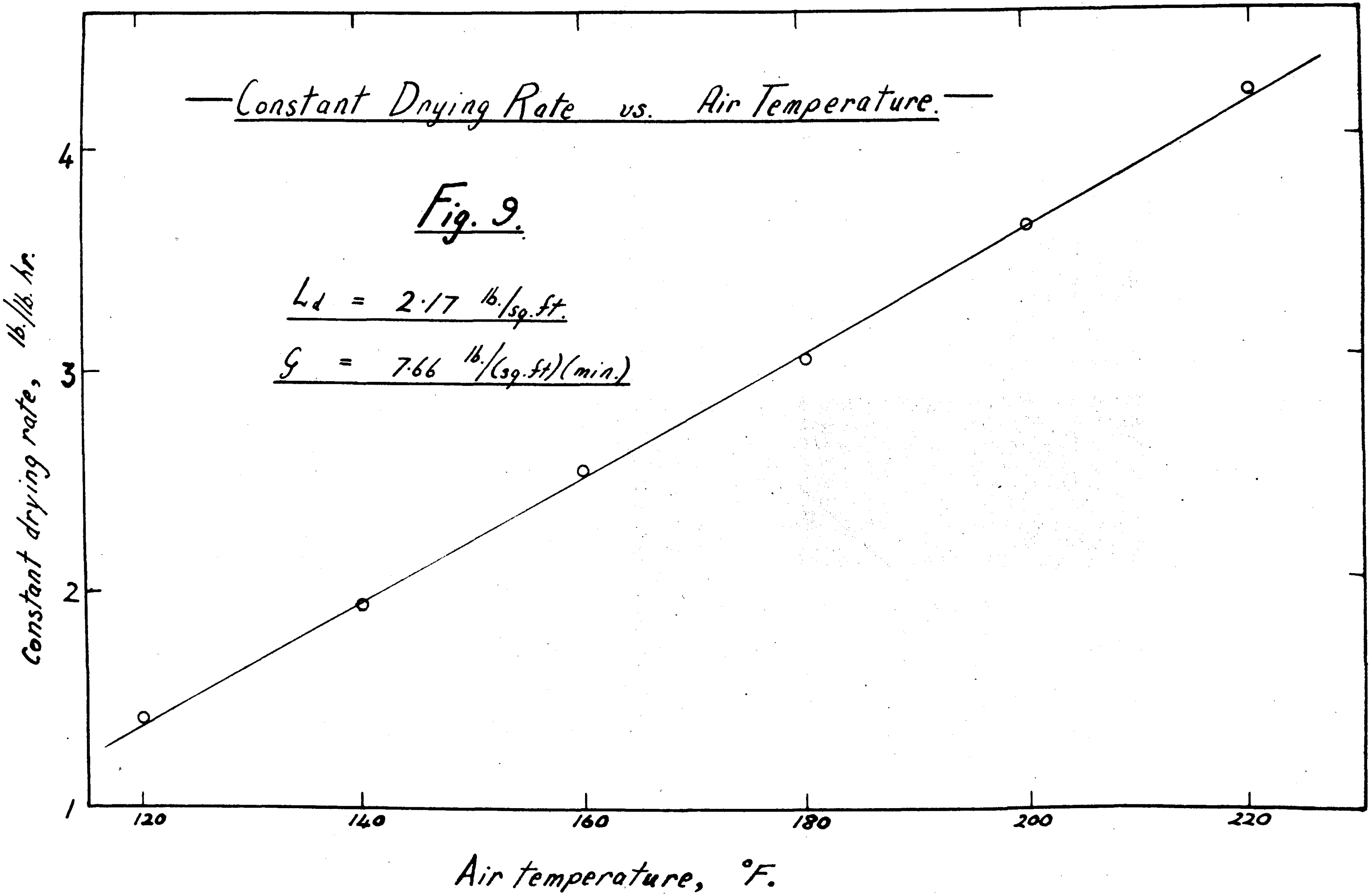
The inlet absolute humidity throughout the tests remained at an almost constant value of .0096 lb.water/lb.dry air, and experimental variations in the loading were less than ± 1% from the standard value.

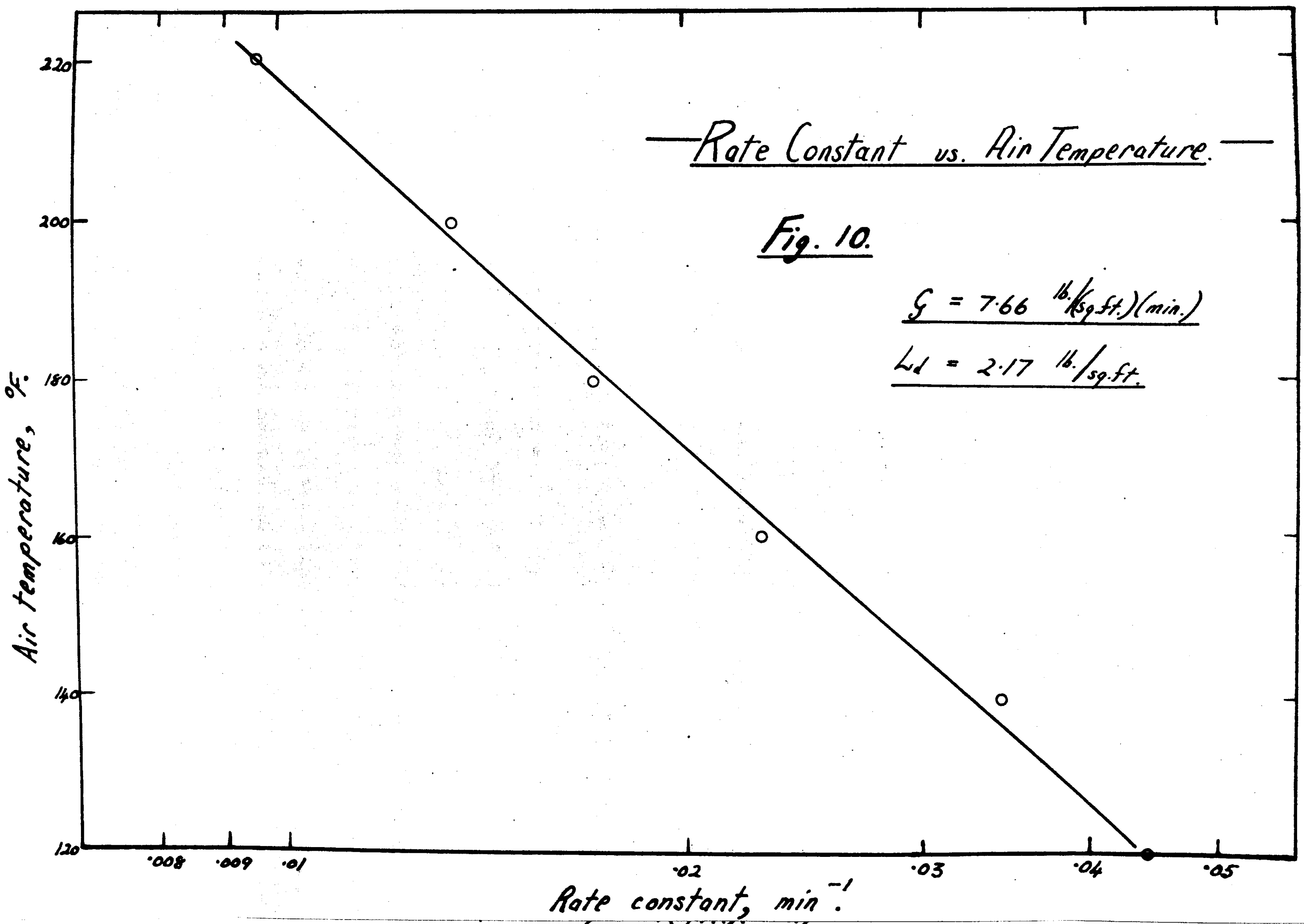
<u>Effect of Varying Velocity.</u>

Bed Depth = 4 in. Temperature = 160°F

G = 5.86,7.66,9.32,10.75,13.17 lb.dry air/(sq.ft.)(min)

The lowest value of air flow was limited by the speed control of the fan and the highest was set by the bed stability. Above the highest value, at low moisture contents the bed developed blowholes and also was more sensitive resulting in collapse of the semi/


Constant Drying Rate vs. Air Temperature.
Fig. 9.
Ld = 2·17 lb./sq.ft.
G = 7·66 lb./(sq.ft)(min.)
Constant drying rate, lb./lb. hr.
1
2
3
4
120
140
160
180
200
220
Air temperature, °F.



Rate Constant vs. Air Temperature.
Fig. 10.
G = 7·66 lb./(sq.ft.)(min.)
Ld = 2·17 lb./sq.ft.
Air temperature, °F.
220
200
180
160
140
120
·008
·009
·01
·02
·03
·04
·05
Rate constant, min.⁻¹

semi-rigid structure if subjected to a slight mechanical shock.

Values of the constant drying rate were plotted against air mass flow, and as theoretically proved, was directly proportional to the flow:-

From Fig.12 $$\left(\frac{\partial T}{\partial \theta}\right)_c = 0.350\ G \qquad (7)$$

The rate constant $\bar{\bar{m}}$ was related to G:-

From Fig.11 $$\bar{\bar{m}} = 0.00175G + 0.00610 \qquad (8)$$

Again, the absolute humidity at inlet was constant, and the variation in loading was small, although values of $\left(\frac{\partial T}{\partial \theta}\right)$ and $\bar{\bar{m}}$ were corrected for slight variation in the loading.

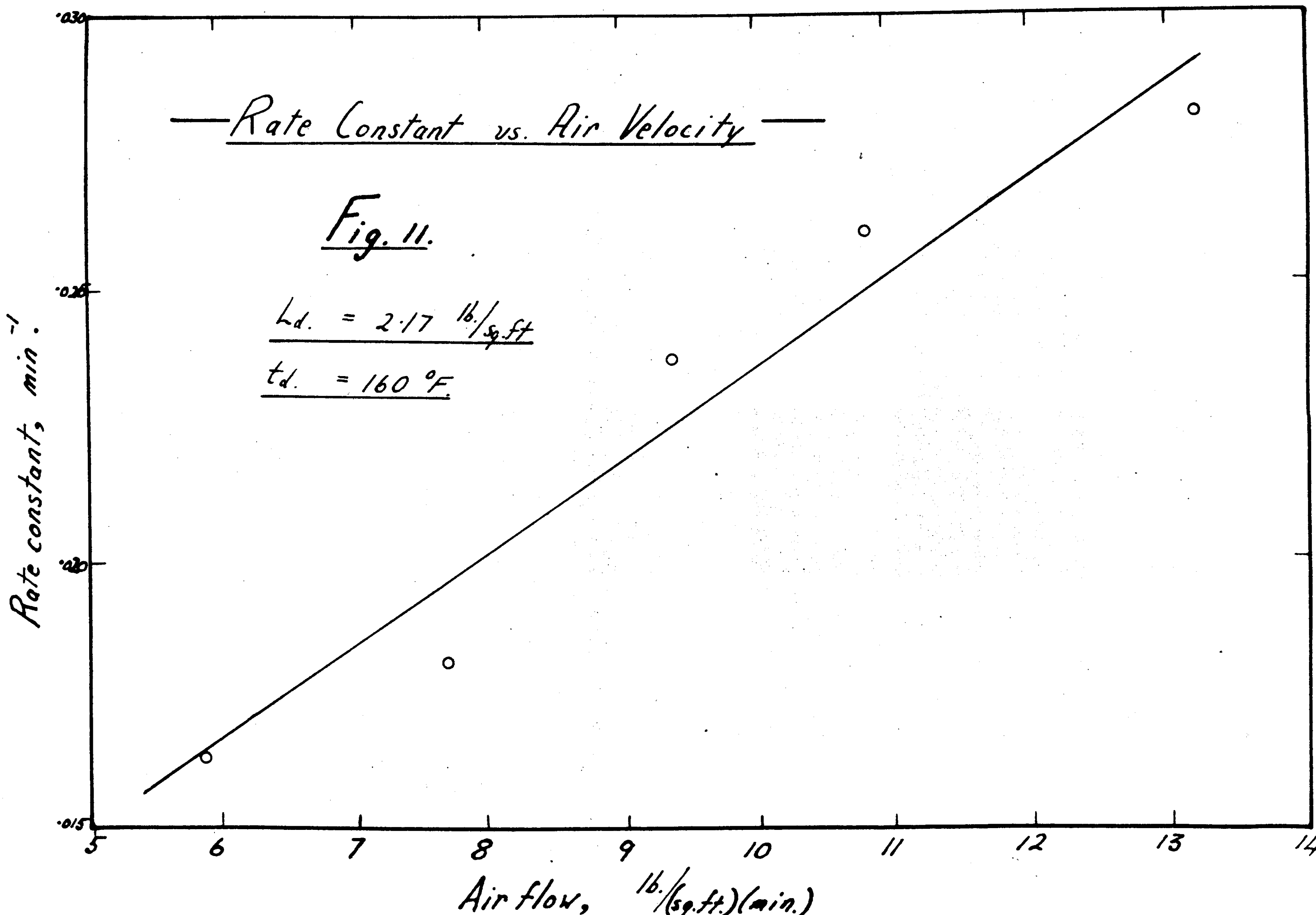
Agitation.

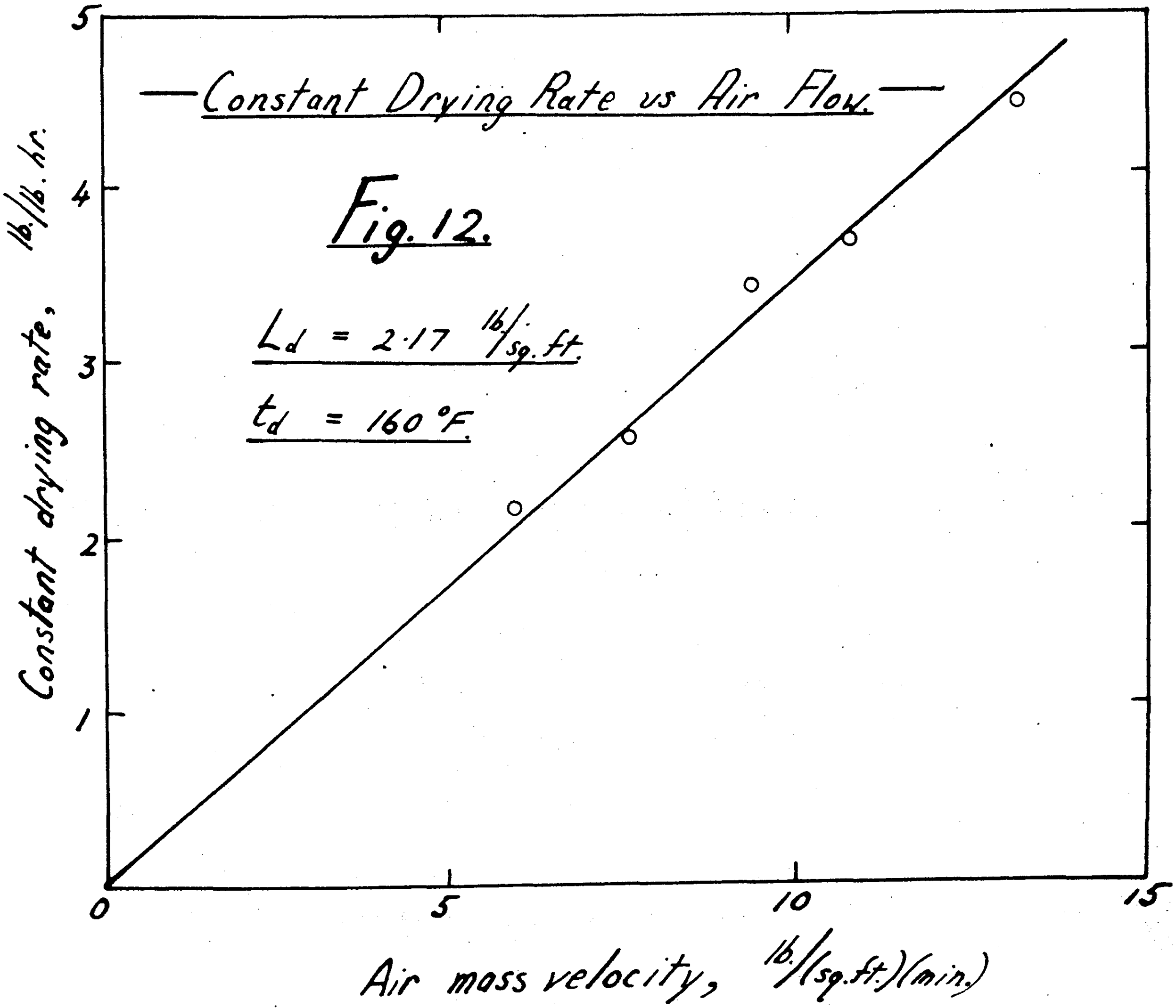
Bed depth = 4 in. Temperature = 160°F. G = 7.66 lb/(Sq.ft.)(min.)

Degree of agitation = 1, 2, 3, 6 agitations/hour.

The bed was agitated by hand stirring at fixed intervals after weighing, for a period of thirty seconds. After each agitation period the bed was carefully levelled, otherwise the uneven packing led to local high air flow with consequent formation of blowholes. From an examination of the graphs it is apparent that the effect of agitation is not to significantly increase the constant drying rate, but to increase the duration of the constant drying-rate period, or in effect, to decrease the critical moisture ratio. Further, it is probable that the drying time could not be lowered very much below the time obtained for the test with six agitations per hour.

One/


Rate Constant vs. Air Velocity
Fig. 11.
Ld. = 2·17 lb./sq.ft
td. = 160 °F.
Rate constant, min.⁻¹
·030
·025
·020
·015
5
6
7
8
9
10
11
12
13
14
Air flow, lb./(sq.ft.)(min.)



—Constant Drying Rate vs Air Flow.—
Fig. 12.
L_d = 2.17 lb./sq.ft.
t_d = 160 °F.
Constant drying rate, lb./lb. hr.
Air mass velocity, lb./(sq.ft.)(min.)
0
5
10
15
1
2
3
4
5

One agitation/hour below the critical moisture ratio results in a decrease in drying time from 117 min. to 90 min. (T = 3.5 to 0.1). But it is evident that much depends on when the agitation occurs. Obviously agitation after the critical moisture content has been reached will have more effect than an agitation in the constant rate period. Thus it is not of primary importance to agitate early in a test. Ideally, drying of the bed should take place completely in the constant-rate period, which would reduce the drying time to around 82 minutes.

Rotary-louvre drying works on such a principle and a special type of drier developed by Lowe et al.[18] also works on the constant agitation principle. One great benefit of continuous bed mixing apart from economic reasons, is that the final product has a more even moisture content. It is likely, however, that with a material such as brewers' spent grain, where the bed readily collapses, that an ordinary conveyor drier would have sufficient vibrations for constant agitation of the bed with resultant increase in efficiency.

<u>Comparison of Grains.</u>

Temperature 160°F. Bed Depth = 4 in. G. = 7.66 lb. da/(Sq.ft.)(min

Grain Types:- Beer, Lager, Stout.

Only a limited number of tests have been conducted for comparison but it seems likely that the packing density determines the relative drying properties. The packing density is/

is least for stout grain and most for lager grain, and hence the drying rate is lowest for lager and highest for stout grain.

Prediction of Drying Times.

It had been thought that a possible method of drying time prediction could be presented from the data on the deep loading tests. However, on attempting such a method, it was found that predictions were as much as 30% in error, owing to the many correction factors involved. Therefore, the results from the loading tests were used to check an alternative method based on the shallow-layer tests, and the account of the method is given hereafter.

In the drying of deep beds of material there is almost always a constant-rate drying period. Throughout this period the exit air humidity is constant and a mass balance gives:-

$$\left(\frac{\partial T}{\partial \theta}\right)_c = G.A.\ (H_2 - H_1)$$

Ideally the exit humidity value, H_2, would be the saturation value at the inlet wet-bulb temperature if adiabatic drying took place. In actual practice, this value only attains about 75% of saturation in the present experimental drier. This is due to air "shortcircuiting" the bed, both round the asbestos joint and at the edge of the bed. This defect of through-circulation work has been found in other cases,[30,40], and is most apparent in deep beds where the static pressure before the bed is high, and where the shrinkage and matting of material is greatest.

If/

If a vapourisation zone is considered (Fig.1) as postulated by previous investigators [54,45], then as this wave of vaporisation passes through the bed, the drying rate remains constant until the top of the bed is reached. The temperature at the top of the bed should then be at the inlet wet-bulb temperature of the air, if saturation had taken place. Saturation does not in fact take place, as given by the readings at the drier exit, but immediately at the top of the bed the air will be saturated or nearly so, the bypass air mixing to give the unsaturated value at the exit. As this top layer dries, the temperature increases until it is at or near the inlet dry-bulb temperature at the end of the test. A mean temperature between the inlet dry and wet bulb temperatures should then give a close approximation to the mean temperature of drying of the top layer.

With this temperature fixed, the drying time of the top layer may be calculated as in the single layer tests. This time of drying may then be added to the constant rate drying time to obtain the total. This gives only the time to dry to a certain water ratio in the top layer, but it is thought that, towards the end of a test, the moisture gradient throughout the bed will be insignificant.

The prediction method assumes that:

(a) there is no initial 'building up' period.

(b) there is no initial condensation on the cool grain in upper layers.

(c) the air has free access to all parts of the bed.

In practice, the increase of drying resulting from (a) and (b) is small in comparison with (c). Agitation tests have shown that without substantial bed mixing, the air does not come into contact with the particles readily. This results in a substantial error between the calculated and actual values and some attempt has been made to surmount this by introducing a correction factor based on the results of the agitation tests.

Summary of Prediction Method.

(1) From Fig. IV read off the value of m, the rate constant, at the desired log. mean temperature of td and tw.

(2) From Fig. IV find the air flow factor x at the desired air mass flow, and multiply m by x to obtain the correct rate constant, m^1.

(3) Find the critical moisture Tc from the equation :-

$$Tc = \frac{1}{m^1} \quad \frac{G. (Ho - H_1)}{Ld.}$$

(4) Find the time of drying at constant rate.

$$\theta c = \frac{Ld}{G} \quad \frac{(To - Tc)}{(Ho - H_1)}$$

(5) Find the time of drying of the top layer.

$$\theta_1 = \frac{1}{m^1} \quad Log_e \frac{Tc}{T_F}$$

(6)/

(6) Total drying time $= \theta_c + \theta_1 = \theta_T$

(7) Multiply θ_T by correction factor of 1.36 to obtain θ_P.

<u>Example.</u>

$L_d = 2.975$ lb./(sq.ft.). $G = 7.65$ lb.d.a./(sq.ft.)(min.)

td = 160°F. tw = 85°F. T = 3.5 - 0.1 lb/lb.

log.mean temp. = 118.6°F. m = .095 x = .76

$m^1 = .072$

$H_s = .0262$, $H_2 = .75 \times H_s = .0196$, $H_1 = .0087$

$H_2 - H_1 = .0109$.

$$T_c = \frac{7.65 \times .0109}{.072 \times 2.975} = .389$$

$$\theta_c = \frac{2.975 \times 3.111}{7.65 \times .0109} = 111$$

$$\theta_1 = \frac{1}{.072} \operatorname{Log}_e \frac{0.389}{0.1} = 18.8$$

$\theta_T = 111 + 18.8 = 129.8$

$\theta_P = 175$

and since $\theta_a = 190$, % error $= -7.9\%$

Prediction Times.

TABLE I

T = 3.5 - 0.1

Ld. (lb.B.D.S./(sq.ft.))	Temperature (°F)	Air Flow (lb.d.a./(sq.ft.)(min.))	θ_a (min)	θ_p (min)	% error.
1.548	160	7.60	100	94.5	-5.5
2.165	160	7.55	117	121	+3.4
2.975	160	7.65	190	175	-7.9
4.773	160	7.65	303	272	-10.2
2.183	120	7.70	203	208	+2.5
2.080	140	7.60	165	153	-7.28
2.182	180	7.60	104	107	+2.9
2.166	200	7.52	77	85	+10.4
2.242	160	5.86	136	149.6	+10.0
2.09	160	9.32	90	100	+11.1
2.116	160	10.75	79	88	+11.4

Table I represents a summary of the actual and predicted values of drying time for a number of loading tests. The predicted values are within ± 11.5% of the actual.

STATIC PRESSURE DROPS

Static pressure drops were measured by taking the draught gauge reading when the bed of spent grain was in position and substracting the reading which was obtained with the empty basket in position at the same air flow rate. Plots of static pressure drop versus air mass flow are given in Fig.13 for four different loadings.

Spaugh[72] studied the resistance to air flow of beds of dried vegetables, up to depths of 36 in. and air flows of 37-170 ft./min. The following equation was found to hold:-

$$Q = C_1 \; V/_{C_2} - b^{\;n}$$

where Q = Static pressure drop in /ft. of bed.

C_1, C_2 = experimental constants.

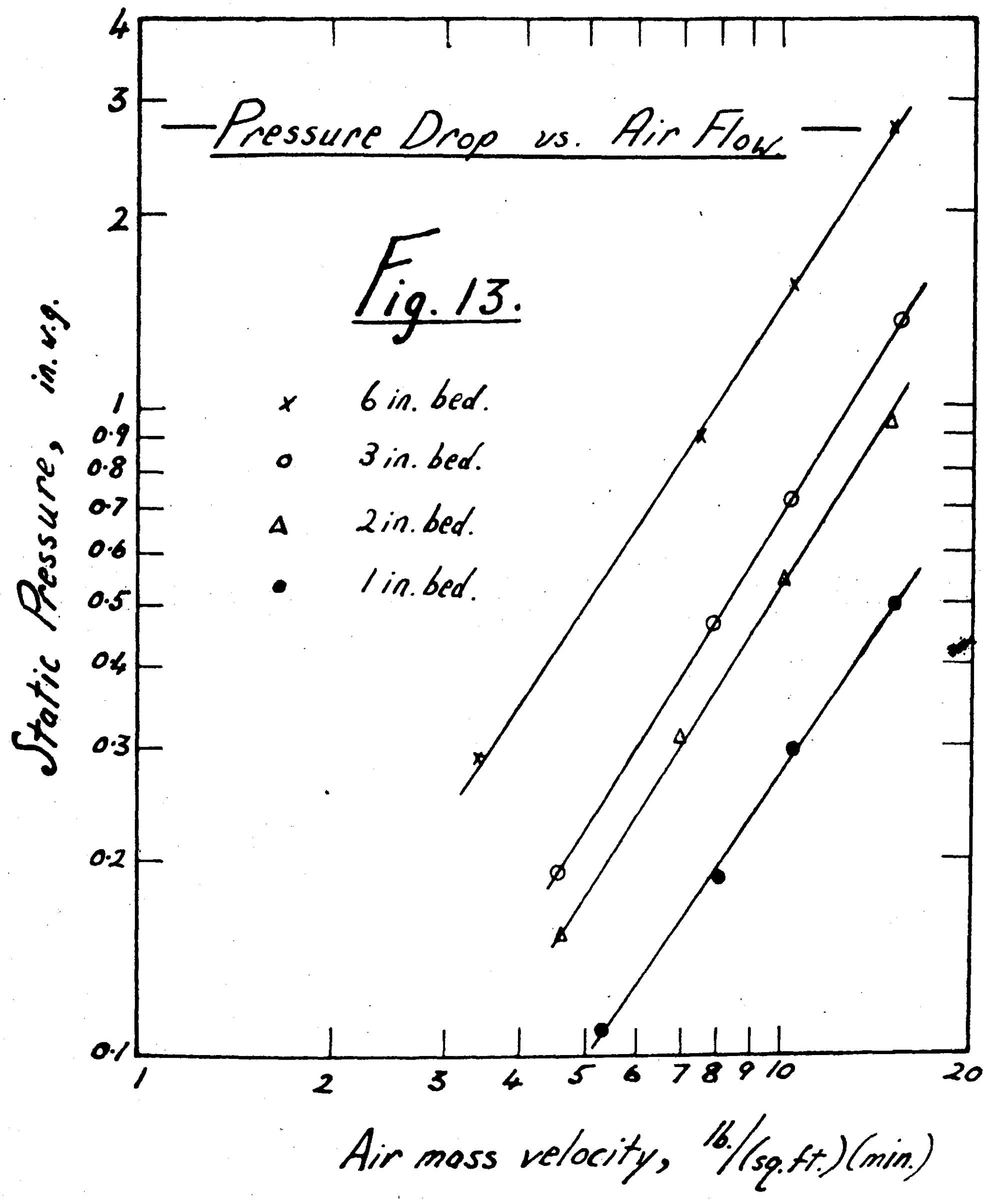
b = ft. of perimeter/sq.ft. of bin cross-section.

n = experimental exponent.

A simpler expression, $Q = C.W.V^n$, was suggested when b was greater than unity, where W is the air density (lb./cu.ft.)

