THE DRYING OF VEGETABLE MATERIALS IN A STREAM OF AIR

A thesis presented by

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SUMMARY

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A rotary drier is a rotating cylinder through which passes a steady stream of material which is agitated and showered through hot air by lifting flights to secure efficient heat and mass transfer. Although this drier is now well established in chemical industry, virtually all the design methods and complete operational studies available are restricted to the treatment of materials which have only surface moisture and are therefore easily dried. Vegetable materials are representative of the substances whose drying rates decrease as they lose moisture, i.e. they dry in the so-called falling rate period. They have therefore been chosen to study the counter-current operation of a small rotary drier built for this purpose.

The operation of the drier is controlled by air mass flow and temperature, the speed and slope of the tube, by the lifting flights, and the feed rate of the material being dried. The effects of these on the drying rates of three vegetable materials which were available in bulk, viz. brewers' spent grain, barley grain and granulated cork, were studied, and to allow for the effects of the time of contact in the drier, the conveying properties of the unit were checked with both wet and dry materials. As considerable deviation from an average contact time is possible, which

may lead to scorching and degradation of part of the feed, the effects of some of the operating factors on dispersion were studied in a smaller unit.

Because of the interdependence of many of the factors involved, interpretation of the results was occasionally difficult, but where possible, particularly in tests on inlet air temperature and velocity, drying rates are compared with fundamental or basic figures obtained from through circulation drying of thin layers. After allowance had been made for the considerable variation in material velocity through the rotary drier, in both types of drying the rate of removal of moisture is shown to be proportional to the moisture content of the material, i.e.

$$\frac{dW}{d\theta} = -m.W \quad , \text{ or } \mathrm{Log}_e W = -m.\theta + k$$

The values of m, the falling rate constant, are employed to compare the effects of each of the operating variables on drying rates. Those calculated from the rotary drier are about one tenth of the values obtained from single layers under comparable conditions of temperature and airflow.

Effects of variables controlling rotary drying

Tests on contact, or retention time and loading show that although relations already proposed for dry materials can be generally accepted, with wet feed considerable differences are observed. The effects of the operating

factors are detailed and discussed. A general correlation for deviation from mean retention time has been developed explaining the effects of the factors, viz. flight action and bouncing, which apparently cause this.

Inlet air temperature

In studies in the range 120°F to 220°F, relations between drying rates and temperature are shown to be similar for both types of drying studied, but rising temperature appears to have less effect in the rotary drier.

Air mass flow

The practicable range of air mass flow was limited by the nature of each material, and a relationship between the limiting velocities for each type of drier is suggested. Drying rate constants showed a similar dependence on air-flow in both types of drying.

Feed rate

Drying rates are shown to decrease with increasing feed rate and empirical equations between them are proposed. It is thought that the effects are caused by the variation in drier loading caused by altering the feed rate.

Speed of the drier tube

Increased drying rates were encountered when drier speed was increased. As the effect appears to be due to several factors, the nature of these is discussed and

relations between them are deduced.

Number of lifting flights

As the result of tests on each material where the number of lifting flights was varied between two and eight, it appears that higher values of the falling rate drying constant can be obtained with fewest flights - the reverse of the effect observed where surface moisture only is being evaporated.

General

Some points relating to the general design and operation of rotary driers are proposed. While a considerable amount of experimental work is still necessary with both more materials and different sizes of drier to determine scale effects, it is suggested that the methods detailed in this work, involving the falling rate drying constant which can be determined readily from single layer tests, can form the basis for a general design method for rotary driers.

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INTRODUCTION.

I. INTRODUCTION

The drying of materials forms a necessary and important step in many chemical processes and need not be associated only with the final stages. The unit operation of thermal drying can be readily distinguished from mechanical processes such as draining or centrifugal dewatering, but the demarcation between drying and evaporation is less well defined. The two are usually classified on the basis of the amount of water evaporated per unit weight of dry solids, or on the nature of the equipment used.

The term "dehydration" is usually applied to the drying of foodstuffs.

A drying operation is often included in a series of operations to facilitate further processing of the material. This may be accomplished either as the result of alteration of its physical properties or simply by effectively increasing the capacity of the following units. Thermal drying, occasionally preceded by mechanical partial dewatering, is frequently carried out before final packaging.

Drying of the final product may be undertaken to prevent subsequent decomposition, to reduce storage and freight charges by reduction of weight and volume, or simply to permit more convenient and satisfactory use of the material. Occasionally a waste or by-product may be dried to increase its commercial value.

To dry most materials it is preferable to apply simultaneously both heat and agitation. The moisture requires a definite amount of heat for its evaporation. Agitation of the material permits rapid absorption of heat and thus shortens the drying time. The principal functions of the drier are to supply the heat necessary to evaporate the water, to agitate the material, and to remove the water vapour.

The choice of drier for a particular task will depend om several factors. The main considerations are the physical properties of the material to be treated. Its shape, size, surface characteristics and the temperature to which it can be heated are all important. Treatment with furnace gases may be feasible for some substances while warm air or indirect heating must be used for others. The throughput and the initial and final moisture content of the material determine the amount of water to be evaporated and will affect the size of the unit. This in turn will involve the amount of space available.

Suitable sources of heat and power must be evaluated and both capital and running costs studied. If the product brings a high price the need for economy in the drying processes will be small and the choice of methods correspondingly larger.

Coupled to the actual choice of drier are the alternatives of a continuous or batch process. Except perhaps for very small

scale operations, modern practice is much in favour of continuous units.

Each group of materials has its own class of driers. Thin slurries are usually dried in drum or spray units, while sludges or pastes may be mixed with dry material and fed to a rotary drier. Substances in definite granules or pieces may be suitable for tray, through circulation or rotary drying. The final choice will depend on the properties of the material.

The mechanism of drying of a solid material is not a simple one. Many workers have met with varying degrees of success in calculation of drying rates, drying times and the effects of various factors thereon, but no universal prediction theory has yet been put forward.

The moisture may be present in the material in a variety of forms; e.g. as free water on an exposed surface, in the interstices between the fibres or granules, inside permeable or impermeable membranes of living cells, adsorbed on surfaces, or combined as water of hydration. The rate of removal of water from the interior will depend on the ease with which it will pass through the substance, either in the liquid or the vapour phase. This in turn will be controlled by the availability and size of capillary passages, by the resistance offered by the cell walls in some materials, and by heat transfer limitations. It is often simpler

and more accurate to conduct laboratory tests on a given material to provide the information necessary for further calculations and design work.

Current tendencies towards continuous systems have produced further problems. When a steady stream of material passes through such a system, an average contact or processing time may be calculated. Some material will, however, usually pass through in longer and in shorter times than this average. To avoid overtreatment of part of the feed it is clearly desirable that any large deviation from this mean time by some of the material should be avoided. Overdrying of a fraction of a sensitive charge will lead in most cases to an inferior product.

While the drying of wet sand and Fullers' earth, substances which contain only surface moisture, has already been studied in rotary driers, no systematic investigation has yet been carried out into the effects of design and operating variables on the drying rates of materials containing a fair amount of internal moisture. The work here reported deals mainly with the properties of the direct rotary drier as they affect both the conveying and drying of some selected vegetable materials.

The Boundary Layer: Heat and Mass Transfer.

When a fluid flows parallel to a solid surface, it can be assumed that the relative velocity at the surface is zero, since otherwise the velocity gradient and therefore the shear stress would be infinite. At points progressively further away from the surface, the velocity will increase gradually as the main stream of the fluid is reached. This variation in velocity is produced by the viscous forces acting within the liquid.

Where the flow is laminar or viscous at low Reynolds number, i.e. below 2000, there is a continuous increase as described above. At Reynolds nos. above 3000 however, the turbulence in the main stream produces an effectively constant velocity in the direction of flow and the velocity gradient is confined to the region immediate to the interface. This slow moving layer or film on the surface allows passage of heat or material only by relatively slow and analagous conduction or diffusion processes. The velocity gradients produce corresponding changes in temperature and concentration in the film.

The factors controlling the formation of, and the velocities in the boundary layer have been summarised by Coulson and Richardson[1].

Mass Transfer.

The dependence on vapour pressures of the evaporation rates from a free water surface was recognised as early as 1802 by John

Dalton[2], who showed that when water was allowed to evaporate from heated pans, the rate at which this took place was directly proportional to the difference between the vapour pressure of the hot water and the air, and that this was independent of the actual temperatures.

The limiting and controlling effects of the surface films were noted by Smith[3] who showed that from consideration only of molecular kinetics, the expected evaporation rate would be about from 10^4 to 10^5 times that actually observed. The existence of a rate controlling film in many transfer processes has now been long accepted and the concept has proved useful in the treatment of a wide variety of problems. The rate of transfer of a material through such a film is given by Fick's[4] law,

$$\frac{dm}{dt} = -\Delta \frac{\delta c}{\delta x} \quad \ldots\ldots\ldots\ldots \quad 1$$

where $\frac{dm}{dt}$ is the molar rate of diffusion per unit area,

Δ is the diffusivity of the material in the film,

$\frac{\delta c}{\delta x}$ is the molar concentration gradient of the material along the line of diffusion.

Where diffusion through a turbulent layer is encountered, an additional term, E_D, the eddy diffusivity may be included to give:

$$\frac{dm}{dt} = -(\Delta + E_D)\frac{\delta c}{\delta x} \quad \ldots\ldots\ldots\ldots \quad 2$$

Following Hinchley[5]'s work on still air evaporation, Hinchley and Himus[6] investigated the evaporation from free water surfaces

into parallel air streams, and showed that

$$W = a(p_e - p_d) \quad \ldots\ldots\ldots\ldots \quad 3$$

where $a = 0.031 + 0.0135V$

and W = Evapn. rate, kg./(M.^{2})(hr.)

p_e and p_d = Water Vap. press in pan and air resp., mm.Hg.

V = Air velocity, metres/sec.

Similar work by Thiesenhusen[7] led to the evaluation of a mass transfer coefficient independent of water film effects, obtained by careful surface temperature measurements. Powell and Griffiths[8] and later Wade[9] and Pasquill[10] carried out more systematic investigations with better equipment. Each obtained similar relationships between the evaporation rate, and the partial pressure difference and air flow.

Actual tray drying by Ceaglske and Hougen[11] of a solid material led to conclusions different from those of Shepherd, Hadlock and Brewer.[12] Each determined experimentally first the evaporation rate from a free water surface and then for both coarse and fine sand. Both found that in the case of the sand there was a considerable period during which the drying rate, $\frac{dW}{d\theta}$, was constant. While Shepherd et al[12] suggested that actual value of this was independent of the mesh of the sand, the former stated that the "constant drying rate" decreased markedly from water to coarse sand, and then to fine sand.

Shepherd[12] et al proposed that allowance for variation in air flow be made according to the relation

$$\frac{dW}{d\theta} \propto G^{0.76} \quad \ldots\ldots\ldots\ldots \quad 4$$

which is of the same form as the relation,

$$K' = 1.42G^{0.37}, \text{ i.e. } \frac{dW}{d\theta} \; G^{0.37} \quad \ldots\ldots\ldots \quad 5$$

quoted by Molstad[13] as applying to air impinging at right angles to a surface. K' is the evaporation coefficient, lb.Water/(ft^2)(hr.) (Unit Humidity Diff.)

Chilton and Colburn[14] correlated heat transfer results with evaporation rates, and extended to cover water evaporation earlier work by Colburn[15] on the derivation of the dimensionless "j" factors. Colburn[15] showed that correlation of transfer coefficients by plotting against a modified Reynolds group, as Sherwood[17] had done with the results of Powell and Griffiths[8], was tantamount to plotting a variable against itself. This he overcame by employing dimensionless groups, "j" factors, where for mass transfer

$$j_d = \frac{k_g \cdot p_{gf} \cdot M_m}{G} \left[\frac{\mu}{P.D_v}\right]^{\frac{2}{3}} \quad \ldots\ldots\ldots \quad 6$$

Where k_g = Mass transfer coefficient.

p_{gf} = Logarithmic mean of the partial pressure of the inert component of the gas film.

M_m = Mean molecular wt. of the gas stream.

G = Mass velocity of the gas.

μ = Viscosity of the gas.

p = Density of gas in film.

D_v = Diffusivity of diffusing substance in gas film.

The "j" factors are normally plotted against a modified Reynolds Number, a similar technique to that used for fluid frictional resistances. This emphasises the relationship between these factors, the "j" group actually being derived from the postulate that the ratio of the momentum lost by skin friction between two sections s differential difference apart, to the total momentum, will be the same as the ratio of the heat actually supplied to the surface to that which would have been supplied if the whole fluid had actually been carried up to the surface, i.e. if there existed no surface film or boundary layer.

The earlier data of Thiesenhusen[7] and Hinchley and Himus[6] agreed well with this approach.

Chilton[16] et al developed the H.T.U., or Height of a Transfer Unit, for distillation problems, but the approach is suitable for some types of drying.

For mass transfer:

$$a(H.T.U.) = \frac{G}{k_g \cdot p_{gf} \cdot M_m} = \frac{aL}{\int_{p_1}^{p_{2dp}} \frac{dp \cdot p_{gf}}{p \cdot p_g}} \quad \ldots\ldots\ldots \quad 7$$

Where p_1 and p_2 are the outlet and inlet partial pressures of the transferred gas

L = Height of the transfer zone.

Gamson, Thodes and Hougen[18] have discussed at length the application of "j" factors to the constant drying rate. Assuming representative values for air viscosity, mean molecular weight, Schmidt no., and the density of the gas film, they deduced the relationship

$$w' = \frac{0.0786a\ (G')^{0.59}}{p_s . D_p^{\ 0.41}} \Delta H \quad \ldots\ldots\ldots\ 8$$

This compares favourably with the experimental equation proposed by Marshall and Hougen[19] for through circulation drying, viz.

$$w' = \frac{a'(G')^{0.8}}{D_p^{\ 0.44}} \Delta H \quad \ldots\ldots\ldots\ 9$$

Where a and a' are constants,

w' = Constant drying rate, lb.water/(lb.Bone Dry Solid)(min.)

p_s = Bulk density of the solid, lb/(ft.^{3}), dry basis.

ΔH = Log. mean humidity driving force.

D_p = Average particle diameter, ft.

G' = Air mass flow rate, lb. dry air/(ft.^{2})(min.).

The exponents of both D_p and G' show reasonable similarity, and both include ΔH as the driving potential. The experimental formula was deduced after showing that the value of the constant drying rate depended on air flow, dry bulb temperature and humidity, and was affected by particle size.

Pearse, Oliver and Newitt[20] have summarised the effects of the stationary air film on "constant rate" drying, and have pointed out

that the rate of drying depends only on external conditions and that the transfer rates observed are similar for a wide variety of substances. This is in agreement with the observations of Chakravorty[21], who reported that, provided the correct values of the vapour pressures in the air, p_a, and at the surface, p_w, are used, the rate of evaporation may be expressed over a wide range of air velocities solely as a function of the carrying capacity and the velocity of the air. For surfaces of moderate dimensions, the overall carrying capacity could be taken as the arithmetic mean of $(p_w - p_a)$ measured at the leading and leeward edges of the surface.

Internal moisture movement during drying.

Drying of a substance which contains internal moisture cannot be long continued before the water evaporated from the surface must be replenished from the interior. If the substance contains communicating pore spaces, water may move in the liquid phase under surface tension or capillary phenomena. As drying proceeds the interior water surfaces may become broken, and the remaining moisture must reach the surface by diffusional processes. It is a complex phenomenon which depends considerably on the material being dried, and is not yet fully understood.

Sherwood[22], for example, classified the two distinct falling rate drying periods observed with paper pulp into

(a) zone of decreasing wetted surface, as capillary action gradually decreased, and

(b) zone of internal diffusion control.

Heat transfer coefficient measurements indicated that in zone (a) the decrease in drying rate resulted from dry patches appearing and reducing the surface available for evaporation. In zone (b) the apparent heat transfer coefficient decreased sharply as drying proceded.

Movement by capillarity.

Moisture held in the interstices of a solid is subject to movement by gravity and capillarity provided suitable passageways are available. In powders and granular solids this will apply to all water above the equilibrium moisture content.

As a substance dries, the water menisci formed in the pores become progressively finer, then collapse, exposing adjacent pores and menisci still interconnected by fluid films. If pore sizes are suitable, water may thus flow from regions of high to regions of low concentration. The influence of passageways on moisture movement through granular materials was pointed out by Slichter[23], and Caeglske and Hougen[24] later suggested that a similar mechanism might occur in some drying operations.

From theoretical considerations, Haines[25,26] developed an expression for the surface potential of the menisci formed in a bed of spheres, and Haines, Newitt et al[27] proposed methods for measuring this factor in granular material with particles of mixed size.

As yet, however, no useful drying rate predictions can generally be made from capillarity considerations.

Movement by diffusion.

When the capillary action already described ceases, the remaining internal moisture must reach the surface of the material by diffusional processes. Diffusion, which may be defined as the spontaneous random intermixing of molecules or very small particles by thermal motion, produces material transfer from regions of high to regions of low concentration, and usually controls drying rates at low moisture contents. It has therefore received considerable attention in the literature.

The general differential equation for variation of water content in a solid with time and distance is, for undirectional flow,

$$\frac{dW}{d\theta} = D \frac{(d^2T)}{(dX^2)} \quad \ldots\ldots\ldots\ldots \quad 10$$

where W = water content subject to diffusion,

θ = elapsed time

D = diffusivity of the liquid through the solid

X = distance from the middle of the solid in the direction of diffusion.

Making several simplifying assumptions, Lewis[28] derived a formula for the falling rate period of drying of sheet material, showing that

$$- \frac{dW}{d\theta} = \frac{8ArW}{a(4A - ra)} \quad \ldots\ldots\ldots \quad 11$$

where r = a constant relating evaporation rate to surface W,

A = a constant

a = thickness of sheet.

Sherwood[22] and Newman[29] continued studies for material of different shapes and both maintained that the falling rate could be covered by the expression

$$\frac{dW}{d\theta} = - K(W - W_e) \quad \ldots\ldots\ldots \quad 12$$

an expression which can easily be derived from Eqn.(11). The integrated form of the equation proposed by Newman[29] which expresses the average moisture content in an infinite slab is identical with that proposed by Sherwood[22]. In simplified form this is

$$\frac{W - W_e}{W_o - W_c} = \frac{8}{\pi^2 e} - D\theta\left(\frac{\pi}{2a}\right)^2 \quad \ldots\ldots\ldots \quad 13$$

where all symbols are as before, and subscripts e and o refer to the average moisture contents at equilibrium with the atomosphere, and at the start of the diffusional flow period respectively. Simplification of this expression results in Eqn.(12).

Sherwood[30] continued studies in diffusion and deduced that the water distribution in an infinite slab, after an initial constant rate period, would be parabolic in nature. This was confirmed experimentally by Troop and Wheeler[31] in the drying of clay cylinders.

The data of Sherwood and Comings[32] for the drying of clays and porous plate do not support Newman's[29] view that there is a finite surface resistance during the second falling rate period.

The existence of such would infer that varying air velocity would affect the drying rates, a point not borne out by Sherwood's[32] experimental data. The limitations of the diffusional approach to drying have been emphasised by Hougen, McCauley and Marshall[33] in a discussion of application of diffusional theory.

The drying of vegetable materials.

The similarity of a piece of cut vegetable material to a fine grain sponge full of water has been remarked up on by Van Arsdel[34]. When exposed to the drying air, the moisture in the outer layers evaporates rapidly and this may be followed by a period where the surface is fed by capillary flow with moisture from the centre of the piece. In turn this is replaced by diffusional flow which controls during most of the drying period. This may be accompanied by the diffusional transfer of soluble materials to the centre of the piece.

The variation in diffusivity produced by the alteration of physical properties, variation in temperatures and deposition of dissolved materials during drying, makes application of diffusion equations normally almost impossible. By calculation, Van Arsdel[34] arrived at moisture distribution curves at very low moisture contents where nearly all shrinkage will have taken place, and change in diffusivities small. These were shown to be of the same form as had been found by Ede and Hales[35] in the drying of slices of potato, and in the drying of wood by Bateman, Hoff and Stamm[36].

In practice it has been found most satisfactory, when dealing with a particular vegetable material, to rely on experimental, rather than theoretical predictions. Ede and Hales[35] developed a prediction method on the basis that for a large number of materials, the drying time was proportional to the "wet bulb depression", being the difference between the dry bulb and ventilated wet bulb temperatures of the drying air.

Guillou[37] showed that the drying time of prunes could be expressed by the relation

$$\theta_{1\rightarrow 2} = \frac{1}{K}\log. \frac{W_1}{W_2} \quad \ldots\ldots\ldots \quad 14$$

where $K = 0{\cdot}2 \left(\frac{t}{165}\right)^{4} \left(\frac{V}{600}\right)^{0{\cdot}2} \left(\frac{100 - H}{60}\right)$

and t = air temperature, $^{o}F.$,

V = air velocity,

H = relative humidity.

Perry[38] showed that, because the equilibrium moisture content of pruned was relatively constant below 40% relative humidity, changes in the air stream humidity below this had little effect on the drying rates.

McEwan, Simmonds et al[39] studied the through circulation drying of wheat grain and established a prediction method for deep beds on the results obtained from the drying of shallow layers. It was considered that, ideally, the drying characteristics of a material could be determined by measuring the drying rate of one suspended

particle - a technique employed by Van Krevelen and Hoftijzer[40] during studies on the drying of granules of marl - but the variability of vegetable material makes this inaccurate. The difficulties were overcome by drying a thin layer of the material in a through circulation drier.

By extrapolation of the drying curves to infinite time, McEwen[39] et al arrived at a value for the equilibrium moisture content of the wheat grain, and showed that, over a large portion of the falling rate period,

$$\frac{dW}{d\theta} = -m(W - W_e), \text{ or } \log_e(W - W_e) = -m\theta + K \quad \ldots \quad 15$$

When the value of W_e is small compared with W, W_e may be neglected and further simplification results.

Gardner and Mitchell[41] and later Mitchell and Potts[42] employed wet bulb depression methods to establish a prediction method for the drying of sublittoral seaweeds. This developed into a general study of the drying of vegetable materials, and Mitchell and Potts[42] and Hughes and Mitchell[43] applied single layer techniques to the prediction of drying times in deeper beds. The materials studied in single layers by these workers included brewers' spent grain and barley grain, substances found suitable for rotary drying in the current series of tests.

The Rotary Drier

The rotary drier is the logical development of the rotary furnace or kiln. The rotary kiln is essentially an inclined tube whose rotation moves its contents slowly along its length. Drying or roasting is accomplished by passing hot air or furnace gases over the material in the tube. Its use nowadays is usually confined to relatively high temperature processes, e.g. in cement manufacture. A general discussion of rotary kilns and their structural design has been published by Dickie[44].

The rotary drier differs from the kiln in having internal blades or baffles fixed to the shell to agitate the charge. The early development of this type of drier took place in Germany and a patent of 1877, "Trockenapparat fur braunkohle"[45], describes a plant for drying lignite, a unit which was virtually a low temperature kiln, exposing little extra material surface, and in consequence being somewhat inefficient. A slightly later patent[46] describes the fitting of blades which produced forward motion with some showering of the contents through the hot air. A "honey-comb" form was developed in 1897 in which the cross-sectional area was divided into many small separate compartments, producing even air and solid distribution over the drier. With this type, heat losses from the outer wall produce a temperature gradient from the centre and there may be considerable variation in the amount of drying accomplished in different compartments[49].