The exponent n varied from 1.60 to 1.82 for different vegetables, and Coles[53] gave a value of 1.5 for a bed of viscose staple fibre.

The value of n is from 1.76 to 1.88 for dried seaweed stipe and from 1.75 to 1.92 for wet stipe slices. The average value of n for the few tests conducted of Brewers' spent grain is 1.61.



—Pressure Drop vs. Air Flow—
Fig. 13.
x 6 in. bed.
o 3 in. bed.
Δ 2 in. bed.
• 1 in. bed.
Static Pressure, in. w.g.
4
3
2
1
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
1
2
3
4
5
6
7
8
9
10
20
Air mass velocity, lb./(sq.ft.)(min.)

S E C T I O N V.

EXPERIMENTAL WORK.

Through-circulation drying of sugar beet.

Introduction

Vegetables are dried mainly to prevent spoilage during storage, but drying may also be desirable prior to the extraction of valuable constituents. In either case the mode of drying is important and must not influence the properties of the material.

In the case of sugar beet, containing 77% water, the root may be dried when harvested to prevent deterioration of the sugar content and allow a prolonged extraction season extending even up to the next harvest period. Also, stronger and purer juices result on extraction from dried beet cossettes, thus easin evaporation loads.

The composition of sugar beet has been studied by Heriot [73] and Mitchell [74].

Table I.

Source	Water	Sucrose	Ash	Organic Non-Sugars	Fibre
Heriot	78.0	15.0	1.0	1.5	4.5
Mitchell	76.5	16.7	0.7	1.3	4.8

The material does not readily conduct heat and must not be exposed to high drying temperatures. The type of drier used must be capable of large output and conditions producing inversion and caramelisation must be known since these seriously affect the economy of the process. The amount of invert sugar formation depends upon the duration of the time of drying and

the/

the temperature of the drying air in relation to the moisture content of the material at the various stages of drying. Caramelisation depends upon the temperature of the drying air in relation to the moisture content.

Production of Invert Sugar.

Under certain conditions of moisture, temperature and acidity, sucrose will decompose giving equal parts of glucose and fructose (invert sugar). During drying, conditions are favourable to this process of inversion, moisture and acids being present at a relatively high temperature. However, although the acidity increases, the moisture decreases as drying proceeds and rapid drying gives less chance for loss by inversion.

Owen[49] found that near the end of a season, when the beets were more acid, more inversion occurred. He stated that the drying of sugar beet offers favourable conditions for the activity of enzymes and micro-organisms, since in the process the beet passes through all ranges of optimum temperature for these agents. It was shown that sugar loss was slow up to a beet temperature of 85°F and then there was a marked loss. Tests indicated that the percentage invert sugar in dried cossettes was about 2% at a surface temperature of 206°F. After 206°F there was a further phase of inversion and caramelisation before 220°F is reached. In the present investigation the drying temperature was normally 200°F, thus keeping the material temperature below the caramelisation point.

Production of Caramel.

Decomposition of sucrose by heat results in loss by formation of caramel, which also hinders sugar production owing to the presence of a dark extract. Obviously, the lower the temperature, the less chance there is of formation of caramel. The principal aim in sugar beet drying is therefore to control as far as possible the physiological changes resulting in sugar loss. Owen found that so long as drying was carried out rapidly within $1\frac{1}{2}$ hours at a temperature of not more than 212°F at the end of the moisture removal period, no deleterious effects ensued. It seemed that conditions were conducive to caramelisation towards the end of the test, and although sulphur dioxide may be used to give beet cossettes of good white colour, it was thought better to aim at the production of white cossettes by drying alone.

Preparation of the Beet.

The root was cleaned thoroughly and peeled. Different cossette knives were available and the "roof ridge" type was chosen, giving a cossette of 2 in x 0.4 in x 0.25 in. These cossettes were generally of good white colour, and any of poor shape were rejected. For the single layer tests the pieces were arranged on the basket so that approximately the same number of cossettes was tested. Random packing was employed in/

in the deep bed tests, the bed being levelled off before drying.

Choice of Drier:

The requirements of a sugar beet drier may be listed as:-

(1) Economic and inexpensive drying.

(2) The use of comparatively low drying temperature (200°F).

(3) Fast drying.

(4) Large output.

Tray or tunnel driers have the disadvantage of low production rates with consequently higher costs. Retention time in such driers is great since the air has difficulty in circulating round all the particles. These types are used primarily for materials where cost is of secondary importance to quality of the final product.

Pneumatic driers can give high drying rates and efficiencies wit small particles where high heat transfer rates to the interior of the material are possible. The material can be dried in a few seconds, but sugar beet would probably have to be recycled to bring it down to the desired moisture content. The particles would possibly have to be smaller than the present cossettes, and also the danger of overheating is great, with subsequent sugar loss. If temperatures are reduced to prevent this loss the efficiency of the system deteriorates markedly. Gordon[75] has stated that recirculation of the feed is undesirable, while

Bailey/

Bailey and Hamblin[48] reported that grass burning occurred in high temperature pheumatic driers. Gardner[76] states that the main application of pneumatic driers for seaweed frond would be as an initial drying stage, so that in effect two driers would be essential.

Through-circulation driers have a wide application in drying many materials, with or without preforming. They have the obviou advantages of simple construction, good efficiency because of the intimate contact between air and particles, ease of air re-circulation, high capacity, and ability to control retention time and temperatures accurately.

Rotary louvre driers have the same advantages as the above type, with the added virtue of continuous bed mixing, giving a more uniform product. The capacity may not be as high for the same floor space although drying times are slightly less.

Other types of driers are unsuitable from the viewpoin of type of feed or low output.

It was decided to use a through-circulation drier because of its relatively simple construction and since agricultural grass driers of this type could be easily converted for drying other vegetable crops.

Apparatus.

The test drier has been described in Section II and

the/

the test procedure is similar to that used in drying brewers' spent grain, the cossettes being placed in a basket, and air at the desired temperature, humidity, and velocity circulated through the bed. These values were closely controlled throughout each test and readings of bed loading were taken at regular time intervals.

Resistance of Beds of Cossettes to Air Flow.

This aspect has been studied by Owen[49]. Observations were made on the consolidation of beds up to 12 in. thick, for which range the amount of consolidation was negligible. Tests were also made on the effect of an air velocity on the resistance of the material, thickness of layer being constant, and also on the effect of thickness of layer on resistance, the air flow remaining constant. The effect of moisture content on these two variables was also investigated.

The cossette sizes used in Owen's work were 2.2 in x 0.4 in. x 0.2 in. as compared with the size in the present series of 2 in.x 0.4 in.x 0.25 in, i.e., almost the same dimensions of cossettes. Thus, it was thought unnecessary to deal with the problem of static pressure drops, but necessary to check some of the values with those from previous work. The values obtained verified the findings of Owen, whose results were summarised by the/

the following formula for solution of pressure drop problems:-

$$W = (0.0015\ V - 0.09)\ T$$

where

W = Water gauge in inches.

V = Velocity of air in ft. per min., over a 1 sq. ft. basket area.

T = Thickness of layer in inches.

There should, of course, be a temperature correction if volumes instead of weights of air are used. This difficulty can be surmounted by plotting pressure drop, not against velocity, but against the air mass flow (lb.air/(sq.ft.)(min)).

Natural Heat Reactions.

The liberation of heat has been detected during the drying of sugar beet in mass, as with many agricultural crops. This generation of heat in sugar beet drying is small, but because of the accompanying physiological processes it is important on account of the loss of sugar during desiccation. These processes involve exothermic oxidation of incompletely oxidised acids, but it is difficult to distinguish between the individual effects of the various mechanisms. In the drying of some crops these natural reactions are deliberately accelerated to increase drying efficiency, but with sugar beet the aim is to control them in order to minimise loss of sugar. The restraint of these changes, such as oxidation and respiration/

respiration, has been successfully attained by Owen, using a deve -opment of the mass drying principle, analogous to drying grass in the stack. If the action of oxidation and respiration were not controlled they would involve decomposition of less complex and intermediate products and finally of the completely metabolised sugars.

Diffusion of Sugar and Other Constituents in Solution.

There are other substances besides water which change position in a particle being dried. The water in vegetable matter exists as a solution of sugars, salts, and other constituents, and during drying some of these substances migrate within the piece. In living vegetable tissue only the water will diffuse readily through the walls of the living cells. Scalding, or blanching, to which many vegetables are subjected before drying, changes the make up of the cell walls, so that not only do they permit more free passage of water but also allow some of these dissolved substances to pass. The reason substances migrate is that a concentration gradient is set up immediately drying starts. At this time water is evaporated from the surface layers, setting up a gradation of moisture content throughout the piece, each succeeding layer from the centre being a little drier. Since the liquid in the cells is a solution, removal of part of the water leaves a more concentrated solution behind, thus constituting a gradation of concentration/

concentration, highest at the surface and lowest at the centre. This gives a driving force for diffusion of the soluble substance towards the centre of the piece, but since this diffusion only takes place at a reasonable rate in solution migration will occur in the early stages of drying, in particular where the moisture content is high and the material has been scalded before drying. Such phenomena have been observed in the dehydration of potatoes by the occurrence of "brown centres", but there has been no quantitative study and therefore the conditions which produce such centres cannot be adequately defined. It seems likely, according to Van Arsdel[6], that the browning takes place most rapidly at an average moisture content of 20 to 30%, and occurs more slowly as the moisture content is reduced below this critical range. Too high a temperature when the moisture content in the centre is at this critical range probably accounts for heat damage to the centre of the piece resulting in localised browning. Conditions which would cause rapid evaporation from the surface would cause a steeper gradation of concentration, providing a higher driving force, but at the same time these conditions would shorten the time during which migration could take place. The individual effects of the opposing influences have not yet been evaluated.

There/

There was little indication of browning with beet cossettes and it was evident that the nature of the material, the temperature of drying, and the fact that no scalding was done, had much to do with this. Of course, although no browning was noted, some migration of sugar may take place, but it is probable that this is not great. The matter is of some importance, since migration of sugar towards the centre might result in protracted extraction times, possibly with greater loss in the subsequent diffusion process.

Shrinkage.

The obvious advantage of shrinkage is space saving in storage. The manner in which vegetable matter is dried affects the degree of shrinkage as well as the constitution of the product Hence, slow drying gives a product of smaller volume, while fast drying gives one of greater volume but of easier reconstitution. A very dense piece loses moisture much more slowly in the final moisture range than a piece which has retained a larger external size. Thus the extent of shrinkage in sugar beet drying is of minor importance, since it has been established that drying should take place as quickly as possible to prevent sugar loss from invert formation caused by prolonged subjection to elevated temperatures at low moisture contents.

Single Layer Tests.

The drying of grain has been related in mass to single layer experiments by McEwen et al[45] and it seemed likely that such/

such a correlation might be possible with sugar beet cossettes. In a series of tests the cossettes were arranged on the floor of the drier basket, at an approximate wet loading of 0.715 lb. and dried with close control of temperature, humidity, and air velocity.

Temperature Tests. Temperature = 140 to 220°F. G = 11.4 lb./(sq.ft.)(min)

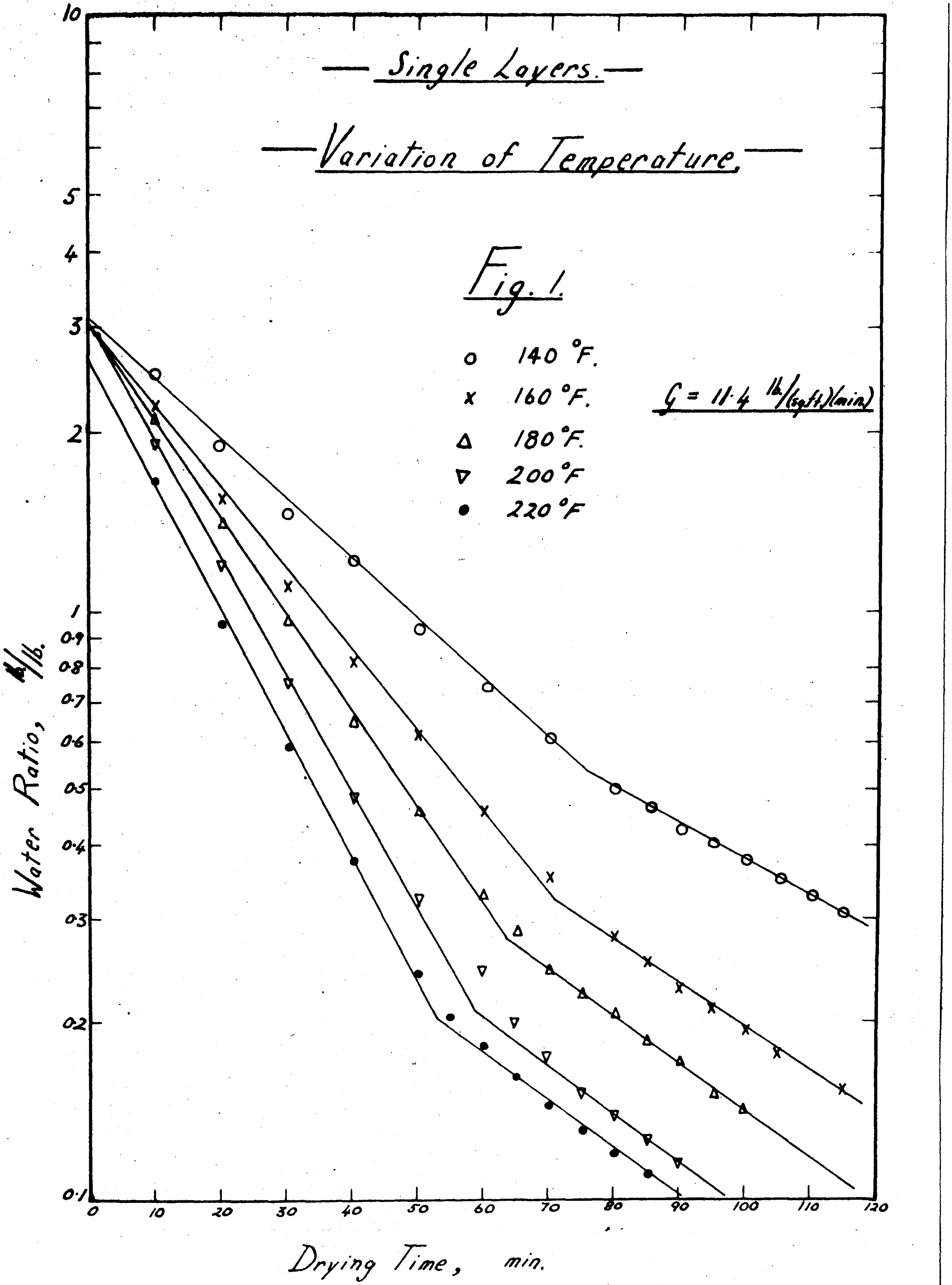
The results of the temperature runs are seen on Fig.I, and the graphs approximate to two straight-line portions within the range of moisture ratios tested. The results are similar to those for wheatgrain and spent grain. However, no second straight line relation was found with wheatgrain, and although evident with brewers' grain, could be neglected since it occurred in the low moisture region towards completion of the test. The results were therefore plotted (Fig.2) as rate constants m_1 and m_2 vs temperature, and intermediate moisture ratio T_{im} vs temperature (Fig.3). This gives a simple method of predicting the drying times of single layers at one particular value of air mass flow and at temperatures between 140 and 200°F.

$$\theta_1 = \frac{1}{m_1} \log_e \frac{To}{Tim} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

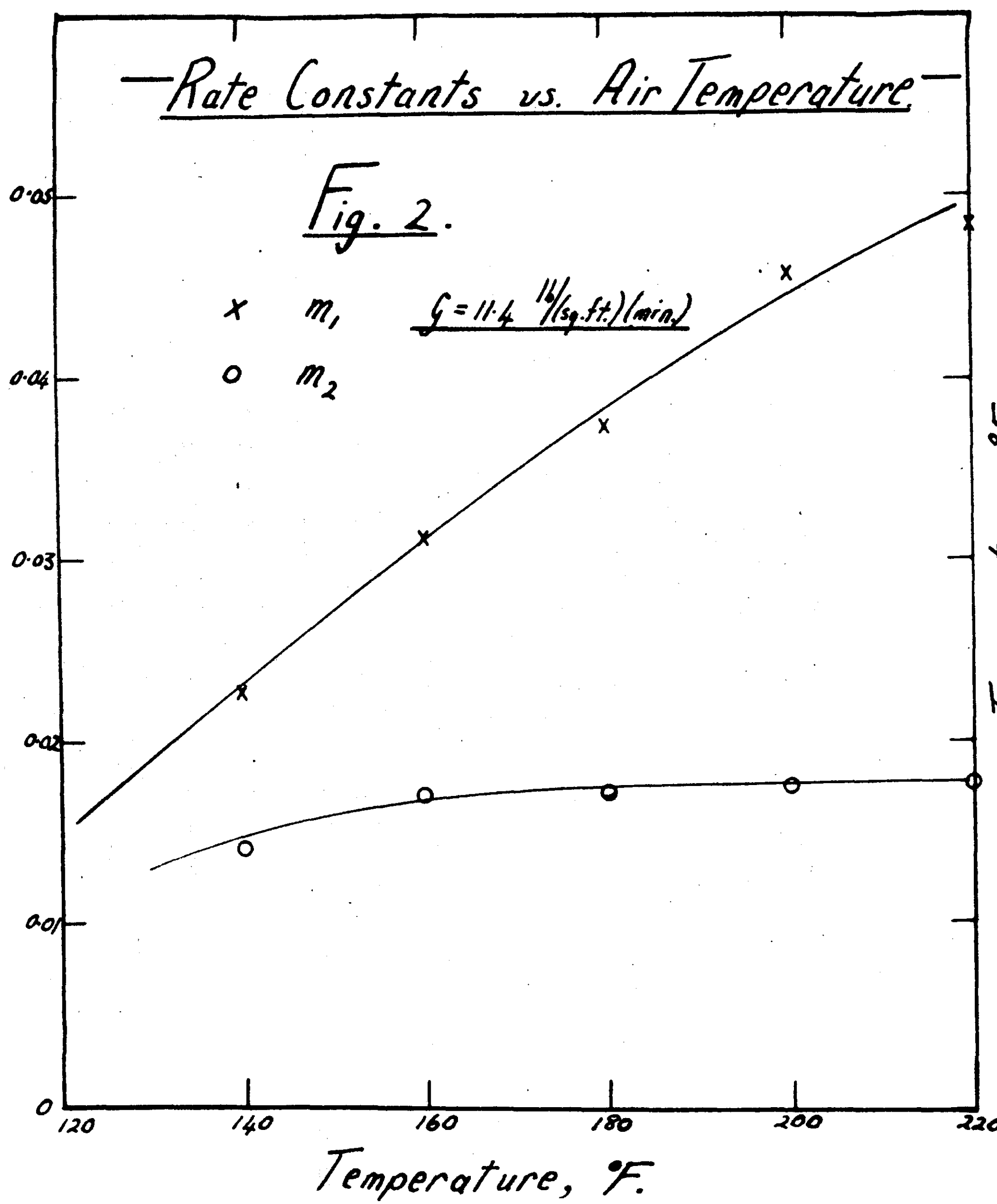
$$\theta_2 = \frac{1}{m_2} \log_e \frac{Tim}{T} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

and $\theta_T = \theta_1 + \theta_2$

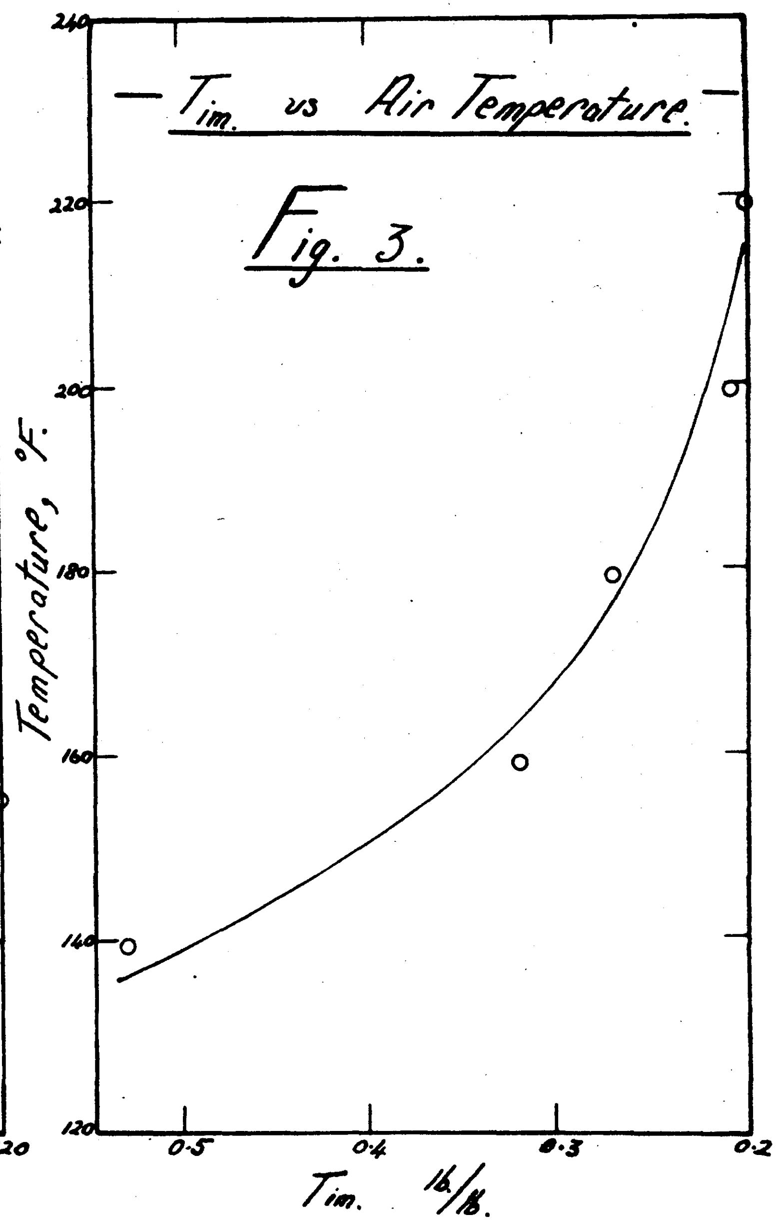
The/



— Single Layers. —
— Variation of Temperature. —
Fig. 1.
o 140 °F.
x 160 °F.
Δ 180 °F.
∇ 200 °F
● 220 °F
G = 11·4 lb./(sq.ft.)(min.)
Water Ratio, lb./lb.
10
5
4
3
2
1
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
10
20
30
40
50
60
70
80
90
100
110
120
Drying Time, min.



—Rate Constants vs. Air Temperature—
Fig. 2.
× m1
○ m2
G = 11.4 lb/(sq.ft.)(min.)
0.05
0.04
0.03
0.02
0.01
0
120
140
160
180
200
220
Temperature, °F.



— Tim. vs Air Temperature. —
Fig. 3.
240
220
200
180
160
140
120
0.5
0.4
0.3
0.2
Tim. lb/lb.
Temperature, °F.

The above relations are simple and give good results down to moisture contents of less than 10%. As with previous work total moisture content has been used because a more suitable correlation is given, although McEwan et al. obtained a satisfactory solution with a free moisture content correlation.

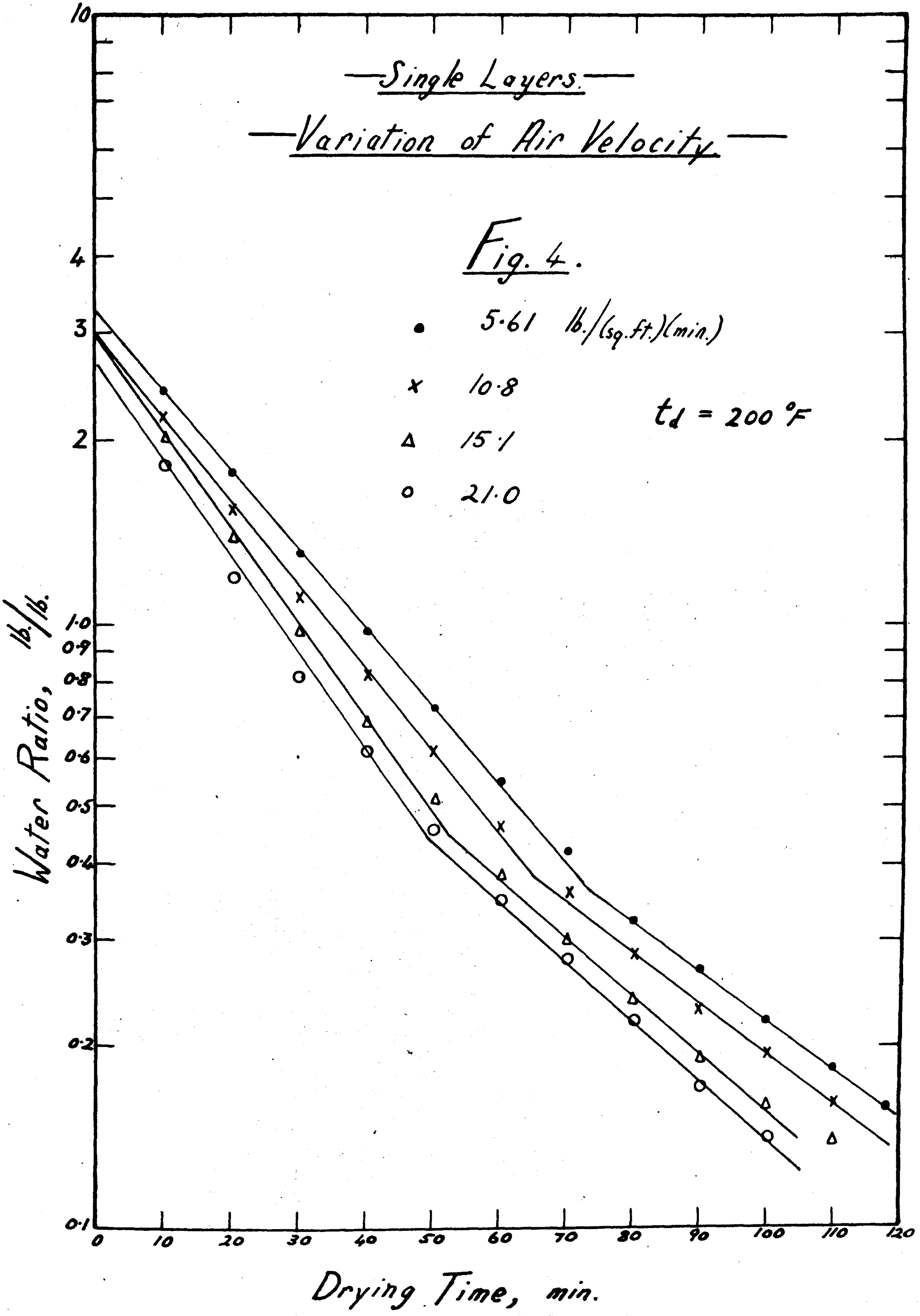
<u>Air Velocity Tests.</u>

Since the material is of the type where moisture diffus only slowly to the surface it seems probably that variation in air flow would produce only a slight difference in the drying rate. The tests corroborated this for a range of air mass flows of 5.61 to 210 lb/(sq.ft.)(min.) and a graph of G vs m_1 showed that for a fourfold increase in air flow the resulting increase in the value of m_1 was from 0.030 to 0.037 (Fig.5). Corrections for air velocity were therefore assumed to be approximately in the same proportion for air temperatures other than the values at which these tests were conducted.

<u>Humidity Series.</u>

(1) Constant D.B.T. (180°F), varying W.B.D. (40 - 90°F) (Fig.6).

In the humidity tests steam was injected to give the desired humidity. It was evident from the range of values covere by the tests that there was no appreciable change in the drying rate with change of humidity at constant dry bulb temperature. For beds of vegetables Brown et al[28] found that for a given in-crease/



Single Layers.
Variation of Air Velocity.
Fig. 4.
5·61 lb./(sq.ft.)(min.)
10·8
15·1
21·0
t_d = 200 °F
Water Ratio, lb./lb.
Drying Time, min.
10
4
3
2
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
10
20
30
40
50
60
70
80
90
100
110
120

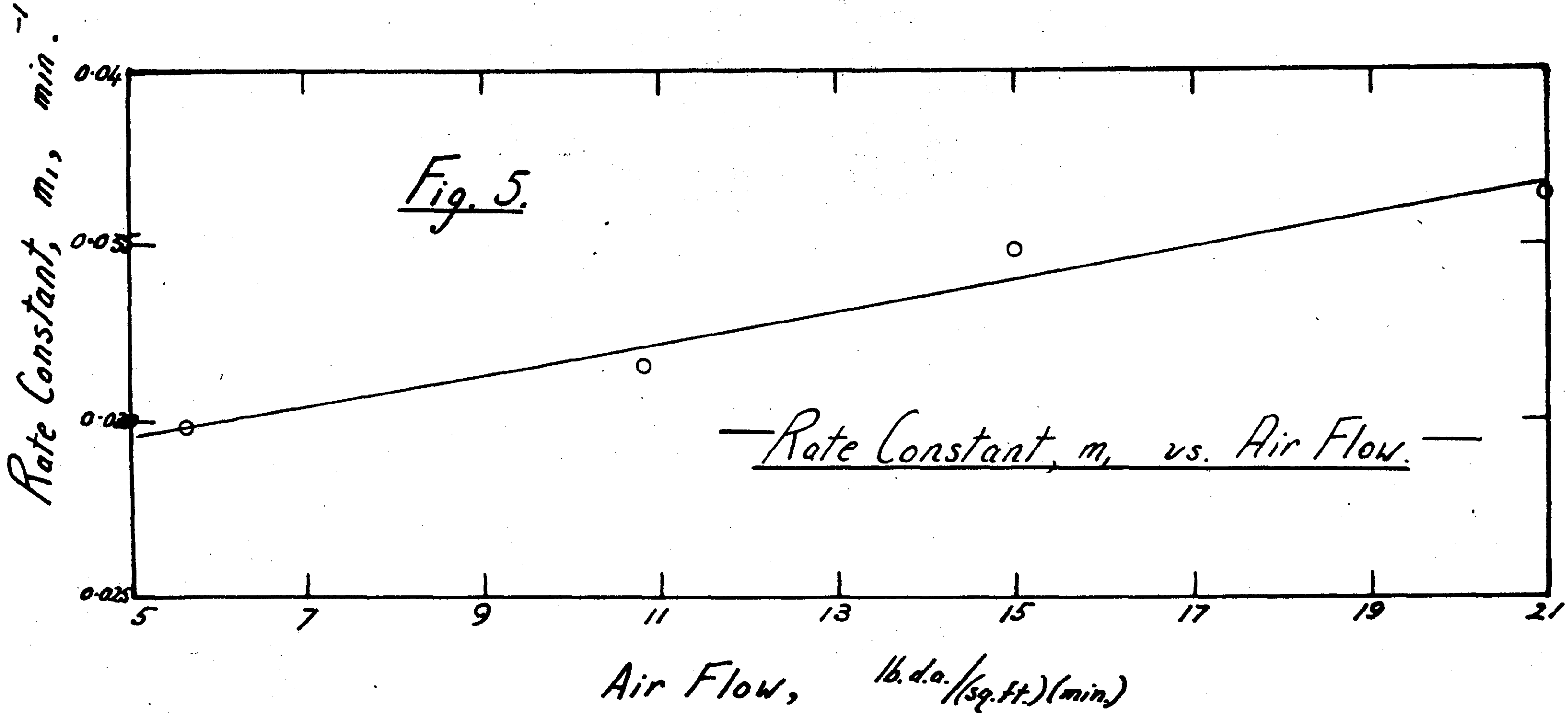
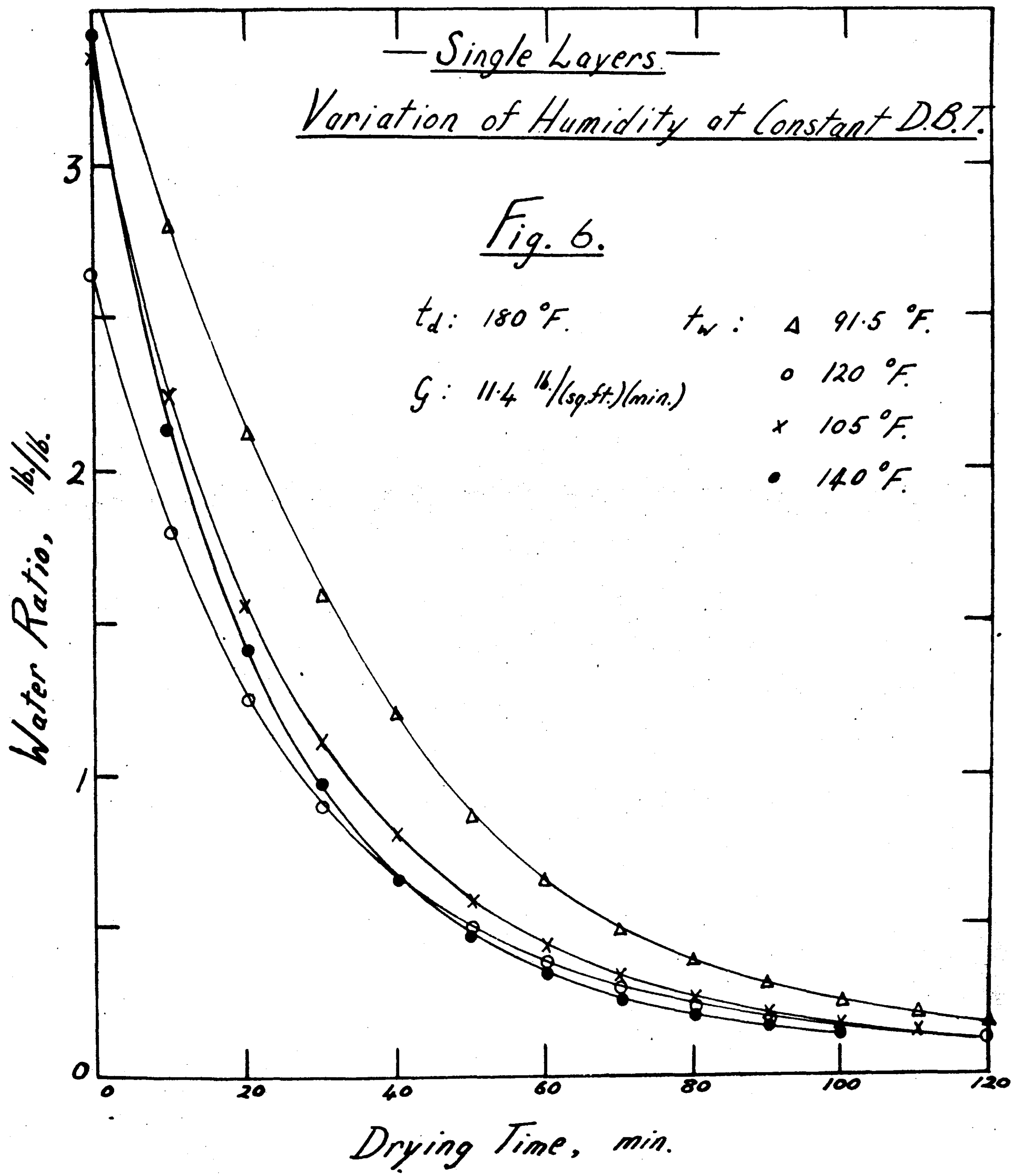


Fig. 5.
Rate Constant, m, vs. Air Flow.
Rate Constant, m, min.⁻¹
0.04
0.035
0.030
0.025
5
7
9
11
13
15
17
19
21
Air Flow, lb.d.a./(sq.ft.)(min.)



— Single Layers —
Variation of Humidity at Constant D.B.T.
Fig. 6.
t_d: 180 °F.
G: 11.4 lb./(sq.ft.)(min.)
t_w: △ 91.5 °F.
○ 120 °F.
× 105 °F.
● 140 °F.
Water Ratio, lb./lb.
0
1
2
3
0
20
40
60
80
100
120
Drying Time, min.

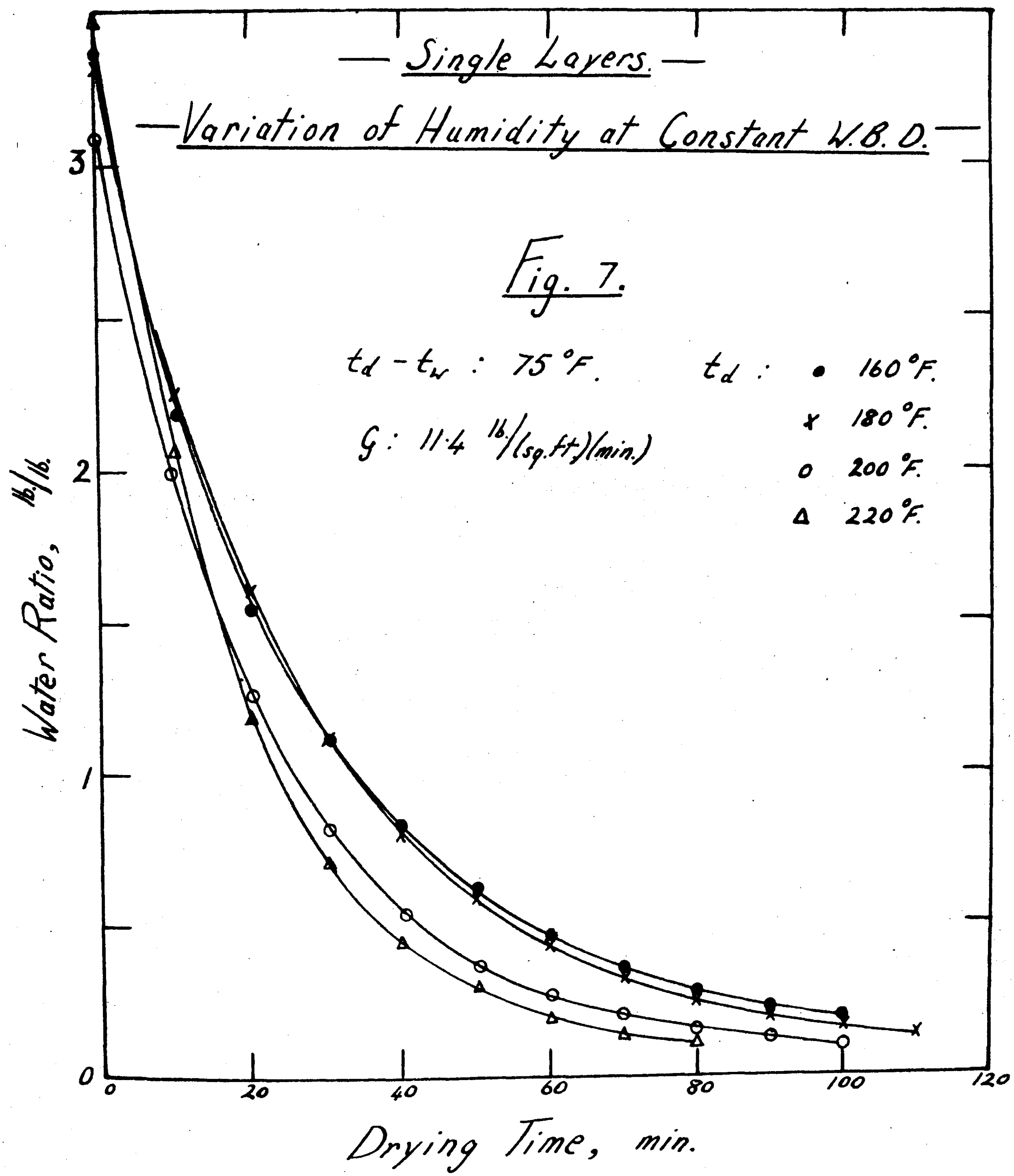
increase in the wet-bulb depression, the change in drying rate was substantial, while in contrast Perry, Gillou[34,35], and their co-workers showed that the rate of drying of prunes above a moisture content of 0.20 was almost independent of wet-bulb depression as long as the relative humidity of the drying air was less than 40%. Ede and Hales[30] and Gardner and Mitchell[40] have reported that the respective drying rates for potatoes, carrots, cabbage, and seaweed in deep beds were proportional to the wet-bulb depression, and on this basis presented a method for the prediction of drying rates for these materials. McEwen and O'Callaghan[45] state that the rate constants in the drying of wheat -grain were unaffected by humidity changes up to a relative humidity of 70%. The present work only covers relative humidities up to 40% but there is no great change in the rate-constant values and indeed below a moisture ratio of about 0.30 the rate-constant is unaffected by humidity. This is in accordance with most work on the drying of vegetable materials where the influence of humidity in the low moisture regions is negligible, especially when the equilibrium moisture content is low.

(2) Constant W.B.D. (75°F), varying D.B.T. (160 - 220°F)(Fig.7).

Increase of air temperature has generally been observed to increase the rate of drying at all moisture content levels (4,6,7,10.)

Wheatgrain work has shown that for the same

relative/


— Single Layers. —
—Variation of Humidity at Constant W.B.D.—
Fig. 7.
$t_d - t_w$: 75 °F.
G : 11·4 lb./(sq.ft.)(min.)
t_d : • 160°F.
x 180°F.
o 200°F.
Δ 220°F.
Water Ratio, lb./lb.
3
2
1
0
0
20
40
60
80
100
120
Drying Time, min.

relative humidity a change in the dry-bulb temperature effects a significant change in the rate-constant value. It is difficult to compare the present work with that of other investigators since most work has been done on deep beds. Van Arsdel[6] has stated that it seems probable that the main effect of a higher drying temperature must be to increase the rate of internal diffusion of moisture. In his investigations the diffusion rate was the controlling factor only during the low moisture end of the run. If such an effect were true, the diffusional flow from the interior of a sugar beet cossette must be the main influence on the rate of drying. It has already been seen that heat is not easily transferred throughout the beet and since no scalding was done this also increases the difficulty of flow of moisture through the cell walls by diffusion, once the surface moisture has been removed. Again, if diffusion is the largest single factor in the change of drying rate, it can be expected that the variables which influence the gas film coefficients of heat and mass transfer will not influence the rate of drying. Air velocity and change of humidity at any one temperature have little effect, and it may therefore be considered that the rate of flow of water through the cell walls is of primary importance in the drying of beet, this rate being markedly affected by the temperature of the drying air.

Drying of Deep Beds.

In/

Drying of Deep Beds.

In these tests the effect of loading, air velocity, and temperature on the drying times and rates was studied. The standard values chosen for each variable were:-

Loading, (Ld) = 4 in. Bed Depth = 2.25 lb B.D.S./sq.ft.

Temperature (td) = 200°F.

Air velocity(G) = 1 in w.g. = 10.8 lb.B.D.S./(sq.ft.)(min)

Ede and Hales have reported irregularities in the dryin of some vegetables, possibly caused by bad spreading, mal-distrib tion of air, or even to partial blocking of the drying bed area by small pieces produced by stripping achines, which tend to pack down and offer high resistance to the air passage. This is unlikely to happen for cossettes which are firm and of uniform size, forming an even porous bed. For the same reasons, no evidence of holes made by air blast was witnessed. Edge effect is of some significance in the drying of deep beds, although not having such great influence as with leafy materials. The larger the drier, the less the proportion of edge, hence this effect is not so marked. The edge effect in wheatgrain drying tests appears to be negligible because of the easy movement of the round particles over one another, helped considerably by motion induced at the weighing intervals. Often the effect of agitating the bed is to increase the drying rate, not only by exposing fresh surfaces to the material, but also by reducing the edge effect to a minimum.

Effect of Varying Loading.

The test conditions were:-

Temperature = 200°F   G = 10.8 lb.d.a./(sq.)(min).

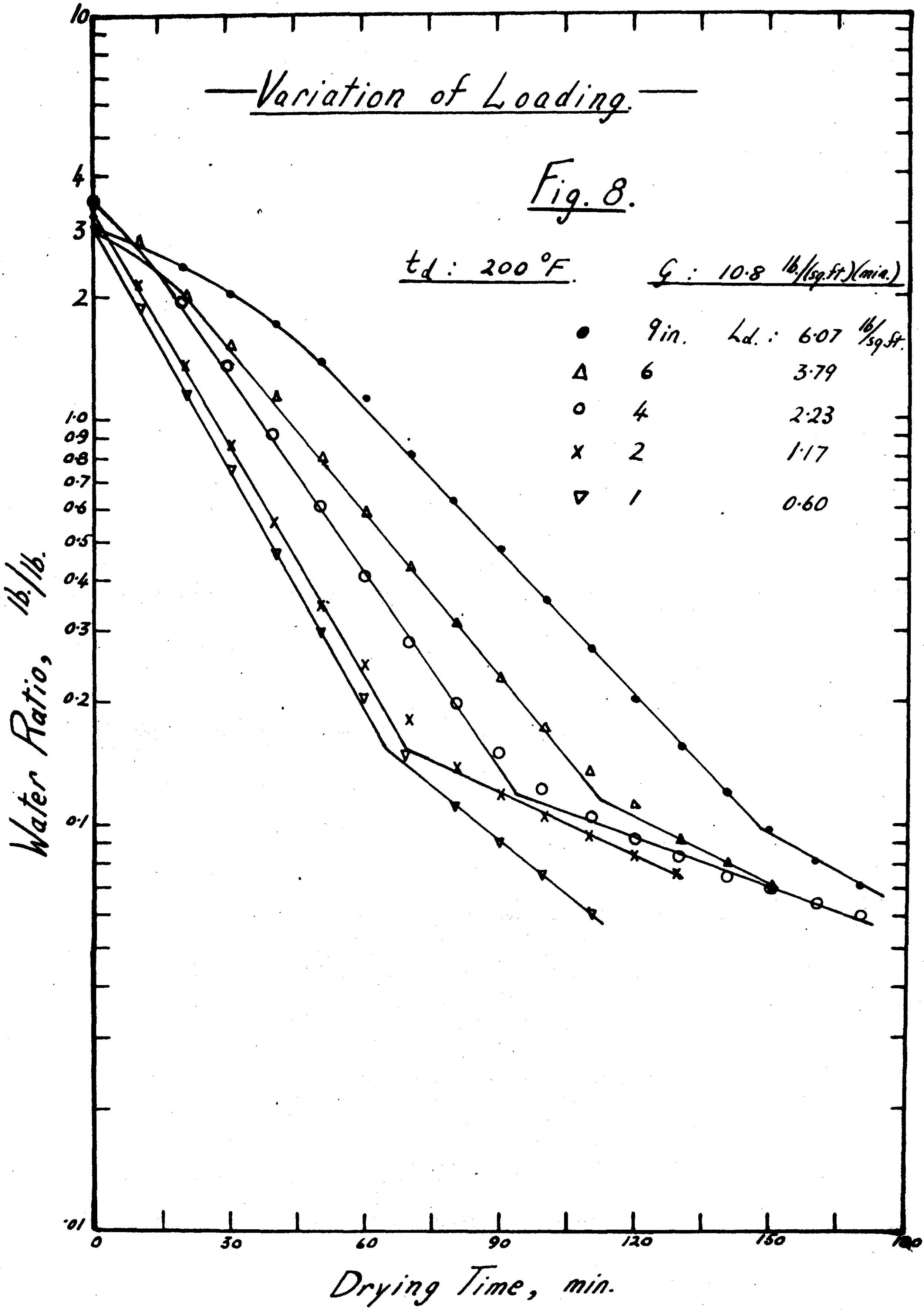
Bed Depth = 1 in., 2 in., 4 in., 6 in., 9 in.

It was found that for beds of 4 in. and above, a constan rate period occurred, the duration of this period growing with increasing bed depth. From a semi-logarithmic plot of moisture ratio vs drying time straight line relations were found to hold (Fig.8). The drying times are much greater than those reported by Owen, for the following reasons:

(a) Owen dried the mass in stages, the first at a much higher temperature than in the present series, with succeedingly lower temperatures towards the end of the run. For systematic examination of the drying properties it would appear necessary to dry at a steady temperature.

(b) The slightly increased thickness of the cessettes increased drying times.

From a graph of loading vs drying time between two definite moisture content limits it is evident that there is proportionality within the scope of the tests. This is mainly caused by the packing properties of the beet, which has already been shown to have negligible consolidation effect up to a 12 in. bed depth. At some higher loading, when the material is compress-ed/



—Variation of Loading.—
Fig. 8.
td : 200 °F.
G : 10.8 lb./(sq.ft.)(min.)
● 9in. Ld. : 6.07 lb./sq.ft.
Δ 6 3.79
o 4 2.23
x 2 1.17
▽ 1 0.60
Water Ratio, lb./lb.
10
4
3
2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
.01
0
30
60
90
120
150
180
Drying Time, min.

compressed, there may be an optimum. There is some evidence that this may be at a loading of approximately 10 lb. B.D.S./sq.ft i.e. a bed depth of about 18 in.

<u>Effect of Varying Air velocity</u>.

Temperature = 200°F. Bed Depth = 4 in. = 2.25 lb.B.D.S./sq.ft.
G = 6 to 21 lb.d.a./(sq.ft.)(min).

Air velocity has considerable effect on the drying rates of deep beds, principally because of its effect on the constant rate period. An increase of velocity increases the value of the initial rate of drying and at the same time reduces the period of constant rate drying. It was found that a positive change of air flow from 85 ft./min. to 288 ft./min. decreased the drying time, between moisture ratio limits of 23.5 to 0.1, from 135 minutes to 85 minutes, i.e. a decrease of 37% for just over a threefold increase in air velocity. Air flow is therefore of some importance in the drying of deep beds, and in a commercial conveyor drier could be kept high in the initial stages, reducing gradually to the end of drying where it has little effect. The constant drying rate varied:-

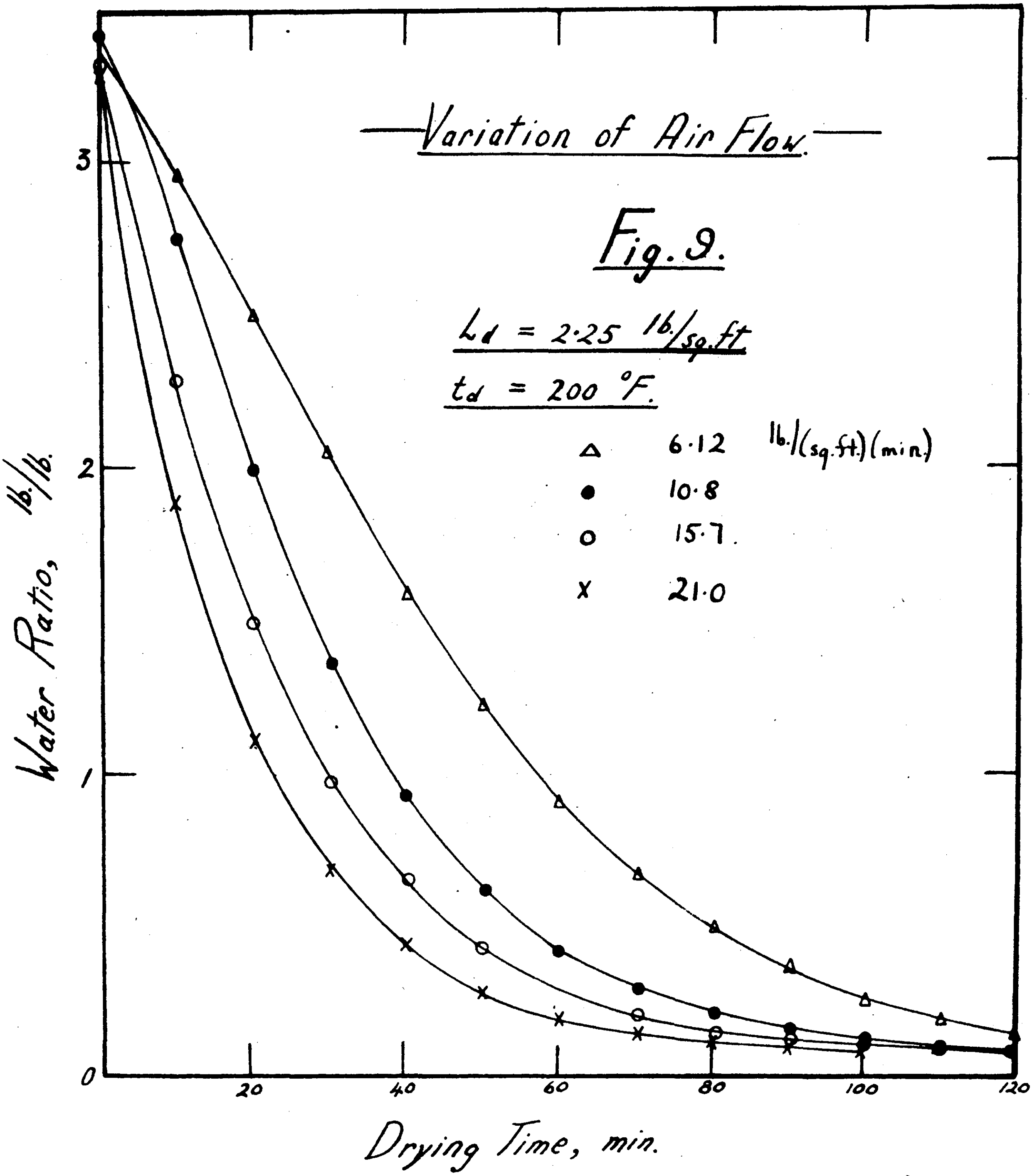
$$\frac{\partial T}{\partial \theta}_c = 0.40\ G. \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

(cf. brewers' spent grain)

<u>Effect of Varying Temperature</u>.

Bed Depth = 4 in. = 2.25 lb.B.D.S./sq.ft. G = 10.8 lb.d.a./(sq.ft.)(min).

Temperature = 140 to 200°F.


Variation of Air Flow.
Fig. 9.
Ld = 2·25 lb./sq.ft
td = 200 °F.
△ 6·12 lb./(sq.ft.)(min.)
● 10·8
○ 15·7.
x 21·0
Water Ratio, lb./lb.
0
1
2
3
20
40
60
80
100
120
Drying Time, min.

The test results have been plotted on Fig.10 Temperature, as in the shallow layer tests, affects the drying rate throughout the whole test, both by evaporating more water from the surface as the temperature rises, and by increasing heat transfer and internal diffusion of moisture. There is a likelihood of some proportionality between θ, the drying time between definite moisture ratios, and the wet bulb depression. i.e. $\theta \propto (td - tw)$ for moisture contents above 0.15.

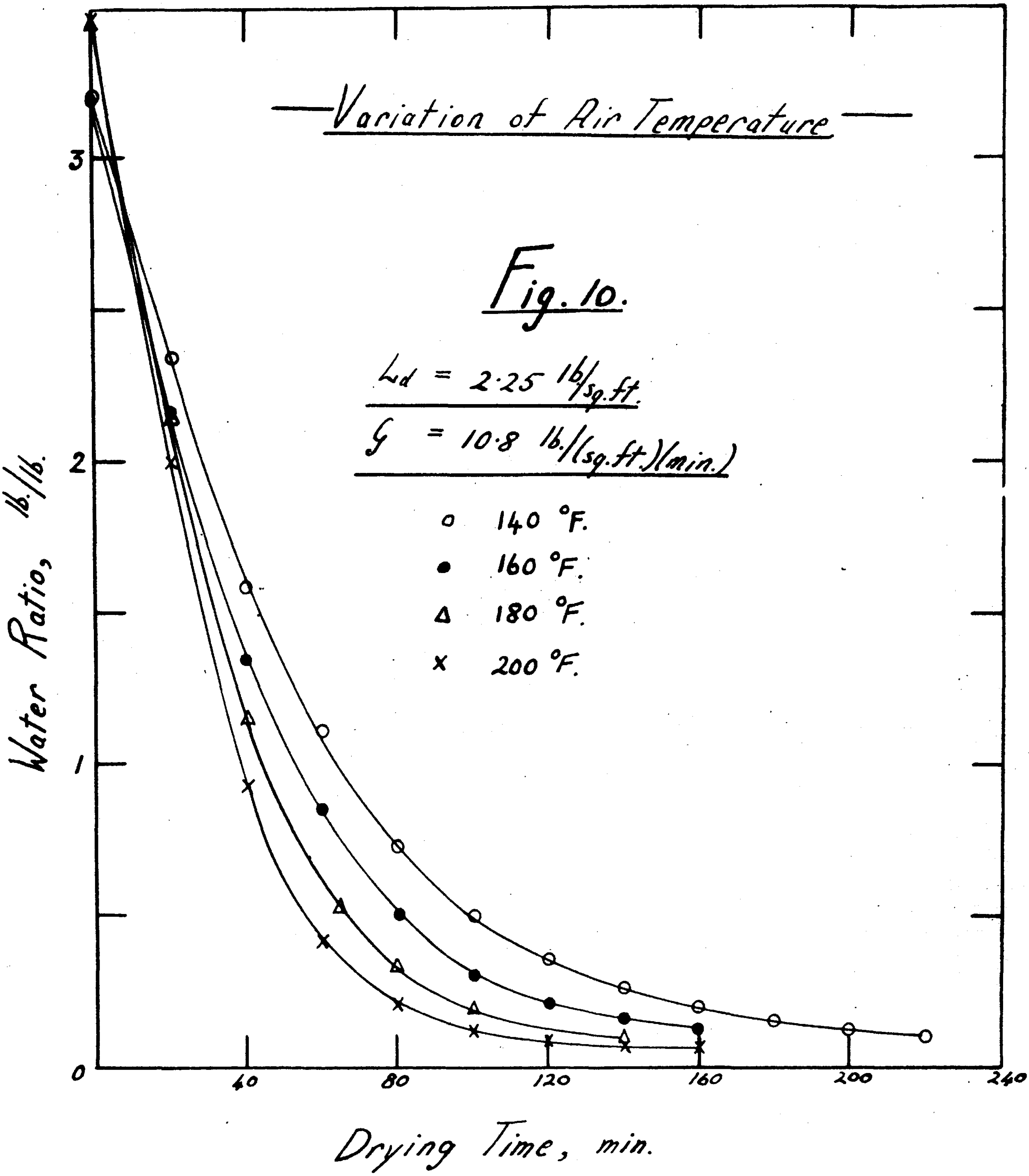
Comparison Between

Comparison Between Predicted and Actual Drying Times.