Quadrant flights were patented[47] and were followed by a cross arrangement, developed by Gerlach of Nordhausen[48]. These complex flight systems have never found much favour outside continental Europe, being somewhat difficult to keep clean and requiring more maintainance.

Simple radial flights were widely adopted in the United States and some ingenious flight systems developed to improve contact and drying[50]. The "type H" drier of the general American Transporter Co. has a series of circular baffles fitted along its axis with this intention.

The majority of the earlier driers were constructed for the treatment of sand or lignite, but the Mackensen[51] drier of the sugar industry was used extensively for the dehydration of pressed sugar beet cossettes.

Clark, Pratt et al[52] described the use of a rotary drier for the partial drying of seaweed. Few other data are, however, available for vegetable drying in this type of unit. Spraul[53] has published some results on the drying of a considerable number of materials, including various inorganic salts, pharmaceuticals, granulated cork and both natural and synthetic rubber. No full investigation of the operation of the unit was made, the tests were apparently intended to demonstrate the versatility of the rotary drier.

Developments of the rotary drier have included the rotary

louvre and the steam tube driers. The rotary louvre drier, whose construction and operation has been described by Erisman[54], is essentially a through circulation drier, the wet material moving along the bottom of the shell as in a kiln, with the drying air being introduced through ducts in the drier shell. Rockwell, Lowe et al[55] have described a form of rotary louvre drier for the dehydration of apple slices, where conditions must be carefully controlled to avoid spoiling the material.

The steam tube drier has been described by Bill[56], and is essentially a rotary drier where the flights have been replaced by steam tubes to heat and dry the charge, and cold air is passed through the drier.

Conveying Properties.

For both the rotary kiln and the rotary drier an average time of passage, or retention time, may be calculated. The majority of previous workers concerned with the conveying properties have given primary consideration to this. Friedman and Marshall[67] believe, however, that the volumetric percentage hold-up is the constant to be fixed for design purposes. This is defined as the ratio of the volume occupied by the solid material in the drier to the total internal volume of the tube. It is usually expressed as a percentage. The hold-up and the retention time are related by the expression

$$\tau = \frac{L\,X}{100\,F} \quad \ldots\ldots\ldots \quad 16$$

Where τ = Retention time, hours.

L = Length of drier, feet.

X = Percentage hold-up

F = Feed rate, $ft^3/(hour)(ft)^2$ of drier cross-section

It must be emphasised that this gives only the average time of passage. Some material may pass through in less than the average time, and some may take correspondingly longer.

The first data for retention times were obtained for rotary kilns. As the result of experimental observations, Sullivan, Maier and Ralston[57] presented the following equation for predicting the time of passage

$$T = \frac{0{\cdot}000517.L.\theta^{\frac{1}{2}}}{Sd.D.N.} \quad \ldots\ldots\ldots\ldots \quad 17$$

Where θ = Dynamic angle of repose of material, degrees

S_d = Slope of kiln, ft./ft.

D = Diameter of kiln, ft.

N = Speed of kiln, R.P.M.

L = Length of kiln, ft.

Ginstling, Zil'berman and Gvozdev[58] independently reported that the movement of material in an inclined rotary tubular furnace could be expressed by

$$T = \frac{0{\cdot}00783.L}{Sd.D.N.} \quad \ldots\ldots\ldots\ldots \quad 18$$

It will be noted that the angle of repese has not been included in this. If a representative value of 40^o is assumed for this in equation 17, expression 18 gives an estimated retention time 2·4 times greater than that from 17.

Other expressions must be used when dams or retaining rings are fitted either within the kiln or at the discharge end. Bayard[59] presented a series of nomographs, essentially modific-

ations of formula 17, in which allowance was made for the effects of these extra obstructions.

In a mathematical analysis of the likely paths of material through a kiln, Saeman derived[60] the expression

$$T = \frac{L \sin \theta}{2\pi r n(\phi . \phi \cos\theta)} \quad \ldots\ldots\ldots \quad 19$$

Where ϕ = angle (radians) between material surface and kiln axis, and other symbols as before.

If it is assumed that the surface of the material in the kiln is flat and parallel to the axis, $\phi = 0$ andthe above reduces to equation 18.

All the above formulae give misleading results for low kiln slopes and certainly cannot be applied to high loadings in horizontal cylinders. Extending earlier work by Vahl[61], Vahl and Kingma[62] deduced the relationship

$$T = 0{\cdot}91 \left(\frac{L}{D}\right)^2 \frac{D}{h_o} \frac{\tan\beta}{n} \quad \ldots\ldots\ldots \quad 20$$

Where T = R. time, mins.
h_o = Depth of bed at inlet, ft.
β = Dynamic angle of repose
n = Speed, R.P.M.

which exhibits good agreement with experimental data.

Kramers and Croockewit[63] studied the flow of granular solids through an inclined kiln and deduced a graphical solution which could make allowance for the effects of baffles and constrictions, and which also successfully correlated the results of earlier workers[57].

Johnston and Singh[64] appear to have been the first to publish information on the passage of material through a rotary drier. On limited data they suggested that a factor of 1·4 should be applied to the formula of Sullivan et al, giving

$$\tau = \frac{0{\cdot}000724.L.\theta^{\frac{1}{2}}}{Sd.D.N.} \quad \ldots\ldots\ldots\ldots \quad 21$$

The main point of difference between the rotary drier and the rotary kiln is that in the former the material being treated actually cascades through the moving air stream. According as the air flow is co-current or counter-current with respect to the material stream, the material will be assisted or retarded in its passage. To allow for this, Smith[65] proposed that the constant 0·00783 in expression 18 should be replaced by a constant k' when air was passed through the drier, i.e.

$$\tau = \frac{k'L}{Sd.D.N} \quad \text{or} \quad X = \frac{100\ k'F}{Sd.D.N.} \quad \ldots\ldots\ldots\ldots \quad 22$$

k' varied from 0·0042 to 0·017 for counter-current driers, and from 0·017 to 0·0058 for co-current driers.

A fairly rigorous series of tests carried out by Prutton, Miller and Schuette[66] included a number of runs with co-current or counter-current airflow. As far as possible employing "optimum loading conditions", i.e. where all the material was carried along by the action of the blades or lifting flights, and the air, and did not move in part along the bottom of the drier by the action similar to that occurring in the rotary kiln, they suggested that

$$\tau = \frac{k.L}{Sd.D.N} + mV \quad \ldots\ldots\ldots \quad 23$$

Where V = Air velocity, ft./min

m = A constant, positive for counter-current airflow, negetive for co-current airflow.

Friedman and Marshall[67] investigated the conveying properties of the rotary drier most thoroughly. They suggested that to maintain a constant hold-up the feed rate must be varied directly with the rate of rotation of the drier raised to some power less than one. This varied from 0·78 to 0·98 for the eleven materials studied, and seemed to increase with increasing angle of repose and decreasing number of flights in the drier. The hold-up appeared to be inversely proportional to the slope of the drier, and so the relation obtained was

$$X = \frac{0{\cdot}294\ F}{Sd.N^{0{\cdot}9}D} \quad \ldots\ldots\ldots\ldots \quad 24$$

The values obtained from this formula tended to be rather low, and a general correlation was obtained by plotting the group

$$\frac{F}{Sd.N^{0{\cdot}9}.D} \text{ against } \underline{X} \quad \ldots\ldots\ldots\ldots \quad 25$$

Over 300 tests carried out by the same workers suggested the relation

$$X_a = X_o + KG \quad \ldots\ldots\ldots\ldots \quad 26$$

as holding for airflow conditions.

Where X_a = Holdup in drier with air flowing

X_o = Holdup in drier with no air flowing

G = Mass flow of air, lb/(ft.^{2})(hr.)

K = Constant, depending on the material

+ ve for counter-current flow,

-ve for co-current flow.

No theoretical relationship between K and the material was found, although the best agreement appeared to be a plot of Kp_B (Defined as β) against the average particle size, suggesting that $\beta = \frac{5.15}{D_p^{0.5}}$ where D_p was the weight average particle size of the feed.

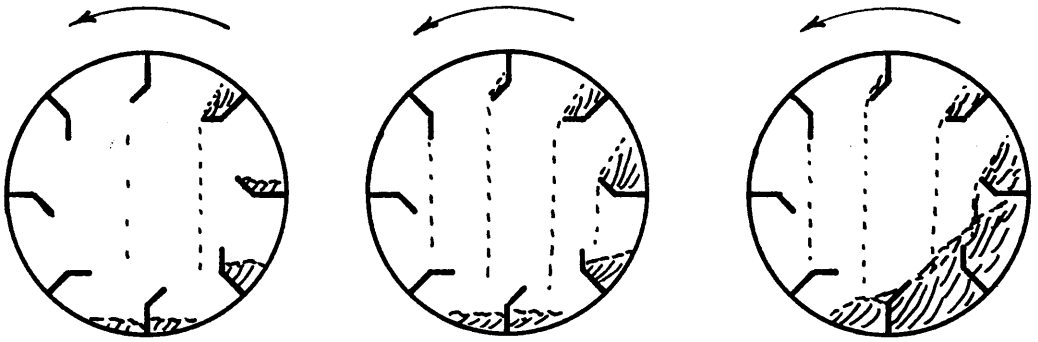
Independently van Krevelen and Hoftijzer[68] calculated the theoretical retention time for granules in a unit fitted with plain and cross lifting flights. The expression

$$\frac{n.\gamma.d'}{p'.L} \tan\alpha = C, > 0{\cdot}10 \quad \ldots\ldots\ldots\ldots \quad 27$$

was put forward, where p' = the number of steps into which the drier diameter is divided by the flights. In the case of the plain rotary drier without cross flights, p' = 1, and in this case C was found to be approximately 0·21. At the low angles of inclination employed, $\tan\alpha = S_d = \alpha$, and this formula is comparable with those proposed by earlier workers, but the constant C is slightly lower, Friedman and Marshall[67] suggesting 0·294.

The constant proposed by van Krevelen and Hoftijzer[68] was obtained by timing directly the passage of some material through an otherwise empty drier. The retention time as measured by this method is lower than would be the case with continuous working, and their results are therefore open to some criticism.

Fig.1 shows how a simple drier may perform at different loading or hold-up. It will be evident that low loadings may produce uneven distribution of the falling material and consequent short-circuiting of some of the airflow, and how overloading will

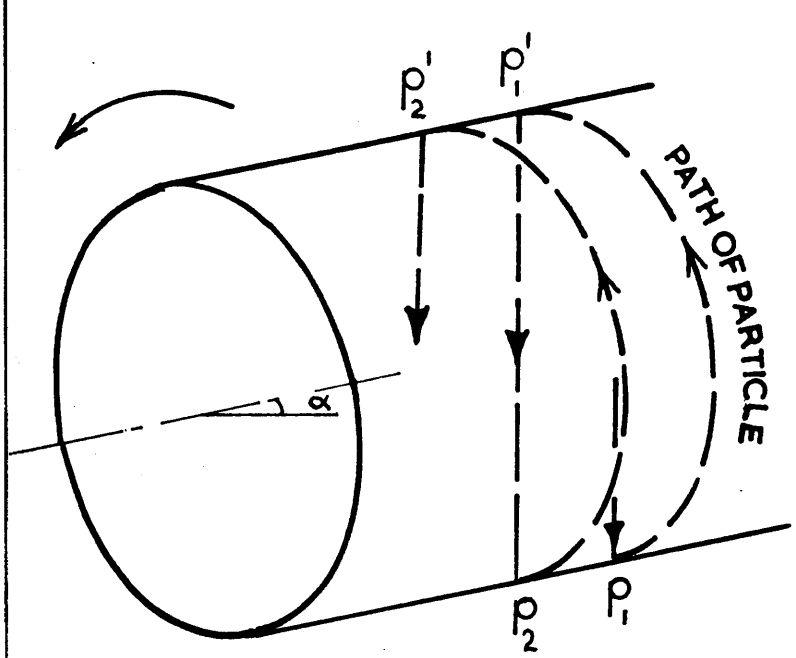


LIGHTLY LOADED

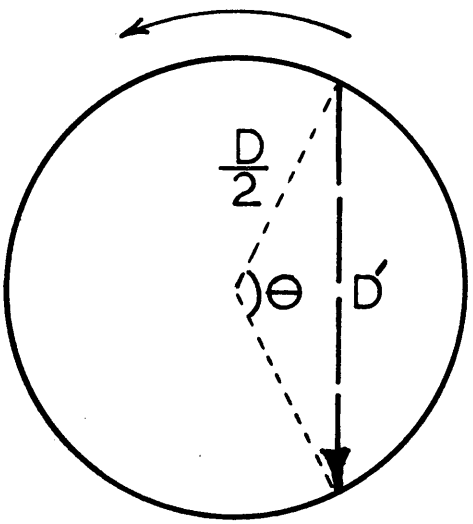
CORRECT LOADING

OVERLOADED

FIG. 1



a.



b.

FIG. 2

not produce denser "curtains" of falling material but will result in a bed of material moving along the bottom of the drier by kiln action.

The mechanism of transport by flight action is illustrated in Fig.2a. A particle on the shell bottom at p_1 will be carried round by the rotation of the tube to the point p_1^1 be the highest point on the tube, the particle will fall through the axis of the cylinder, and in this case it will strike the tube at a distance D.tanα in front of the original point. If, however, the mean discharge point is not at the highest point and falls through a chord other than the diameter, as in 2b, then an angle θ, which could be slightly greater or slightly less than 180°, will be subtended by this chord at the centre. The distance moved forward as the particle falls will now be D'tanα. D' will be a constant fraction, k', of D, and in a normally loaded drier where the falling material is spread evenly over the cross-section of the tube, the average value of θ will be 180°, or π radians. If the speed of rotation of the drier is $\underline{N}$ R.P.M. and its length L Feet, then the time taken by the average particle to pass through will be

$$T = \frac{L\theta}{D'\alpha.2\pi N} \quad \text{or} \quad T = \frac{L\theta}{KD\alpha.2\pi N} \quad \ldots\ldots\ldots \quad 28$$

Thus, from first principles, a relation can be deduced which is similar to the experimental expressions proposed by many of the workers quoted above.

If the drier is assumed to produce a uniform spread of

material over its area, the average height of fall will be

$$D' = \left(\frac{\pi D^2}{4}\right)\left(\frac{1}{D}\right), \text{ i.e., } \frac{\pi D}{4} \text{ or } 0{\cdot}78\ D.$$

Equation 28 becomes $T = 0{\cdot}95\ \frac{L}{D\alpha N}$. The constant 0.95 is considerably larger than that suggested by Friedman and Marshall[67], eqn.24, and it seems that kiln action and movement by sliding on both the flights and the drier shell must account for the difference.

When dealing with all the above equations for time of passage, and hold-up, it must be remembered that they apply strictly only to dry material. Friedman and Marshall[67] reported considerable difference when wet sand was used instead of dry sand, and Spraul[53] considers that the equations are not valid if change in feed rate, hold-up or time of passage produces an appreciable change in the handling characteristics of the material in the drier.

Deviation from average retention time.

It has been realised that, except in the case of pure "plug flow" where the material moves in small discrete sections and no mixing takes place, some will take a longer or a shorter time to pass through than the mean retention time. The importance of this when dealing with rotary driers is obvious, especially where heat sensitive material is being dried. While the product may have the final required average moisture content, some of it may be overdried and scorched, and some still damp.

The movement of material may conveniently be followed by the addition to the feed of a small quantity of some easily estimated

tracer. Under normal conditions the time taken for 50% of this to appear at the outlet is equal to the retention time of the main bulk of the feed. The theoretical implications of this have been studied by Spalding[69], and Danckwerts[70] has proposed a correction factor where there may be diffusion of the tracer material upstream from the feed point.

If the rate of tracer discharge ($dQ/d\theta$) or its instantaneous concentration q, to which it is proportional, be plotted against time, θ, a relationship which tends to zero as $\theta \rightarrow$ infinity will be obtained. Fig.3 illustrates some possible variations with different systems.

(a) This shows the exponential plot obtained where the tracer is added instantaneously to the feed of a perfectly mixed vessel, and the concentration is measured at the outlet.

(b) Illustrates the more normal case where mixing is never perfect.

In other types of unit, including rotary driers, where "plug flow", illustrated by (c) would be the ideal, a curve such as (d) may result. In this case it is taken from one of the current series of experiments on the small rotary drier.

In all the above cases, the rate of tracer discharge $dQ/d\theta$ is at all times proportional to the outlet concentration q.

If V = Effective capacity of the unit

v = Material flow rate

Q = The amount of tracer, Q' being the total amount added.

θ = Time

T = Mean retention time

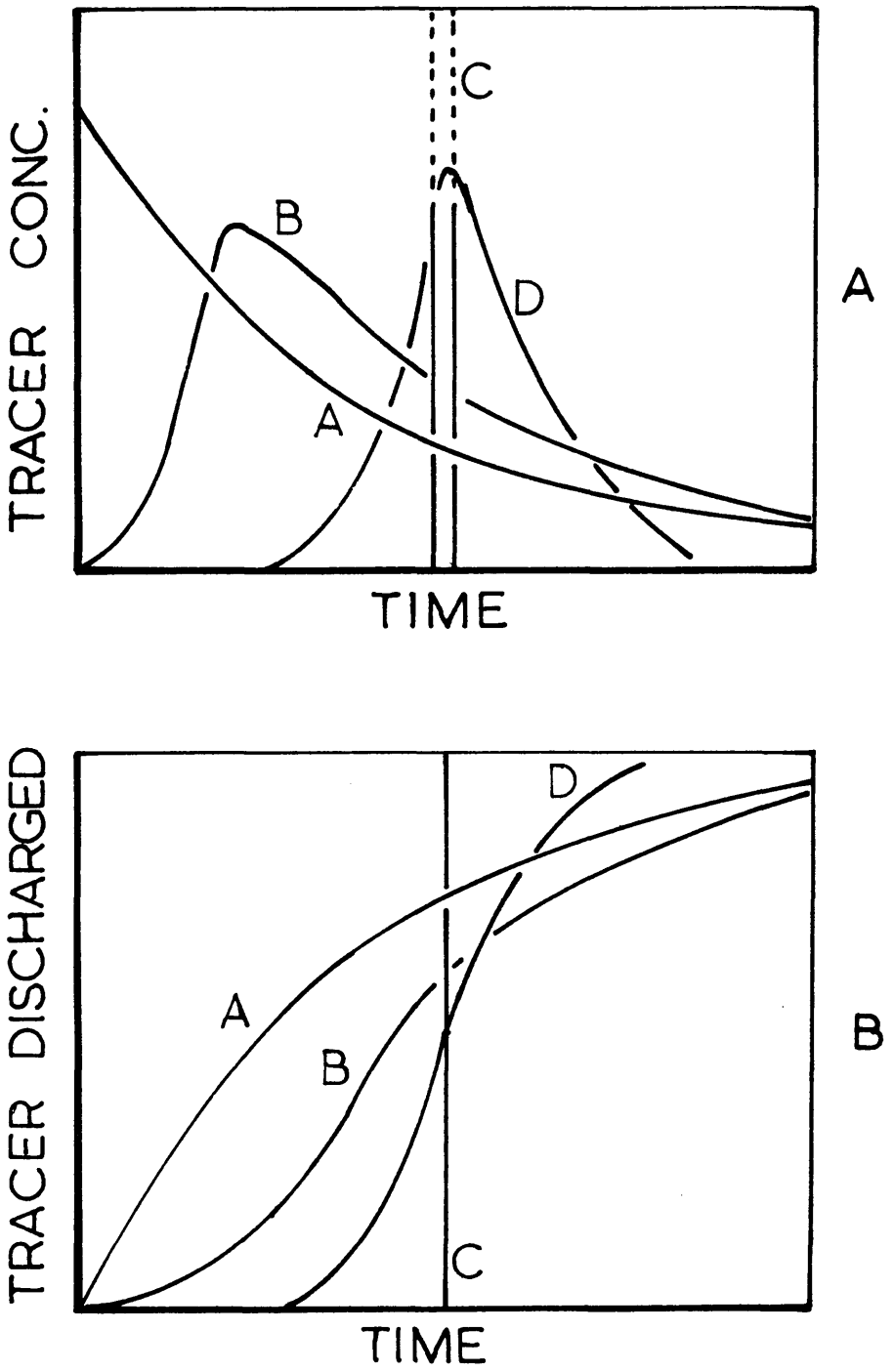


FIG 3

Then $Q_{(\theta)} = q_{(\theta)}v$; and if the curves in Fig.3 are expressed by $q = f(\theta)$, then

$$Q = v.f(\theta) \text{ and } Q' = \int_0^{\infty} f(\theta).d\theta \quad \ldots\ldots\ldots \quad 30$$

Also $= \frac{V}{v}$ and $\int_{\theta=\mathfrak{v}}^{\theta=r} v.f(\theta).d(\theta) = \frac{Q'}{2}$, assuming no upstream diffusion from the point of tracer injection.

The actual shape of the distribution curve has already received some attention. Saeman and Mitchell[71], from consideration of the distribution of material on the lifting flights, suggested that a curve with two peaks should be obtained. This appeared to agree with earlier results published by Smith[72] but later workers, Miskell and Marshall[73], found no evidence to support this theory. As the result of considerable experience in the operation of rotary driers, Smith[74] now states that, in general, only one main peak will be observed. During tests on the rotary louvre drying of seaweed frond, Gardner, Mitchell and Scott[75] observed a series of minor peaks in the distribution curve, which were, however, attributed to the sticky nature of the material causing erratic movement in the drier.

The tracer used in this type of work should have the same physical properties as the normal feed material. Smith[72] used alkali in his tests, but better methods were employed by Gardner and Mitchell[75], and Miskell and Marshall[73]. The former used as tracer, samples of seaweed which had absorbed radioactive iodine. The concentration of tracer in samples of discharge was measured by Geiger-Muller counter. The latter used white sand, some

coated with Uranium Oxide, and the counter was linked to a recorder to provide a continuous trace. On their results Miskell[73] et al suggested that there might be an optimum value of the loading for every drier to produce least "spread" of the retention time, but no general explanation of the factors which might be causing this phenomenon were put forward.

Drying rates.

Many attempts have been made to predict the drying rates in rotary driers. Alliot[76] discussed drying times, but made scant reference to applications in this field. Horgan[77] carried out some experimental work but produced no useful design method, nor did he attempt a full investigation of the factors which might affect the drying rate. He pointed out, however, that "one should know the rate at which the material to be dried gives up its moisture", the partial dependence of drying rates on the substance itself being dried being somewhat neglected by later workers.

An elementary analysis of the heat transfer mechanism, was attempted by Smith[65]. Design points suggested were, however, few, and were confined to the observations that the thermal efficiencies were from 30% to 80%, depending on whether low or high temperatures were employed. The amount of heat actually available for drying gave some indication of the material throughout.

Thefirst systematic study of the factors involved was carried out by Miller, Smith and Schuette[79], who considered the rotary drier from the point of view of a heat exchanger where the heat transferred from the air to the material being dried was given by the standard[78] overall heat transfer equation $\frac{Q}{\theta} = u_a . A \Delta t_m$ 31

Where Q = Amount of heat transferred

θ = Time

u_a = Heat transfer coefficient, area basis

A = Area available for heat transfer

Δt_m = Effective mean temperature driving force

They observed that the flights picked up the contents and allowed them to cascade in thin streams or "curtains" parallel to one another, and extending throughout the drier. As the cylinder turned, these curtains appeared, to the observer, to pass from one side to the other. The warm air flowing through the drier came into direct contact with the moist material on either side of the curtains, and it was considered that the area available for heat transfer should be the total area of the curtains. On this basis it was suggested that

$$\frac{Q}{\theta} = 2 \times U.L.D'.N_f.G\,\Delta t_m \quad \ldots\ldots\ldots\ldots \quad 32$$

Where U = Heat transfer coefficient, B.T.U./(hr.)(ft^2)(^oF)

D' = Average height of the falling curtains

N_f = Number of flights actively generating falling curtains at any instant

$$= \frac{(\text{Total number of flights}) - 1}{2}$$

L = Length of the drier, ft

G = Airflow, lb./(ft^2)(hr.), $x = 0{\cdot}46$ for $N = 6$; $= 0{\cdot}60$ for $N = 12$.

If λ is the Latent Heat of evaporation of water, then

$$\frac{Q}{\theta} = \frac{2.U.L.D'.N_f.G^x.\ t_m}{\lambda} = \frac{W}{\theta} \quad \ldots\ldots\ldots\ldots \quad 33$$

where $\frac{W}{\theta}$ is the overall drying rate, lb.water/hr.

The theory is to some extent in conflict with the evidence presented, as increase in the number of flights actually decreased the overall drying rate, although, according to the above, N_f would

increase.

Friedman and Marshall[80] suggested that allowance be made for the area term in the general heat transfer equation by consideration of the drier on a volumetric basis

$$\text{i.e.} \quad \frac{Q}{\theta} = U_a . V . t_m . \quad \ldots\ldots\ldots\ldots \quad 34$$

where Q,O and t_m were as before, and

U_a = Overall volumetric heat transfer coefficient B.T.U./(ft^3)(hr)

V = Volume of the drier, ft^3.

This is based on the somewhat complex expression resulting from consideration of the heat transferred in the drier

(a) from the air to the falling material

(b) from the air to the material lying on the flights and on the shell

(c) from the drier shell to the material, and

(d) from the drier shell to the surroundings.

It assumes that unit volume of the drier will present an average effective surface area for heat transfer.

A most extensive series of trials was carried out to investigate the heating of sand in a pilot plant unit to determine the factors affecting U_a , and it was found that hold-up, speed of rotation, number of flights and airflow all had some influence. As each was increased, so U_a tended to rise, but except for air-flow, all appeared to produce finally a limiting value of the heat transfer

coefficient. It was suggested that: $U_a = \frac{10.G^{0.16}}{D}$ 35

Few detailed figures are available for commercial units, but Kawabuti's results[81] for the drying of ammonium sulphate in a 2 ft. diameter drier indicate an overall heat transfer coefficient of 9.75 B.T.U./$(ft^3)(^oF)(hr)$, which compares favourably with the value 11.3 B.T.U./$(ft^3)(^oF)(hr)$ calculated from equation 35. The slight discrepancy can be accounted for by the comparatively low values of 3 R.P.M. and 142.2 lb/$(ft^2)(hr)$ for speed of drier and the airflow.

Data on the drying of bauxite in a 1 ft. diameter drier published by Gutzeit and Spraul[82] indicate an actual heat transfer coefficient of 51.8 B.T.U./$(ft^3)(hr)(^oF)$, while the calculated value was 31 B.T.U./$(ft^3)(hr)(^oF)$. Complex baffle systems such as have been developed by the General American Transporter Company[50] can raise the efficiency of the unit. A small drier of equal diameter, also working on bauxite showed a valumetric heat transfer coefficient of 75 B.T.U./$(ft^3)(^oF)(hr)$.

When the drier is handling a material, such as a vegetable, which is relatively difficult to dry as it exhibits a high internal resistance to moisture flow, the problem becomes one not of heat transfer but rather one of controlling the drying conditions so that the movement of moisture to the surface of the material is not hindered by the creation of additional surface resistances. The heat transfer coefficient as calculated from equation 35 becomes invalid and observed

values are much lower. While Gutzeit and Spraul's[82] results suggest a value 50% above the suggested figure from the diameter and the airflow for the drying of bauxite, the same drier showed an apparent heat transfer of 18.5 B.T.U./(ft^3)(^oF)(hr) when drying wood flour, the value from equation 35 being 30 B.T.U./(ft^3)(hr)(^oF).

On the evidence from heating trials on Ammonium Nitrate, Saeman and Nitchell[71] suggested that the cascade rate, i.e., the actual rate of discharge of all the material falling from all the flights, was a function of a heat transfer coefficient based on the length of the drier:

i.e. C = A.N.R. and assuming contents cascade twice per revolution,

C = 2.H.R., and

$$\frac{Q}{t.L.\Delta T_m} = C(0{\cdot}6 + 2{\cdot}5e^{-4{\cdot}8M}) \quad \ldots\ldots\ldots \quad 36$$

Where C = Cascade rate, Cu.Ft./(ft.)(min.) or lb./(ft.)(min.)
A = Flight loading, Cu.Ft./Ft., or lb./Ft.
N = No. of flights
R = Rate of rotation, Revs./Min.
Q = Quantity of heat, B.T.U.
L = Length of drier, Ft.
t = Time, Min.
ΔT_m = Mean temperature difference, ^oF.
M = Radial flight depth, ft.
H = Hold-up, by volume or lb. weight

Both Friedman and Marshall,[80] and Miller et al[79] concluded that the amount of heat transferred, based on unit length of the drier, should vary in direct proportion to the drier diameter.

The former preferred to base the actual heat transfer coefficient on volume, and the latter on curtain area. If the peripheral speed of the drier shell is kept constant, the cascade rate, and hence the heat transferred, will, by Saeman and Mitchell's[71] argument, also be proportional to the drier diameter. As mentioned by Perry[83], the range of peripheral speeds in normal use in rotary driers is fairly limited. It appears therefore that all three studies of heat transfer, applicable to "constant rate" drying, lead to approximately the same conclusions on the effect of drier size.

The determination of air and material temperatures and resultant temperature differences presents considerable difficulty in rotary drying. Although a satisfactory method of estimating the material temperatures was developed by Friedman and Marshall[80], no similar reliable technique could be applied to the measurement of the air temperature gradient along the length of the drier. Numerous attempts were made to solve this problem using a high velocity filtered thermocouple. The results were erratic and not reproducible, probably as some air travels relatively unmixed between the curtains of falling material, and it is therefore possible for considerable temperature striation to occur. In addition to this, insertion of any measuring instrument must inevitably alter ambient flow and equilibrium conditions, and this will be aggravated by withdrawal of any sample.

Under constant pressure, the condition of moist air can be defined by any two of dry bulb temperature, relative humidity, wet bulb temperature or total heat content, or moisture content. The moisture content of the inlet air can be readily measured by wet and dry bulb methods, and the inlet enthalpy determined from this and the drier air inlet temperature. Knowledge of material moisture contents and temperatures permit calculation of air enthalpy and moisture content through the drier, and hence an actual average air dry bulb temperature may be determined at any point by reference to a psychrometric chart.

The change of condition of the drying air through the drier may be represented by a curve on a standard psychrometric chart. A similar technique can be applied to through circulation units where adiabatic passage of air drying a material at its wet bulb temperature will produce a virtually linear section on the humidity/temperature diagram, as the total enthalpy of the air will remain unchanged.

Inazumi[84] developed a method for the prediction of air conditions during humidification, dehumidification or water cooling processes and introduced modifications for heat losses. Kawabuti[81] developed this with particular reference to rotary driers and deduced a formula for the inclination of the temperature/humidity curve on the psychrometric chart:

$$\frac{dH}{dt} = \frac{-K_g' \, a \, C_H}{h_g \, a} \left[\frac{(H_1 - H)}{t - t_1 + (1 - x)(t_1 - T) + \frac{C}{B}(t - t_o')} \right] \quad \ldots 37$$

Where H = Absolute air humidity, Kg./Kg.dry air.

t = Gas temperature, ^{o}C.

K_g' = Mass transfer coeff. for gas phase Kg./($m.^2$)(hr.)(unit humidity difference).

a = Area of transfer surface per unit gross volume, $m.^2/m.^3$

X = A constant, depending on the properties of the material.

c_H = Humid heat

h_g = Heat transfer coeff. for gas phase. k.cal/(m^2)(hr)(^{o}C)

T = Solid temperature, ^{o}C.

C and B are constants, and the subscripts "1" and "O" refer to interface and initial conditions respectively.

It is based on the assumption of a constant value of the ratio of the heat and mass transfer coefficients and includes "a", the "efficiency" term, of effective surface area exposed per unit volume to the drier. Its utility depends also, however, on the factor "x", as defined by

$$x = \frac{1}{\frac{Wc}{Wc} - 1} \cdot \frac{W}{Wc} - 1$$

where W is moisture content, expressed on a dry basis, the subscripts c and e referring to the critical and equilibrium points respectively. A further modification was proposed where the falling rate period was subdivided. In the constant rate period $0 \leq x < 1$

This treatment assumes that decrease of the drying rate in

the falling rate period is due to gradual decrease in the wetted surface area, and not to diffusional kinetics. For this reason it may have somewhat limited application.

The temperature differences in a rotary drier are not constant along the drier tube. It is usually feasible to measure the temperatures of both the material being dried and the air at the inlet and the outlet, and thus evaluate the thermal driving potential at these points. It is not unreasonable, if these are similar, to assume that the mean overall value in the unit will be the average of these two. It has been shown[85,86] that it is most accurate, where there is considerable difference between them, to employ the logarithmic mean value. The heat transfer coefficients proposed by Miller et al[79] were calculated on this basis. The derivation of a logarithmic mean overall thermal driving force is, however dependent on several factors:

(a) The heat capacities of both fluids or materials must be constant.

(b) The heat transfer coefficient must be constant; and

(c) The heat transfer rate must be proportional to the temperature difference. In a rotary drier the heat capacity of the air is not constant, and that of the material varies considerably as the moisture content decreases. Also, as Friedman and Marshall[80] showed, the heat transfer coefficient may not be constant along the length of the drier. If only surface water is being evaporated, it will for the most part evaporate at the wet bulb temperature of the air, and the material will remain at that temperature until

the critical moisture content is reached[80], when the falling rate period of drying begins. This also will introduce considerable error if the validity of the logarithmic mean temperature difference be complacently assumed.

Friedman and Marshall[80] and other later workers[81] concerned with heat transfer divided the drier into a number of smaller sections for the purposes of calculation, as it was found that over small sections, changes in the heat transfer coefficients, specific heats and temperature differences were negligible.

Kamei and Toei[87] have proposed methods of calculating drying times from standard laboratory tests and show how these may be used in designing pneumatic and belt driers. They suggest that the method may also be applicable to rotary driers.

APPARATUS

and

EXPERIMENTAL PROCEDURE.

Apparatus and Experimental Procedure

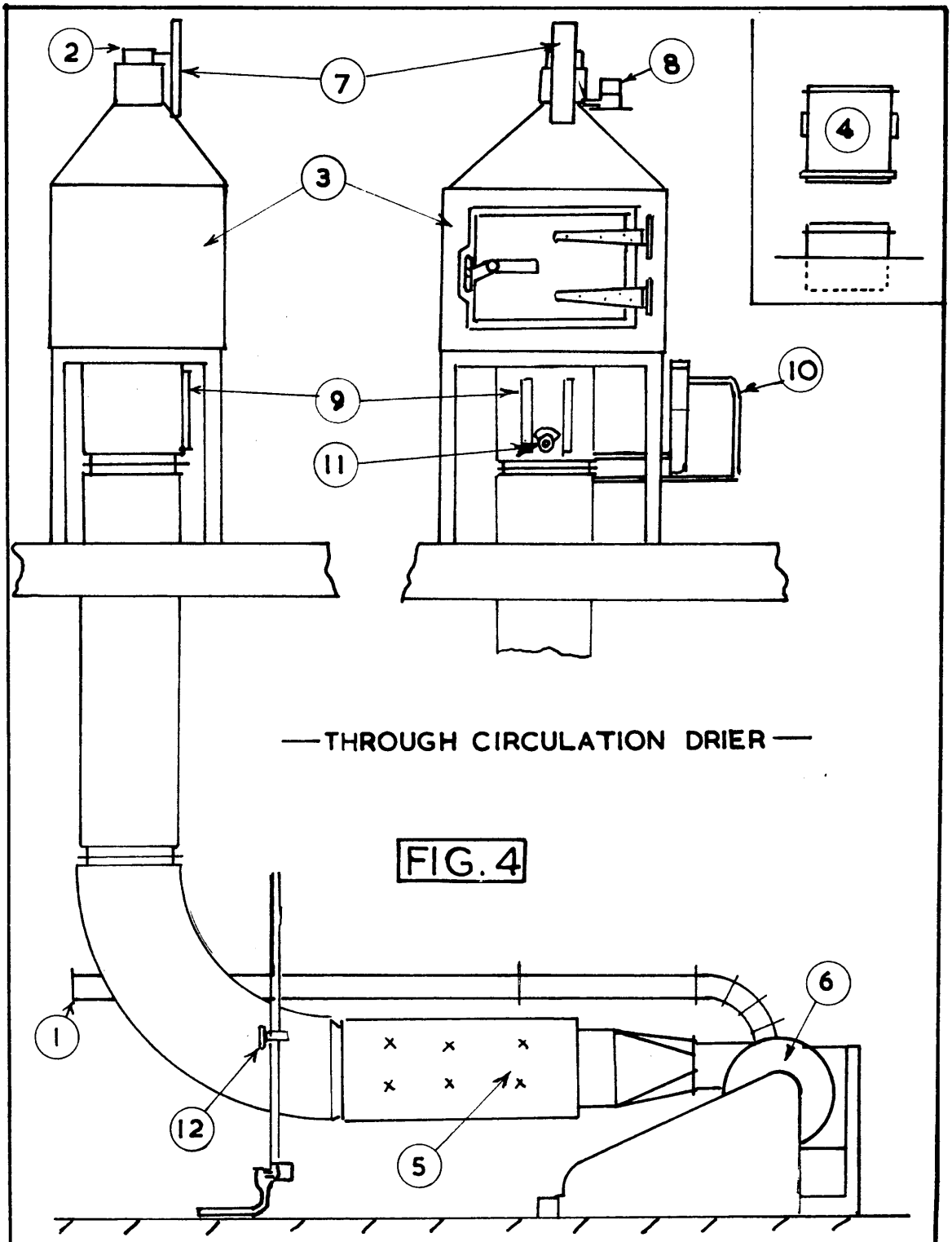
Two types of driers were used in these tests, a through circulation drier for the static tests and a rotary drier for the continuous runs.

Through Circulation Drier

A through circulation drier which had already been developed for vegetable dehydration was used for the static tests. This was designed as the result of previous experience with other driers, and has proved most efficient in service. A sketch of the unit is shown in Fig.4.

Air, measured by an orifice plate in the inlet duct, was forced by a fan over a bank of 18 one Kw. heaters, and after flowing through a one foot square smoothing duct passed through a chamber containing the material under test. The material was actually held in a removable basket with a wire mesh floor through which all the air must pass before leaving the drier. To minimise heat losses, all sections carrying hot air were insulated with a one inch thick layer of magnesia lagging.

The mass flow of air was readily varied by alteration of the speed of the D.C. powered fan, and the temperature of the air delivered to the drying chamber was controlled to within $\pm\frac{1}{2}^{o}$F. by a thermostatic fitted immediately below the bed. The temperature and condition of the air above and below the bed were determined by permanently fitted wet and dry bulb thermometers.



—THROUGH CIRCULATION DRIER—

FIG. 4

1- AIR INLET.
2- AIR OUTLET.
3- DRYING CHAMBER.
4- BASKET.
5-HEATING CHAMBER.
6- FAN.
7-OUTLET T'MOMETERS.
8- " WET BULB RSVR.
9-INLET T'MOMETERS.
10- " WET BULB RSVR.
11- THERMOSTAT.
12- STEAM CONTROL.

Experimental Procedure

The method of using this particular drier has already been described[42].

Briefly, the drier was first allowed to heat up to the operating temperature at the required air flow rate. The desired quantity of the material under test was distributed uniformly over the floor of the basket, which was then weighed with its contents and replaced in the drier. The course of drying was followed by interruption of the test, removal and reweighing of the basket and contents. The drying time was considered only as that actually spent by the material in the drier. This method has already been shown to have no appreciable effect on the course of drying[18,41,42]. The actual weighing was carried out to $\pm 0{\cdot}001$ lb.

On completion of a run, the material was ground in a small hammer mill and the residual moisture content determined by heating a small weighed sample under vacuum for a standard length of time and at a temperature determined by the nature of the material.

Preliminary Tests

The calibration of all thermometers was checked against a standard before they were inserted in the drier.

The air flow was measured by an orifice plate fitted to the inlet duct, the pressure tappings from which were taken to an inclined manometer. The readings from this were calibrated against a vane anemometer held in the outlet duct of the drier.

Calculation of Results

The "bone dry" weight of the experimentally dried material was calculated from its final weight and moisture content. The moisture content, lb. water/lb. B.D.S., was then calculated for each point of the run where the sample had been reweighed. The plot of moisture content versus time of drying was then drawn.

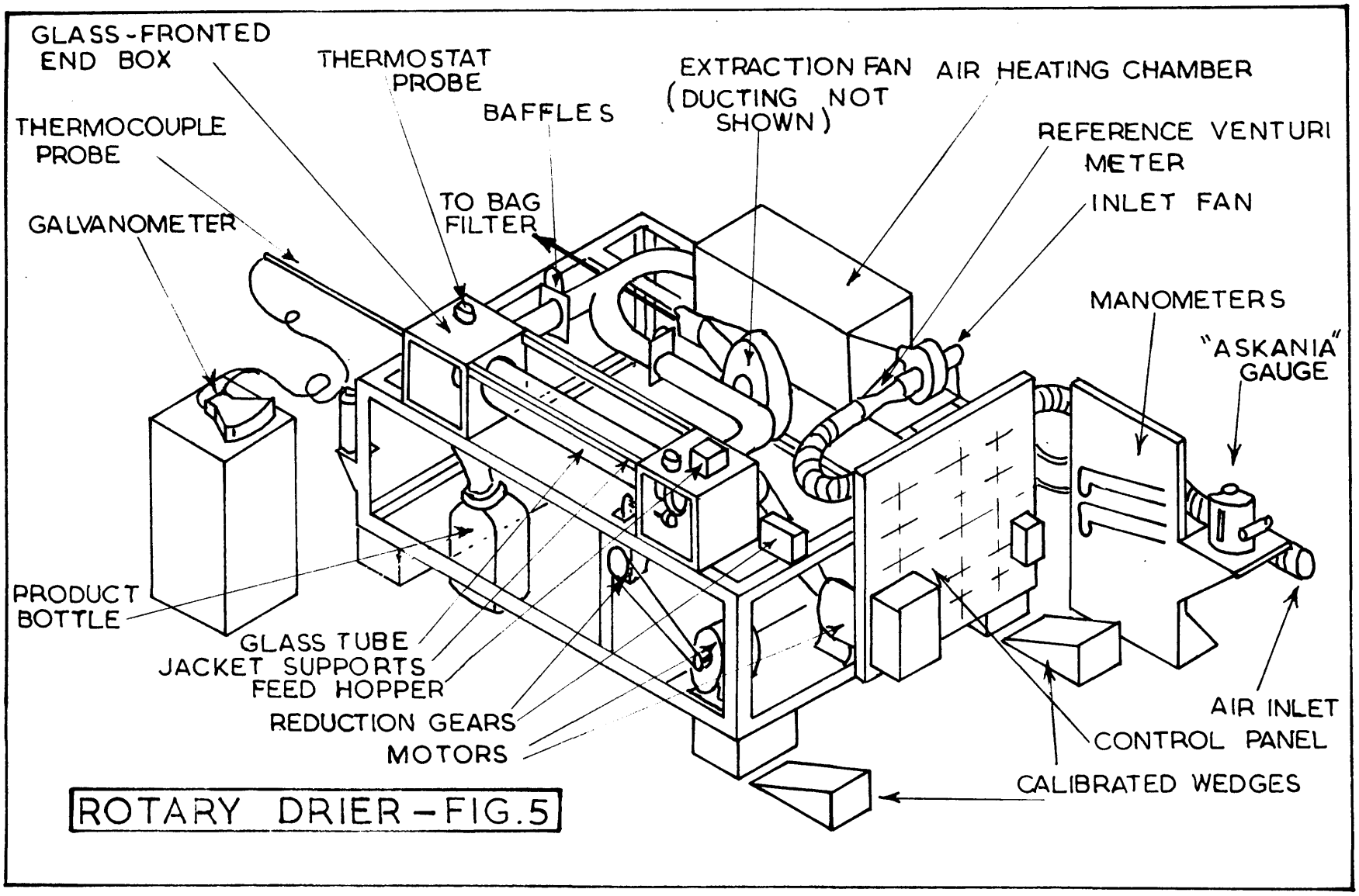
It was found most convenient to plot the actual drying curves on semi-logarithmic graph paper, as this work is mainly concerned with the falling rate period where faster initial rates of drying are replaced by much slower processes as drying continues. The method also allows readier comparison of results.

Rotary Drier

The rotary drier used in this investigation is shown in Fig. 5 .

A great deal of consideration was given to the size of the actual drying cylinder. On the dimensions of this were determined the capacities of fans, heating loads, additional motors, and the general size of theapparatus. The internal diameter of 5 inches was chosen as the material throughput of driers operating under similar conditions depends on the cross-sectional area of the tube, i.e. on the square of the diameter. For a given length of drier operating at a definite percentage volumetric hold-up and retention time, increase in internal diameter from 5 to 6 inches would necessitate an increase in feed rate of almost one half. As the drier is intended to deal with materials which have to be prepared by hand, the feed rate had to be kept within reasonable limits, and some calculations showed that a 5 inch diameter tube would be the largest feasible size.

The actual drying tube obtained was made from "Pyrex" heat resisting glass, 5 inches in internal diameter and 40 inches long. Turned brass rings fitted to each end held the lifting flights and could accommodate 2,3,4,6,8 or 12 with even spacing. The actual flights were made from aluminium and both flat and angled sections were used. Springs were fittedto the tie rods at one end to maintain a constant tension on each to allow for the appreciable



ROTARY DRIER – FIG. 5

expansion of the aluminium at higher temperatures. As the flights held the brass rings in place, without these there was a tendency for the rings to revolve slightly relative to each other, so producing a slight spiral form in the flights, resulting in a definite gap between the shell and the flights in the centre of the drier.