The method adopted for prediction rates is the same as that used for brewers' spent grain and again the second rate constant was neglected for the range of moisture ratios 3.5 to 0.1. Below this latter value, m_2 would be brought into use. For tests in which there is no constant rate drying period, slight modifications must be made to the prediction method. In such cases there is no critical moisture content, and the air will not be saturated, hence the outlet temperature will be higher than if a constant rate period occurred. Thus the rate constant will be lower, resulting in higher prediction times. The modified rate-constant value was found by substituting the value of the initial moisture ratio in the equation

$$T_1 = \frac{G \times (H_o - H_1)}{m \times L_d}$$

Results. Drying from 3.5 to 0.1 * No constant rate period.


Variation of Air Temperature
Fig. 10.
L_d = 2.25 lb/sq.ft.
G = 10.8 lb./(sq.ft.)(min.)
○ 140 °F.
● 160 °F.
△ 180 °F.
× 200 °F.
Water Ratio, lb./lb.
3
2
1
0
40
80
120
160
200
240
Drying Time, min.

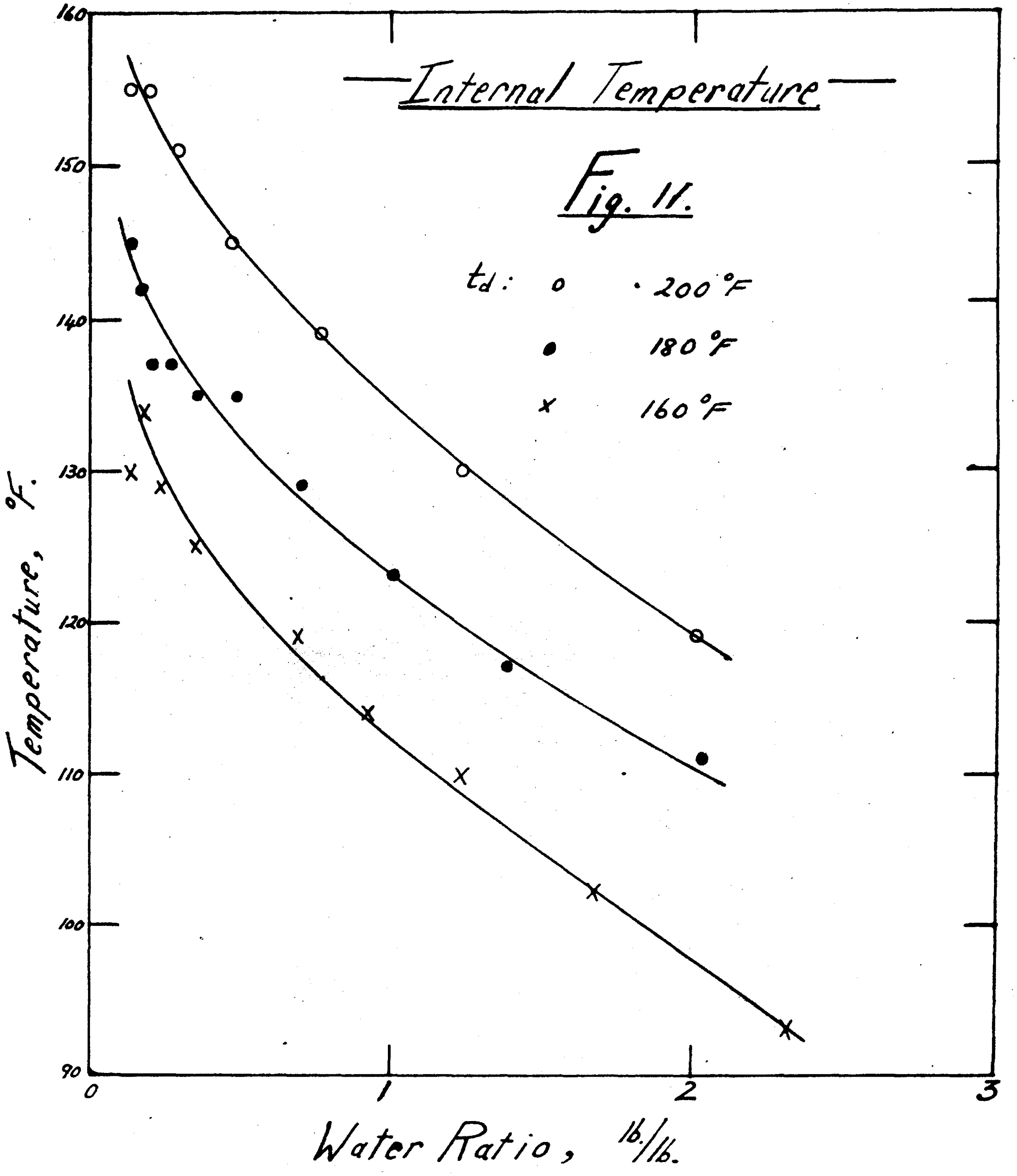
Bed.	Ld.	G	td	tw	θ_a	θ_p	% error.
4 in.	2.234	10.8	200	99	115	131.5	+ 14.36
5 in.	3.149	10.8	220	99.5	115	111	- 3.5
6 in.	3.789	10.8	200	98.5	128	132	+ 3.1
9 in.	6.075	10.8	200	98	150	150.8	+ 0.5
4 in.	2.315	6.12	200	98.5	131	142	+ 8.4
* 4 in.	2.323	15.7	200	96	102	193.6	- 8.2
* 4 in.	2.248	10.8	180	91	137	158	+ 15.3
* 4 in.	2.327	10.8	160	86	170	171	+ 0.59
* 4 in.	2.357	10.8	140	82.5	220	240	+ 9.1

Observations of Caramelisation

A few tests were conducted to find evidence of this sugar loss, in the range where caramelisation is first in evidence, i.e., at temperatures of 190, 200, 210 and 220°F. Each test was continued until some of the pieces showed signs of browning, these pieces then being selected for moisture content determination. It was found that only in the experiments at 210°F and 220°F after 80 minutes of drying was there any degree of caramelisation, although if the test at 200°F was continued for upwards of 2½ hours, some pieces showed the characteristic signs. The moisture content of the pieces which showed such signs was between 4 and 5%.

Internal Temperature of Material.

It has been stated that sugar beet is the type of material where heat is not easily conducted to the interior. In order to verify this the internal temperature of the cossettes was measured throughout some typical drying runs. The readings of weight, temperature, and air velocity were made at the usual time intervals, and before each weighing the internal temperature was taken by inserting a calibrated thermocouple into the cossettes. A time-temperature graph was obtained from milli-voltmeter readings and by extrapolating the curve to zero time the temperature, corresponding to the particular moisture content, was found. From Fig. 11, it can be seen that the temperature drop between the surface and the interior of the piece is large, much greater than for many other vegetable materials, although in some cases where a tough outer skin is formed during drying, the temperature difference may be of similar proportions.



Internal Temperature
Fig. 11.
t_d: o 200 °F
• 180 °F
x 160 °F
Temperature, °F.
160
150
140
130
120
110
100
90
0
1
2
3
Water Ratio, lb./lb.

SECTION VI

EXPERIMENTAL WORK.

Through-circulation drying of Carrots.

Introduction

Processes for preserving vegetables must create and maintain conditions in which they will remain stable, and it is difficult to accomplish this without causing some abnormality at one stage or another. Quick freezing can arrest physiological changes, but this is a difficult technical problem, while it destroys the make up of the material without, in fact, inactivating all unstable chemical sbustances which may be inherent. These can undergo slow oxidation or other changes in the frozen state and can react rapidly on thawing. Some of these difficulties also arise in dehydration where the water is evaporated, instead of being rendered less available by freezing. The temperature of the drying air must be below some critical value above which the material is unstable and readily oxidisable, but if the temperature is too low, there will be sufficient time for chemical changes or for the growth of micro-organisms. The temperature must therefore be closely controlled. Damage to the material must also be kept to a minimum when subdividing it. It has been found that it is in the borderland between the raw and cooked states that abnormal chemical activity occurs, and to cross this region quickly, scalding or immersion in boiling water, is carried out for a few minutes.

Hearne and Tapsfield,[83] with dehydrated potato, and Gooding and Tucker,[84] with dehydrated carrot, have noted the possibility of in-package desiccation for reducing the moisture content below the normal 5% and hence increasing storage life.

The/

The outstanding value of carrots as food lies in their very high content of pro-vitamin A (β-carotene). They contain about 6% of sugar and moderate amounts of iron, calcium and vitamin B_1, but have little value as anti-scorbutics. In processing carrots, the aim is to avoid the leaching out of sugars, the most important soluble nutrients, and to preserve culinary quality and the pro-vitamin A.

An analysis of raw carrot showed the following composition:-

Water..............	88.2%	Ash...............	1.0%
Protein............	1.2%	Carbohydrates.....	8.3%
Fat................	0.2%	Fibre.............	1.1%

Preparation.

The material was thoroughly washed and peeled, in this case by scraping. The peeled and trimmed root was cut into suitable sizes of pieces, according to requirements. The pieces were then immersed in boiling water for five minutes, taken out, and the water drained from the pieces. The scalding water was used for subsequent batches of carrots to prevent excessive leaching-out of sugars. The best way to prevent such loss is by scalding in steam[28]. Gooding[85] has shown that losses are thus cut down by more than 50%, although the appearance of steam scalded dehydrated carrot is unattractive compared with water scalded material. About 0.25% of sodium phosphate was added/

added to the scalding water to prevent darkening of the carrots because of the presence of iron in the scalding liquor[77].

Storage Properties.

The main cause of deterioration is the loss of carotene. The smaller the size of the pieces, then the more surface area is presented to the air and the more deterioration there is. Dried carrot powder freely exposed to the air at ordinary temperatures loses its carotene completely in about 100 days, through oxidation to β-ionone, and its colour becomes pale brown. It has been found[7] that the storage life of dried carrot is prolonged considerably through protection of carotene by the addition of 2½% of starch to the scald water.

Single Layer Tests.

Effect of Shape and Size of Piece. G = 11.28 lb.d.a./(sq.ft. min.)

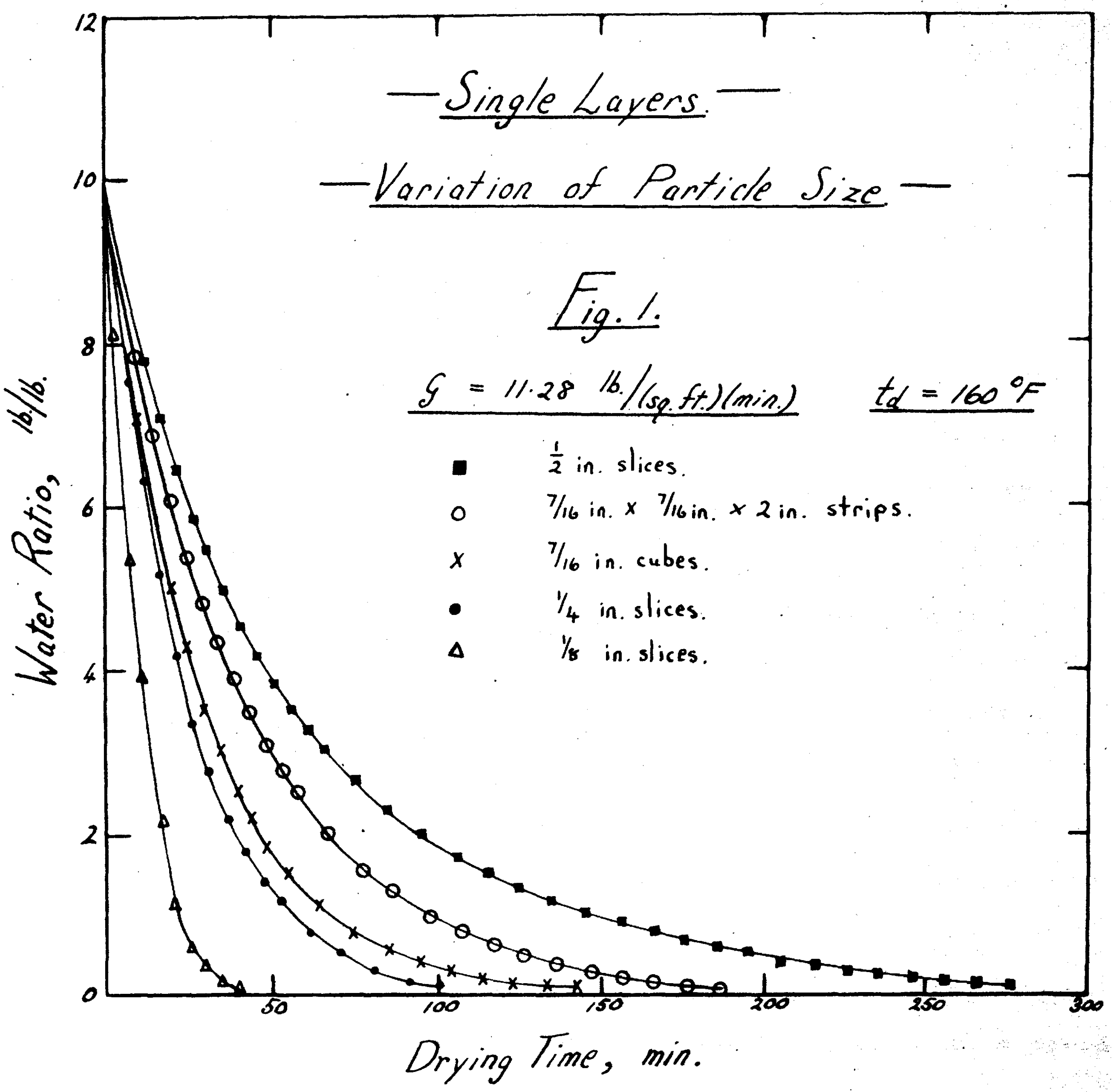
Temperature = 160°F.

Drying curves for five different sizes of carrot pieces are given in Fig. 1. It is plain that a small difference in size can cause a very large change in the drying time. It has been shown that for certain materials the effect of change of thickness may vary, according to the drying law governing.

By Diffusional law $\theta_f = \frac{4L^2}{D\pi^2} \log_e \left(\frac{Tc - Te}{T - Te}\right)$ ....(1)

(i.e. Drying time proportional to the square of the thickness)

By Proportionality/



—Single Layers.—
—Variation of Particle Size—
Fig. 1.
G = 11.28 lb./(sq.ft.)(min.)
td = 160 °F
1/2 in. slices.
7/16 in. x 7/16 in. x 2 in. strips.
7/16 in. cubes.
1/4 in. slices.
1/8 in. slices.
Water Ratio, lb./lb.
Drying Time, min.
0
2
4
6
8
10
12
50
100
150
200
250
300

By Proportionality

$$\theta_f = \frac{Ps\ L}{h_t} \frac{(Tc - Te)}{(Ta - Ts)} \log_e \frac{(Tc - Te)}{(T - Te)} \quad \text{........(2)}$$

(i.e. Drying time proportional to the thickness).

The time of drying of carrot slices from a moisture ratio of 8 down to 0.1 is proportional to the 1.42 power of the thickness in the range of thickness 1/8 in. to ½ in. The results of Ede and Hales[30] show a somewhat similar relation although the drying times in their work were greater. McEwen et al.[46] found that there was strict proportionality between drying time and particle diameter, in the drying of wheatgrain. For the drying of seaweed stipe, Gardner and Mitchell[40] found the drying time in deep beds varied as the 0.523 power of the thickness. Although the total surface was not exposed to the air stream, these workers considered that the fractional amount exposed was possibly similar in each case and that, therefore, it was possible to compare the effect of slice thickness with a certain degree of accuracy. Marshall and Friedman[55] have drawn up a table of materials obeying the above two laws, but vegetables are not included in the table. The behaviour of different piece sizes of vegetable is difficult to assess. It must be noted that the original dimensions of the material are not necessarily the controlling factors in the rate of drying. It is the thickness of the nearly dry pieces which is often important; thus, if

carrot/

carrot dice and potato dice of exactly the same initial size are compared, there is only about half as much solid matter in a carrot piece; if therefore the composition of the materials were otherwise identical, as drying nears completion the potato piece would be much thicker and diffusion would be much more gradual.

The effect of length of strip is also evident from Fig. 1 7/16 in. cubes and 7/16 in. x 7/16 in. x 2 in. strips were compared. The drying time showed an increase of about 30% in the initial stages of drying. The decrease of surface area obtained by joining cubes to form long strips is of the same order (27%). This is to be expected for the initial stages of drying where surface evaporation is taking place. It has been mentioned[5] that in view of the extreme distortion of vegetables upon drying, and the occasional formation of internal shrinkage holes, there is no point in attempting theoretical calculation of comparative drying rates in the low moisture range.

It was decided, to use the 7/16 in. cubes for later tests. This size differs from that used by the Services (Strips

of 3/16 in. x 5/16 in. cross section), adopted mainly because of the ease of reconstitution. It was found that 7/16 in. cubes reconstituted satisfactorily although it must be emphasised that no comparisons were made with other sizes.

Effect of Temperature.

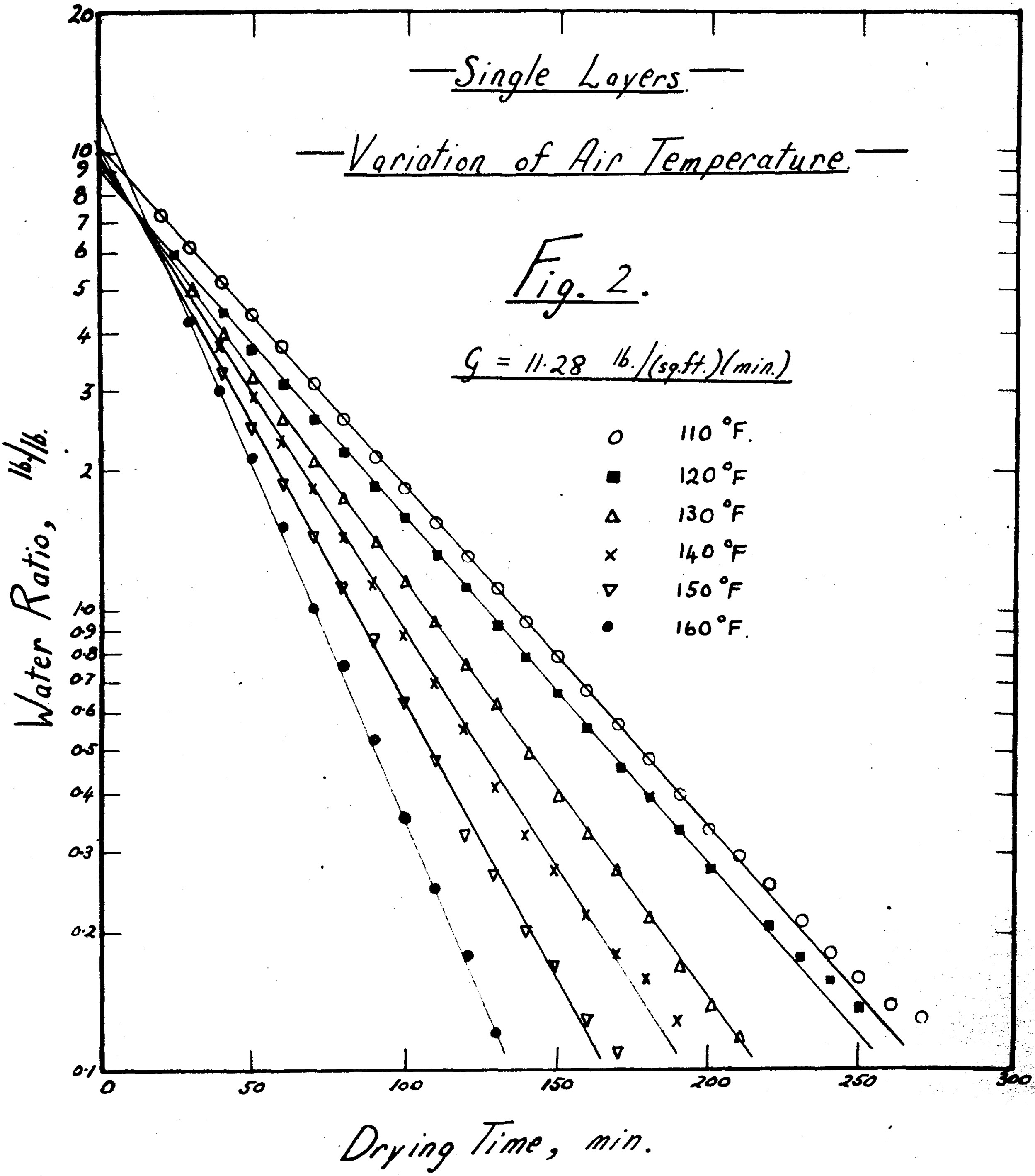
(1) Varying dry bulb temperature: 110, 120, 130, 140, 150, 160°F. G = 11.28 lb/(sq.ft.)(min.)

Von/

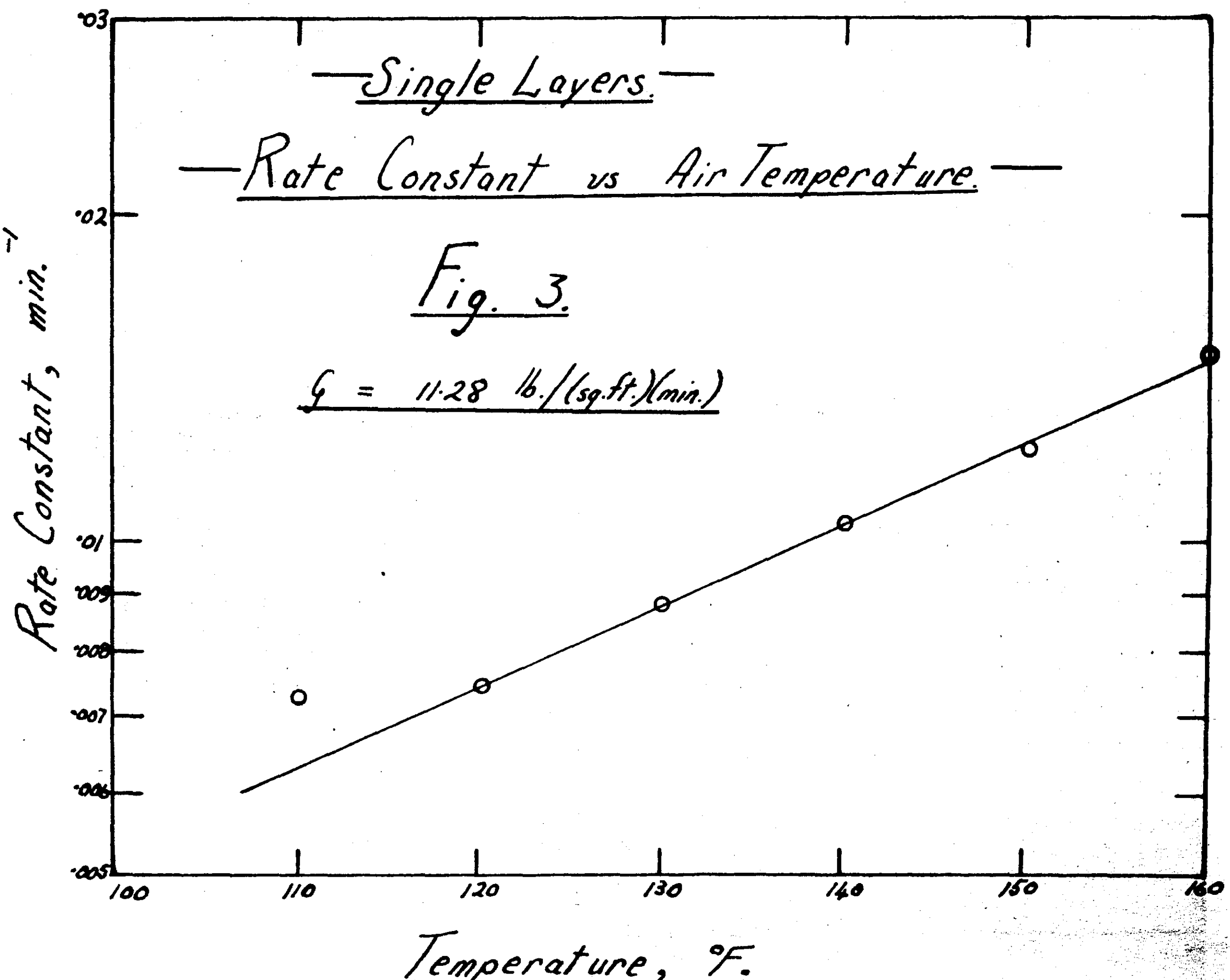
Von Loesecke[37] states that at no time should the temperature of the product exceed 165°F, although Gooding and Rolfe[86] now regard this as being excessively high. This means that the actual drying temperature could remain above this value for a large part of the drying time, since it is only in the low moisture range that the dry bulb temperature and the surface temperature of the pieces approach coincidence. It is much safer to keep the temperature below the critical at all times, to ensure reliability of product quantity. The air temperature was therefore set at a maximum of 160°F.

Ede and Hales used a wet-bulb depression method of correlating drying data for carrot strips, and for the calculation of probable drying times. This method proves to be somewhat approximate, especially when the drying times to moisture contents below 0.2 are required. The method of solution used by McEwen et al and found to hold for other work on brewers' spent grain and sugar beet is simple and of known accuracy (under 10-15% error). This method is certainly accurate for these materials down to a moisture ratio of 0.1, and is fairly accurate below this in deep bed prediction times. With such a solution in mind, the carrot cubes were dried at temperatures ranging from 110 to 160°F, at constant air humidity and velocity. The results are plotted in Fig.2, showing the straight line relation holding, from a semi-logarithmic plot of moisture ratio vs drying time.

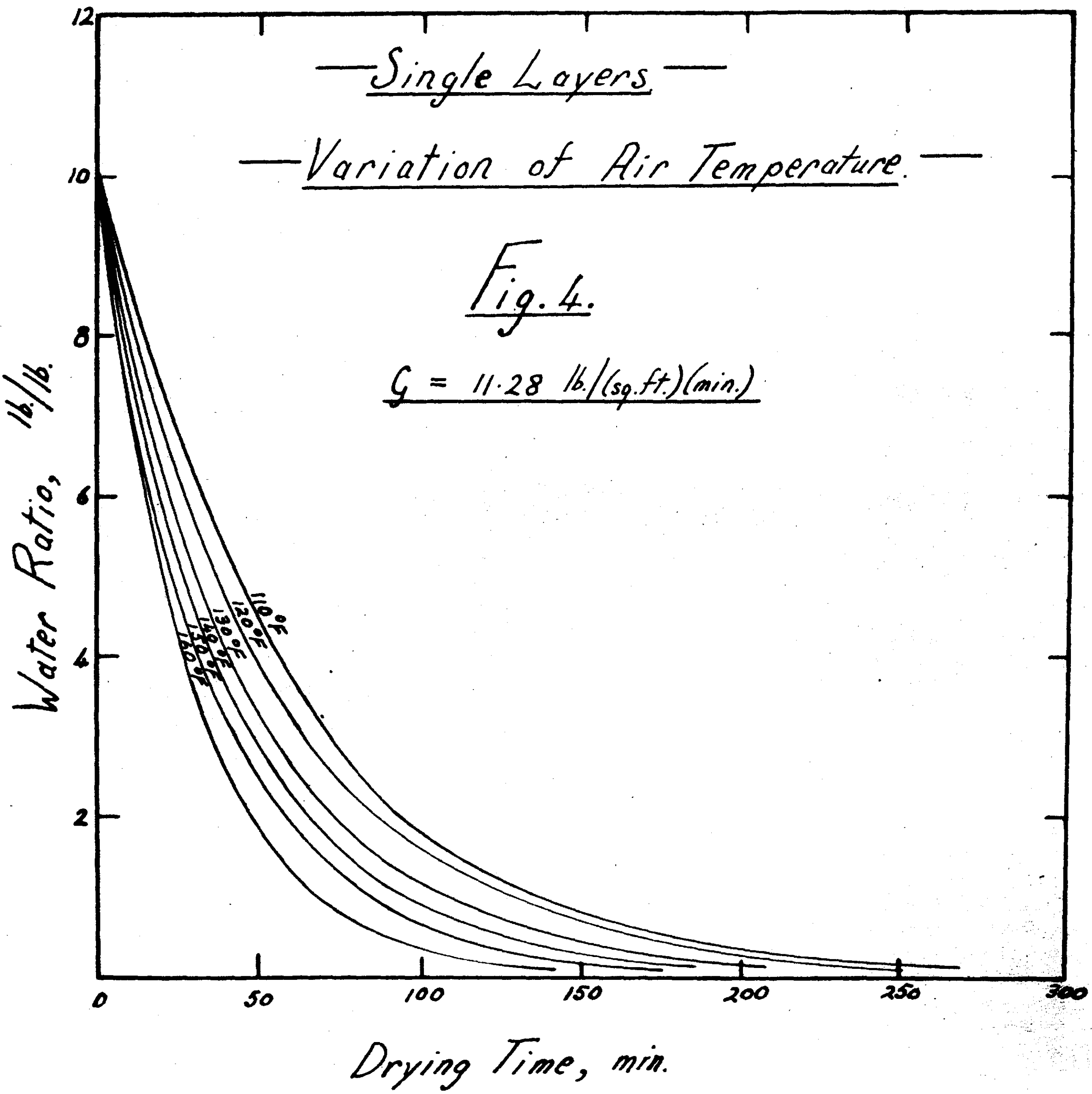
The/



—Single Layers—
—Variation of Air Temperature—
Fig. 2.
G = 11.28 lb./(sq.ft.)(min.)
110 °F.
120 °F
130 °F
140 °F
150 °F
160 °F.
Water Ratio, lb./lb.
Drying Time, min.
20
10
9
8
7
6
5
4
3
2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50
100
150
200
250
300



Single Layers.
Rate Constant vs Air Temperature.
Fig. 3.
G = 11·28 lb./(sq.ft.)(min.)
Rate Constant, min.⁻¹
·03
·02
·01
·009
·008
·007
·006
·005
100
110
120
130
140
150
160
Temperature, °F.