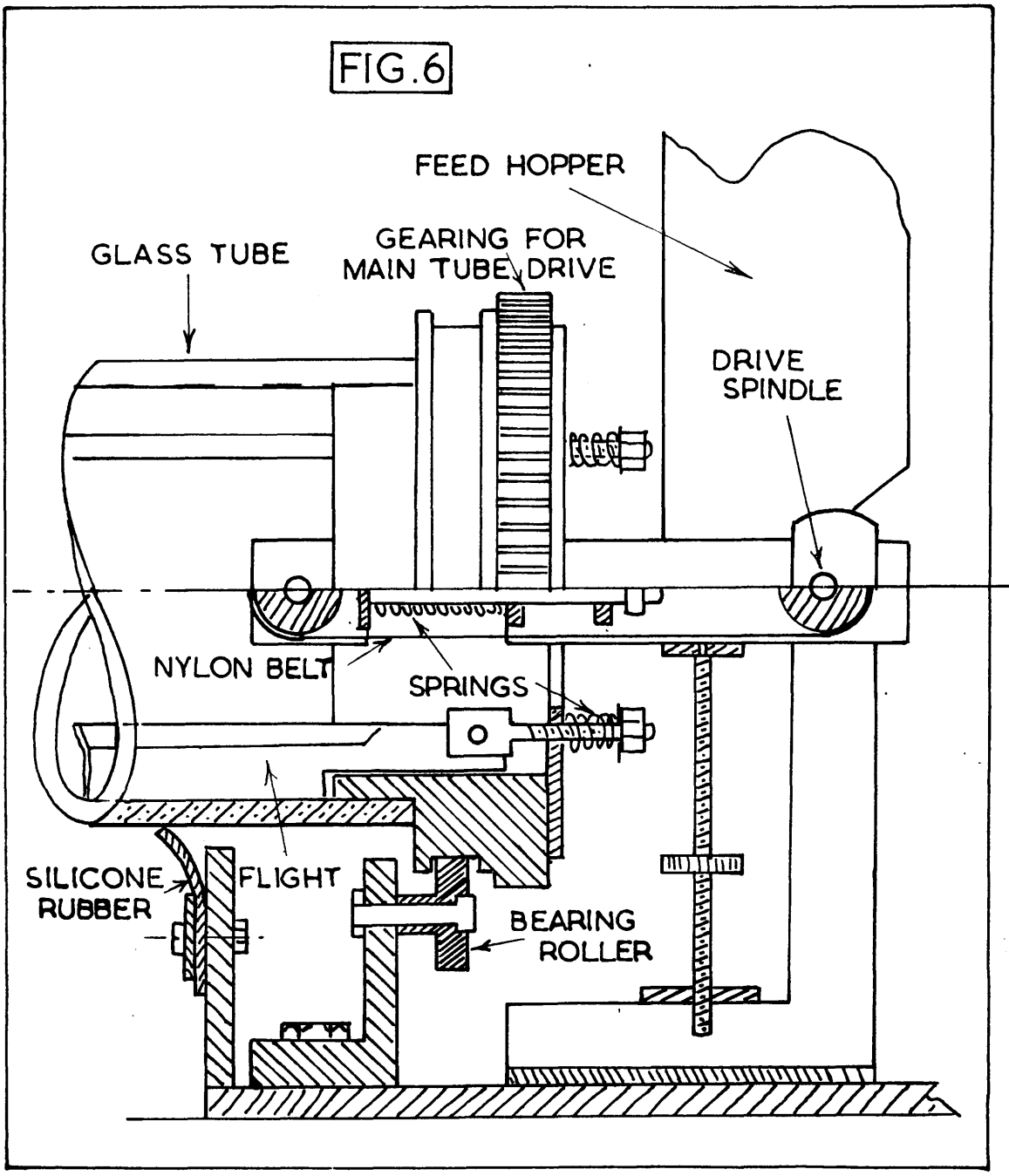
Peripheral teeth on the ring at the feed end engaged with a pinion which was driven from outside the casing by a D.C. motor through a reduction gearbox. Two and three step pulleys were fitted to the motor and gearbox respectively, and these, together with the speed variation possible with the motor itself gave a continuous range of speeds to the tube of from 3 to 24 R.P.M.

Free running rollers supported each flight retaining ring, the channel section on that at the feed end, Fig, 6 , preventing axial movement of the rotating tube. All bearings were treated with molybdenum disulphide dry lubricant as it was found that the gradual accumulation of fine dust tended to stick to and foul oiled surfaces.

The material fed to the drier was carried into the tube by the conveyor belt also shown in Fig. 6.

The belt material was nylon, and a tensioning device was incorporated to maintain a positive drive. Guides were fitted to keep the material in the centre of the belt, and an aluminium hopper attached to the frames. A screw adjustment was used to set the unit accurately in the optimum position for each material

FIG.6


FEED HOPPER
GLASS TUBE
GEARING FOR MAIN TUBE DRIVE
DRIVE SPINDLE
NYLON BELT
SPRINGS
SILICONE RUBBER
FLIGHT
BEARING ROLLER

to avoid any significant spillage of material from the end of the drier tube. The conveyor was driven, independently of the main drive, via a reduction gearbox, by a constant speed A.C. motor giving a belt speed of 15 ft./min.

Preliminary trials with a screw conveyor had shown that this type of unit tended to damage some soft materials. Trouble was also experienced at low angles of inclination of the tube when feed material tended to spill from the open end, a fault normally corrected in larger units by fitting a short section of spiral flights. These could not be fitted easily to the glass tube used here, but it was found that a short conveyor belt fitted as shown virtually eliminated the trouble. The belt dropped the wet material about $2\frac{1}{2}$ inches inside the tube, and any material which, by reason of material gradient or airflow, started to travel in the reverse direction was lifted by the flights and dropped on to the exposed conveyor.

The main frame of the unit was constructed from proprietary slotted angle iron, reinforced in places with sheet material. As the whole apparatus was constructed on one frame, variations in the slope of the drying tube were easily obtained by jacking up one end and inserting calibrated wedges.

Chambers enclosing the feed and discharge mechanism were made from sheet asbestos insulating board material and were fitted

with glass fronts. The discharged dried material was collected in a large glass bottle attached to the aluminium hopper under the discharge end of the drying tube by a double ply canvas sleeve.

The air flow was supplied by two fans. The smaller drew the air in through a long duct incorporating a metering venturi tube, and discharged through a larger chamber enclosing the heating elements. The warm air could then be directed via lagged copper ducting to either end of the actual drying tube. After contact with the material being dried, the moist air was removed through flexible ducting connected to a larger fan. Initially the discharge from this was through a small cyclone to remove entrained dust, but experience showed that the cyclone was efficient over only a narrow range of air flow. It was accordingly replaced by a bag filter.

The output of each fan was controlled by speed variation, both being powered by D.C. motors. To permit greater range in air flow than would be possible by this alone, detachable throttle or orifice plates could be fitted in the ducts to each fan. Fine control was, however, always accomplished by fan speed. The venturi meter on the inlet fan was preferred to an orifice plate as a greater proportion of the velocity head lost was recoverable. The tappings from the venturi were connected to an "Askania" differential pressure gauge. This, and the inclined manometers connected to the

end boxes, were mounted on a separate frame to avoid errors caused by tilting the main unit.

Sealing the rotating glass tube in the end boxes presented some difficulty. Airtight gaskets were finally cut from 1/8th inch. silicone rubber, flexible enough to take up the slight ovality of the tube, and fitted to each end chamber. Glycerol proved an effective lubricant for the seal.

The air was heated electrically by elements enclosed in the duct shown in the sketch. The load was divided into 2 units of 2kw., 2 or 1kw., and 1 of $\frac{1}{2}$kw. One of the 1kw. units was thermostatically controlled, the probe being fitted to either end box to allow for co-current or counter-current operation.

Since the amount of drier shell per unit volume is inversely proportional to the drier diameter, a small unit of this type has proportionally more shell surface per unit mass flow of hot air. In this way heat losses will tend to be more important with a small unit. To help eliminate these, a glass jacket was fitted round the drying tube, and was provided with a separate controlled supply of hot air. The heat input was adjusted manually by means of a "Variac" and in use, it was found that required jacket temperatures could easily be obtained to within $\pm$ 1^{o}F. A high speed propeller fan was fitted in the jacket to provide a uniform temperature. After initial trials with brewers' spent grain, a 1 in. layer of asbestos lagging was wound round the drying tube as heat

balance showed that a not inconsiderable amount of heat was passing from the jacket to the material being dried.

Temperatures in the drier were measured by a calibrated copper-constantan thermocouple. This was fitted to the end of an aluminium tube which in turn slid through a bush in the wall of the discharge chamber. This allowed rotation of the thermocouple and enabled it to be positioned accurately at any point on the axis of the drier. The hot junctions were shielded by an asbestos lined thin brass cover. When inverted, this protected the detecting elements from the material spilling from the flights, but as it was turned some of the material fell into the cup formed and came into intimate contact with the thermocouples.

To provide a higher scale reading on the high resistance galvanometer, two couples were used for both the hot and the cold junctions. The cold junctions were kept in iced water to provide a steady reference temperature.

Initial Experimental Work

Measurement of air flow.

It was obviously desirable to meter the air at standard conditions of temperature, pressure and humidity. The venturi was therefore fitted before the first fan. To allow for any leaks from the sliding gate valves in the ducts or from the end boxes, the reading given by the "Askania" gauge was calibrated against the observed flow in the glass drying tube. This was measured in several ways. At higher air mass flows, corresponding to 3 ft./sec. and above, a small vane anemometer was positioned half way along the drying tube and its reading noted against the pressure drop indicated by the "Askania" gauge. Variation of the position of the anemometer across the tube produced no significant difference in the velocity indicated, results agreeing to within $\pm 2\%$, but a mean was taken and a calibration graph of air mass velocity against Askania reading was constructed.

Lower air flows presented some difficulty. A thermocouple type of hot wire anemometer proved sufficiently sensitive to detect steady air streams as low as $\frac{1}{2}$ft./sec. with a fair degree of accuracy viz. $\pm 7\%$. When used in the drier, however, readings were obtained which were inconsistent with those obtained at higher air flows and the vane anemometer. Mass balances over drying runs showed the latter were correct and the values from the hot wire anemometer were discarded. This instrument gave neither an integrated

reading over a fair cross-section of the drier tube as did the vane anemometer, nor a true point reading essential for a correct traverse. While an impact or pitot tube is ideal for this, it cannot be used successfully at such low air velocities.

To cover lower air velocities, the feed conveyor was finally removed and an aluminium cone leading to a vane anemometer was finally attached to the brass ring at this end. The reduction in diameter produced a higher linear air velocity, within the working range of the instrument. Where this method could be used concurrently with an instrument in the tube itself, as described above, agreement was within 2%, that is, within the accuracy of the vane anemometer itself.

In countercurrent operation, one side of the feed chamber was removed and the exhaust air allowed to discharge into the atomosphere unless excessive dust was produced, when the larger fan was used to filter the air.

Under co-current conditions, the feed chamber was closed and the second fan operated continuously. By suitably balancing the speed of the fans the pressure in the former could be maintained at atmospheric, and was indicated by one of the inclined manometers. In this way the feed hopper could be left open during the test. The venturi was recalibrated for this mode of running, the anemometer being placed in the drying tube as before. Presumably

because of the altered sequence of pressure drops and introduction of more gate valves, the calibration curves were not quite coincident.

Measurement of temperatures.

Material temperatures throughout the unit were measured with the thermocouple and insulated basket fitted to the probe described above. For calibration purposes a standard thermometer was clamped with the bulb between the two hot junctions and the E.M.F. noted at various steady temperatures resulting from arbitrary settings of the thermostat. After calibration the temperatures measured by the couples could be estimated to within $\pm$ 0·5°F.

The dry bulb temperature of the air entering the drier tube was measured by placing the couples just inside the tube. The inverted basket protected the couples from falling material and allowed the hot air to stream freely past the unit.

Material temperatures were obtained by allowing a sample of the cascading solid to fall into the basket. A slight time lag here was inevitable, but by taking the readings in a steady sequence along the drier, this was kept to a minimum.

Movement of the probe along the drying tube exposed a varying length of the leads to the drying air. The leads were protected to some extent by thin glass tubes acting as both thermal and electrical insulation. The total resistance of the copper components subject

to temperature fluctuation was approximately 0·45 ohms, which would not increase by more than 40% in the range 50°F to 240°F. This was small compared with the resistance of the galvanometer, viz. 197 ohm., temperature effects were neglected. A nul-point potentiometer proved too slow for satisfactory operation and was not so convenient for following time/temperature variations.

Apart from the inlet, where the air was of uniform temperature and condition, no other air temperatures were estimated by the thermocouples. Initial trials showed considerable temperature variation across the tube and it was not possible to take a representative sample at any one point. This was also observed by Friedman and Marshall[80] in their heat transfer work, and a similar method of heat and material balances was finally employed for air temperature estimation.

Under counter-current working conditions, a standard mercury in glass thermometer was to estimate air outlet temperatures when using higher air flows. It was found here that the turbulence and mixing produced by the projection of the conveyor belt into the mouth of the tube allowed reasonably accurate estimation of the air temperature.

Material velocities and moisture contents.

To deduce the actual drying curve, and hence the drying rates in this drier, it was necessary to estimate the actual velocity at

several points along the tube. A uniform velocity under constant feed conditions implies that the loading of the unit will be equal at all points. Trials at higher slopes and conveying trials where the material passing through was dry and had constant properties showed fairly uniform loading, but normally this was not the case when drying took place. Alteration in moisture content affected surface properties and bulk densities, and produced a marked variation in the velocity of material as it passed through the drying tube.

Velocity at any point is inversely proportional to the loading. It was found convenient to measure the loading in the drier as gm. of dry solid per inch of length of the drier. If the actual feed rate is $\underline{f}$ gm./min., and the loading at any point is $\underline{M}$ gm. B.D.S./inch, then

$$\text{Velocity } V = \frac{f}{M} \text{ (inches/min.)} \quad \ldots\ldots \quad 38$$

A steel trough 6" longer than the drier was constructed which could be fitted quickly in position along the axis of the drier tube. Rotation of the tube transferred all the material resting on the flights or lying on the bottom to the trough, dropping it in the same vertical plane. The trough could then be withdrawn with its load, leaving the drier empty.

Removable transverse sections, 9/16" between parallel faces, were fitted along the trough and collected material as the latter filled. The width of the sections was determined by the size of the samples required for the petri dishes for moisture determination.

These sections could be removed quickly and their entire contents weighed and moisture content found.

The loading in gm. B.D.S./inch at each point was calculated at each point on the assumption that the 9/16" section would trap material in proportion to its length. To check this the drier was filled to a definite loading, allowed to rotate for some time at zero slope with the discharge end sealed to produce a uniform known loading, and the contents transferred to the trough containing the sampling sections. The amounts actually found in each section corresponded fairly closely with the calculated value for each material and for the various loadings used. The overall average value was near the theoretical :

wt. in gm.

Barley Grain Position		2	3	4	5	6	7	8	9	Average	Theoretical
Loading % X	5	3.8	3.6	3.6	3.7	3.5	3.7	3.7	3.6	3.71	3.64
	10	7.4	7.25	7.2	7.4	7.0	7.35	7.2	7.2	7.24	7.28
	15	11.0	10.9	10.85	11.20	10.60	10.95	10.8	10.8	10.88	10.92
Cork	10	2.4	2.3	2.3	2.35	2.2	2.35	2.3	2.3	2.30	2.35

A curve of velocity against position in the drier was drawn to provide information for further calculations.

Operation

The required number of flights was fitted to the drier tube and

they were tensioned to allow for expansion. The fans were started and set to produce the desired air-flow as indicated by the "Askania" gauge. The thermostat and "Variac" were set to the inlet dry bulb temperature and the heaters switched on. The drying tube was allowed to revolve slowly to avoid local overheating and the whole unit allowed to come up to working conditions when any further slight adjustments were made to airflow or temperature.

When steady conditions had been attained, the tube was set to the desired speed, the conveyor started and feeding of wet material commenced. This was regulated by adding a weighed amount over equal intervals of time. The wet material was weighed in approximately 50 gm. lots on a balance sensitive to 0.1 gm. In investigation of the effects of variation of feed rate, it was found convenient to add the same amount by weight over 2,3,4,5,6 or 8 minutes, in successive tests. Some of the wet material was added at each full minute to give a reasonable approximation to continuous working.

The drier was operated steadily until the loading at the discharge end had built up to a constant value, and was thereafter continued for twice the estimated retention time before temperature readings were taken.

To cool the thermocouples approximately to the temperature of the material, the shield at the end of the probe was filled with discharging dried material by rotating it near the outlet. After

a few second this was discharged and the couples moved quickly to a point 6 inches inside the drier and the shield again allowed to fill by exposing the couples to the falling material. This initial sample was discarded and the process repeated. A steady temperature was usually indicated within a few seconds, and this was noted. The process was repeated at 6 inch intervals along the drier.

Depending on the retention time, the unit was allowed another hour or so to regain equilibrium working conditions. All air temperatures, speed of the tube, and ambient laboratory air conditions were checked throughout the test.

At the end of the run all heaters and fans were switched off and the trough with the sampling sections inserted immediately, to which the entire contents of the drier were transferred by rotation of the tube. The trough was withdrawn without delay and the contents of each sampling section emptied into one of a marked series of air-tight aluminium weighing dishes. Samples were also taken of the material fed to the drier and of the discharged dried product.

Each of the series of dishes was weighed and the contents were then dried by heating under vacuum at a standard temperature, depending on the material, for 48 hours. The loss in weight was attributed to moisture and the moisture content and weight of bone-

dry solid in each dish calculated.

In pure conveying trials where no drying actually took place, and where there was no change in the condition of the material passing through, steady running conditions were adjudged to have been reached when the discharge rate, measured by collection over each minute, proved equal to the feed rate. The hold-up and retention time were here found simply by weighing the entire contents of the drier.

Miniature units.

Initial trials on dispersion with the unit intended for actual drying operations were discontinued as it proved too large for convenient single handed operation.

A smaller model, shown in Fig.7, was constructed from glass and "Perspex" and fitted with interchangeable angled aluminium flights. This was powered by a 1/6th H.P. synchronous motor which drove the rubber covered rollers bearing the tube through a reduction gearbox. This was fitted with a three step pulley system to allow speed variation.

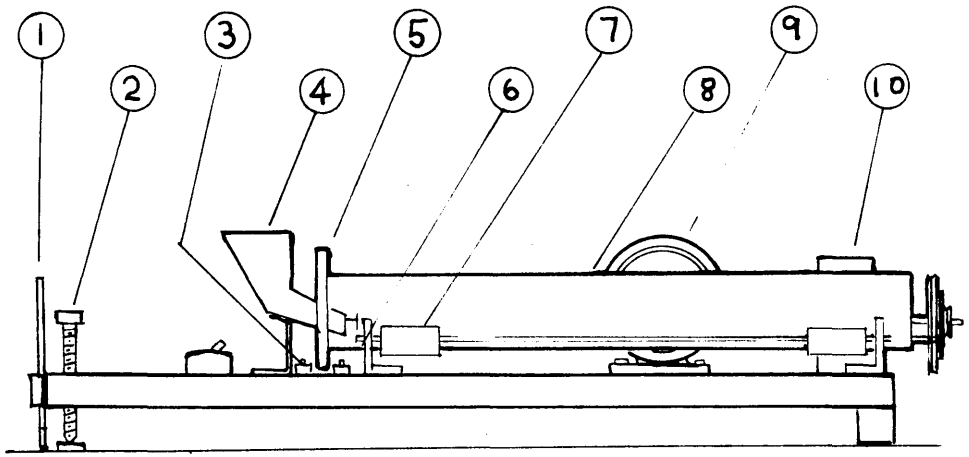
A secondary unit, sealed at both ends, was constructed to allow study of flight action alone. This was essentially a short section of the longer unit shown in Fig.7 and could be revolved on the same roller system.

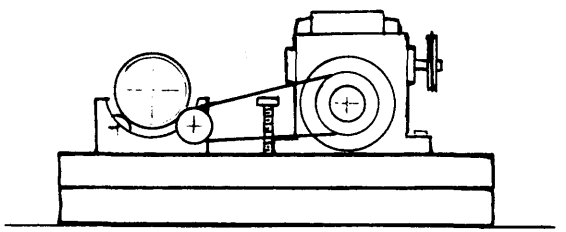
Operation

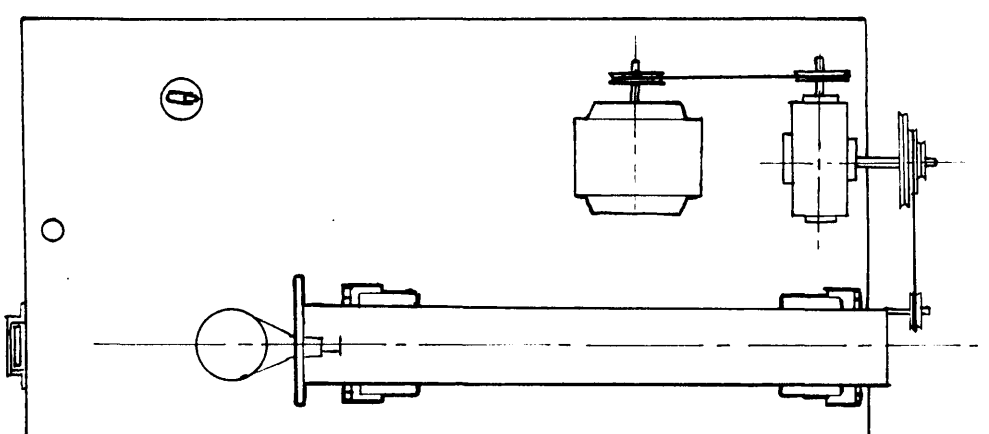
The feed was measured by volume, a definite amount being added over each minute. This was continued until the discharge rate had become equal to the feed rate. The unit was then stopped and the tracer material placed about 4" from the feed end by a long handled spatula. This technique was found necessary as early tests had shown that addition of the tracer via the feed chute resulted in some initial dispersion.

In the trials with the P.V.C. granules from 40 to 120 tracers

FIG. 7







1. INCLINATION GAUGE
2. SCREW.
3. ROLLERS
4. FEED CHUTE
5. PERSPEX FLANGE
6. BEARINGS.
7. RUBBER ROLLERS
8. GLASS TUBE
9. MOTOR
10. REDN. GEAR

were used, depending on the hold-up of the unit. Where experimental conditions produced low % hold-up the minimum number of tracer granules was used. About 0.1 gm. of sized Potassium Permanganate was used in the tests with the white sand.

The tube was restarted and normal feeding continued. As the first of the tracer granules or Permanganate crystals approached the discharge end, the large receiver was replaced by a series of small dishes which were replaced regularly at from five to thirty second intervals. The amount of tracer present in each sample was estimated - by counting in the case of the P.V.C. granules and by solution in dilute sulphuric acid, followed by a standard Iodide/ starch Thiosulphate titration in the case of the permanganate.

The cumulative numbers of granules or the cumilative titre was noted against time of issue. These were then converted into percentages of the total.

The feed rate in c.c./min., percentage slope and volumetric hold-up, the speed of the tube and the number of flights used in each trial were recorded.

RESULTS.

The Conveying Properties of the Rotary Drier

The first series of tests was carried out to compare the conveying properties of this type of drier with serveral different materials. The effects of variation of feed rate, rate of rotation, slope of the drier, number and shape of lifting flights, and air mass flow were studied.

The contrasting materials chosen were crystalline preserving sugar and cubes of dried potato. The sugar is fairly dense and the individual particles just sufficiently large enough to prevent material slipping between the flights and the shell. The potato cubes are much less dense, prone to movement by bouncing as they land on the exposed tube, and intentionally somewhat out of scale with the apparatus. Their physical properties are contrasted in the table below.

Material	Particle shape	Wt. average particle size	Bulk density lb./ft^3	True density lb./ft^3	Angle of repose ^{o}
Sugar crystals	Parallelopiped	4.17 m.m.	55.2	106.0	39.5
Potato cubes	Cube	10.9 m.m.	19.1	52.4	49
Barley grain	Ovoid	7.11 x 2.84 mm	38.8	71.9	39
P.V.C. granules	Cylinder	3.01 mm	43	87.5	41

True densities were obtained by measurement of the displacement

volume of the material in an inert non-solvent. The dynamic angles of repose were obtained by rotating the material in glass ended cylinders. Average particle size measurements were carried out on a random sample of 50 particles of each type.

Some tests were carried out with the barley grain and the P.V.C. granules, but in the majority the first two were used.

Procedure.

Both the larger unit used mainly for the actual drying trials and the smaller unit used for the deviation tests were used in these preliminary studies.

Experimental procedure has already been described in detail under "Apparatus and Experimental Procedure", pp.43 - 58 . Notes on measurement of feed rate and hold-up are given on p.55 .

Results - Hold-up with no airflow

About 150 runs were made to determine the effects of feed rate, slope, and drier speed. The majority were conducted with the simplest flight arrangement - 4 radial flat flights - and the rest were made with 6 flat flights and 4 or 6 angled flights.

The curves shown in Fig.8 illustrate the effect of drier slope on hold-up at different feed rates and rates of rotation. No exact relationship between hold-up and slope is proposed at this stage, although the reasonablylinear section of the curves below

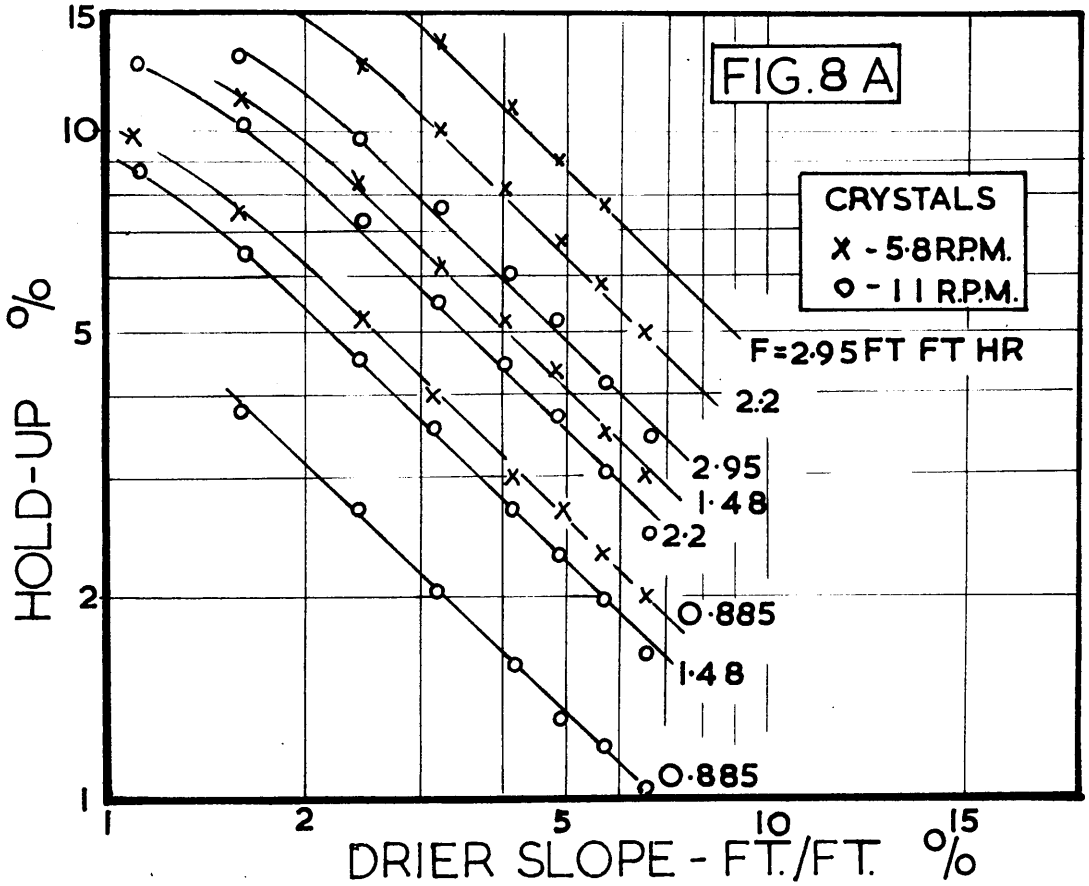


FIG. 8 A
CRYSTALS
X - 5·8 R.P.M.
O - 11 R.P.M.
F=2·95 FT FT HR
2·2
2·95
1·48
O 2·2
O·885
1·48
O·885
HOLD-UP %
DRIER SLOPE - FT./FT. %
15
10
5
2
1
1
2
5
10
15

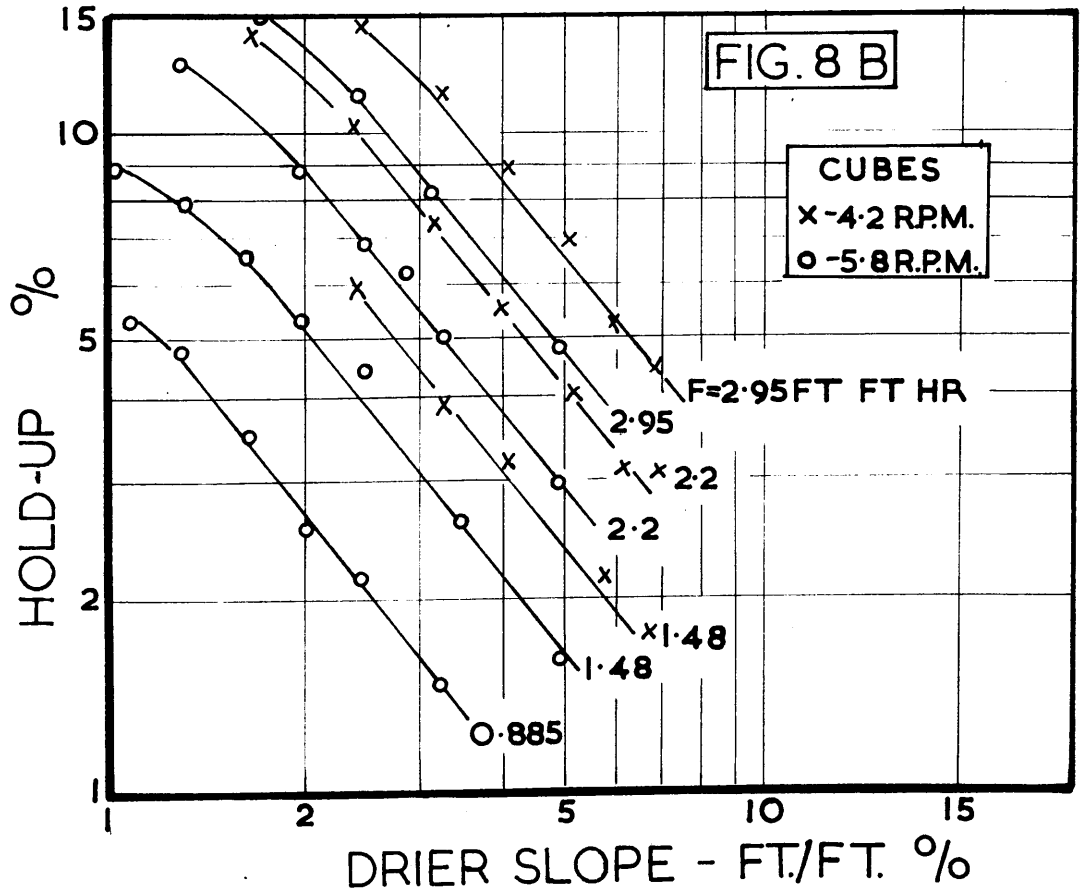


FIG. 8 B
CUBES
X - 4·2 R.P.M.
O - 5·8 R.P.M.
F=2·95 FT FT HR
2·95
X 2·2
2·2
X 1·48
1·48
O·885
HOLD-UP %
DRIER SLOPE - FT./FT. %
15
10
5
2
1
1
2
5
10
15

$X = 10\%$ suggests $X \propto S_d^{-1}$ 39

By plotting the hold-up against the feed rate at a particular drier slope, 3.25%, a relation between hold-up and feed rate of the form $X \propto F^{b'}$ 40
is indicated, Fig. 9. As will be shown later, however, b' can be approximated to unity without introducing too great an error.

The cross plots of feed rate against rate of rotation, Figs.10 and 11, for different flight designs suggest that to maintain a constant hold-up the feed rate must be raised directly with the rate of rotation raised to some power, n, less than one. For the materials studied by Friedman and Marshall[67], n appeared to vary from 0.78 to 0.98. For the potato cubes and the sugar, the values of n were found to be 0.71 and 0.94 respectively. The two values agree closely for all flight arrangements studied. The low value of 0.71 encountered for the potato cubes is thought to be caused by the shape preventing increased rolling at higher speeds. A similar tendency was noted with cork granules which were later employed in drying tests, p.119. In the general correlation referred to later, an average value of 0.9 is used for n, and the values of $N^{0.9}$ are included in Figs. 12a and 12b.

A plot of hold-up against $\frac{F}{N}0.9$, Figs. 12, indicates a linear relationship for sugar, but of the form

$$X \propto \left(\frac{F}{N^n}\right)^{b_2} \quad \text{..... 41}$$

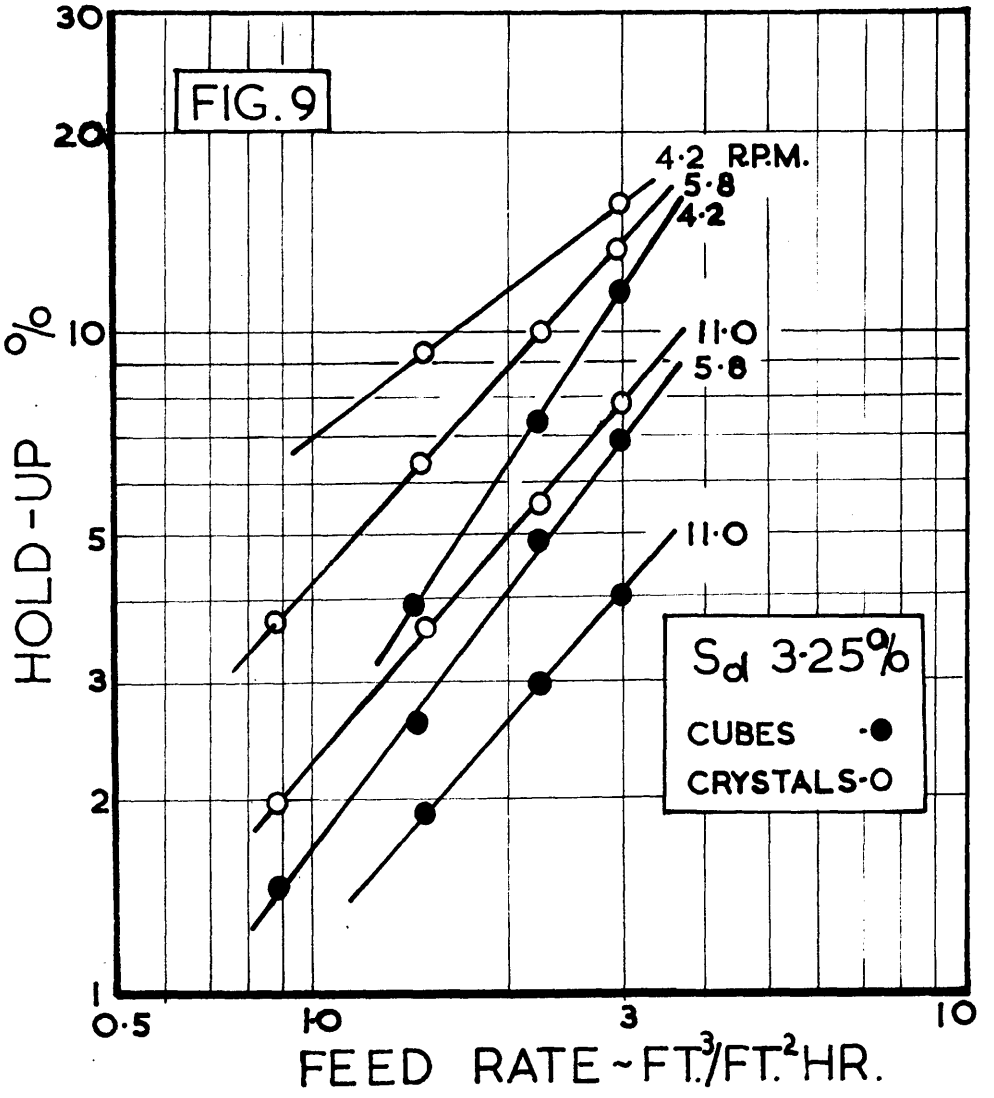
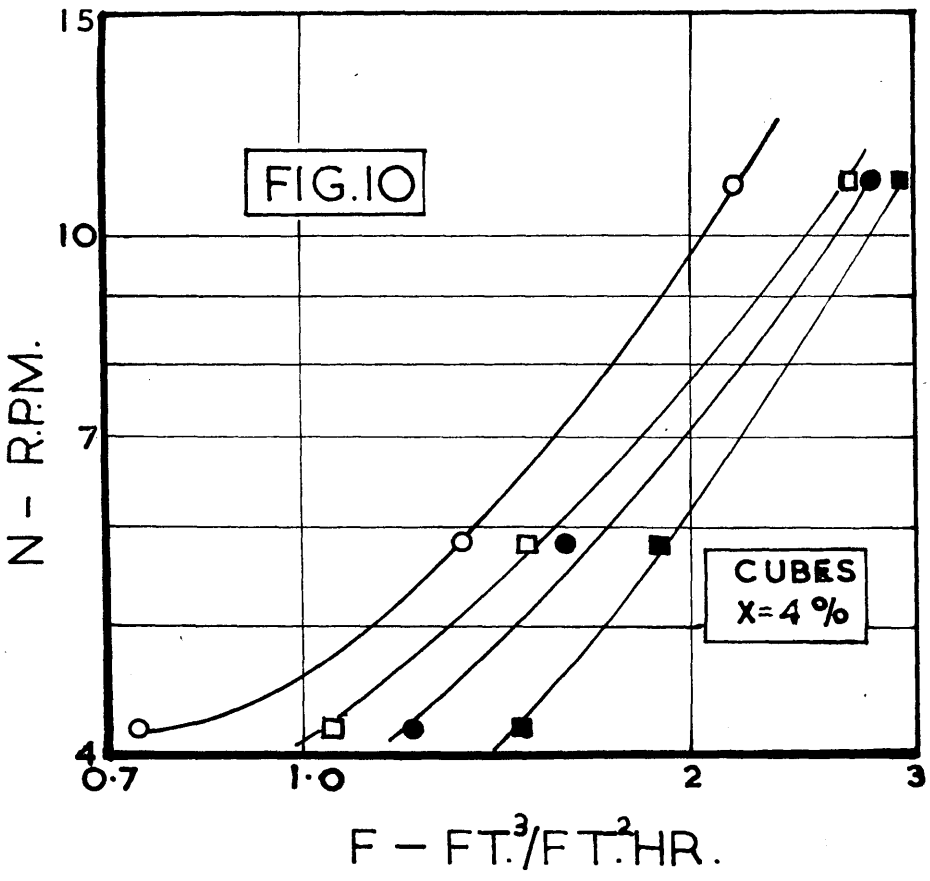
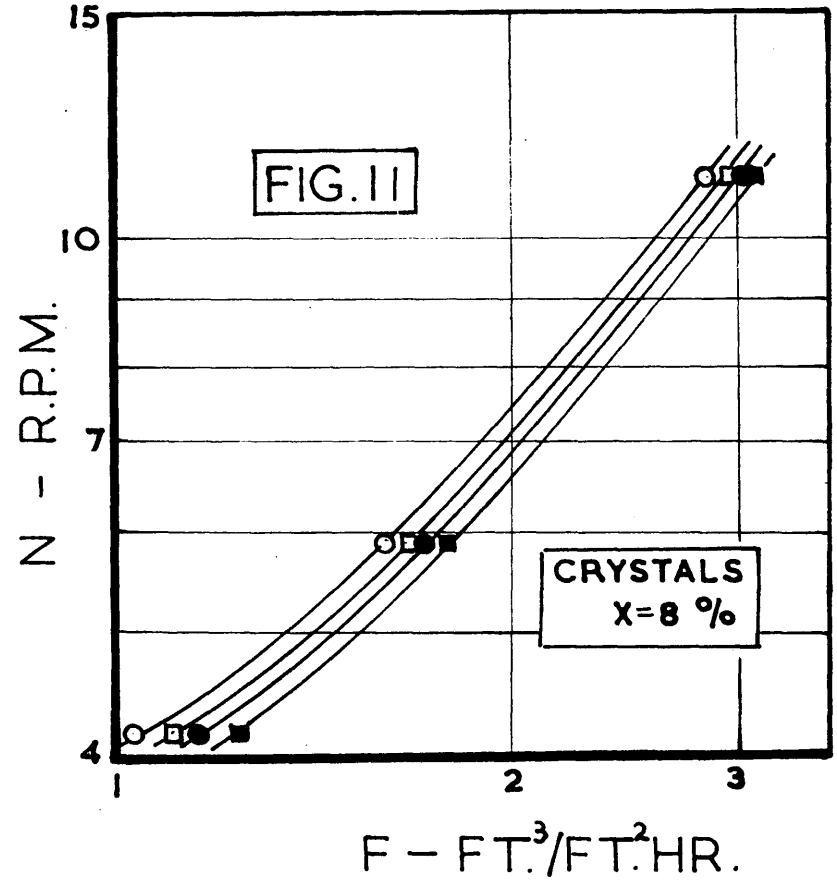
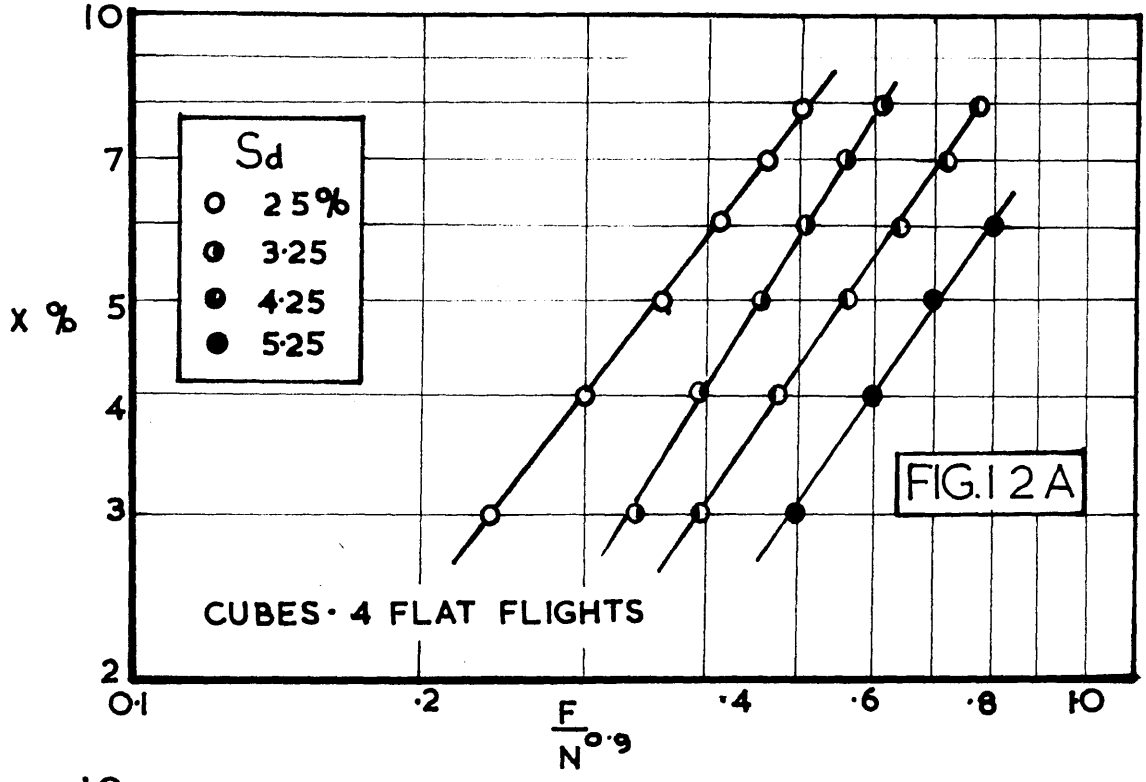


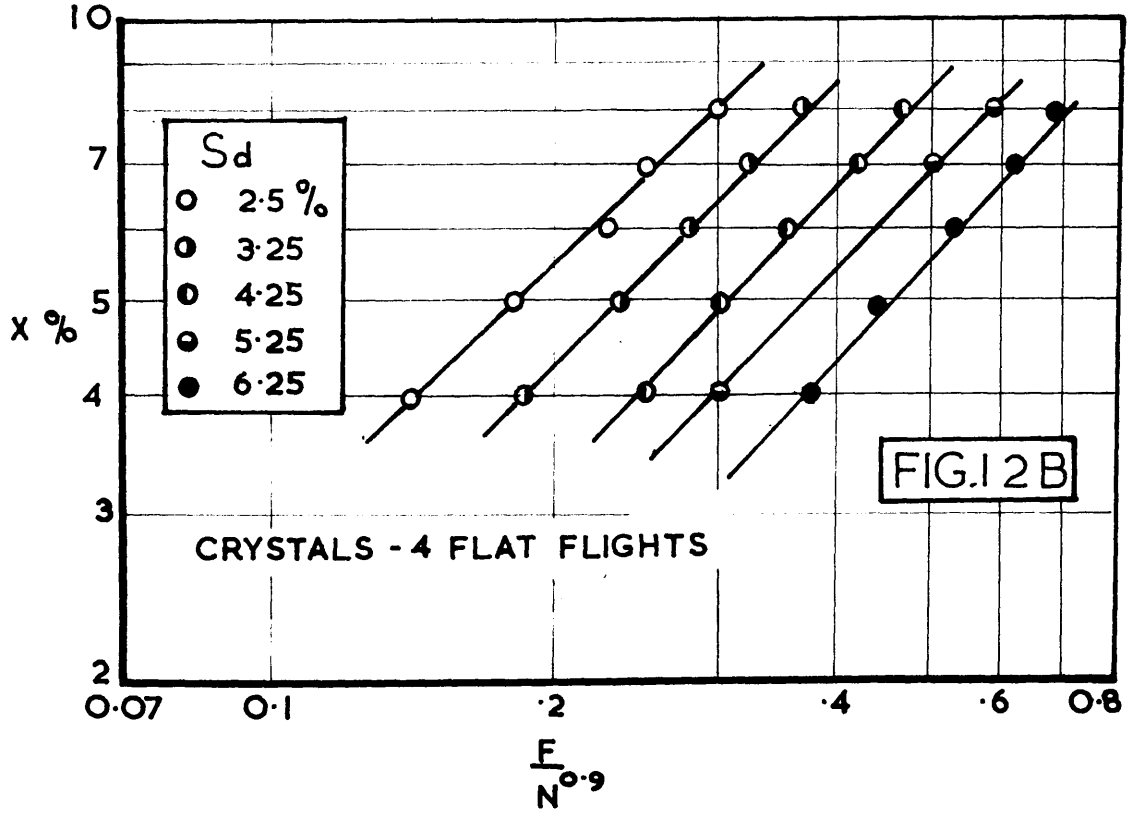
FIG. 9
30
20
10
5
3
2
1
HOLD-UP %
0·5
10
3
10
FEED RATE ~ FT.³/FT.²HR.
4·2 R.P.M.
5·8
4·2
11·0
5·8
11·0
Sd 3·25%
CUBES
CRYSTALS-O





FOUR FLAT FLIGHTS ■
SIX " " ●
FOUR ANGLED " □
SIX " " ○


10
7
5
4
3
2
X %
Sd
0 2·5%
3·25
4·25
5·25
CUBES · 4 FLAT FLIGHTS
FIG. 12 A
0·1
·2
·4
·6
·8
1·0
F / N^0·9


10
7
5
4
3
2
X %
Sd
0 2·5 %
3·25
4·25
5·25
6·25
CRYSTALS - 4 FLAT FLIGHTS
FIG. 12 B
0·07
0·1
·2
·4
·6
0·8
F / N^0·9

for the potato cubes, where b_2 is of the order of 1.4. This more complex relation is again thought to be produced by the rather odd material characteristics of the potato cubes.