—Single Layers—
—Variation of Air Temperature.—
Fig. 4.
G = 11.28 lb./(sq.ft.)(min.)
110 °F
120 °F
130 °F
140 °F
150 °F
160 °F
Water Ratio, lb./lb.
0
2
4
6
8
10
12
0
50
100
150
200
250
300
Drying Time, min.

the controlling influence. Ede and Hales and Gardner and Mitchell have reported proportionality at moisture levels above 0.2, whereas McEwen et al found that there was no correlation between the drying rate at any moisture content and the wet bulb depression (td - tw). Perry, Guillou,[34,35] and their co-workers showed that the drying rate of prunes above a moisture ratio of 0.2 is substantially independent of wet-bulb depression provided the relative humidity is below 40%. It has been noted[30,34] that the drying rates of common vegetables below a moisture content of 0.10 to 0.20 are little affected by wet bulb depression. To investigate this further, a few confirmatory tests were carried out.

(3) <u>Different dry bulb temperatures. Constant Wet bulb depression.</u>

Table II

td	tw	H_i	θ (10 - 0.5)	θ (0.5 - 0.12)	θ (10 - 6)
140	90	0.019	138	92	22
150	100	0.0306	125	75	21
160	110	0.0462	110	65	20
170	120	0.0678	107	63	21

There is a difference in drying time at most moisture levels due to change of dry bulb temperature. It is clear/

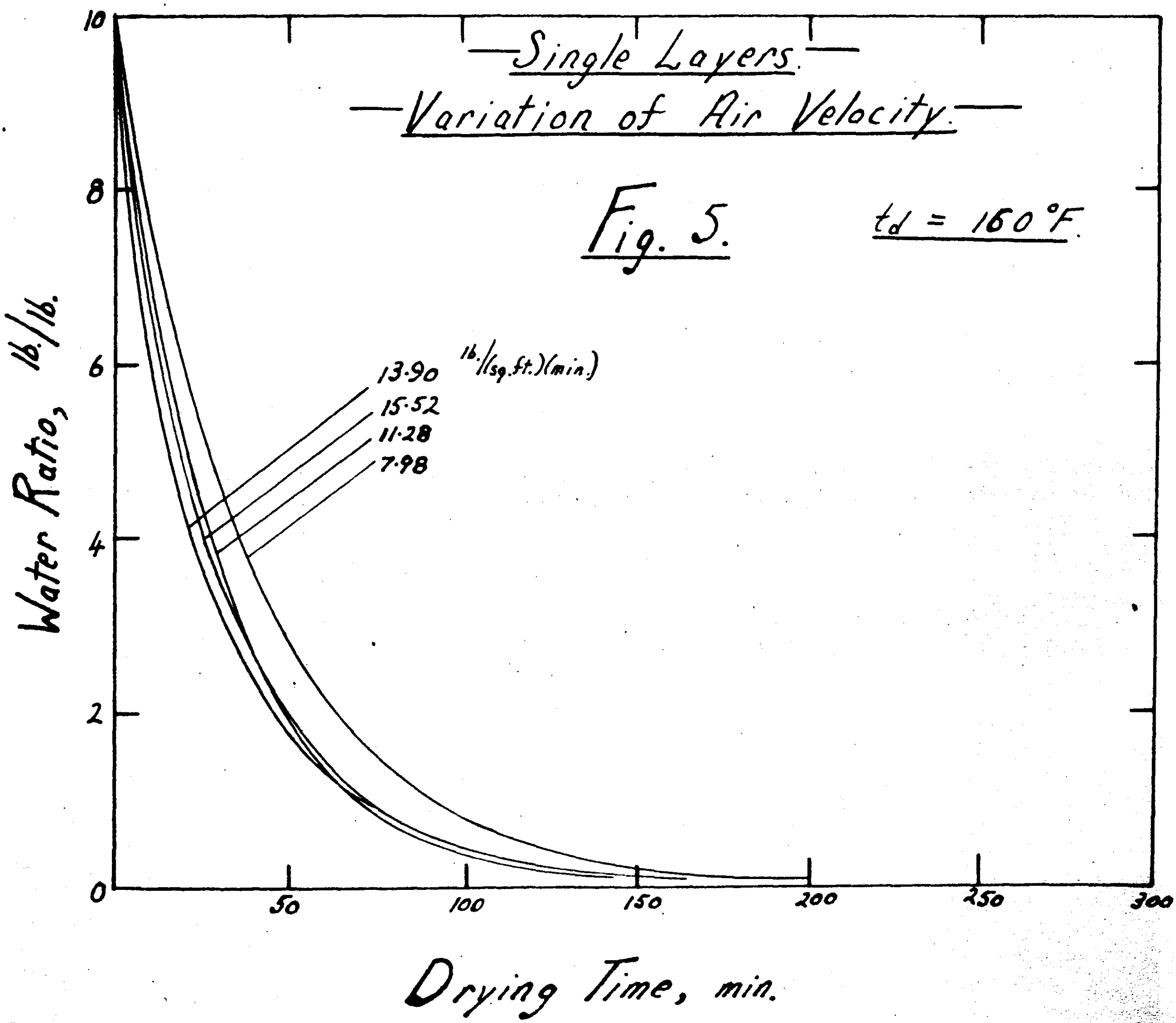
clear from the results of the two series that wet bulb depression has an affect only during free evaporation at a surface. In this series, although the wet bulb depression is constant, the drying times vary considerably, below a moisture ratio of 6.0. The drying time between T = 10 and T = 6 is almost constant indicating the validity of a relation such as that used by Ede and Hales. It may be better in this instance to use a vapour pressure correlation of the type used in the drying of wheatgrain. Examination of Table I shows that only a large increase in the value of the absolute humidity of the drying air effects a substantial decrease of drying rate. The effect is small in comparison with the effect of dry bulb temperature change, and it is thus possible to predict the drying time from a knowledge of the dry bulb temperature alone, provided that exceptionally high humidities do not occur.

<u>Effect of Air Velocity.</u>

G = 8, 11.28, 13.90, 15.52 lb.d.a./(sq.ft.)(min)

t_d = 160°F.

[illegible] An analysis of the results shows that a two-fold increase of air velocity effects a percentage decrease in drying time between T = 10 - 0.14 of 8% over the whole test and over the lower moisture range shows an even smaller/



Single Layers.
Variation of Air Velocity.
Fig. 5.
td = 160 °F.
13·90 lb./(sq.ft.)(min.)
15·52
11·28
7·98
Water Ratio, lb./lb.
Drying Time, min.
0
2
4
6
8
10
50
100
150
200
250
300

smaller change. Therefore if drying is continued to low moisture ratios, this percentage variation will decrease still more and have but small effect. However, some allowance can be made for the change in the value of the rate constant from the figures quoted in Table III.

Table III.

G	td	tw	θ (10 - 0.14)
7.98	160	84	162
11.28	160	90	165
13.90	160	82	149
15.52	160	82	148

The test at G = 11.28 was at slightly higher humidity and on a different batch of carrots. This probably accounts for the unexpected increase in drying time. Disregarding this reading it seems that there may be no advantage in increasing the velocity beyond a value of about 14 lb.d.a./(sq.ft.)(min). This cannot be taken as conclusive, but similar observations have been made on wheatgrain, seaweed and other materials.

Deep Bed Tests

Effect of Loading

Diced carrots (7/16 in.cubes) were dried by air at 160° F and an air mass velocity of 11.28 lb.d.a./(sq.ft.)(min). The bed depths investigated were a single layer, a double layer

2 in/

2 in., 3 in. and 4 in. layers.

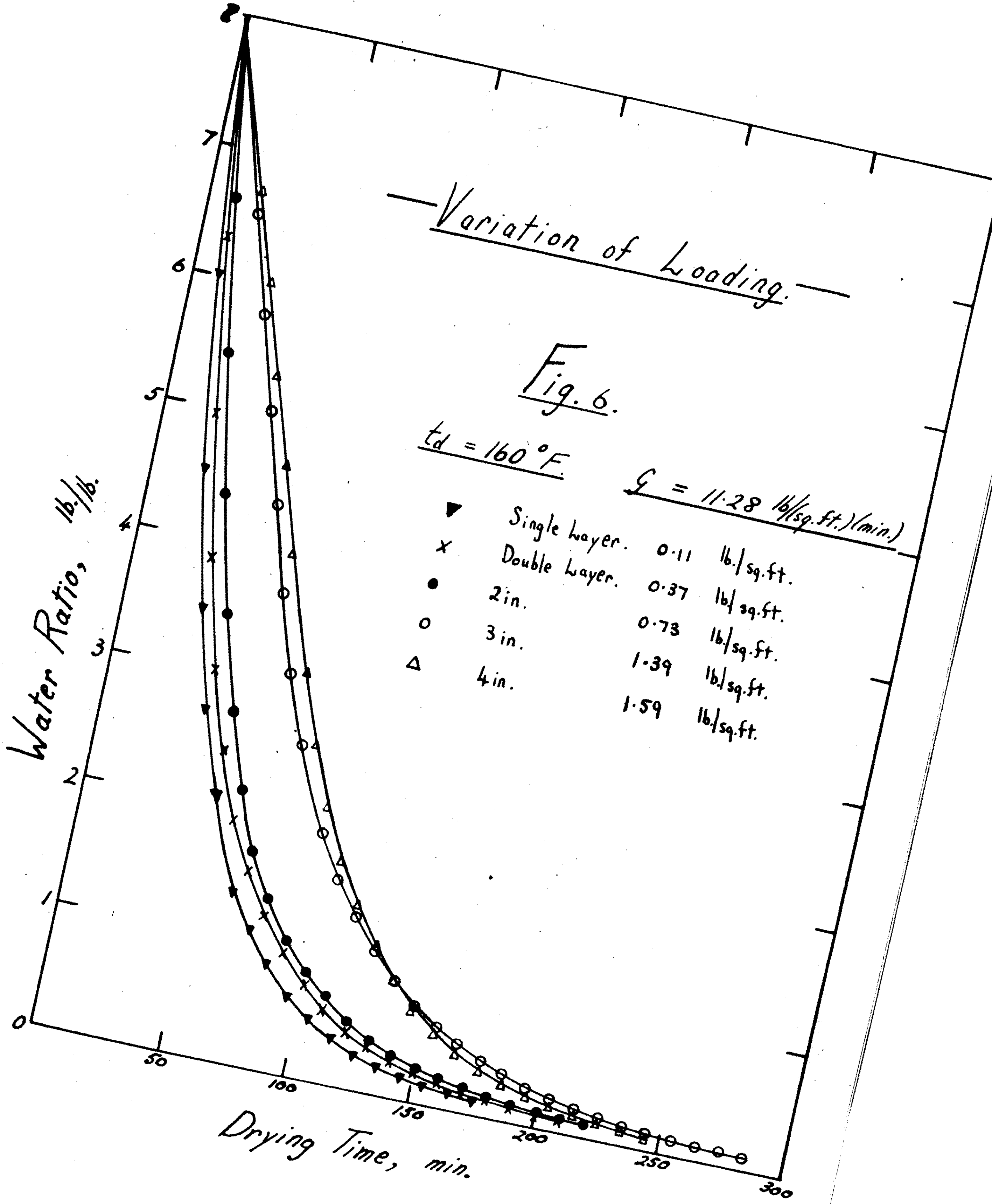
Drying times varied considerably from the single layer to the 4 in. layer owing to the occurrence of a constant rate drying period at bed dppths of over 2 inches. It is noted from Fig.6 that the 3 in. bed took longer to dry than the 4 in. bed. This was apparently due to using a different batch of carrots in this one test alone, which were obtained towards the end of the season and were rather dried up. They had a moisture content lower than the other batches even when scalded, and had a tougher core.

No correlation was attempted for deep beds, since many more tests are required. The few tests carried out were used to check the prediction method as outlined by McEwen et al and used for brewers spent grain and sugar beet.

The comparison of predicted drying times and actual drying times is given in Table IV. Agreement is to within 10%. Because of air bypassing the bed in the deep bed tests, a saturation efficiency of 70% was obtained. It is possible that the air flow was also too high for saturation to occur, for it is not essential that exit air saturation takes place during a constant rate period.

<u>Effect of Agitation.</u>

A test was made on a 2in. bed of diced carrots to find/



Variation of Loading.
Fig. 6.
td = 160 °F.
G = 11·28 lb/(sq.ft.)(min.)
Single Layer. 0·11 lb./sq.ft.
Double Layer. 0·37 lb./sq.ft.
2 in. 0·73 lb./sq.ft.
3 in. 1·39 lb./sq.ft.
4 in. 1·59 lb./sq.ft.
Water Ratio, lb./lb.
Drying Time, min.
0
1
2
3
4
5
6
7
8
50
100
150
200
250
300

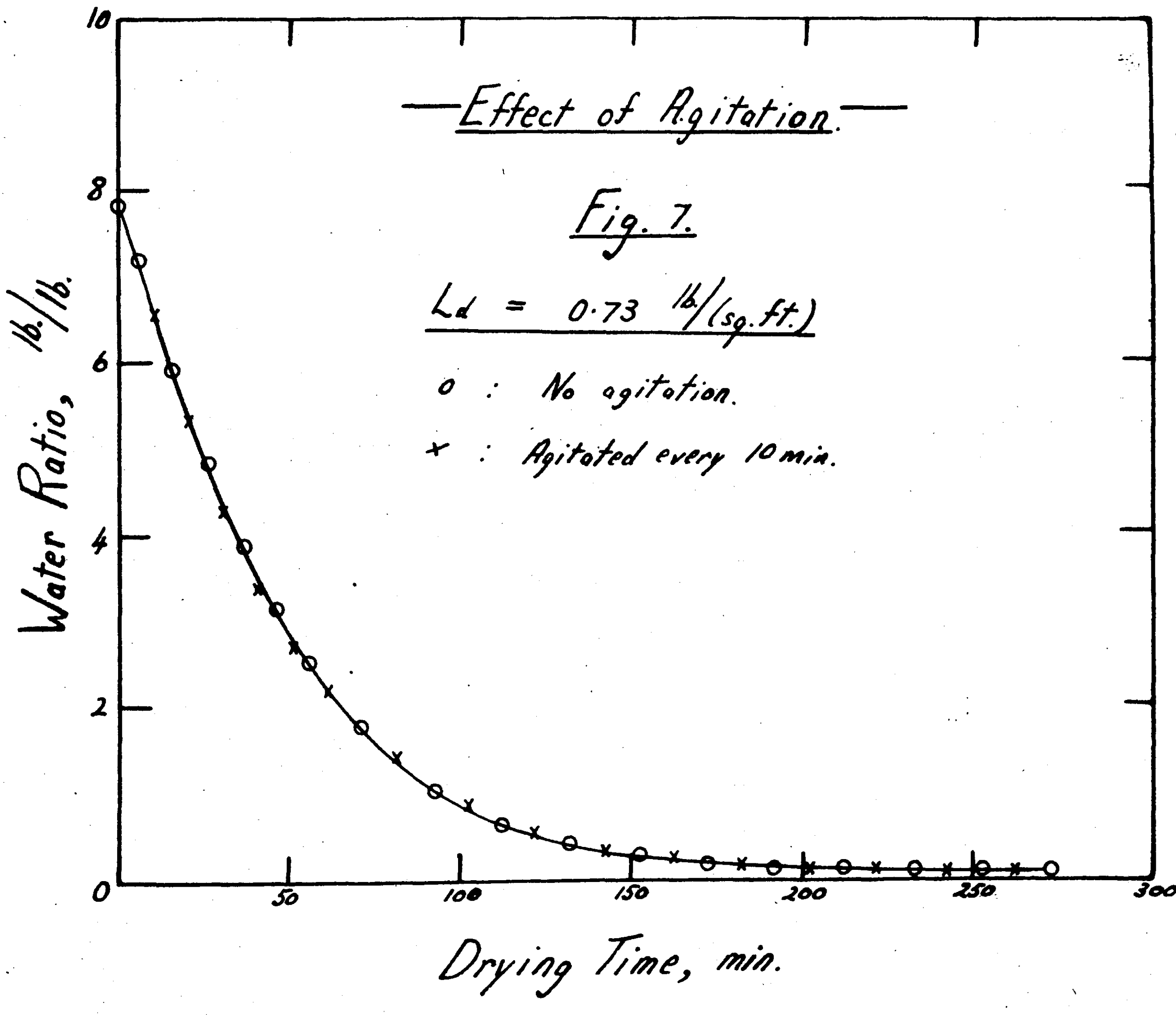
find the effect of agitation. Agitations were made by hand at 10 minute intervals from the start of the run. It can be seen from Fig.7, that the effect of agitation on the drying rate, at this level of bed depth, is negligible. It is porbable that, at very deep bed depths, agitation will expose fresh surfaces thus increasing, not the value of the constant rate, but the period over which it extends.

Prediction Times.

Table IV. (All times were taken for the range $T = 8 - 0.1$)

Bed Depth Inches.	Loading Ld. lb.B.D.S. /sq.ft.	Inlet temperatures td	Inlet temperatures tw	θ_d min.	θ_p min. (using log. mean temp.)	Error % (using log. mean temp.)	θ_p min. (using arith. mean temp.)	Erro % (using arith. mean temp.)
Double Layer	0.372	160	85.3	210	238	+13.8	231	+10
2	0.731	160	86.0	229	258	+12.6	242	+5.[illegible]
3	1.393	160	87.0	279	286.5	-3.76	253	-9.3[illegible]
4	1.59	160	85.3	254	278.7	+9.74	261	+2.7[illegible]

There is a significant difference between using the logarithmic and arithmetic mean temperatures for calculation of the rate constant, m, and the results obtained with the arithmetic mean show closer agreement between predicted and observed values.



Effect of Agitation.
Fig. 7.
Ld = 0.73 lb./(sq.ft.)
o : No agitation.
x : Agitated every 10 min.
Water Ratio, lb./lb.
Drying Time, min.
0
2
4
6
8
10
50
100
150
200
250
300

SECTION VII.

EXPERIMENTAL WORK.

Through-circulation drying of peas.

Introduction.

The drying of peas is very widely practised to prevent their decomposition and great care is taken to preserve culinary quality and colour. Blair and Ayres[79] have developed a technique, in which peas are soaked in a 2% solution of sodium carbonate for an hour before canning to improve the colour of the final product. This soaking process has been applied before dehydration with good results. Von Loesecke[2] has outlined the conditions of drying for satisfactory production of dried peas and has given the most suitable conditions of loading, temperature and humidity. Ede[80] has applied a low temperature vacuum drying process to peas, consisting of the sublimation of ice contained in the frozen material and its deposition upon a cold surface. The quality of the final product was influenced by the temperature of the material at each stage of the process. It was found possible to improve the quality by puncturing the skin, for without this there was incomplete expansion on reconstitution, giving a product of inferior quality.

McCance and Widdowson[87] give an analysis for dried peas:

Water	8.7%	Carbohydrate	21.3%
Sugar(as invert)	2.4%	Sugar(as glucose)	47.6%
Total nitrogen	3.45%		

Bitting[81] has reported the analysis of shelled peas, in three size-grades (see Table I)

TABLE I/

TABLE I.

Grade	Total Solids	Protein	Sucrose	Starch	Pento-sans	Fibre	Ash	Undetermined.
Petit Pois	14.23	3.44	0.72	5.57	0.75	1.08	1.03	1.04
Sifted	22.08	5.31	0.99	10.23	0.96	2.21	1.36	1.01
Marrow-fat	22.22	5.13	0.94	10.48	0.98	2.18	1.02	1.49

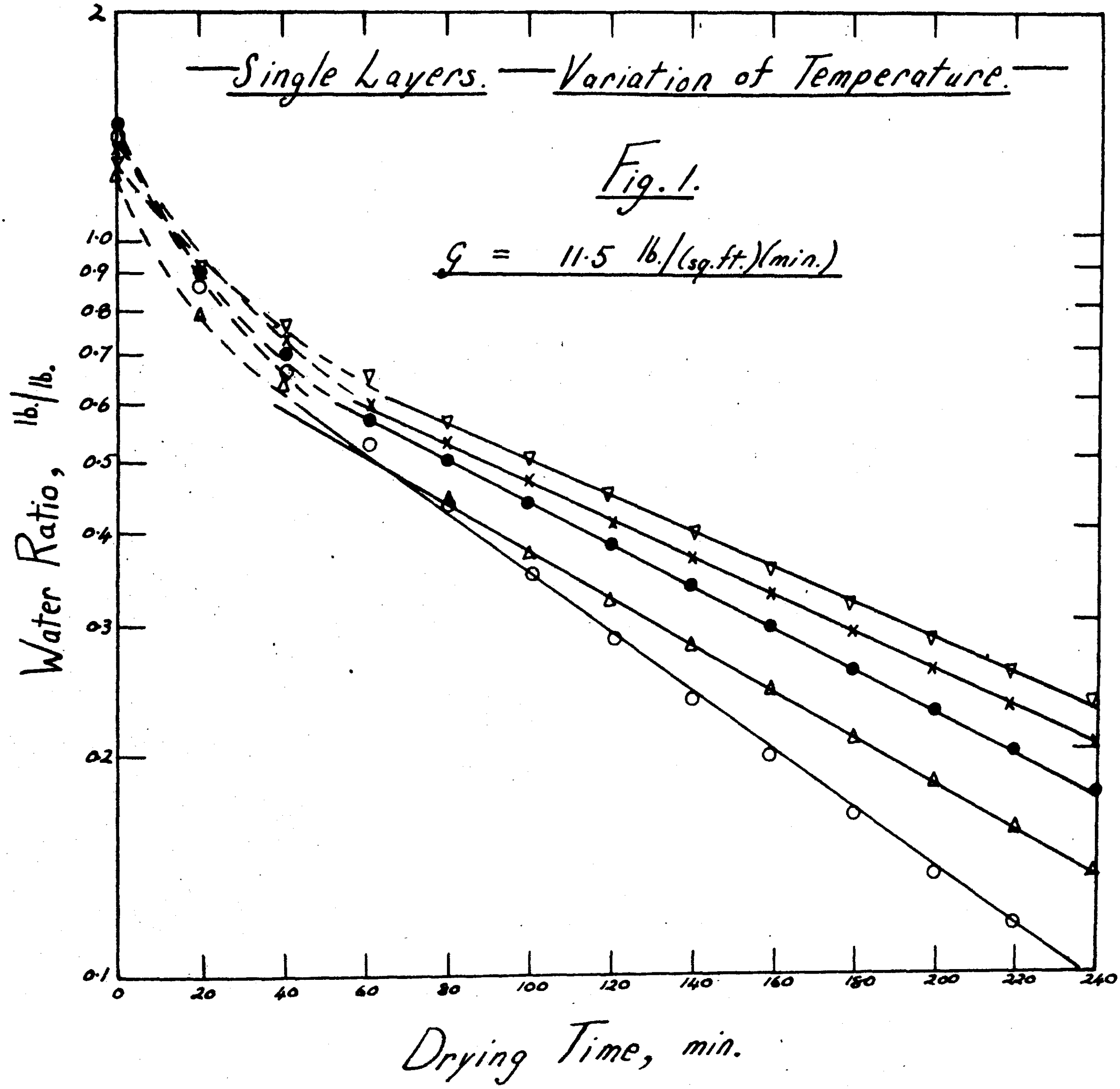
Single Layer Tests

Ede[80] has reported that carefully freeze dried peas, on reconstitution, are of the same quality as fresh peas. Unfortunately, at the time of the investigation, the only reliable supply of peas of uniform quality and size were dried peas of commerce. Those were therefore soaked and used in the drying tests. While certain fundamentals of the drying process can be found in this way, the results may not be applicable to the dehydration of fresh peas since water of rehydration is almost certainly bound in a different way from that in fresh (or scalded fresh) peas. The low water content of the cooked peas was evidence of this. However, drying tests using this material would provide a comparison with other vegetable drying conducted in the present work

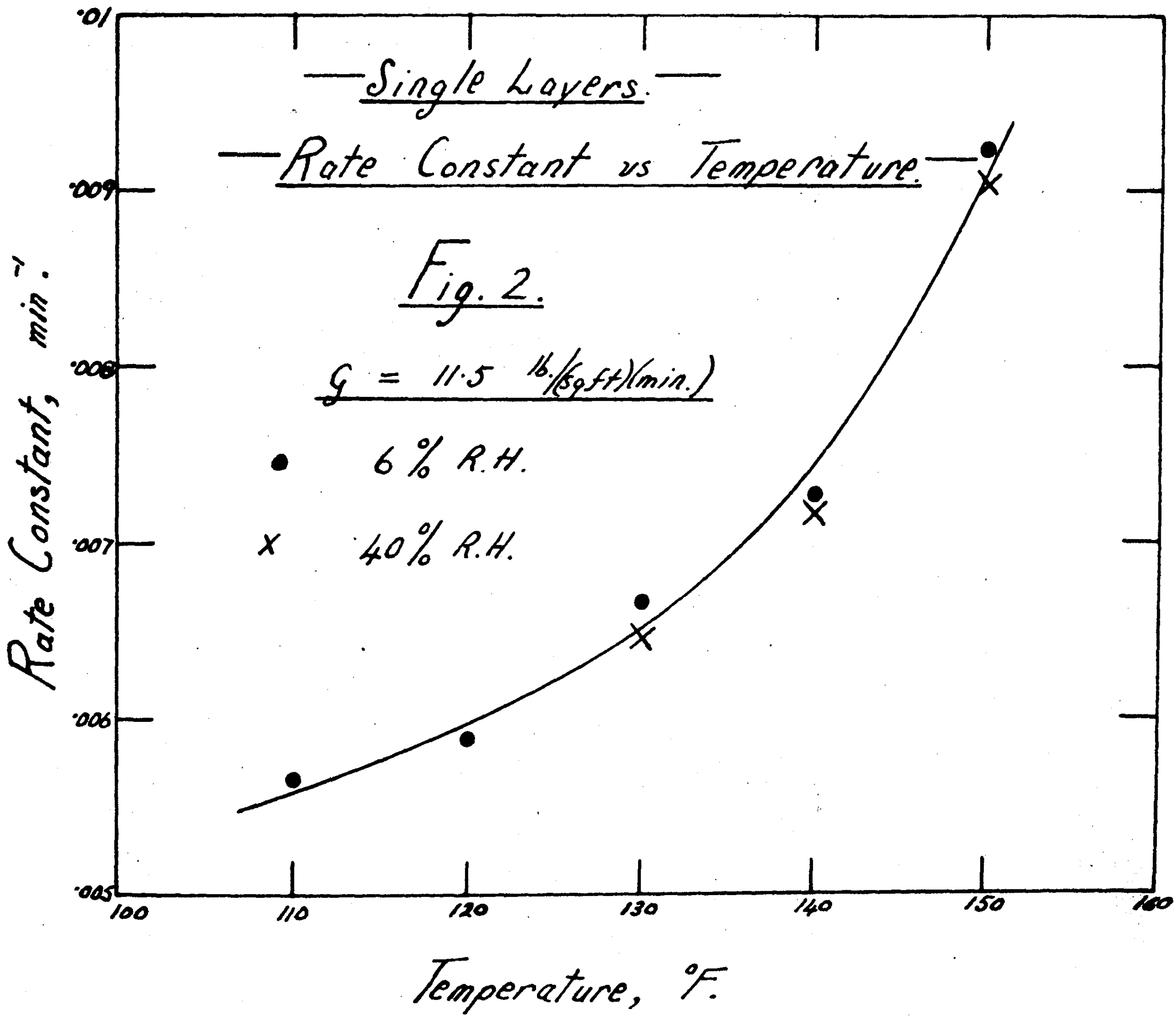
Temperature Tests

Temperature = 110 to 150°F. G = 11.5 lb.d.a./(sq.ft.)(min.)