As most of the results appeared to be in agreement with the general conclusions of Friedman and Marshall[67], a correlation of identical with that proposed by these workers was attempted, and is shown in Fig.13. The data cover a range of drier slope from 2.5 to 6.25%, speeds from 4.2 to 11 R.P.M. and feed rates of from 0.885 to 2.95 $ft^3/(ft^2)(hr.)$.

For the purposes of comparison, Eqn.17 of Sullivan et al has been included, assuming a value of 0.9 for n and an angle of repose of 40°, the formula obtained being

$$X = \frac{0.294.F}{S_d.N^{0.9}D} \quad \ldots\ldots\ldots \quad 42$$

Friedman and Marshall[67] obtained curves which, except one, were placed to the left of equation 42 when plotted as shown. It will be observed that the curve for sugar has this position, but that for potato cubes is displaced considerably to theright. It is thought that materials which would be prone to movement by bouncing, will give results similar to those obtained for potato cubes.

Number of flights.

To keep Fig.13 as clear as possible, only data for 4 flat

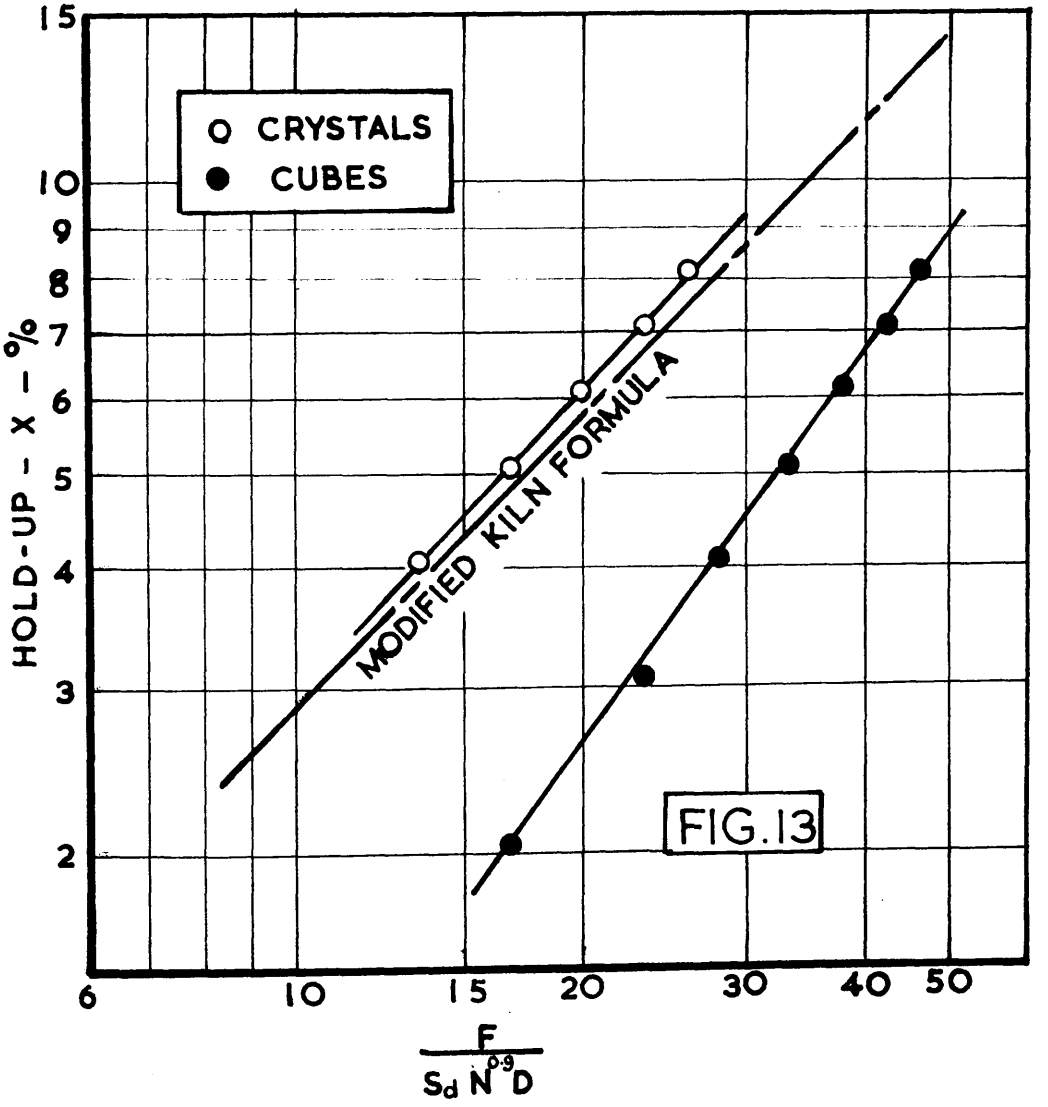

15
10
9
8
7
6
5
4
3
2
HOLD-UP - X - %
O CRYSTALS
● CUBES
MODIFIED KILN FORMULA
6
10
15
20
30
40
50
F / Sd N^0.9 D

FIG.13

flights has been included. In Fig.14 the effect of the other flight arrangements used in the larger unit is shown.

Although the variation in numbers of flights is small, this indicates clearly that for a given feed rate, a closer flight spacing will minimise kiln action, slowing the material and increasing the retention time and hold-up. It also shows that the shape of the flights has considerable effect, the angled flights producing a higher hold-up and longer retention time than the same number of the flat blades working under similar operating conditions.

Similar results were obtained with the smaller unit, and values obtained with from 2 to 8 angled flights are shown in Fig.15.

Hold-up with airflow in the drier

A number of tests were conducted with countercurrent airflow affecting the passage of the granulated sugar, dried potato cubes and the barley grain.

The results are shown in Fig.16, $\underline{n}$ being again assumed 0.9 for all materials. Working on more dense materials, Friedman and Marshall[67] suggested the relation

$$X_a = X_0 \pm KG. \quad \ldots\ldots\ldots \quad 26$$

It appears however, especially for lighter vegetable materials which are more affected by airflow, that the results obtained can

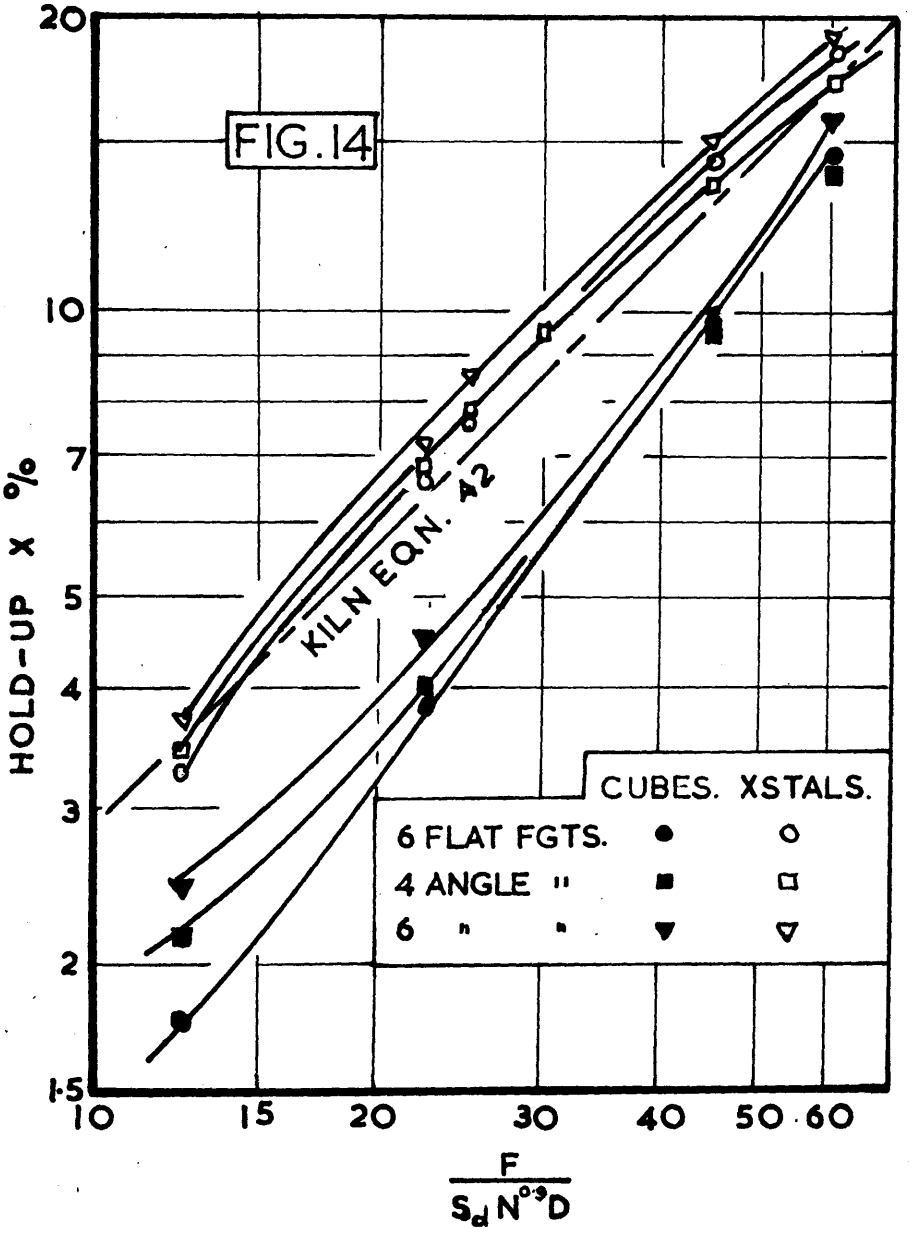
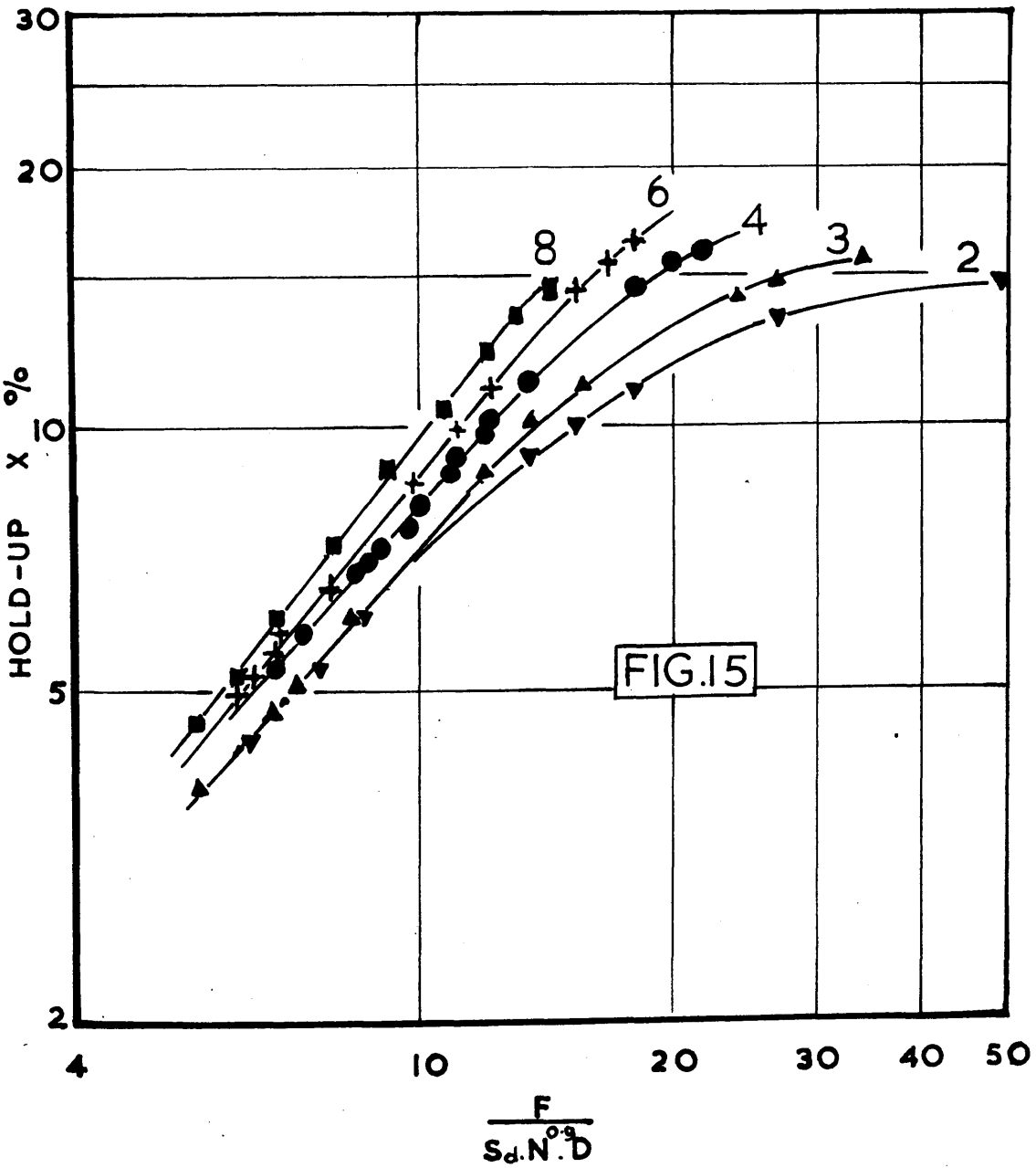


FIG. 14
HOLD-UP X %
20
10
7
5
4
3
2
1·5
KILN EQN. 42
CUBES. XSTALS.
6 FLAT FGTS.
4 ANGLE "
6 "
10
15
20
30
40
50
60
F / S_d N^0·9 D


30
20
10
5
2
HOLD-UP X %
8
6
4
3
2
FIG.15
4
10
20
30
40
50
F / Sd.N^0.9.D

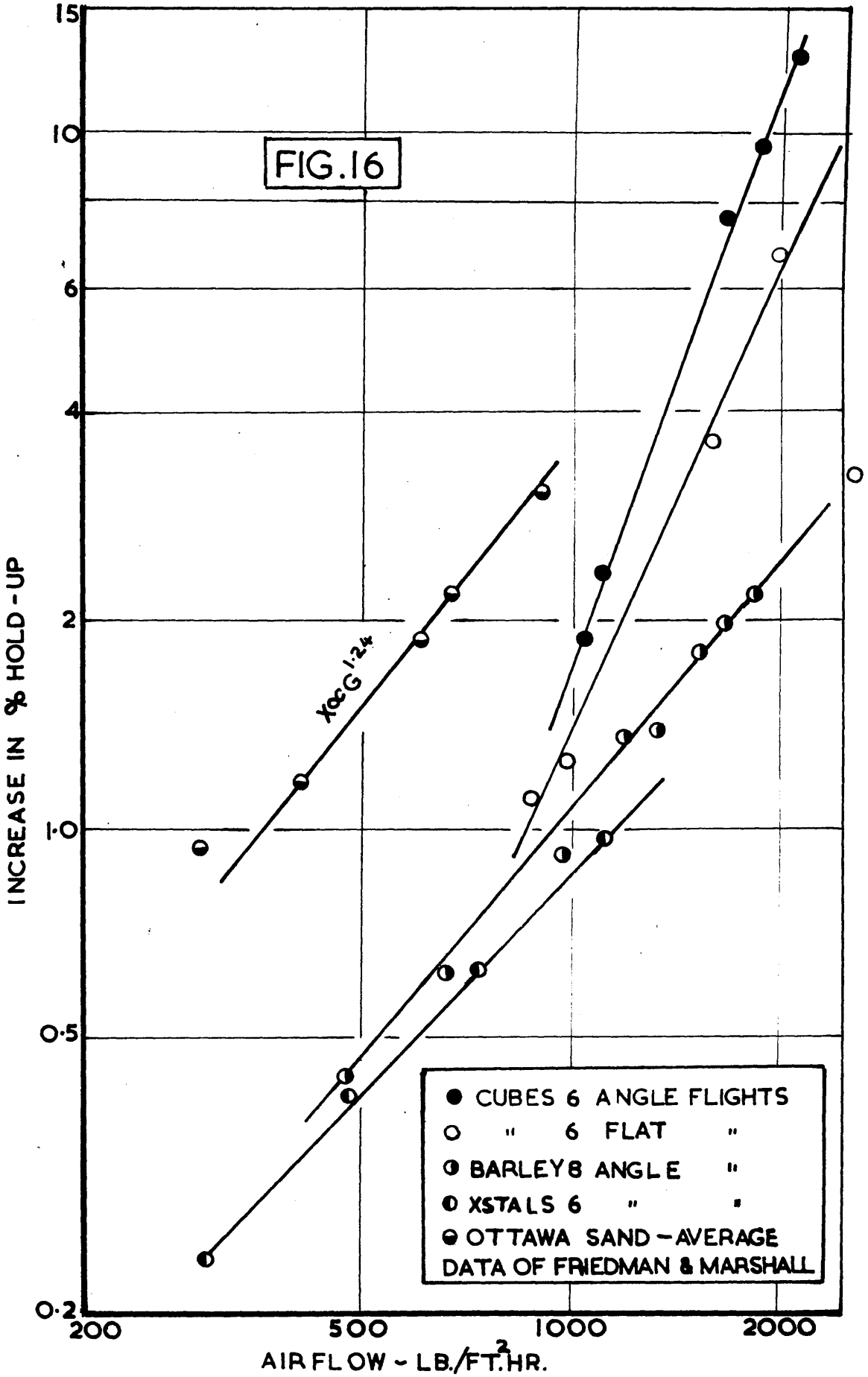


FIG.16
INCREASE IN % HOLD-UP
AIR FLOW ~ LB./FT.²HR.
15
10
6
4
2
1·0
0·5
0·2
200
500
1000
2000
X∝G 1·24
CUBES 6 ANGLE FLIGHTS
" 6 FLAT "
BARLEY 8 ANGLE "
XSTALS 6 " "
OTTAWA SAND – AVERAGE DATA OF FRIEDMAN & MARSHALL

better be expressed by the relation $(X_a - X_o) = \pm K(G^c)$ 43

where c is a constant > 1,

K is a constant also depending on the material,

X_a hold-up with airflow G, X_o under similar conditions with no airflow

the +ve sign referring to counter-current airflow and the -ve to co-current.

From Fig.16 it appears that the constants are fairly similar for both feed rates as far as the angled flights are concerned, but vary for the flat versions. This cannot be fully explained but it is thought that variation of loading producing altered distribution of the falling material may be responsible. Photographic studies showed that the angled flights dropped most of the material through the full diameter of the tube, independent of the loading, but that flat flights altered their point of main discharge considerably with loading. The length of the falling path will influence the magnitude of the accelerating or retarding effects of the airflow.

As a check on these results, an effort was made to find out how the drier slope must vary at different rates of rotation to maintain constant hold-up as air is flowing through the drier.

SUGAR. 4 FLAT FLIGHTS

Slope at 5.8 R.P.M. G=0,%	Slope at 11.0 R.P.M. G=0, %	Airflow. Slope at 5.8 R.P.M. %	Feed Rate $ft^3/(ft^2)(hr)$	Hold-up %	Air-flow
5.45	2.95	6.5	1.48	3.88	1715
5.05	2.80	6.5	2.95	8.55	1784
4.42	2.37	5.67	2.95	9.85	1810
4.32	2.32	5.67	1.48	4.96	1717

It is apparent that the introduction of counter-current air-flow has the same effect as decreasing the drier slope. If the air mass flow can be considered approximately constant, the change in slope to maintain a constant hold-up is apparently independent of feed rate and hold-up, agreeing with the conclusions for sugar drawn from Fig.8.

Hold-up with wet feed

The first series of trials was carried out under "ideal" conditions - where material properties were constant along the drying tube. When dealing with wet feed, the position is much more complicated. Gradual alteration of the surface properties and densities as it passes along the drier continually alter the flow characteristics. Tests on sugar crystals showed that, apart from a slight increase towards the discharge end where the material gradient had some effect, the material passed through with a uniform velocity. During actual drying trials, the velocity had to be determined along the drier to permit accurate estimation of the drying rates.

Considerable difficulties were encountered with the different materials and operating conditions used and it was found that, in general, it was very difficult to apply strictly any of the formulae deduced above from dry materials.

The effects of some of the operating variables on the handling of wet feed material are detailed below. With the variation in velocity and density, volumetric hold-up becomes difficult to determine, and average values calculated from retention time, feed rate and drier dimensions may be somewhat meaningless. Only retention times are normally quoted in this section, although where conditions are suitable, hold-up may be referred to.

The three materials used in the drying trials were brewers' spent grain, barley grain and granular cork. Each had to be dried under conditions of feed rate, speed, slope, air temperature and velocity most suited to its own properties. This makes comparison of the results from material to material somewhat difficult.

Feed rate.

According to the simpler relationships deduced above for the dry materials, feed rate should have little, if any, effect on the retention time. In practice it was found that increased feed rate produced markedly lower residence times with all three wet materials, and a wetter product from the same feed material.

The variation in retention time with feed rate is shown graphically in Fig.17. While it appears that a relation of the form

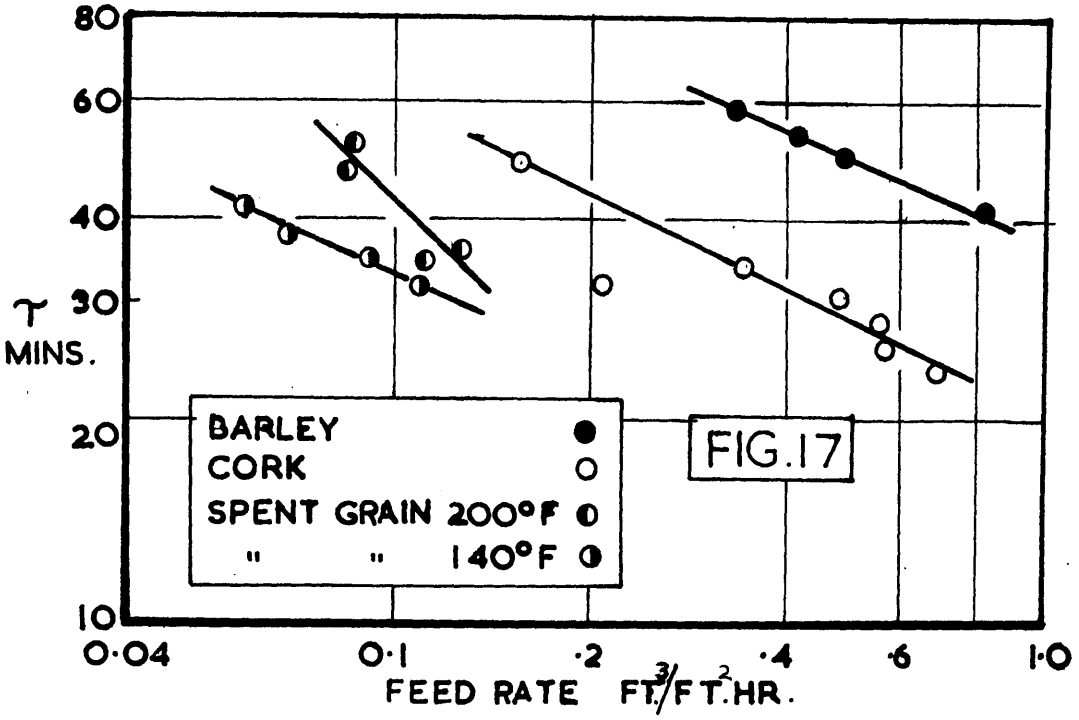
$$X \propto F^{b_3} \quad \ldots\ldots\ldots \quad 44$$

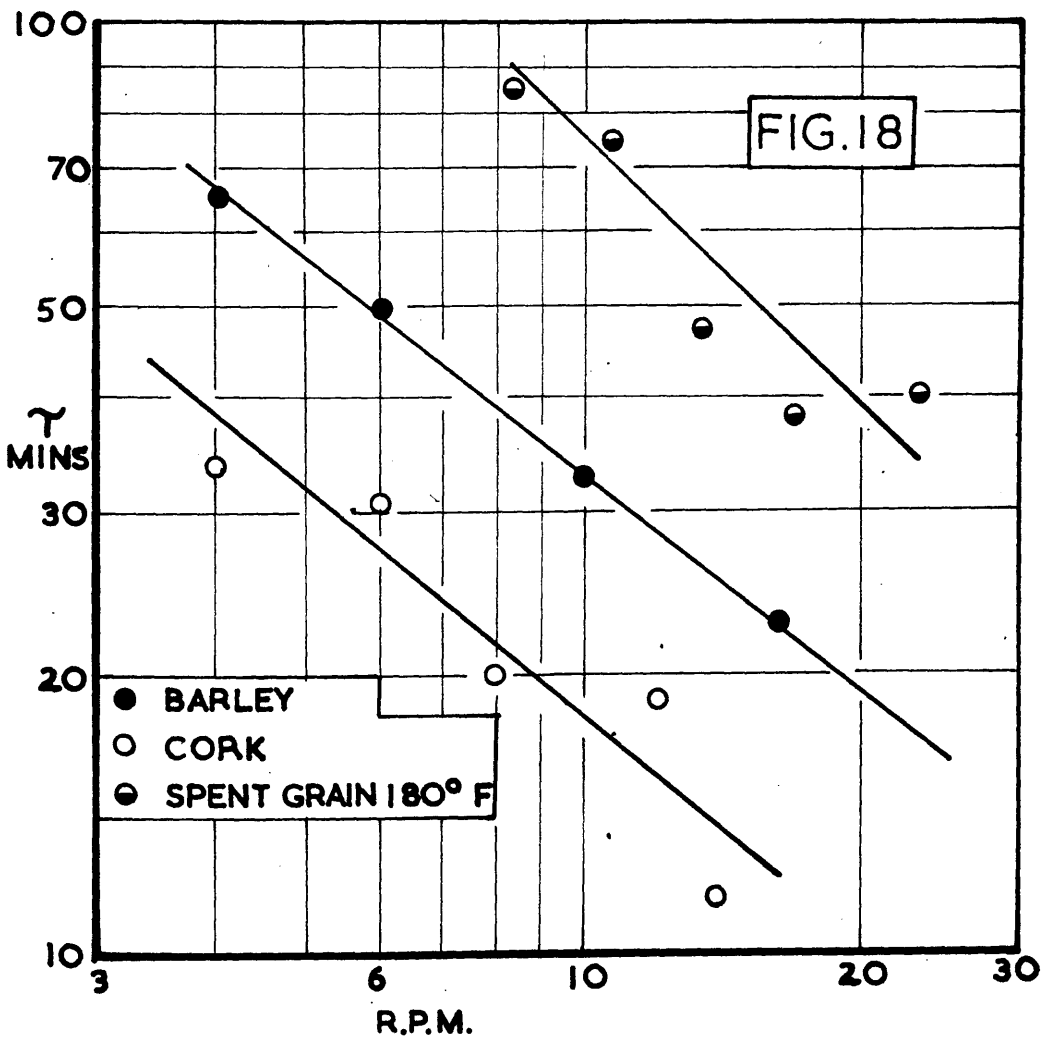
may apply, there can be no attempt to predict the values of b_3 at other values of drier speed, air mass flow and temperature. It will probably vary with temperature, as the higher temperatures will produce drier material which will be further retarded by counter-current air, a factor illustrated by some of the results for brewers' spent grain, p.100 .

Rate of rotation

Decrease in drier speed produced an expected rise in retention time. The results from the appropriate tests are shown in Fig.18. As with all other drying tests, apart from the variable under-study, all other factors affecting the operation of the drier, i.e. slope etc., are as described for the "standard" comparison test for each material. Details are included in the appropriate section on the drying of each of the three.

It might be expected that in drying runs with counter-current airflow, decrease in drier speed would have more effect on retention time than would be anticipated from the relation $T \propto N^{-0.9}$, which is another form of the general hold-up correlation, equation 25. Increase of retention time by slower speeds would be expected to produce a slightly drier material, which, in turn, would be retarded


80
60
40
τ 30
MINS.
20
10
0·04
0·1
·2
·4
·6
1·0
FEED RATE FT.³/FT.²T.HR.
BARLEY
CORK
SPENT GRAIN 200°F
" " 140°F
FIG.17


100
70
50
τ
MINS
30
20
10
3
6
10
20
30
R.P.M.
BARLEY
CORK
SPENT GRAIN 180° F
FIG.18

still further by the airflow. This is shown in the tests on brewers' spent grain at speeds below 15 R.P.M. At higher speeds the material will pass through more quickly, and the proportional alteration in density will be smaller.

A general tendency for the wet material to move forward more quickly was noticed in the drying tests, and it is thought that this accounts for the proportional higher retention times encountered with cork and barley at higher speeds, i.e., longer than would have been suggested from $\tau \propto N^{-0.9}$. In the range of the investigations, the relation appears to be $\tau \propto N^{-n}$ 45

where n = approx. 0.95 for both barley and cork.

Airflow

As the drying tests progressed, it became obvious that the rigorous treatment applied to the runs with dry feed was out of the question. In airflow trials, for instance, the satisfactory working range for each material was fairly limited. At low air mass flows the air soon became very moist, limiting drying and making comparison between tests difficult. Above a limiting value severe "dusting" took place and made estimation of the actual effective feed rate inaccurate, affecting velocity determinations and the overall retention time. The limits for each material were:

"G" - $lb/(ft^2)(hr)$

	Minimum G	Maximum G
Brewers' spent grain	290	510
Barley grain	410	710
Granulated cork	250	392

Equation 43, deduced from tests on dry material, could not be applied as it proved impossible to determine experimentally, X_0, the hold-up with no air flowing. Under these conditions, the surface moisture on the material remained and produced an entirely new set of working conditions through building up a coating on the walls of the tube.

Fig.19 illustrates the increase in retention time encountered with all three materials.

Fig.20 shows the general correlation factor $\frac{F}{Sd.N^{0.9}.D.}$ plotted against volumetric hold-up for cork, where limited velocity changes allow significant values of the hold-up to be calculated. It was originally hoped to deduce the hold-up at zero airflow from Fig.55. This proved impossible owing to the apparently complicated nature of the relationship. While it appears that equation 43 may apply at lower airflows, above a certain point the rate of increase of hold-up with airflow becomes less, and finally, when part of the feed becomes airborne, actually decreases.

The feed rate trials, described in more detail on p.122 , suggest that the increase in hold-up due to the standard test air-flow of 288 lb/(ft^2)(hr) is 1.8%. If this is deducted from the experimental values of the correlating group, the remaining figures satisfy the mean line, of gradient unity, as shown.

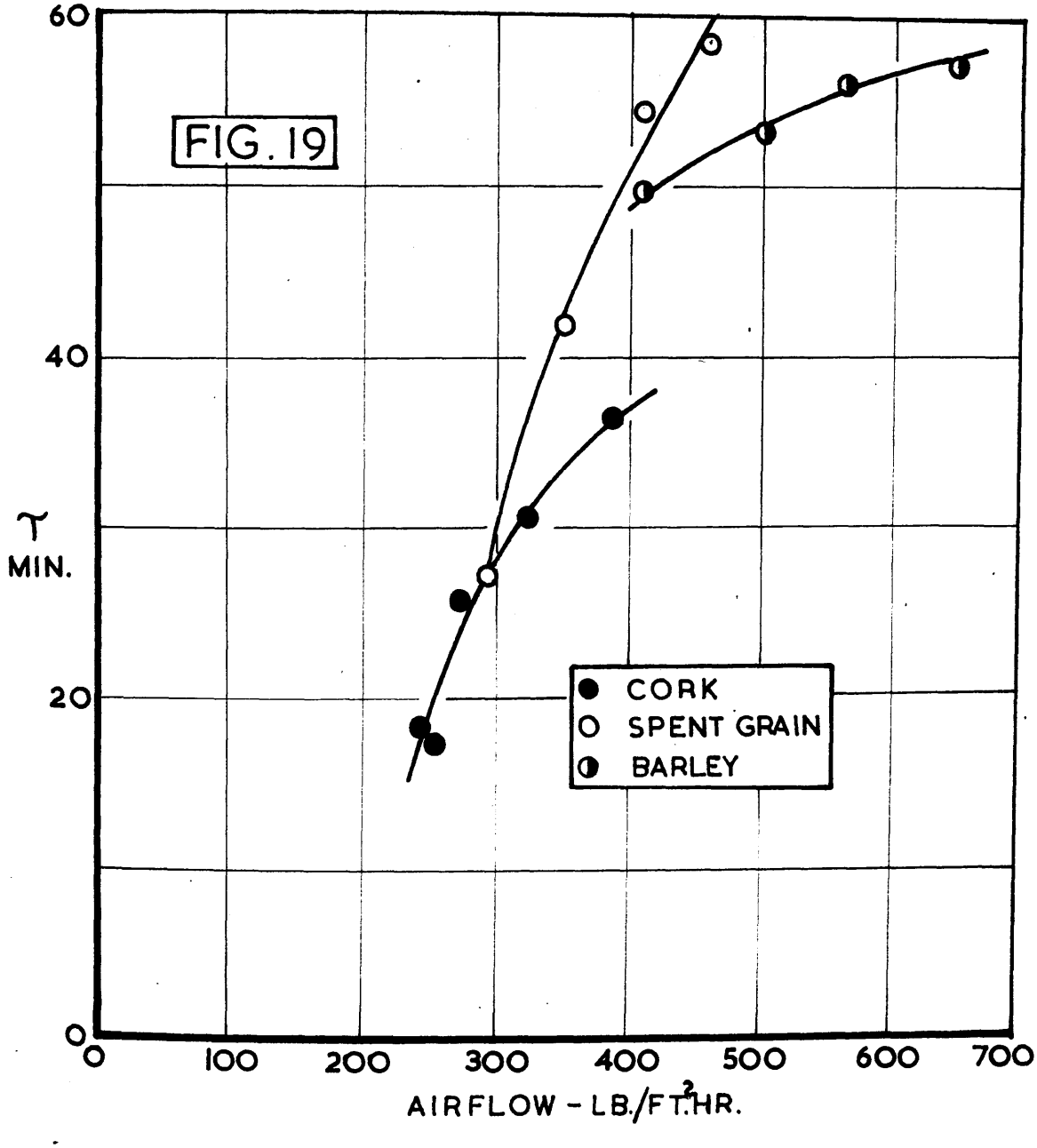


FIG. 19
60
40
20
0
τ
MIN.
0
100
200
300
400
500
600
700
AIRFLOW - LB./FT.²HR.
CORK
SPENT GRAIN
BARLEY

Number of flights

Increasing the number of flights fitted to the drier invariably increased the retention time. These results are presented in greater detail in the sections on the rotary drying of each material.

No. of flights	8	6	4	3	2
Brewers' spent grain 200°F	47	44.3	33.7	30.39	16.56
Barley grain	49	28.1	38.0	27.02	27.45
Cork Granules	25.77	21.7	14.82	16.51	10.89

R. Time in minutes

Deviation from the mean retention time

It has already been noted, p.27 , that while a definite retention time may be calculated or found for a rotary drier, this is a mean figure, and some material will pass through in longer and in shorter time. When heat sensitive vegetable materials are being dried, overtreatment may scorch and degrade part of the feed, while some will still contain unwanted moisture, although an average might indicate satisfactory operation of the drier.

It is obviously desirable to know what factors affect the amount of this "scattering" or deviation from the mean retention time, and the following trials were conducted to investigate the effects of some of the factors which actually control the motion of the feed through the tube.

Procedure

The smaller unit described on p.59 was used for the majority

of the tests. The scattering action of the flights was investigated with a short sealed version of the same apparatus.

The test procedure described in detail in the experimental section, p. 59 , was adhered to.

The scattering action of the flights at different loadings, corresponding to varying percentage hold-up, was checked by comparing the effect of a definite number of free falls on a group of selected granules.

The short unit was loaded to a definite fraction of its volume, closed and rotated for a few minutes. The point of maximum discharge from the flights was noted and the angle through which the tube would have to be rotated to produce a standard number, taken as 3, cascades of any particular group of granules.

The unit was stopped when there was 16 granules on the discharging flight. These were then replaced by an equal number of coloured granules, and after rotation through the calculated angle, the distribution of the coloured granules over the flights was noted. This was repeated several times at each of five percentage hold-ups.

Results

The method of calculation of the results is illustrated in Appendix IV . A standard value of the relative deviation from the

mean retention time was calculated according to the expression

$$\% D_1 = \frac{\text{time for a standard \% of tracer to leave - time for 50\% to leave}}{\text{time for 50\% of tracer to leave}}$$

80% was chosen as the standard amount of tracer leaving. The actual figure adopted affects the magnitude of D_1, and must be held constant throughout the series. Conclusions, such as the valves of hold-up at which minimum valves of D_1 occur, are however, not affected by the choice of final percentage.

The figures for the above were obtained from a plot of time Vs cumulative % of tracer leaving, constructed on arithmetic probability scales. Examples of the histograms and resulant integral curves are shown in Figs.62 and 63.

Varying the percentage hold-up only by alteration of the drier slope, Miskell and Marshall[73] suggested that a definite minimum relative deviation should occur at a particular value of this variable.

Accordingly a series of runs was carried out at constant drier speed and flight arrangements, where the percentage hold-up was varied from 4 to 26. The trend of results did not appear to agree entirely with the published data. A minimum did in fact occur, at around 7.5% hold-up, but a maximum and a point of inflexion were also apparent.

Further series of tests at different feed rates produced similar

curves, illustrated in Fig.21, and some "spot" tests at other feed rates carried out later for correlation purposes showed that relative deviation was not dependent purely on percentage hold-up, but was affected by, among other things, feed rate.

A second series of tests was carried out at an intermediate feed rate and constant speed to investigate the effect of the number of lifting flights fitted on dispersion. The number of evenly spaced flights was varied from two to eight. Experimental details were as before, the hold-up being controlled by the slope of the unit.

The results of this series are shown in Fig.22. With the exception of the curve for 2 flights only, it appears that, in the case of the particular unit under study, above 5% hold-up, relative deviation increases steadily with added flights.

The scattering action of the flights at different loadings, corresponding to varying percentage hold-up, was checked by comparing the effect of a definite number of free falls on a group of marked granules.

A measure of the scattering effect was obtained by drawing a smooth curve through the averaged distribution graph of number of granules against angular position, and determining the angle over which the central 8 granules were distributed. The distribution

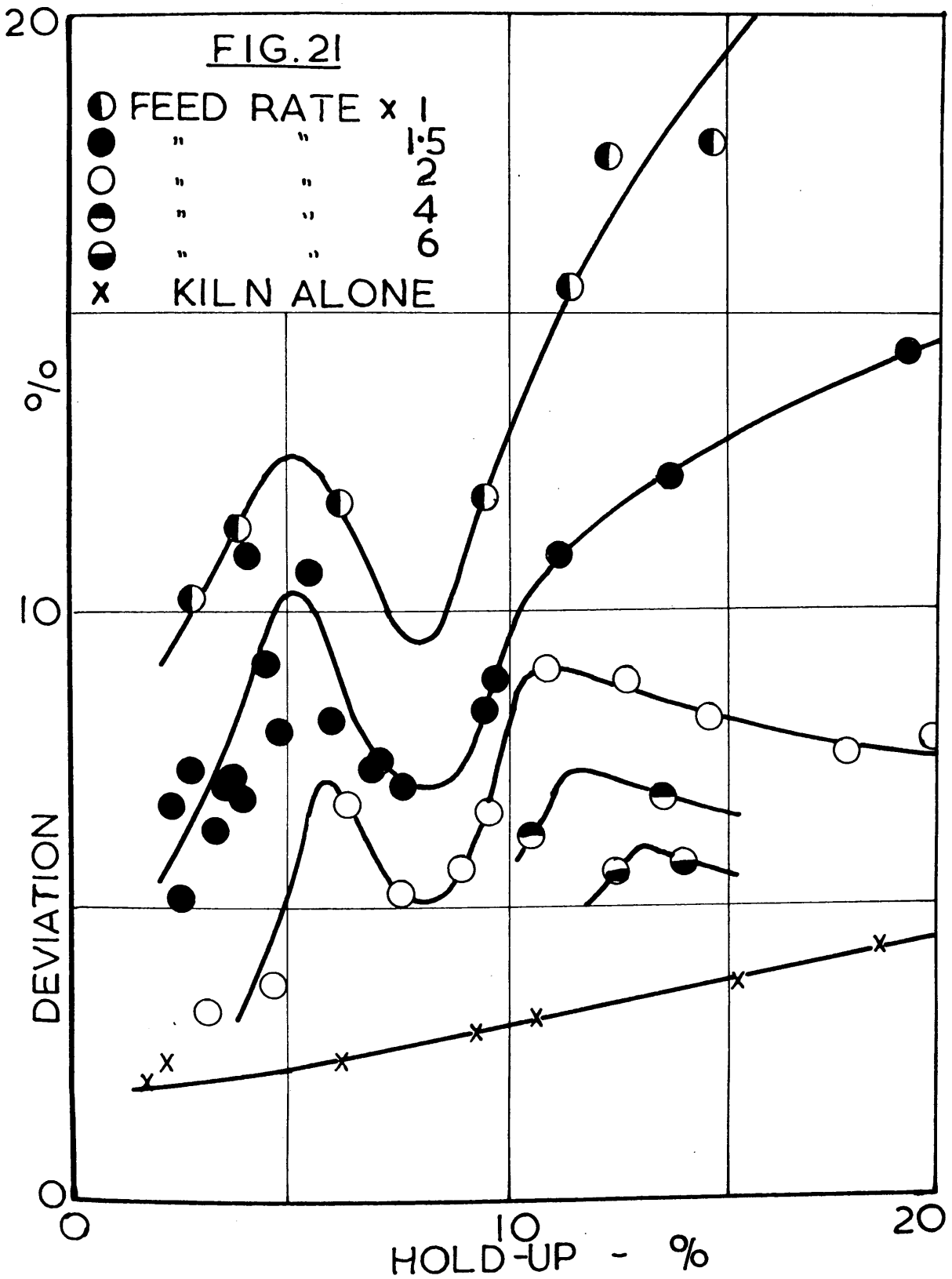
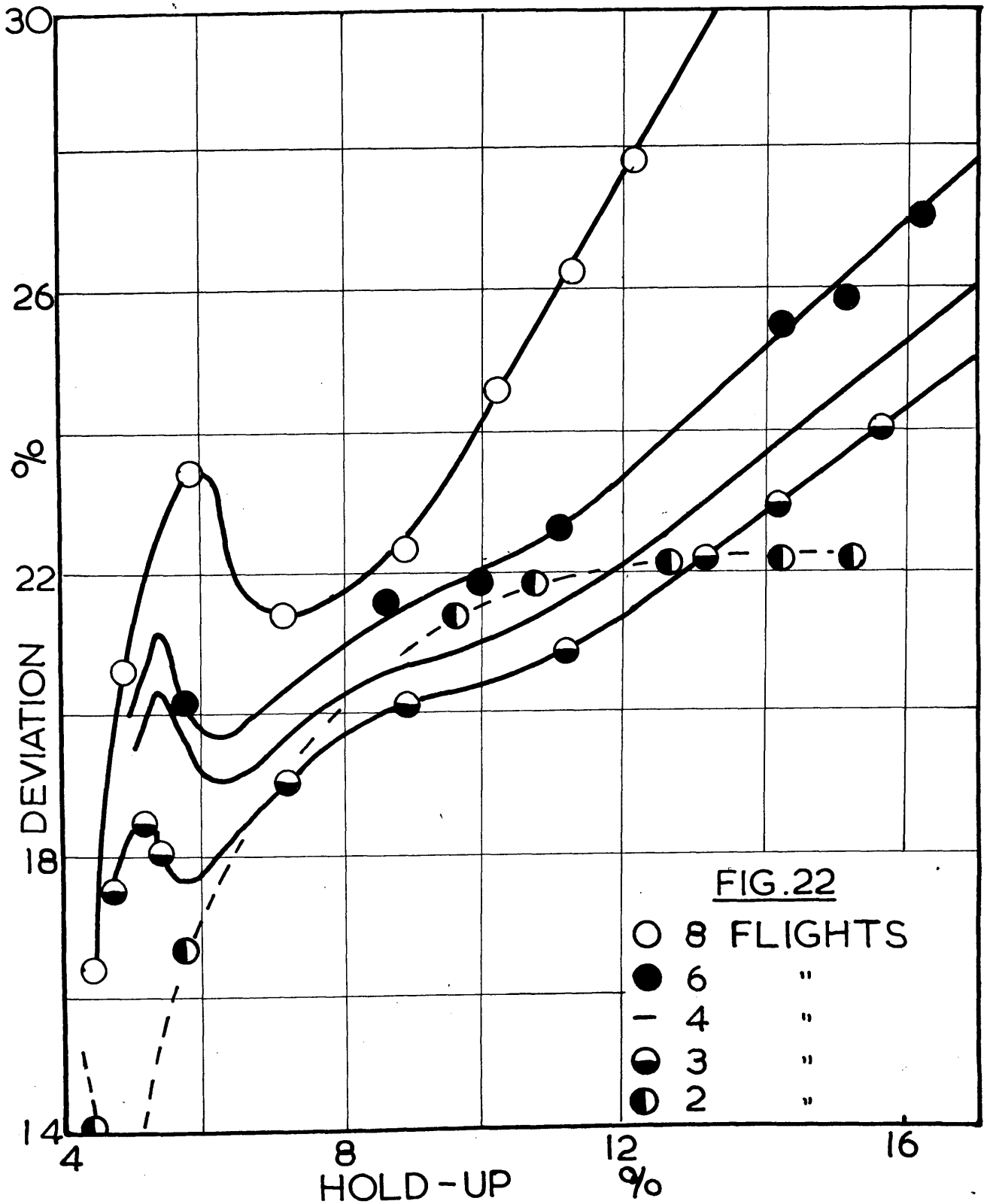


FIG. 21
FEED RATE x 1
" " 1·5
" " 2
" " 4
" " 6
KILN ALONE
%
DEVIATION
HOLD-UP - %
0
10
20


30
26
%
22
DEVIATION
18
14
4
8
12
16
HOLD-UP
%
FIG.22
8 FLIGHTS
6 "
4 "
3 "
2 "

function was of the familiar "bell" shape familiar in statistical work.

8 Flights

% Hold-up	2.5	5	10	15	20	25
Angle for 50% of marked load, Radians.	72	64	63	80	88	94

While these show some variation, there is little to suggest that variation of the "mixing" action of the flights at different loadings is the major factor in the production of the relationship shown in Fig.21.

The general form of the relationship between percentage relative derviation, hereafter referred to as "deviation", vs. hold-up, illustrated in Figs21 and 22, show, except for very high feed rates involving low retention time, similar trends in the range studied.