The results are plotted in Fig.1 and Fig.2. High temperatures give high drying rates, but the product quality is poorer, because of case hardening of the skin. This results in/



—Single Layers.—Variation of Temperature.—
Fig. 1.
G = 11·5 lb./(sq.ft.)(min.)
Water Ratio, lb./lb.
Drying Time, min.
2
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
20
40
60
80
100
120
140
160
180
200
220
240


Single Layers.
Rate Constant vs Temperature.
Fig. 2.
G = 11·5 lb./(sq ft)(min.)
6% R.H.
40% R.H.
Rate Constant, min.⁻¹
·01
·009
·008
·007
·006
·005
100
110
120
130
140
150
160
Temperature, °F.

Effect of Air Velocity

Temperature = 150°F. G = 8.12, 11.5, 23 lb.d.a./(sq.ft.)(min.)

The results are plotted in Fig. 3. Increase of air velocity increases the initial drying rate when surface evaporation and skin drying occur, but does not appreciably affect the drying rate in the later stages.

The ability of the air to remove moisture is greater at higher air flows, thus increasing the initial drying rate, and since it is the rate of moisture diffusion to the surface which is the controlling factor thereafter, it is reasonable to expect that temperature of material and not air velocity will affect the drying rate.

This has been noted in the drying of wheatgrain, where drying rates were unaffected by change of air velocity[7].

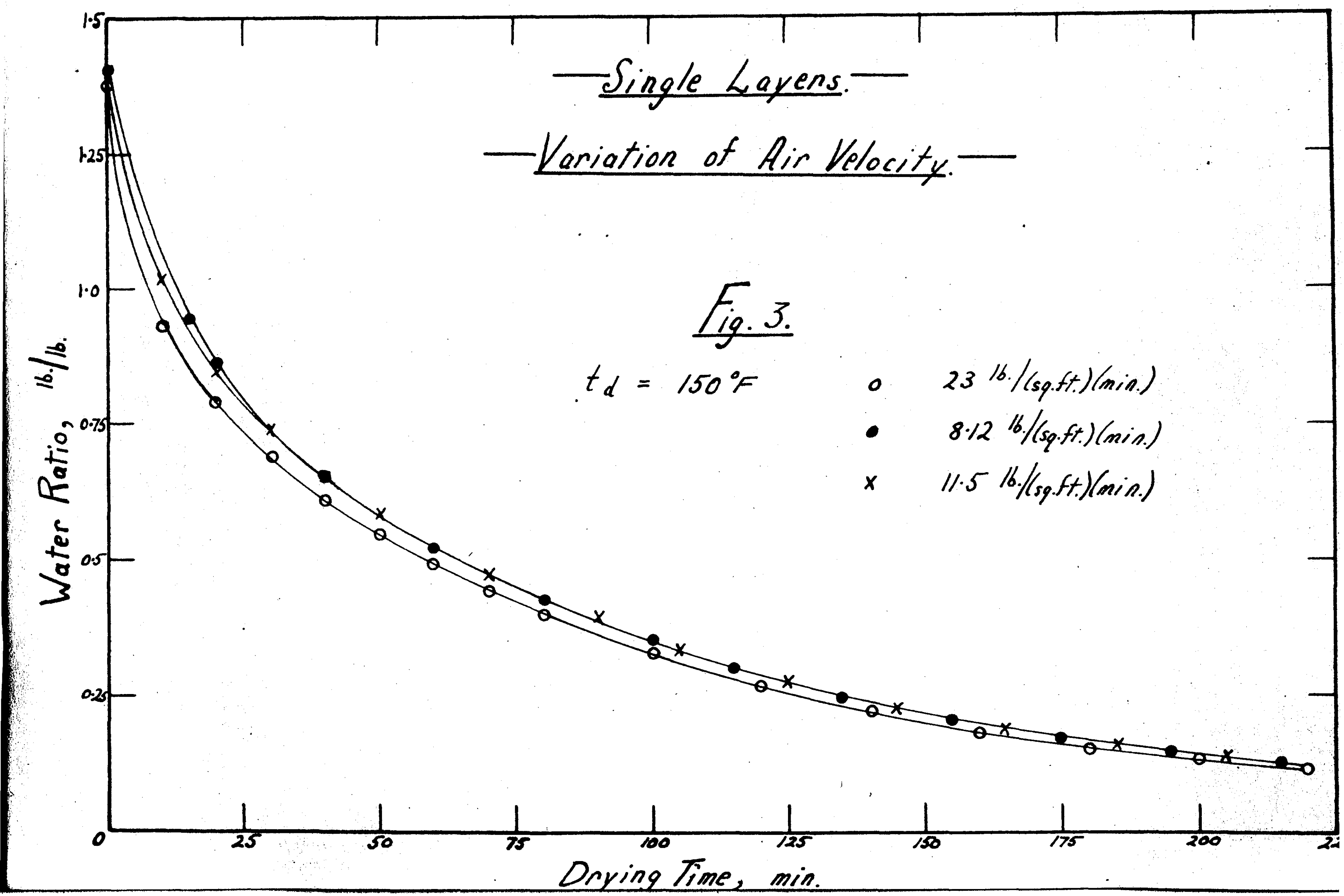
Effect of Humidity. (Fig.4)

Temperature = 130, 140, 150°F. G = 11.5 lb.d.a./(sq.ft.)(min.)

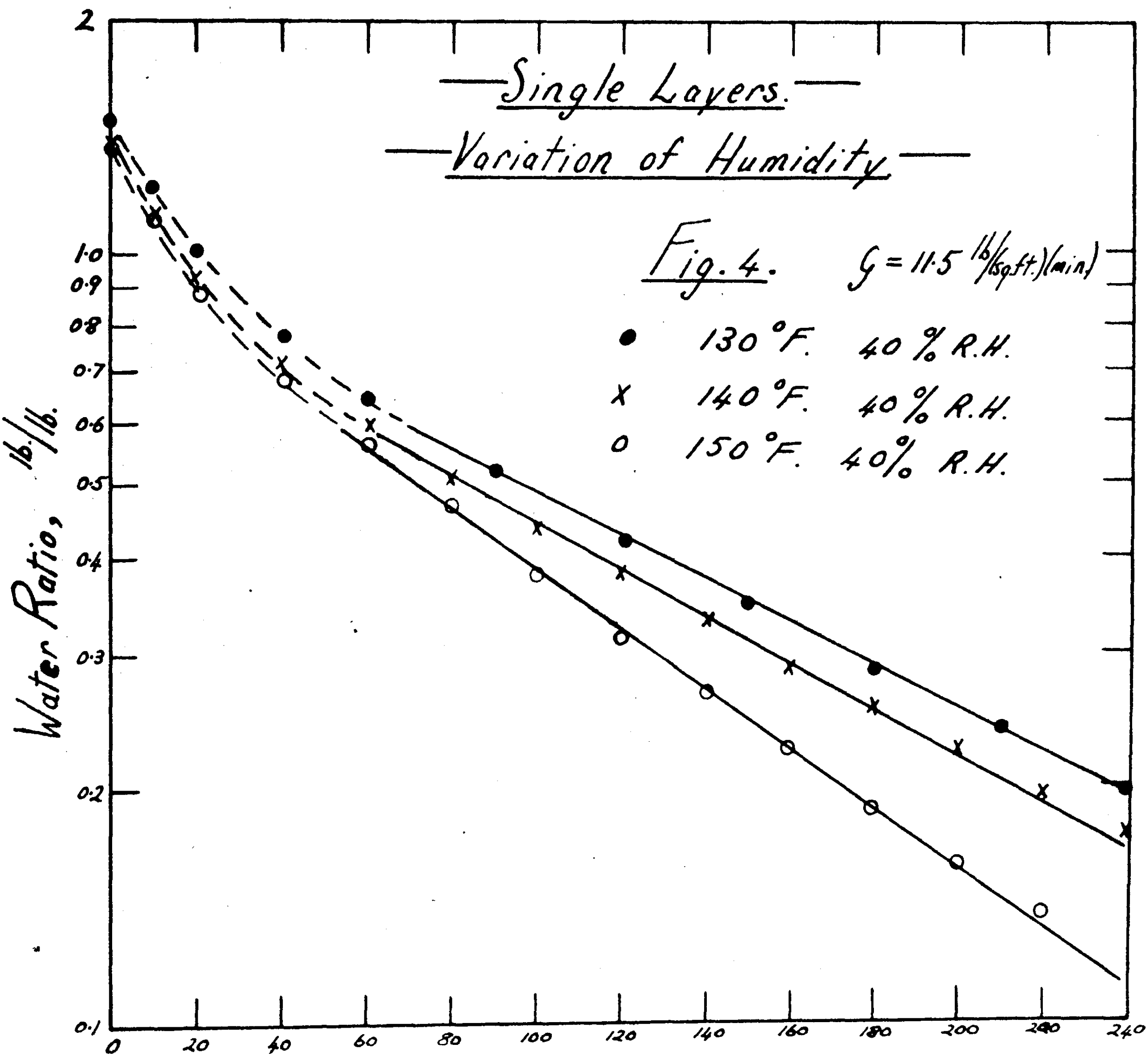
Relative humidity = 40%

The plots of log T vs time of drying exhibit the same characteristics as the temperature curves. Although the relative humidity remained constant, change of dry-bulb temperature also changed the value of the rate constant. The change of rate constant with change of humidity was negligible, up to 40% relative humidity (Fig.2). This agrees with work on wheatgrain and with previous work by the present investigators.

It/



Single Layers.
Variation of Air Velocity.
Fig. 3.
td = 150°F
o 23 lb./(sq.ft.)(min.)
● 8·12 lb./(sq.ft.)(min.)
x 11·5 lb./(sq.ft.)(min.)
Water Ratio, lb./lb.
1·5
1·25
1·0
0·75
0·5
0·25
0
25
50
75
100
125
150
175
200
Drying Time, min.



—Single Layers.—
—Variation of Humidity.—
Fig. 4.
G = 11.5 lb/(sq.ft.)(min)
● 130°F. 40% R.H.
X 140°F. 40% R.H.
O 150°F. 40% R.H.
Water Ratio, lb./lb.
2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
40
60
80
100
120
140
160
180
200
240
Drying Time, min.

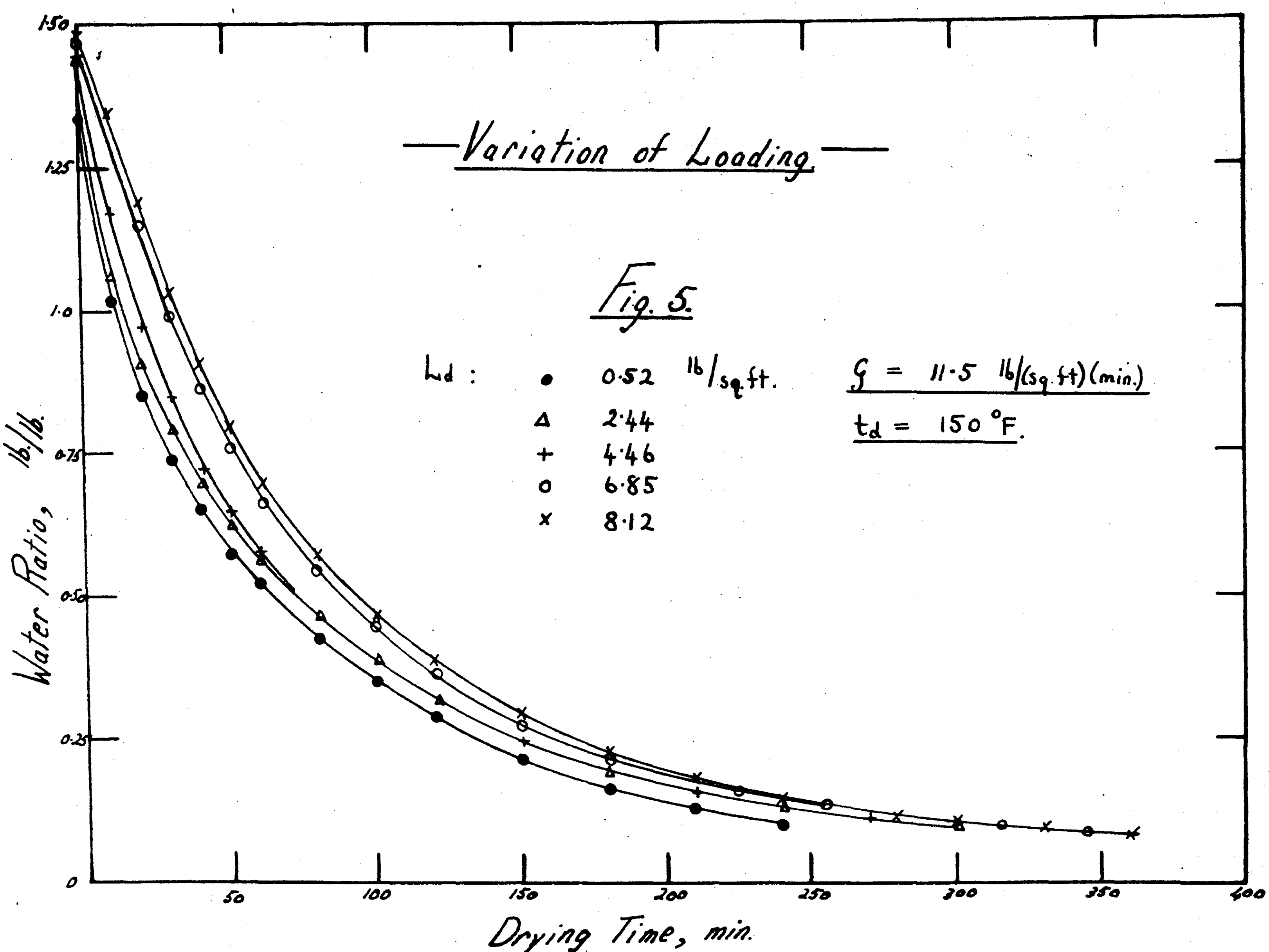
It would appear, on resolving the effect of temperature, humidity, and air velocity, that the ultimate drying rate of peas is dependent upon the rate of moisture diffusion to the outer surface, and that this rate of flow depends upon the temperature to which the interior of the peas is heated.

It has been stated that case hardening took place within the range of temperature studied. Von Loesecke[37] has stated that the relative humidity should initially be approximately 40% to reduce this effect. Present observations did not confirm this, possibly because of the different mode of drying, the change of initial moisture ratio, and because no scalding was done.

<u>Effect of Varying Loading</u> Ld = 2.44 to 8.12 lb./(sq.ft.)

Temperature = 150°F. G = 11.5 lb.d.a./(sq.ft.)(min).

The occurrence of initial surface evaporation and skin drying meant that constant rate periods were followed by slow drying with the result that the outlet temperature increased rapidly thereafter. The deeper the bed, the longer was the time of drying. The results of drying beds up to six inches in depth have been plotted in Fig.5. The percentage difference in drying time between the larger loadings is small which indicates that beds of peas may be loaded deeply. Since, commercially, a hard shrunken product is required, it is necessary to dry slowly. This necessitates the use of low drying temperatures and high humidities, suggesting that in practice, heating of the inlet air could be by direct steam injection and that recirculation of air could be used.



—Variation of Loading—
Fig. 5.
Ld : ● 0.52 lb/sq.ft.
△ 2.44
+ 4.46
○ 6.85
× 8.12
G = 11.5 lb/(sq.ft)(min.)
td = 150 °F.
1.50
1.25
1.0
0.75
0.50
0.25
0
50
100
150
200
250
300
350
400
Water Ratio, lb./lb.
Drying Time, min.

Agitation should make little difference to the times of drying, and may damage the skins of the peas. Agitation resul[t] in a more uniform moisture content, but this can be attained by alternate up and down draughts in a commercial conveyor drier.

Prediction of Drying Times

Examination of the single layer and loading tests is necessary before a prediction method can be devised.

This method must be different from that previously put forward for brewers' grain, sugar beet, and carrots, since th[e] proportionality between drying rate and moisture content does not exist throughout the whole test. Straight line relationships below a moisture ratio of 0.6 were drawn on the scale of log T vs θ, to intersect the line T = 0.6. The drying time between 1.50 and 0.60 was measured and plotted against temperature (Fig.6[)]. From the values in Fig.6, the gradient of the line drawn from the intersection of the rate constant lines with T = 0.6 was calculated. This gave a value of m^2 which was plotted vs temperature on Fig. 7.

This gives a possible basis for the prediction of drying of deep beds in which there are three drying phases:-

(1) Constant-rate drying, with surface evaporation and skin dryin[g]

(2) Falling rate phase, with mainly skin drying.

(3)Falling rate phase, with drying of particle interiors.

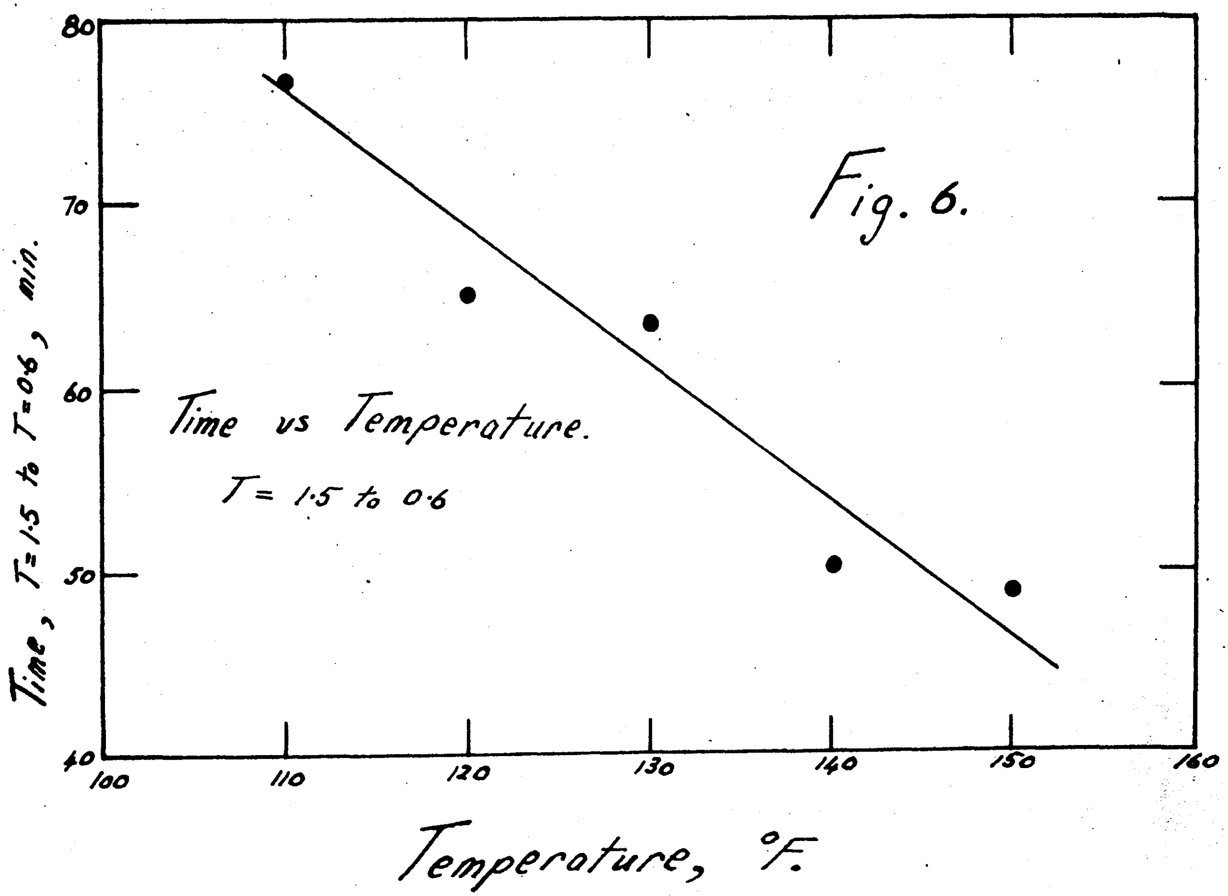


Fig. 6.
Time vs Temperature.
T = 1·5 to 0·6
Time, T=1·5 to T=0·6, min.
80
70
60
50
40
100
110
120
130
140
150
160
Temperature, °F.

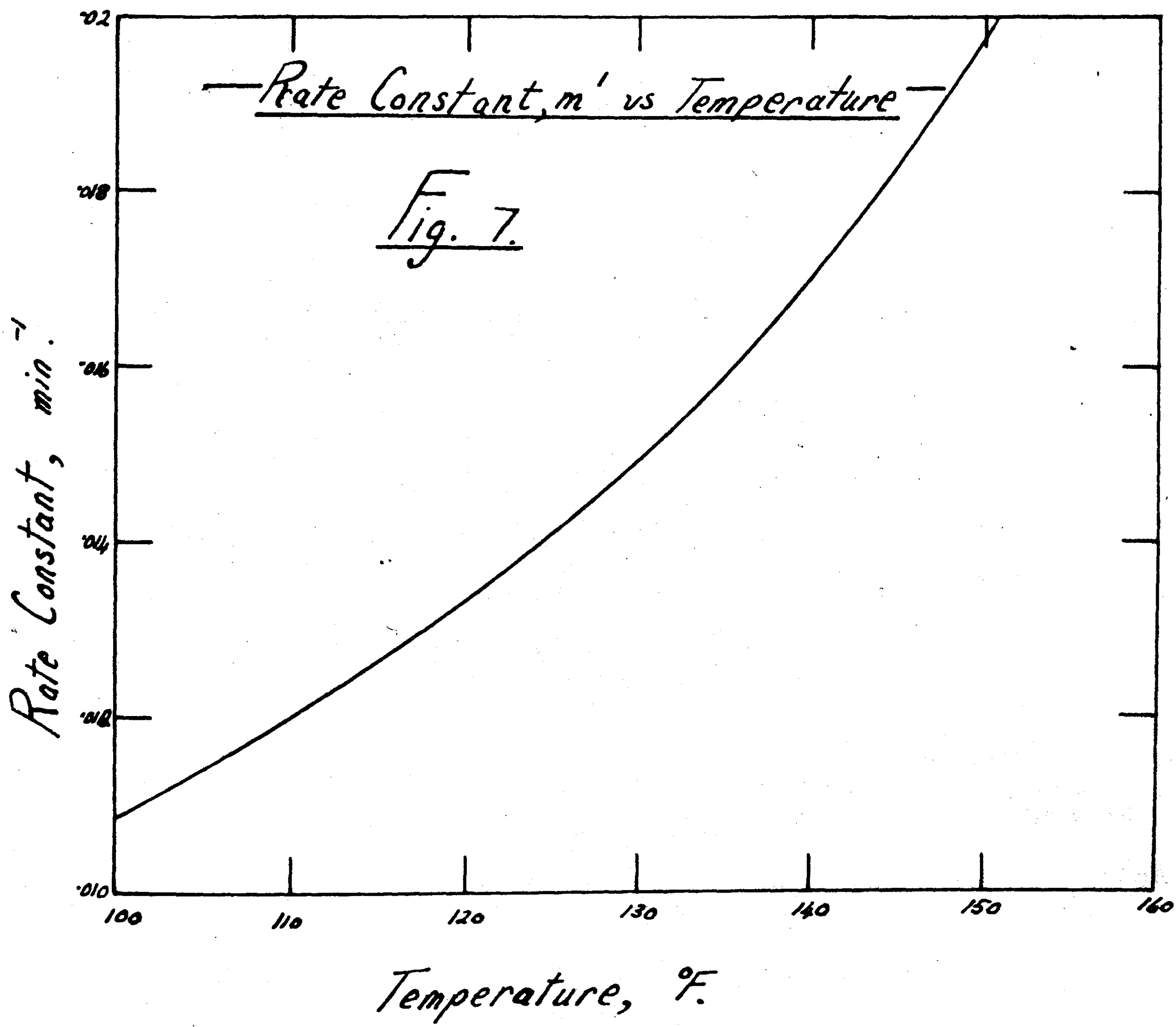

Rate Constant, m' vs Temperature
Fig. 7.
Rate Constant, min.$^{-1}$
·02
·018
·016
·014
·012
·010
100
110
120
130
140
150
160
Temperature, °F.

TABLE II. (T = 1.5 - 0.1)

Bed.	Ld.	td.	tw.	G.	θa	θp	Error.
in.	lb./sq.ft.	°F	°F	lb/(sq. ft)(min)	min.	min.	%
5	6.857	150	84.5	11.5	285	271.3	-3.49
6	8.121	150	85.5	11.5	295	284.7	-4.80

SECTION VIII

Discussion.

I. NATURE OF MATERIAL

Chemical analysis alone does not help greatly in determining the through-drying characteristics of vegetable materials. It may, however, indicate the temperature limit to which the material may be subjected without harming the constituents. Rather is it the manner in which the constituents are bound into the cellular structure which determines the drying rate.

It is generally possible to predict whether a material is suitable for forming into a through circulation bed. Thus leafy materials may be unsuitable since the total surface area is not readily exposed. Firmer, more definite particles are much more suitable. Stickiness of pieces is detrimental, resulting in matting and preventing free access of air to parts of the bed. Obviously, porous materials will dry faster than hard dense pieces since flow of water by diffusion or capillarity is much more easy.

The ability of the material to keep the surface supplied with moisture from the piece interior will determine whether high air velocities are practicable, particularly towards the end of drying. The duration of the constant rate period is also partly determined by this property, allied with the total moisture content of the material.

Thus it is that chemical analysis in drying work has been studied by workers to determine the effects of drying on the important constituents, rather than the influence of the constituents on the rate of drying of the material.

II <u>Preparation of Vegetable Materials.</u>

Some of the materials used in this work required no preparation, while others required peeling, subdivision, or scalding, depending on their initial size and the type of produc made.

For sugar beet and carrots it was necessary to clean and peel the roots before subdivision so that accurate compariso of tests could be made. The effect of the layer of skin was to set up a resistance to the flow of water by diffusion and hence decrease the rate of drying so that the time of drying increased. Several pieces of material with skin attached in single layer drying would have upset comparative tests, and hence those vegetables were peeled to avoid this possibility.

With sugar beet, carrots and seaweed, different methods of subdivision were found necessary. With seaweed, mincing appeared to squeeze out a fair amount of liquid to the surface of the piece, and in fact, a small percentage of the water was lost on mincing. This tended to decrease the drying time and somethin of the same effect was obtained in cutting sugar beet and carrots owing to exposure of fresh, moist surfaces.

The scalding of carrots had the effect of increasing the initial water ratio and the cell walls were made more permeable, enabling more rapid drying to take place. These factors were incidental to the real purpose of scalding, which was to promote easier reconstitution of the product. One detrimental result of scalding was that the vegetable surface became much more moist and sticky, resulting in matting of beds, and indeed chopped, scalded cabbage has been reported completely unsuitable for through drying.

Sometimes vegetables require chemical treatment to retain their colour during drying and storage, notable examples being sulphur dioxide treatment of apples and sodium carbonate treatment of peas. No precautions of this nature have been taken in the present work.

III Size Reduction.

The optimum particle size for beds of vegetables to be dried by through circulation is usually determined by the size most convenient for subsequent use and the size giving optimum drying properties as determined by drying rate tests. Another consideration is whether the packing density of the bed permits free passage of air. The ideal bed for through drying is one composed of very small, but firm particles giving fast rates of diffusion of water from their interiors. Unfortunately, this ideal is virtually impossible to attain in practice.

The optimum cut size for each material was determined experimentally. Seaweed was cut into a suitable size by mincing and examination of the test results showed that an optimum depth of bed was obtained. This optimum was lower for minced seaweed than for uncut material because the increased packing density resulted in partial blocking of the bed at bed depths lower than normal. This did not mean however, that mincing was bad, for the optimum loading was as high for the minced/

minced material, while the output rate was increased. Brewers' spent grain did not require further subdivision, the bed being a mass of small, moist, soft, ill defined particles which, although drying rapidly, were really not ideal for through circulation drying. Sugar beet and carrots were much more suitable materials since their particles were firm. The standard beet cossette chosen was 2 in x 0.4 in. x 0.25 in., of roof ridge cross section. The carrot pieces have been discussed in Section 6. The selection of an optimum size must include consideration of surface characteristics and packing effects and density, in addition to having a particle small enough to dry sufficiently rapidly.

IV <u>Optimum Loading</u>

Loading tests were carried out for all materials, and for the three types of seaweed studied, optimum values of loading were found above and below which the output rate fell. The effect of packing has already been mentioned, and it was thought probable that this was the controlling factor. However, the packing density of brewers spent grain was higher than that of seaweed and yet no optimum loading point emerged although a larger range of bed depths was studied. It was noted that seaweed was much more prone to stick and mat, preventing free access of air to some parts of the bed. Evidently, it was the combination of the packing and matting effects which gave an approximate optimum loading. With the materials of more rigid structure, cut into larger pieces, the loading-time graph was more linear than for beds composed of small irregular particles. The shape of the particles in the bed was very important, soft flat leaves drying very slowly compared with round particles like peas where the point contact allowed air to flow readily to all parts of the surface.

The optimum loading values were obtained for particular values of temperature and air velocity. At higher temperatures and air velocities it is probable that optimum loading will also be higher.

Theoretically the constant drying rate varied with loading in the following manner:

$$\left(\frac{\partial T}{\partial \theta}\right)_c = 60.G.(H_s - H_1) = K.Ld^{-1}$$

The constant, K, was approximately the same for the three seaweeds and Brewers' spent grain and was 5.2. This compared with the theoretical value of 8, the discrepancy being due to the exit humidity never attaining the saturation value Hs.

V <u>Effect of Temperature</u>

(A) <u>Single Layers</u>.

The effect of air temperature on single layers of all the materials, with the exception of the seaweeds, has been studied.

The general tendency in a semi logarithmic plot of water ratio vs drying time is for a very short initial building-up period to take place, usually of up to 10 min. duration in the present work, except for peas where the period was as much as/

as 70 min. This was taken to represent a period of initial surface drying, and with peas was a more prolonged period of skin drying. It was, in most cases, of such proportions as to be discounted from the total drying time of the layer. At all levels of temperature studied, there followed a "rate constant" period which lasted for the greater part of the drying run. The value of the "rate constant" varied significantly with temperature and the variation from material to material at a temperature of 150°F was:

Brewers' spent grain: 0.143 Sugar beet: 0.027 Carrots: 0.0292
Peas: 0.0091

There can be little accurate comparison of material composition and its effect, since the size, shape and water ratio of the pieces varied greatly. However, there was such variance that it was evident that brewers' spent grain, with its small particles and loose structure, dried many times faster than sugar beet, carrots, and peas. Peas dried much more slowly because of the somewhat impervious skin and the very compact structure within.

With brewers' spent grain and sugar beet there was a distinct "tailing off" period, at water ratios less than 0.5, which approximated to a secondary linear semi-logarithmic relationship with sugar beet over the test period. The "tailing off" period could be neglected without undue error, provided the final water ratio was not reduced below 0.1, particularly with Brewers' spent grain, in the calculation of deep bed drying times. It was considered that it could be included in sugar beet predictions. "Tailing off" periods existed with the other materials, generally below a water ratio of 0.2, although they have not been considered in the prediction methods, since drying times were not calculated below 0.1 water ratio.

(B) Deep Layers.

Increase of air temperature in deep bed tests had the effect of increasing the drying rate. The enthalpy of the air was greater, allowing greater transfer of sensible heat for use in evaporation. The constant rate increased linearly with air wet-bulb depression for the three seaweeds, brewers' spent grain, and sugar beet, as was to be expected in a period where free surface evaporation is predominant. In these cases, the constant rate is actually a combination of surface and internal drying but, as stated, with surface drying predominating. An examination of the prediction method shows that since wet and dry bulb temperatures are higher, then the mean drying temperatur of the top layer will be higher and the rate constant for the falling rate will therefore be greater. A similar effect will occur in drying deep beds of carrots at various temperatures, but it is likely that free water drying at the surface will not predominate with beds of peas, owing to the presence of the skin.

VI. Effect of Air velocity.

(A) Single Layers.

The effect which change of air velocity had on the drying rates of single layers of the test materials, has been reported. From the very nature of the materials, the different influence on each could be forecast. So it was that with brewers' spent grain, with its abundant surface moisture, that increase of air velocity resulted in a sharp increase in the initial drying rate; sugar beet showed less initial increase; carrots, having a much higher initial moisture ratio than sugar beet, displayed a more marked change; only a small change occurred in the drying rates of peas at different air velocities owing to there being no free water surface.

Since brewers' grain had its moisture in a relatively free state, the increase in drying rate with air velocity increase was maintained to a marked degree up to the point at which fluidisation or "Spouting" of the bed occurred. Any resulting blowholes allowed bypassing of air and consequently the disturbed grain which had been heaped up dried at a slower rate, thus decreasing the average drying rate. The air velocity at which this occurred was regarded as the maximum allowable for single layers. After initial surface drying in sugar beet and carrot tests, the drying rate was affected slightly by change of air velocity. The value of the rate constant for sugar beet changed from 0.030 when G = 5 lb/(sq.ft.)(min). to 0.037 when

G/

G = 21 lb/(sq.ft.)(min). A similar type of change was evident with the drying of carrot cubes. At low levels of water ratio, where internal diffusion was controlling, the change was very small, and this was corroborated in tests on peas where such control occurred. The temperature of the interior of the piece was important in such cases and it appeared that surface temperature, and hence the internal temperature, would be increased very slightly by an increase of air velocity, resulting in a greater rate of drying.

(B) Deep Layers.

The constant rate of drying has been proved to increase in proportion to the increase in air velocity. Theoretically, during constant rate drying, the air should leave the bed saturated with water vapour, and

$$\left(\frac{\partial T}{\partial \theta}\right)_c = \frac{60\ G\ (Hs - H_1)}{Ld} \quad \text{lb.water}/\text{lb.(B.D.S.)(h}$$

$(Hs - H_1)$ and Ld are constant

Hence $\left(\frac{\partial T}{\partial \theta}\right)_c = KG$ where $K = \frac{60\ (Hs - H_1)}{Ld}$

The actual and theoretical values are summarised below:

Material	Temperature	Loading	K actual	K theoretical
Ascophyllum nodosum	160°F	1.75	0.41	0.60
Fucus vesiculosus	160°F	1.52	0.45	0.69
Fucus serratus	160°F	1.40	0.52	0.75
Brewers' spent grain	160°F	2.08	0.35	0.50
Sugar Beet	200°F	2.25	0.40	0.65

The difference in the actual and theoretical values of K may be explained by the fact that a percentage of air bypasses the bed and also because the air which does pass through the whole of the bed never quite attains saturation.

The effect of air velocity on the falling rate period was governed by the same laws as in shallow bed tests.

VII <u>Effect of Humidity</u>

(A) <u>Single Layers.</u>

Tests on the effect of humidity have been carried out on sugar beet, carrots and peas.

At constant dry bulb temperature, sugar beet and carrots gave the same drying rates in low moisture regions, although the humidity was appreciably changed. A change of humidity at high moisture levels, again with dry bulb temperatu constant, resulted in a change of drying rate, particularly with carrots where the water ratio was greater than with sugar beet or peas. This suggested some agreement with the wet-bulb depression theory of Ede and Hales where the rate of drying of a free water surface was proportional to the wet-bulb depressio

In tests where the dry-bulb temperature was varied and the wet-bulb depression was constant, the initial drying rate was constant, especially with carrots, but it gradually increased owing to increased dry bulb temperature. It must be noted that although the wet-bulb depression was constant, the absolute humidity changed. The change of rate constant with change of humidity was negligible for the drying of peas, up to a relative humidity of 40%, although the initial drying rate varied very slightly.

It could therefore be concluded that if a material had a moist surface exposed to the air stream, and if the humidity of the air stream were changed, the rate of evaporation from the surface also changes. When the surface has partially dried, the drying rate will be almost unaffected by the air humidity, but affected markedly by air temperature.

(B) <u>Deep Layers.</u>

With the constant rate period, the humidity driving force affected the rate directly, since theoretically,

$$\left(\frac{\partial T}{\partial \theta}\right)_c = \frac{60G}{L_d} \times (H_s - H_1)$$

Assuming Ld and G constant, the only variables are Hs and H_1.

Hs = adiabatic saturation humidity at the inlet wet-bulb temperature.

H_1 = inlet humidity.

If then inlet wet-bulb temperature is constant and the inlet dry-bulb temperature decreases then Hs remains constant and H_1 increases. Hence the humidity driving force decreases, with consequent decrease in $\left(\frac{\partial T}{\partial \theta}\right)_c$.

If the inlet dry-bulb temperature is constant and the inlet/

inlet wet-bulb temperature increases then H_s and H_i both increase. The increase in H_i, however, is greater than the increase in H_s and the humidity driving force is therefore less, decreasing $\left(\frac{\partial T}{\partial \theta}\right)_c$.

For the falling rate period, $\left(\frac{\partial T}{\partial \theta}\right)_f = mT$

The rate constant is evaluated at the mean drying temperature of the top layer. This is taken as the logarithmic or arithmetic mean of the inlet dry and wet-bulb temperatures. If the humidity is increased by increasing the wet-bulb temperature then the falling rate, $\left(\frac{\partial T}{\partial \theta}\right)_f$, would increase since the mean temperature is higher. If the humidity is increased by a drop in dry-bulb temperature, then theoretically the falling rate would decrease, because of the drop in the mean drying temperature of the top layer.

VIII <u>Agitation</u>.

There is little object in agitating single layers of material, since practically all the surface is exposed to the air stream.

For deep beds, a preliminary examination of the particle size, shape and structure usually gave the probable behaviour of the rate at which material dried, with or without agitation. Although no agitation tests were conducted on seaweed, agitation would almost certainly have an effect, since the material was soft and pliable, having a reasonably high water/

water ratio. This was confirmed by the fact that seaweed exhibited an optimum loading which was probably caused by matting of the bed.

The importance of agitating at the correct moment in the test has been noted, there being little point in agitating within the constant rate period compared with the falling rate period, as tests on brewers' spent grain have shown. Moreover, with this material, no more than 6 agitations per hr. were necessary, since above this value there was no significant decrease in drying time. It was thought probable that a vibrating conveyor would give, or could be adapted to give, sufficient movement to cause adequate agitation of the material. Beds of sugar beet cossettes, carrot cubes, and peas, within the range studied, showed little variation of drying rate with agitation. Possibly the vibration which occurred during weighing intervals was sufficient to agitate the beds of materials.

IX <u>Recirculation</u>.

The amount of air which can be recirculated depends on the temperature and humidity of air leaving the bed. If air is leaving during the low moisture end of a run, then it can be recirculated immediately. It may be necessary to reheat the air if the temperature is low or the humidity is near saturation. The drier must be designed first and perhaps pilot plant trials made to give the necessary information to determine the amount and condition of the recirculation air. These details could also be obtained by calculation from the predicted drying rates.

Recirculation tests on seaweed and brewers' spent grain showed that, for the low moisture end of the run, about 80% recirculation could be attempted without significantly decreasing the drying rate. Peas were more suited to recirculation than the other materials tested since high inlet humidities are required for satisfactory product quality. They also dry very slowly giving only slight changes between inlet and outlet humidity values.

The amount of recirculation may best be determined, therefore, by plant tests on temperature and humidity gradients within the drier.

Pressure drop over deep beds.

A general equation for pressure drops over beds of vegetables has been given by Spaugh[72].

$Q = (C_1V/C_2 - b)^n$ where Q = P.D., in.w.g./ft.bed depth.

C_1, C_2 = Experimintal constants.

V = Air velocity, ft./min.

b = ft. of perimeter/cross sectional area.

n = velocity index.

A simplified form of this equation held for a number of vegetable materials:-

$(Q = CG^n)$ where G = Air mass velocity lb.d.a./(sq.ft.)(min.)

If the porosity value was kept constant then C remained constant. Any variation in the values of the experimental constants between different loadings was normally due to a change in porosity. Values of C and n for various materials, from present and past work are:

Material	n.	C.
Onion flakes	1.60	
Strip potatoes.	1.82	
Viscose staple fibre	1.50	
Dried L.cloustoni stipe	1.83	0.011
Fresh L.cloustoni stipe	1.80	0.027
Dried L. digitata stipe	1.85	0.018
Dried F.serratus	1.82	0.015
Fresh F.serratus	1.81	0.030
Dried F.vesiculosus	1.75	0.019
Fresh F.vesiculosus	2.06	0.014

Sugar beet tests by Owen[49] showed that the following equation held

$$X = (0.0015V - 0.09)\ Z$$

where X = Static pressure drop in w.g.

Z = Bed thickness, in.

V = Air velocity, ft./min.

The size and shape of the cossettes used in this work were somewhat similar to those used by Owen, and it was confirmed that this equation gave reasonable results for pressure drop over the beds tested.

McEwen, Simmonds and Ward[45] have presented data in graphical form for the resistance to air passage of beds of granular materials, including peas. Their results formed the basis of the following correlation.

$$H_w = 9.475 \times 10^7 \cdot \frac{L^{0.95}}{d_m^3} \cdot \frac{\mu^2}{g \cdot \rho_a} \quad f(Re_m),\ f_1(X_b), f_2\left(\frac{l_{max}}{d_e}\right), f_3(e)$$

where H_w = Pressure drop, in w.g.

L = Bed depth, in.

d_m = Equivalent diameter, in.

ρ_a = Air viscosity.

a = Air density.

$f\ (Rem) = (Re)^{n.Re}/(100)^{n.100}$

$f_1\ (Xb) = (0.40/Xb)^{2.75}$

$f_2\left(\frac{l_{max}}{d_e}\right)$ = Shape factor.

$f_3(e)$ = Unity for peas.

Some/

Some difficulties were found in the method of preparation of the bed in order to obtain a constant porosity. The most reliable method, and the method used in the present work, was to pour the materials into the basket from a fixed height and disturb as little as possible. What measurements of pressure drop as were made in present tests were slightly low compared with the information given by McEwen *et al*. This was due to some air bypassing the bed and thus registering a higher value of air flow through the bed than the actual value.

Extensive tests on carrot dice were not conducted because of preparation difficulties and lack of supplies at the end of the season. Approximate solution of the pressure drop problem would probably have been given by one of the simple correlations but adaption of Roses[82] equation as made by McEwen *et al* might also be attempted.

S E C T I O N   I X.

Prediction of drying times and rates.

Prediction of drying times and rates, and design methods.

The prediction methods finally arrived at were chosen from a number of methods detailed in the literature:

I Diffusion theory.

II Mass transfer calculations.

III Nomographs based on drying tests.

IV Wet-bulb depression correlation.

V Single layer basis.

VI Simulation of drier conditions.

The following pages outline these ways of dealing with the problem, giving reasons why they may or may not apply to the materials under study.

I <u>Diffusion Methods.</u>

(a) Van Arsdel[21], working on approximate diffusional solutions to drying problems, has directed study towards the moisture diffusion principle of Sherwood and Newman, and certain modifications of it, rather than to the pore flow theory of Ceaglske and Hougen[24], because the materials (vegetables) resembled solid gels in structure. Many workers have postulated a solution to the diffusion equation, and have shown that the predicted drying rates of some industrial solids agreed reasonably well with the experimental rates. Divergence is most apparent in the region of very low moisture content. This means that diffusivity alters considerably, and is a function of moisture content. The mathematical complexity of the solution is considerable and no really satisfactory analytical solutions have been found. Van Arsdel has solved the equation approximately on the basis that the potential producing diffusion is a concentration difference and that diffusivity is independent of moisture content. Shrinkage and temperature gradients were considered negligible. For the type of materials studied in the present investigation it is apparent that such assumptions cannot be made. While it may be taken that concentration difference produces diffusion in a vegetable material, the diffusivity varies considerably with moisture content. In addition, shrinkage and temperature gradients occur.

(b) Peck, Griffith and Rao[22] have attempted to differentiate between/

between the surface air film and internal resistances in the drying of rectangular balsa wood slabs. They have also given some consideration to the variation of diffusivity, slab temperature, area available for diffusion and heat transfer. It should be remembered that in each of these investigations, uni-directional diffusion was being studied. This is not the case with the diverse shapes and sizes tested in the present work. Three directional diffusion takes place in such test pieces, the rate varying widely with change of moisture content. Even if a solution of the above type were forthcoming for a single piece, the variation of air temperature from point to point in a deep bed throughout drying would remain to be considered. The effective area for diffusion and heat transfer would also change in a composite bed.

On consideration of the effect of all these variables it is probable that a solution based on the moisture diffusion theory would be too complex for the drying of vegetable materials.

II <u>Mass Transfer methods.</u>

Marshall and Hougen[55] correlated the constant drying rate in through circulation drying of solids against the dimensionless ratios, (a) A modified Reynolds number (b) The Schmidt number. The expression was simplified and the drying rate was found to vary with the air flow to the n^{th} power, multiplied by the humidity driving force. The falling rate period was found to give curves of the type

This/

This type of equation only holds for certain cases and indeed does not hold for most vegetable materials. Again, for constant rate drying it was assumed that particle diameter remained constant which, in the present case, it does not do throughout the composite bed. The duration of the constant rate period cannot be calculated from this correlation and for the falling rate period, the critical moisture content is not known unless it is determined experimentally.

Gamson, Thodos and Hougen[12] correlated the j numbers for heat and mass transfer with various heat and mass transfer terms. This is generally possible for the constant rate period, but in the falling rate period, difficulties arise because of variations in heat and mass transfer coefficients, diffusivity, particle size and driving force.

Allerton, Brownell and Katz[54] have studied mass transfer in the drying of filter cakes of crushed quartz and glass balls and postulated a "vaporisation zone" of drying moving up through the bed. A correlation was arrived at including the driving forces, the j number, and the Schmidt number. The latter two and the partial pressure of water on the particle surface were taken to be constant, which is not true in the present work. These workers in fact only claim that the correlation is valid for through drying from surfaces of crystalline, non-adsorbing, non-porous, insoluble particles in porous beds.

III <u>Nomographic Methods</u>.

Brown/

Brown, Van Arsdel and Lazar[29] have correlated and summarised data for the drying time of several important vegetable materials in the form of nomographs for easy practical use. Normal drying tests were made on the vegetables, i.e. variation of loading, humidity, and air velocity. A nomograph was constructed for the drying time, at a particular value of loading and air velocity, relating any two moisture contents within the studied range to the air wet-bulb depression. Corrections were made for change of loading and air velocity, and the drying time was subdivided into (a) the time to dry down to 0.1 to 0.2 moisture ratio (b) the time to dry below this moisture ratio.

The experimental factors used to correct the drying times for change of loading were found by keeping temperature and velocity constant. It was assumed that these proportionality factors would be the same for a different temperature and velocity. This is an assumption which may hold for certain temperature, loading and velocity ranges but it was considered that this method of solution of the prediction of time of drying should be held in reserve to check other methods which did not depend on this assumption. Brown et al claimed an accuracy within 20% for this method.

IV Wet-Bulb Depression Methods.

Ede and Hales[30] have correlated the rate of drying and time of drying with water content on the basis of unit wet-bulb depression. Corrections of a somewhat similar nature to those made by Brown, Van Arsdel and Lazar, have been made for/

for variation of loading and air velocity. The use of wet-bulb depression is an accurate measure of the drying capacity of the air only when in contact with free water surfaces. Most cut surfaces of vegetables behave as such only for a limited time, and normally, after initial surface evaporation has ended, the surface cannot be supplied with water from the interior fast enough to maintain it as a free water surface. These workers state that, provided that due allowance is made for the effects of the cut surface becoming dry, the wet-bulb depression can be used as a means of correlation and approximate prediction of drying times. While the greater part of this work was concerned with cross flow drying, some tests have been conducted for the suitability of certain vegetables for through circulation work. The solution is approximate, owing to the use of air velocity and loading factors, as with Brown et al.

Gardner and Mitchell[40] have adopted the above method to their work on the through circulation drying of sub-littoral seaweeds. Obviously it suffers from the same limitations as above, the accuracy of prediction falling off rapidly below a moisture ratio of 0.2 since the solution follows constant rate drying principles. These workers have formed a graphical method for the design for continuous multistage driers. Since the moisture rati value for stored seaweed is about 0.15 compared with below 0.1 for vegetables, the prediction was that much more accurate and it was therefore thought that, from the point of view of uniformity, the/

the same method could be used for the littoral seaweeds, Ascophyllum Nodosum, Fucus Vesiculosus and Fucus Serratus.

V Single Layer Basis Method.

Simmonds, Ward and McEwen [45] have investigated the rates of drying of single layers of wheatgrain, finding the rates to be proportional to the free moisture content of the grain. This allowed a simple method to be devised for the calculation of single layer and deep bed drying times.

This method of known accuracy (± 10%), and it therefore seemed that if a relation could be found for rates of drying in single layer experiments for the range of materials studied, the method would be most applicable to deep bed drying. A modificatio of the method has been made by McEwen and O'Callaghan [46] for use in a semi-graphical solution of the problem, applicable to single stage driers. This method breaks up a deep bed into a series of layers and treats each as a single shallow layer. The intermediate condition of the air between each layer may be determined by a mass balance. The moisture gradient from layer to layer is found at chosen increments of time and the absolute accuracy is dependent on the duration of these increments and the number of layers in the bed.

Both the original and semi-graphical solutions have better accuracy than other methods for the prediction of vegetable drying times and it therefore seemed probable that a method develope on the single layer basis would provide an adequate solution for the/

the materials studied.

VI Simulator Method.

This method, outlined by Broughton and Mickley[58], approaches the problem from a different angle. Instead of giving design data for the construction of a conveyor drier, they present a method whereby, once a drier has been designed, the drying time or the rate and conditions of throughput can be calculated. The conditions of drying proposed in the operating instructions are simulated in an experimental unit and the test is continued until drying is complete.

While such a method does not help initial design, it is apparent that it would serve as a valuable check on the design and operation details formulated by single layer or wet-bulb depression methods.

Proposed Design Methods.

I Seaweed: A. nodosum; F. vesiculosus; F serratus.

Under constant entry air conditions, the drying time may be calculated from the basic unit wet-bulb depression curve as stated in Section III.

Gardner and Mitchell have detailed a graphical design method for multi stage through circulation driers. This method is based on a water content vs time per unit wet-bulb depression curve.

Before design, the following points must be considered:-

(a) The maximum temperature should be 225°F, since scorching occurs/

occurs above this temperature.

(b) There is no great reduction in overall drying time using air velocities above 10 lb/(sq.ft.)(min.). However, the constant drying rate varies linearly with air velocity, so that higher velocities could be used in the constant rate stage with interstage reheating of all or part of the air for use in subsequent stages.

(c) The minimum initial bed depth should be 3 in. since the output rate falls rapidly below this value. Indeed, this is an optimum value, although with sufficient agitation this value would probably be higher.

(d) Shrinkage and edge effect may be negligible if vibration is enough to keep the bed structure loose by preventing matting.

The advantage of this method is the ease with which the solution can be derived. The limit of accuracy of a wet-bulb depression type of correlation has already been discussed.

The method attempts to deal with multistage drying, with the characteristic variation of air conditions from point to point within the drier, whereas most other methods predict the drying time under constant air conditions.

The outline of the method for a double stage drier is as follows:-

(1) From the basic drying curve calculate the water content vs time curve of the lower belt under the given conditions and plot it on a reversed time scale.

(2) Select suitable time increments and interpolate the terminal water ratios for each increment from the curve.

(3) Calculate the water picked up by the air passing through each increment/

increment of the bed as $\frac{Ld(T_o - T_1)}{G\ \theta}$ lb. water/lb. dry air.

(4) Add the water picked up to the inlet air humidity to give the humidity of the air leaving each section of the lower belt. Assume a constant W.B.T. for the hot air and obtain the D.B.T and hence the W.B.D. from the psychrometric chart.

(5) From the basic drying curve and the appropriate W.B.D. compute the water content of the seaweed on the top belt as it reaches the end of each successive time increment.

(6) Plot the water ratio/time curve for the upper belt until it intersects the corresponding curve for the lower belt. This intersection gives the water content at the turnover and the drying time on each belt (Fig.1)

II <u>Brewers' spent grain; sugar beet; carrots; peas.</u>

There are several methods for the calculation of the drying time under constant entry air conditions, and these have been described in the text:

(a) By calculation and summation of the constant rate and falling rate drying times.

(b) From the nomographs (Figs. 2,3,4) based on constant rate and falling rate equations (Appendix 3).

(c) By a modification of the graphical method described by McEwen and O'Callaghan[46], as follows:

A deep bed may be represented by a number of thin layers, say 0 at the entrance and 5 at the exit (Fig.5).

Consider an interval of time θ,

Then at the entrance, at the start of drying, for the bottom layer

$$\frac{\partial T}{\partial \theta_1} = M_o\ T_o$$

The/

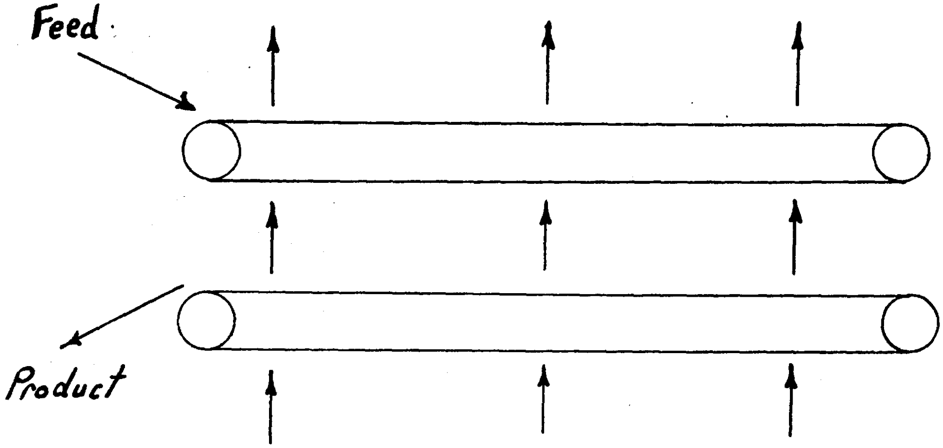
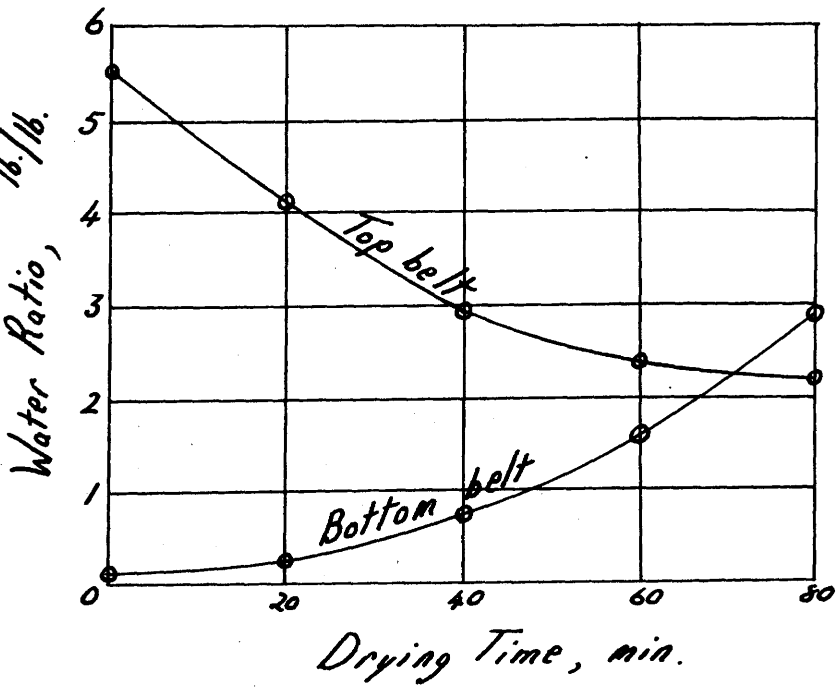


Fig. 1.

— Double stage drier — equal belt speeds —



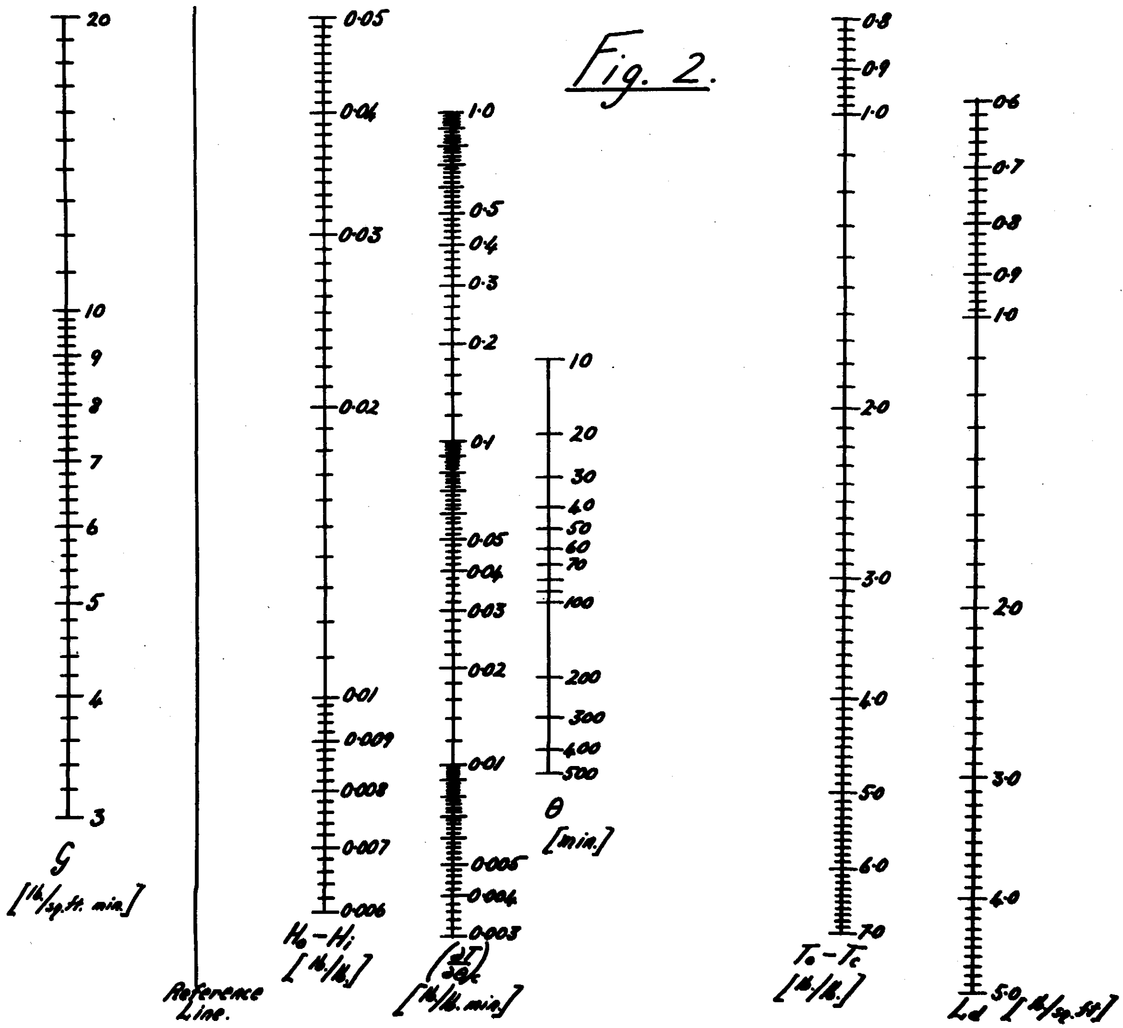

20
10
9
8
7
6
5
4
3
G
[lb./sq.ft. min.]
Reference Line.
0·05
0·04
0·03
0·02
0·01
0·009
0·008
0·007
0·006
$H_o - H_i$
[lb./lb.]
1·0
0·5
0·4
0·3
0·2
0·1
0·05
0·04
0·03
0·02
0·01
0·005
0·004
0·003
[lb./lb. min.]
10
20
30
40
50
60
70
100
200
300
400
500
θ
[min.]
0·8
0·9
1·0
2·0
3·0
4·0
5·0
6·0
7·0
$T_o - T_c$
[lb./lb.]
0·6
0·7
0·8
0·9
1·0
2·0
3·0
4·0
5·0
Ld [lb./sq.ft.]

Fig. 2.

Fig. 3.

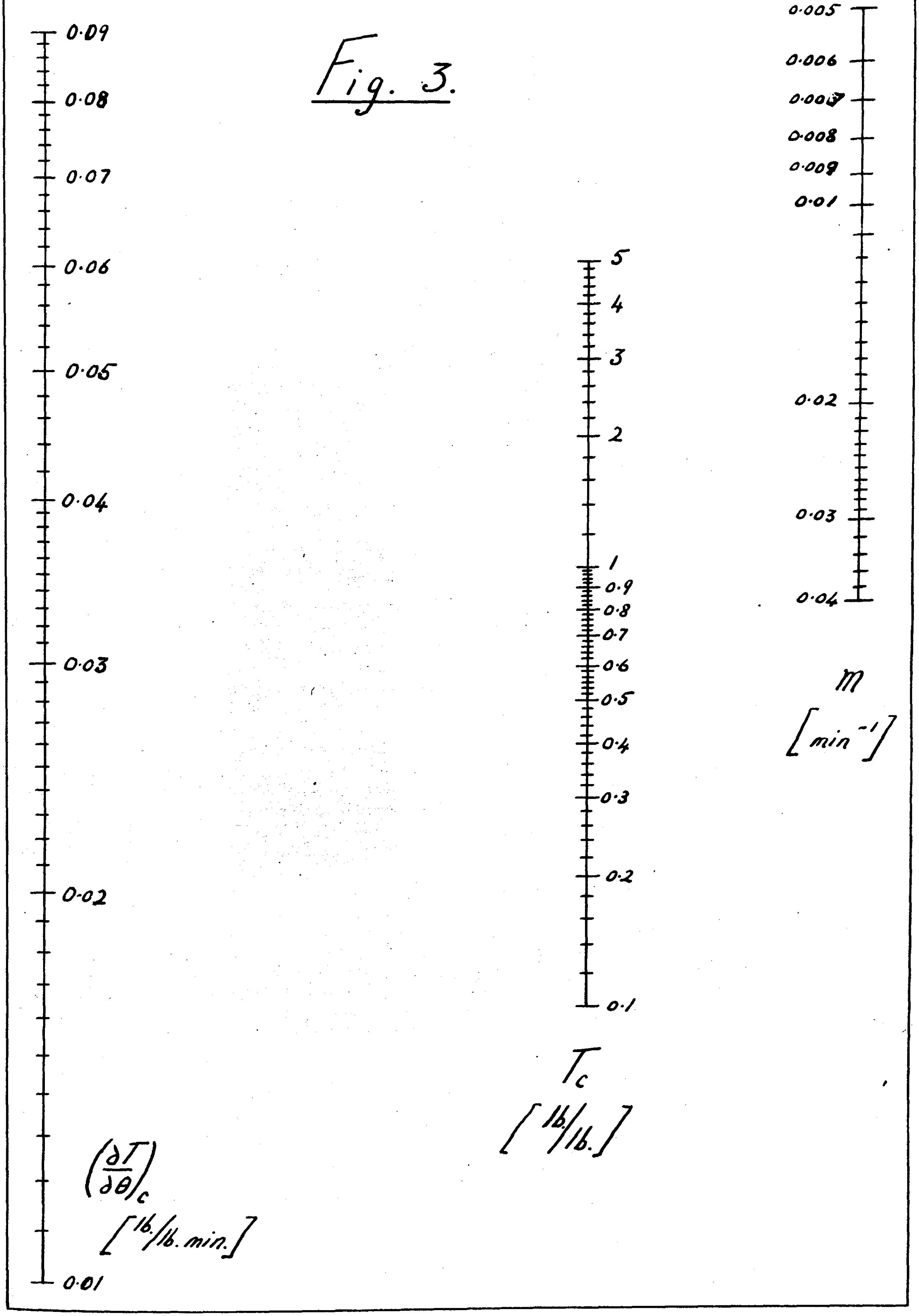
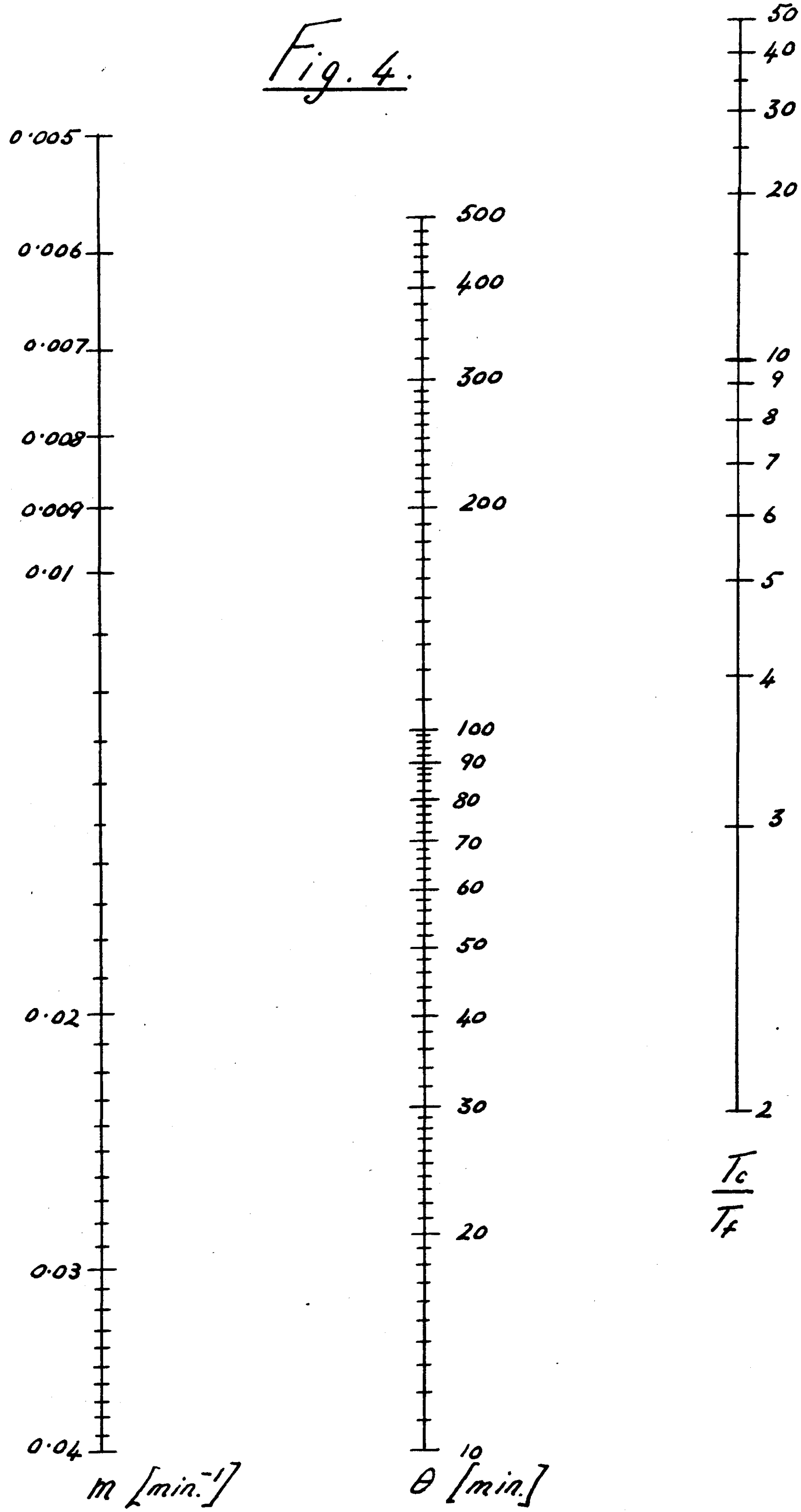

0·09
0·08
0·07
0·06
0·05
0·04
0·03
0·02
0·01
$\left(\frac{\partial T}{\partial \theta}\right)_c$
[lb./lb. min.]
5
4
3
2
1
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
T_c
[lb/lb.]
0·005
0·006
0·007
0·008
0·009
0·01
0·02
0·03
0·04
m
[min^{-1}]

Fig. 4.


0·005
0·006
0·007
0·008
0·009
0·01
0·02
0·03
0·04
m [min.⁻¹]
500
400
300
200
100
90
80
70
60
50
40
30
20
10
θ [min.]
50
40
30
20
10
9
8
7
6
5
4
3
2
Tc / Tf

The weight of water liberated per minute = $M_o L_1 T_o$

The increase in humidity of the air, $\Delta H = M_o L_1 T_o / G$

From the increase in absolute humidity, ΔH, of the drying air in passing through the first layer, conditions at entry to the second layer can be located. Similarly, conditions can be found at entry to, and exit from, each subsequent layer. The moisture ratio can be calculated for each layer and a smooth curve of water ratio vs number of layer can be drawn for the time period, θ. This procedure is repeated for succeeding time intervals, in order to obtain a plot of moisture distribution with time and position throughout the bed.

The above methods apply only to single stage drying where the air entering the bed is at a constant temperature and humidity. They can, however, be adapted to multi stage drying. Consider a double stage drier of the type shown in Fig.1. Since conditions at entry to the first stage remain steady, the drying curve for this stage can be found by one of the methods stated above, and plotted on a reverse time scale. The air temperature and humidity at inlet to the second stage can then be calculated. Hence, again by one of the above methods, the drying curve for the second stage can be plotted as shown by Gardner and Mitchell, and the intersection of the curves for the first and second stages gives the water ratio at the turnover point and the total drying time.

III <u>Simulation check.</u>

The simulator method may be used to check the results of any/

any design of a multistage drying system. For a double stage drier the time of drying of the first stage can be easily checked since entry conditions are constant. By simulating the conditions at inlet to the second layer in an experimental unit the drying curve for this layer can be found, consequently giving the intersection value of water ratio and the time of drying.

Scale factor.

The scale factor must be analysed to take account of the difference between laboratory and industrial operations.

Ede and Hales[30] found in certain cases that weak spots occurred, in a through circulation drying test, in the vegetable bed causing air to flow through these parts preferentially. Gardner and Mitchell[40] concluded in their work that agitation during the weighing intervals was sufficient to prevent formation of weak parts. In the present work, this occurred sometimes in a badly packed seaweed bed, but usually no channelling was noticed. The results of the test were disregarded when this was noted.

The shrinkage of the bed away from the walls of the basket was evident with all the materials except peas. In full scale practice the edge effect will have much less effect since the bed perimeter per unit area is less. The predicted drying time from laboratory scale plant should therefore be conservative for industrial plant. Conduction of heat from the walls to the material/

material should also be of less effect in the larger plant.

It would seem that these two effects are in opposition, although shrinkage is of greater importance. Continuous movement caused by a conveyor could give sufficient vibration to prevent this.

APPENDIX 1

Typical test readings:

Material: Sugar beet. **Test No.:** 5 **Date:** 15-11-55.

Variable: Bed Loading **Loading:** **Airflow:** 16/(sq.ft)(min.)

Time (min.)	Inlet temp. (°F) D.B.T.	Inlet temp. (°F) W.B.T.	Outlet temp. (°F) D.B.T.	Outlet temp. (°F) W.B.T.	Weight (lb.)	Airflow (in.w.g.)	Static (in.w.g.)
0	200	96.0	198	95.1	24.060	1	–
10	201	95.8	94.5	90	22.395		0.[illegible]00
20	200	96.2	96.8	92.2	20.405		0.540
30	200	97.8	97.5	92.5	18.397		0.500
40	200	98.0	98.0	93.0	16.453		0.440
50	200	97.2	107	92.2	14.558		0.400
60	200	97.8	115	93.0	12.830		0.360
70	200	98.2	125	93.2	11.330		0.330
80	200	98.0	134	93.0	9.962		0.290
90	200	98.0	147	93.0	8.978		0.270
100	200	98.0	156	93.0	8.252		0.244
110	199	97.8	164	93.5	7.707		0.228
120	200	98.0	170	94.0	7.305		0.225
130	200	98.0	175	94.0	7.018		0.222
140	200	98.0	179	94.2	6.824		0.218
150	200	98.0	181	94.1	6.679		0.214
160	200	97.5	184	94.8	6.580		0.210
170	201	98.2	184	95.0	6.510		0.209
180	200	98.2	185	94.6	6.463		0.208
190	200	98.0	185.5	94.4	6.425		0.20[illegible]

APPENDIX 2.

Results of Test No. 5.

Material: Sugar beet. Test No. 5 Variable: Bed Loading.

Average moisture content of product = 5.45%

Bone dry solid = 6.425 - (0.0545 x 6.425) = 6.075 lb.

Time (min.)	Weight of Water (lb.)	Water ratio (lb./lb. B.D.S.)
0	17.985	2.96
10	16.220	2.67
20	14.330	2.36
30	12.322	2.028
40	10.378	1.708
50	8.483	1.395
60	6.755	1.112
70	5.055	0.832
80	3.887	0.638
90	2.903	0.480
100	2.177	0.358
110	1.632	0.269
120	1.232	0.202
130	0.943	0.155
140	0.749	0.123
150	0.604	0.099
160	0.505	0.083
170	0.435	0.072
180	0.388	0.064
190	0.350	0.058

APPENDIX 3.

Nomograph Section IX, Fig. 2.

(a) To find the constant drying rate, $\left(\frac{\partial T}{\partial \theta}\right)_c$, lb.water/(lb.B.D.S.)(min.)

The equation is $$\left(\frac{\partial T}{\partial \theta}\right)_c = \frac{G\,[Ho - Hi]}{Ld}$$

Solution:

Join the G value to the $[Ho - Hi]$ value to cut the reference line. Join this point of intersection to the Ld value to give the required figure of $\left(\frac{\partial T}{\partial \theta}\right)_c$ on that scale.

(b) To find the constant rate drying time, θ_c min.

The equation is $$\theta_c = \frac{Ld\,[To - Tc]}{G\,[Ho - Hi]} = \frac{[To - Tc]}{\left(\frac{\partial T}{\partial \theta}\right)_c}$$

Solution:

Join the $\left(\frac{\partial T}{\partial \theta}\right)_c$ value to the $[To - Tc]$ figure, cutting the θ scale at the θ_c value.

Nomograph Section IX, Fig. 3.

To find the critical water ratio, Tc , lb.water/lb. B.D.S.

The equation is $\left(\frac{\partial T}{\partial \theta}\right)_c = m.\,Tc$, i.e. $Tc = \left(\frac{\partial T}{\partial \theta}\right)_c / m$

Solution:

Join the m value to the $\left(\frac{\partial T}{\partial \theta}\right)_c$ value to give the Tc reading on that scale.

Nomograph. Section IX, Fig. 4.

To find the falling rate drying time, θ_f , min.

The equation is $\theta_f = \frac{1}{m} \log_e {}^{T}c/T_f$

Solution:

Join the m figure to the ${}^{T}c/T_f$ value to give the θ_f value on the θ_f scale.

NOMENCLATURE

B.D.S.	=	bone dry solid;	lb.
Ld.	=	Dry loading;	lb. B.D.S./sq.ft.
C.D.S.	=	commercial dry solid;	lb.
T	=	total water content;	lb.Water/lb. B.D.S.
G	=	mass air flow;	lb. d.a./(sq.ft)(min).
R	=	output rate;	lb. C.D.S./(Sq.ft.)(hr)
t_d	=	dry bulb temperature = D.B.T.	°F.
t_w	=	wet " = W.B.T.	°F.
$t_d - t_w$	=	wet bulb depression = W.B.D.	°F.
m	=	rate constant in shallow layer tests;	$min.^{-1}$
$\bar{m}$	=	rate constant in deep bed tests;	$min.^{-1}$
H	=	absolute humidity;	lb. d.a./(sq.ft.)(min). ?
θ	=	time of drying;	min.

for θ,
- a refers to actual time.
- T " " total time.
- p " " predicted time.
- 1 " " first falling rate period.
- 2 " " second " " "
- c " " constant rate period.

for m,
- 1 " " 1st f.r.p.
- 2 " " 2nd f.r.p.

for T,
- o " " original conditions
- f " " final "
- e " " equilibrium "
- c " " critical "
- i.m. " " intermediate conditions between 1st & 2nd falling rate period.

1 refers to cond. at start of 1st f.r.p.
2 " " " " " 2 2nd "

for
- c " " constant rate period.
- 1 " " 1st f.r.p.
- 2 " " 2nd f.r.p.

s = standard conditions.
e = experimental "

for H i refers to inlet air conditions.

o " " outlet " "

s " " saturated " "

LITERATURE

1. Coulson, J.M. and Richardon, J.F., "Chemical Engineering", Vol. I. Pergamon Press, London.
2. Fick, A., Ann.Phys. 94, (1855), 59. Ueber diffusion.
3. Chilton, T.H. and Colburn, A.P., Ind.Eng.Chem. 26, (1934), 1183.
4. Gilliland, E.R. and Sherwood, T.K., Ind.Eng.Chem. 26, (1934), 516.
5. Hinchley, J.W. and Himus, G.W., Trans.Inst.Chem.Engrs. 2, (1924), 57.
6. Powell, R.W. and Griffiths, E., Trans.Am.Inst.Chem.Engrs. 13, (1935), 175.
7. Wade, S.H., Trans.Inst.Chem.Engrs. 20, (1942), 1.
8. Pasquill, F., Proc.Roy.Soc. A182, (1943), 50.
9. Sherwood, T.K. and Pigford, R.L., "Absorption and Extraction", 2nd. ed., McGraw Hill, 1952.
10. Linton, W.H. and Sherwood, T.K., Chem.Eng.Prog. 46, (1950), 258.
11. Maisel, D.S. and Sherwood, T.K., Chem.Eng.Prog. 46, (1950), 172.
12. Gamson, B.W., Thodos, G., and Hougen, O.A., Trans.Am.Inst.Chem.Engrs, 39, (1943), 1.
13. Wilke, C.R. and Hougen, O.A., Trans.Amer.Inst.Chem.Engrs. 41, (1945), 445.
14. Taecker, R.G. and Hougen, O.A., Chem.Eng.Prog. 45, (1949), 188.
15. Hobson, M. and Thodos, G., Chem.Eng.Prog. 47, (1951), 370.
16. McCune, L.K. and Wilhelm, R.H., Ind.Eng.Chem. 41, (1949), 1124.
17. Gamson, B.W., Chem.Eng.Prog. 47, (1951), 19.
18. Sherwood, T.K., Ind.Eng.Chem. 21, (1929), 12.
19. Bateman, E., Hoff, J.P. and Stamm, A.J., Ind.Eng.Chem. 31, (1939), 1150.
20. Hougen, O.A., McCauley, H.J., and Marshall, W.R., Trans.Am.Inst.Chem.Engrs. 36, (1940), 183.
21. Van Arsdel, W.B., Chem.Eng.Prog. 43, (1947), 13.
22. Peck, R.E., Griffith, R.T., and Rao, K.N., Ind.Eng.Chem. 44, (1952), 664.
23. Newman, A.B., Trans.Am.Inst.Chem.Engrs. 27, (1931), 203, 217, 310.
24. Ceaglske, N.H. and Hougen, O.A., Trans.Am.Inst.Chem.Engrs. 33, (1937), 283.
25. Schlichter, C.S., U.S. Geo.Survey, 1897-98, Part 2, 301.
26. Haines, W.B., J.Agric.Sci. 17, (1927), 264.
27. Pearse, J.F., Oliver, T.R., and Newitt, D.M., Trans.Inst.Chem.Eng. 27, (1949), 1.
    Oliver, T.R., and Newitt, D.M., Trans.Inst.Chem.Eng. 27, (1949), 9.
    Newitt, D.M., and Coleman, M., Trans.Inst.Chem.Eng. 30, (1952), 28.
    Corben, R.W., and Newitt, D.M., Trans.Inst.Chem.Eng. 33, (1955), 52.
    King, A.R., and Newitt, D.M., Trans.Inst.Chem.Eng. 33, (1955), 64.

28./

28. Brown, A.H., and Kilpatrick, P.W., U.S.Dept.Agric., Pub.AIC - 51 - (I-VIII)

29. Van Arsdel, W.B., U.S.Dept.Agric. Pub.AIC - 300.

30. Eis, A.J., and Hales, K.C., D.S.I.R. Food Invest.Rep., No.53, (1942), H.M.S.O.

31. Kamoi, S., and Shiomi, S., J.Soc.Chem.Ind. (Japan), 40, (1937), 257.

32. Culpepper, C.W., and Moon, H.H., U.S.Dept.Agric.Tech.Bull. 592, (1937).

33. Smith, A.J.M., "Dehydration", U.K.Prog.Repts. Sect. X, Part 2, D.S.I.R. & M.O.F, 1943.

34. Guillou, R., Agric.Eng., 23, (1942), 313.

35. Perry, R.L., Trans.Am.Soc.Mech.Engrs. 66, (1944), 447.

36. Cashmore, W.H., "Drying in Agric.", E. mid. Sect.Inst.Fuel. 21st March, 1951.

37. Von Loesecke, H.W., "Drying and Dehydration of Foods". Reinhold. Publ.Corp. New York.

38. Morris, T.N., "The Dehydration of Food", Chapman and Hall Ltd., London.

39. Marshall, W.R., Heat, Pip. & Air Cond. 14, (1942), 724.

40. Gardner, R.G., and Mitchell, T.J., J.Sci.Fd.Agric. 3, (1953), 113.
5, (1953), 237.
8, (1953), 364.
10, (1954), 481.

41. Hendry, R., and Scott, A.W., J. Inst.Fuel, 23, (1950), 285.

42. Bailey, P.H., "Drying of Grass", E.Mid.Sect.Inst. of Fuel. 21st March, (1951).

43. Bailey, P.H. and Hamblin, H.J., "The Testing of Grass Dries", Nat.Inst.Agric.Engng. (1950).

44. Oxley, T.A., "Scientific Principles of Grain Storage", Northern Publ. Co., London.

45. Simmonds, W.H.C., Ward, G.T., and McEwan, E., Trans.Inst.Chem.Engrs. 31, (1953), 265, 279
32, (1954), 115, 121
130.

46. McEwan, E., and O'Callaghan, J.R., The Engineer, Dec. 10th (1954).

47. Reeve, R.M., Food Res., 8, (1943), 128.

48. Burges, A.H., "Hop Drying", E.Mid.Sect.Inst. of Fuel. March, 21st (1951).

49. Owen, E.J., "Desiccation of Sugar Beet and the Extraction of Sugar", Min. of Agric. and Fish., (1927), H.M.S.O.

50. Scott, A.W., J.Roy. Tech.Coll., Glasg., 4, (1940), 725.

51. Marshall, W.R., and Hougen, O.A., Trans.Am.Inst.Engrs., 38, (1942), 91.

52. Kreybill, H.R., Ind.Eng.Chem., 35, (1943), 46.

53. Coles, W.V., J.Inst. Fuel, 25, (1952), 60.

54. Allerton, J., Brownell, L.E., and Katz, D.L., Chem.Eng.Prog. 45, (1949), 619.

55. Marshall, W.R., and Friedman, S.J., Perry, J.H., "Chemical Engineers Handbook", McGraw Hill, p.

56./

56. Mounfield, J.D., J.Soc.Chem.Ind., 62, (1943), 93.

57. Lowe, E.,Ramage, W.D., Durkee, E.L., and Hamilton, W.E., Fd.Eng. July 1955, 43-44.

58. Broughton, D.B. and Mickley, H.S., Chem.Eng.Prog. 49, (1953), 319.

59. Black, D.B., and Duthie, A.J., Rep.Scot.Seaweed Res.Ass., (1947), p.83

60. McLean, A.C. and White, T.T., Rep.Scot.Seaweed Res.Ass., (1948), p.92.

61. Hyndman, R.W., McEwan, I.R., and Mitchell, T.J., Chem. & Ind., (1954), p.560

62. Rankin, W.D., Thesis R.C.S.T. Glasgow, (1953).

63. Gardner, R.G., Mitchell, T.J., and Scott, R., Chem. and Ind. (1952), p.448.

64. Jackson, P., Rep.Scot.Seaweed Res.Ass., (1947), p.83.

65. Clark, D.E., Pratt, L.D., Coleman, S.A., and Green, H.C., U.S.Pat. 2,350,209.

66. Gardner, R.G., Rep.Scot.Seaweed Res.Ass., (1951), p.145.

67. Mitchell, E.K., E.Mid.Sect.Inst. of Fuel, March, 1951.

68. Exelsonn, J., Svenska Bryggareforen Manadakad, 57.

69. Oxley, T.A., "The Scientific Principles of Grain Storage". The North Pub. Co. (1948).

70. Stansfield, E., and Cook, W.H., Nat.Res.Council of Canada. Rep. 24, 25, (1932).

71. Treybal, R.E., "Mass Transfer Operations", McGraw Hill Book Co., (1955).

72. Spaugh, O.H., Fd.Tech., Champaign, 3, (1948), 33.

73. Heriot, "The Manufacture of Sugar from the Cane and Beet", Longmans Green, 1920, 138.

74. Mitchell, T.J., J. Roy. Tech.Col., 5, (1950), 110.

75. Gordon, C.W., Chem.Eng.Prog., 45, (1949), 477.

76. Gardner, R.G., Ph.D. Thesis, Glasgow.University, 1954.

77. Morris, T.N., "The Dehydration of Food", 1947, Chapmans and Hall, London.

78. Tomkins, R.G., Mapson, L., and Wager, H.G., J.Soc.Chem.Ind., 65, (1946), 384.

79. Blair, and Ayres, J., Ind.Eng.Chem., 35, (1943), 85.

80. Ede, A.J., J.Soc.Chem.Ind., 68, (1949), 330, 337.

81. Bitting, U.S. Dept.Agric.Bur.Chem., 1909, Bul, 125.

82. Rose, H.E., Proc.Instn.Mech.Engirs., 153, (1945), 141.

83. Hearne, J.F., and Tapsfield, D., J.Sci.Fd.Agric., 7, (1956), 210.

84. Gooding, E.G.B., and Tucker, C.G., Fd.Man., 30, (1955), 447.

85. Gooding, E.G.B., Fd.Man., 31, (1956), 569.

86. Gooding, E.G.B., and Rolfe, E.J., J.Sci.Fd.Agric., 6, (1955), 427.

87. McCance, R.A., and Widdowson, E.M., "Chemical Composition of Foods".