At low hold-up, deviation is low, but apparently does not tend to zero as the hold-up decreases. Deviation increases with hold-up to a maximum, and then falls off to a definite minimum - e.g. around 7.5% hold-up when 8 flights are used. From this point, deviation first increases fairly rapidly and then an almost linear relation is produced.

It now seems probable that three main factors are responsible for

deviation effects. These are

(a) haphazard bouncing of falling particles on either the uncovered shell of the drier or on layers of other particles;

(b) chance variations in falling paths resulting in some of a group of adjacent particles being picked up by a flight other than that collecting the main bulk of the group; and

(c) variation in hold-up, and consequently flight loading, affecting (b).

It has already been shown that (c) has limited effect, consequently only (a) and (b) will be considered.

Material falling on the exposed shell of the unit showed a marked tendency to bounce either forwards or backwards, along the axis of rotation. This tendency decreased at higher percentage hold-up, presumably as interference between particles in the denser "curtains" of falling material increased and as the shell became more deeply covered. When the flights become fully loaded, and kiln action of material starts along the bottom of the drier, this cushion will be permanent. This would suggest a relation of the form (A) in Fig.23.

Where there is a definite mathematical probability of one particle being lifted by a flight other than that which picks up its fellows during one falling movement, doubling the number of falls will obviously proportionally increase dispersion effects

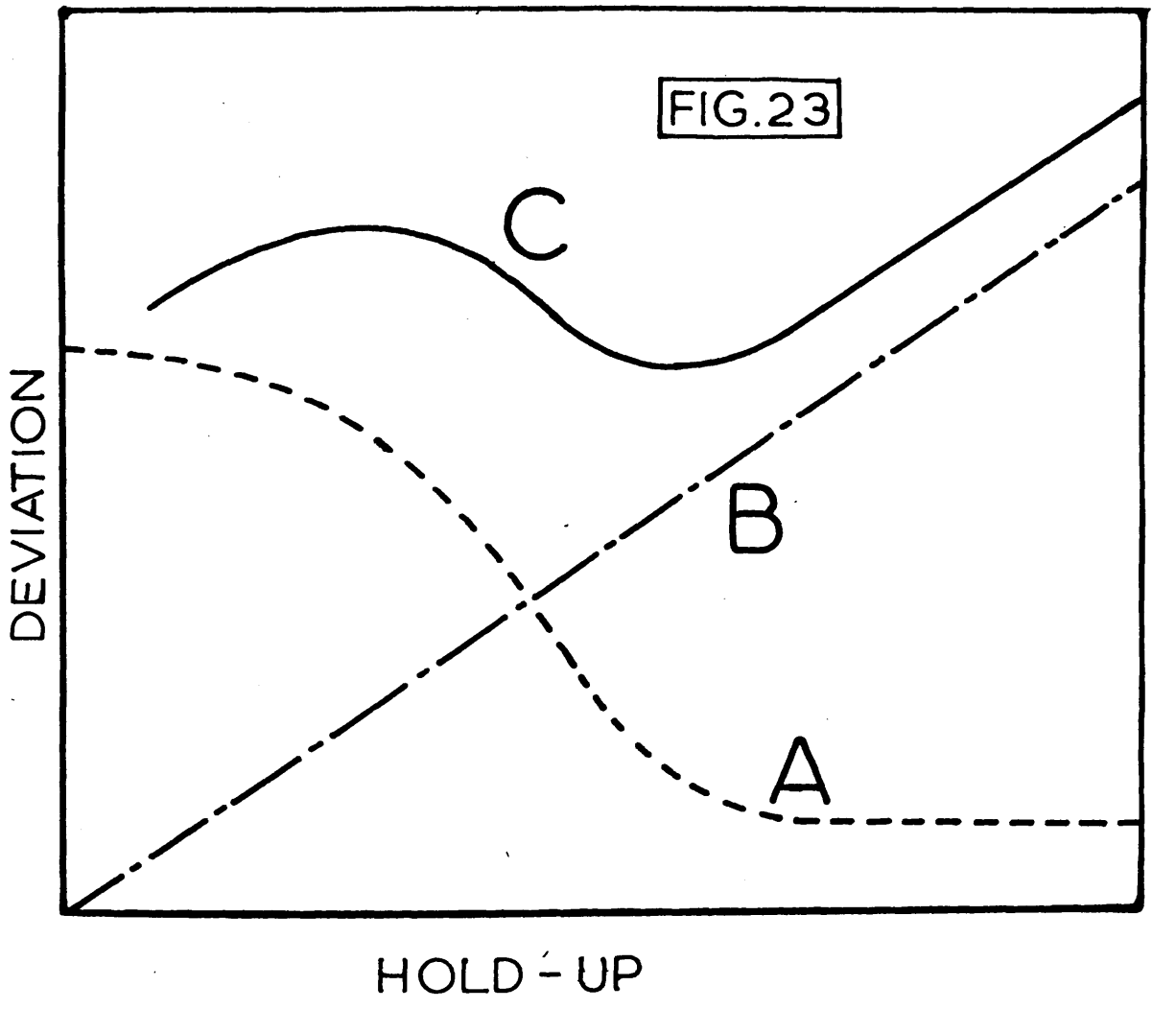


FIG.23
C
B
A
DEVIATION
HOLD - UP

caused in this way. At a constant speed the number of falls experienced by the average particle will be proportional to T, the retention time. This will at constant feed rate be proportional to the hold-up. Thus the effect of increasing hold-up on deviation caused by mixing in flight action may be expressed by (B) in Fig.23.

The effect of (A) and (B) together can be expressed by the additive curve (C). This has much the same form as the majority of the deviation/hold-up relations shown earlier, where there is an almost linear portion of the curve at high hold-up. The flattening of some of the curves at high feed rates is probably produced by secondary effects not covered by this elementary treatment. These may include factor (C) discussed above, and increased interparticle interference in the falling curtains.

A few tests where movement was by kiln action alone, Fig.22, showed a slight but linear increase in deviation with hold-up. Movement by kiln action in a unit fitted with flights will increase with hold-up and will have a slight but inestimable effect on resultant deviation.

As the number of flights fitted is increased, the value of the hold-up at which the flights become overloaded, and some material is left on the bottom of the shell, will also rise. This will affect curve (A) - the postulated horizontal section will occur at higher values of hold-up, and so the minimum in (C) will also

appear at increasingly higher values of $\underline{X}$. This point is illustrated in Fig.22.

Two further points of interest emerge. At higher values of hold-up, the curves, as has been noted above, approximate to a straight line. The gradient of these lines, $\frac{dD_1}{dX}$ increases with increasing number of flights Fig.22. This is to be expected. Increasing n_f, the number of flights, raises the number of alternative routes through the drier and will affect the gradient of the line (B) in Fig.23. Extrapolation of these lines to zero hold-up should indicate the limiting deviation by bouncing for each flight arrangement. The values found show a gradual fall in this for increasing number of flights, that is, as more uncovered edges of angled aluminium flights are presented to the falling granules, features which presumably do not produce as much longitudinal dispersion as a plane glass surface.

No. of flights	3	4	6	8
$\frac{dD_1}{dX}$	0.66	0.74	0.92	1.40
Lt. D_1 as $X \rightarrow 0$	13.5	13.2	12.4	7.2

At the lowest feed rate and highest hold-up used, less deviation was found than would have been expected from combination of the smooth curve from lower values of $\underline{X}$. A test carried out at 20% hold-up and at the lowest feed rate used should have, Fig.21, produced a deviation of about 50%. The experimental value

found was 36%, with a non-linear plot on arithmetic probability paper above 50% tracer. This is probably due to the large amount of upstream diffusion of the tracer which is possible, inferred by the high figure of 50% for the deviation, being prevented by the sealed feed of the drier.

To cover unexplained second order effects, a general correlation to include variation of hold-up, drier speed, feed rate, and resulting deviation was attempted for one flight arrangement.

It was found that, over the range 6% to 20% hold-up,

$$D_1 \propto (F)^{\alpha'} \quad \ldots\ldots\ldots\ldots \quad 46$$

where α' is an approximately linear function of hold-up. To allow for variation in the speed of the drier, $\underline{F}$ was replaced by $\underline{\Upsilon}$, to which it is inversely proportional at any hold-up.

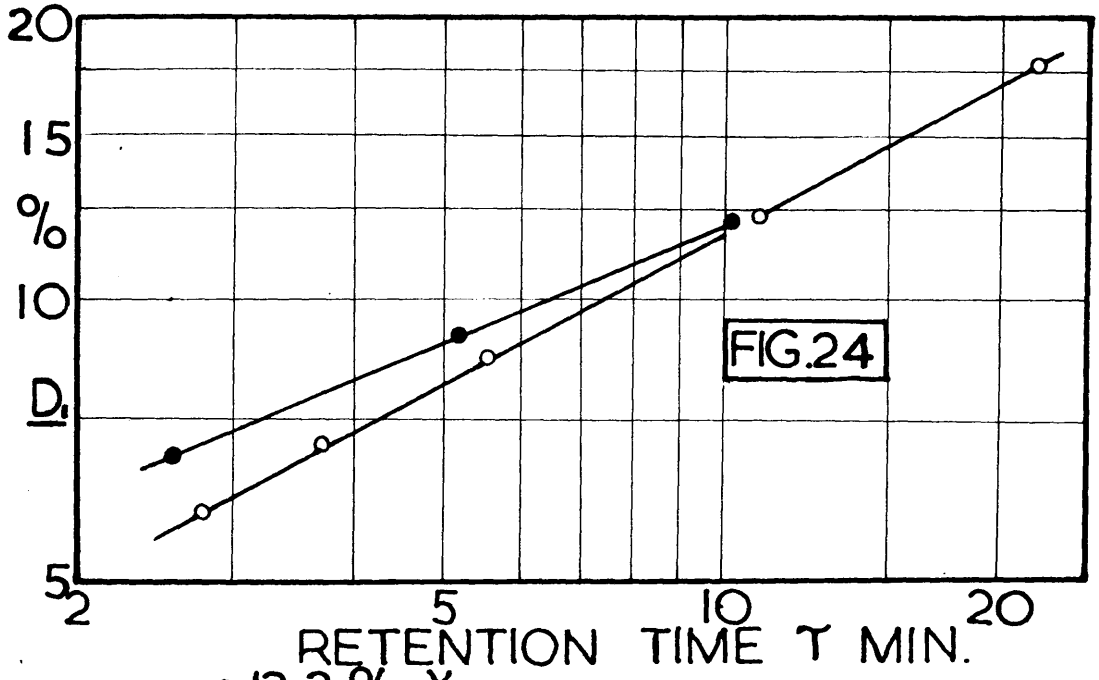
Two specimen plots of the relation

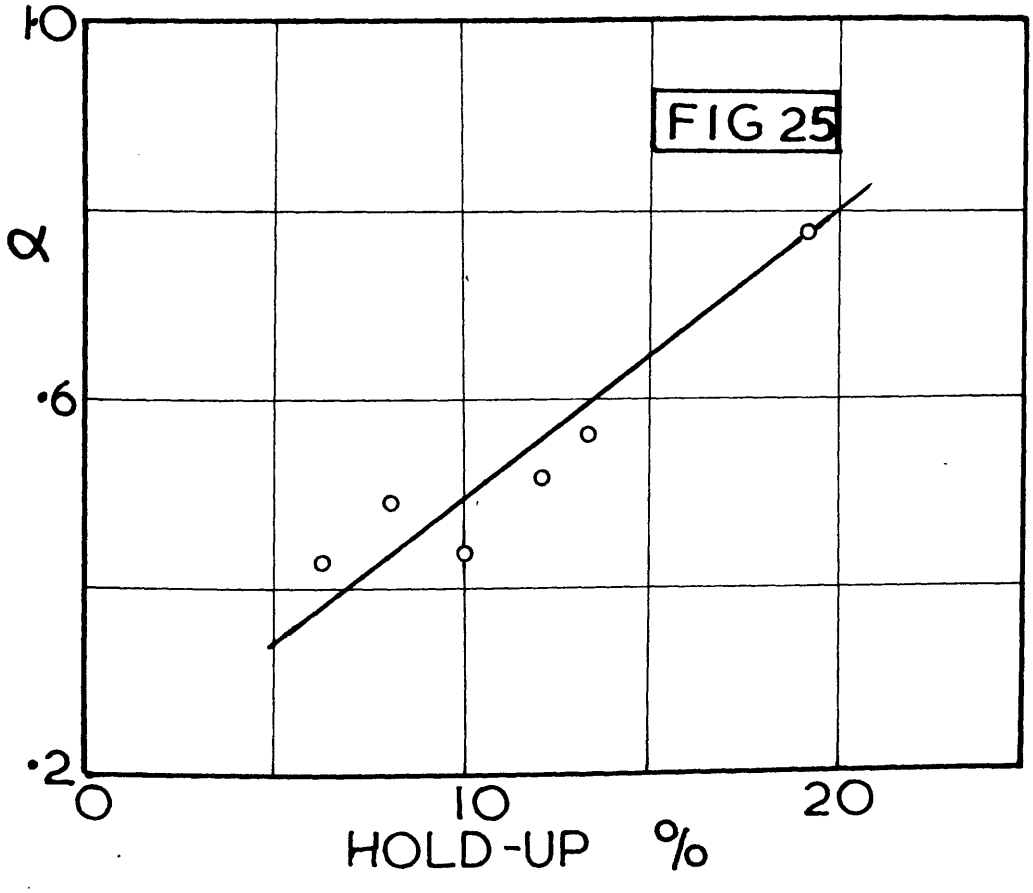
$$D_1 = k \Upsilon^{\alpha} \quad \ldots\ldots\ldots\ldots \quad 47$$

are shown in Fig.24, and some values of α are plotted against hold-up in Fig.25.

The general correlation produced by plotting $\frac{D_1}{\Upsilon}\alpha$ against $\underline{X}$ is shown in Fig.26. The mean line included corresponds to the smooth curve drawn through the "4x" feed rate plot of Fig.21.

The correlation is unreliable at values of $\underline{X}$ below 5%, but


20
15
%
10
D.
5
2
5
10
20
RETENTION TIME T MIN.
FIG.24
○ 13·3 % X
● 7·5 " "


1·0
α
·6
·2
0
10
20
HOLD-UP %
FIG 25

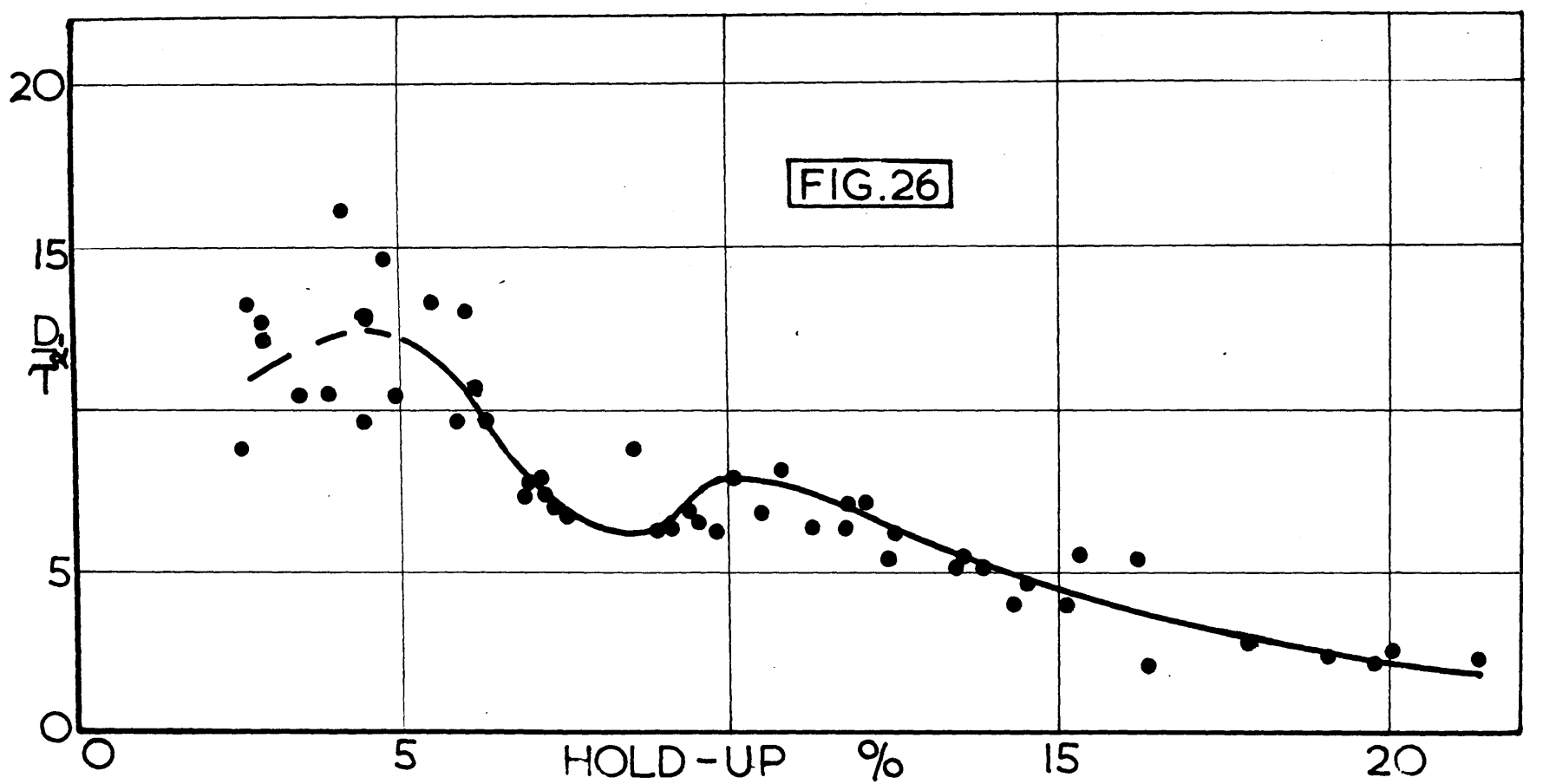


FIG.26
20
15
5
0
D%
T
0
5
HOLD-UP %
15
20

above this, to 20%, it shows reasonable agreement with experimental results. It covers a threefold variation of drier speed and an eightfold variation in feed rate, with drier slopes varying from 0.65% to 8% in the region 5% to 21% hold-up.

White sand

A smaller number of tests was carried out with white sand, using Potassium Permanganate as a tracer as described on p.59 .

The deviation, calculated as for the plastic granules, was considerably lower than had been encountered with the P.V.C.

At 8% Hold-up, Feed Rate 1.48 $ft^3/(ft^2)(hr)$, the deviation with white sand was 4.7% compared with 8.25% for the granules.

A straightforward plot of deviation D, against hold-up X was of similar form to Fig.21, and tests conducted at different feed rates indicated values of α which lay on the lower portion of the mean line in Fig.25. Values of α were accordingly taken from this, and a correlation of $\frac{D}{T\alpha}$ against X was attempted. This is illustrated in Fig.27, and covers a range of Feed Rate from 0.37 to 1.48 $ft^3/(ft^2)(hr)$, drier slopes from 1 to 10.5% and Hold-up from 2.3 to 15.5%.

The relation is of similar form to Fig.28, the point of inflexion, however, occurring at a lower value of hold-up. This indicates, that as might be anticipated, curve A of Fig.23 falls off more rapidly with the sand, which was observed to

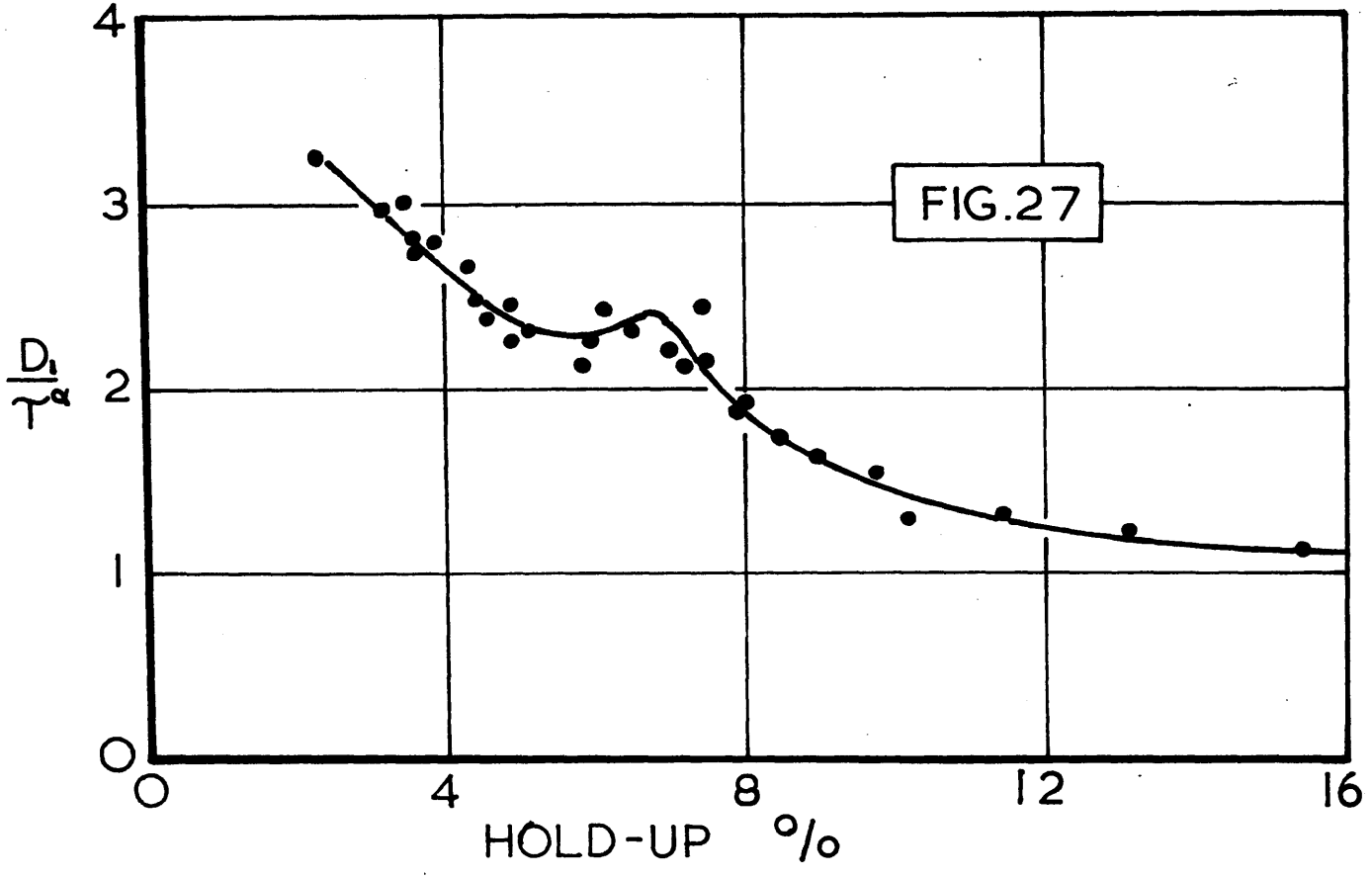


FIG.27
$\frac{D_1}{\tau_a}$
4
3
2
1
0
0
4
8
12
16
HOLD-UP %

bounce much less than the granules on the drier shell. The final linear section of the "Deviation Vs. Hold-up" curve is therefore evident at lower hold-up, viz. 8%.

Further tests suggested that, as with the plastic granules, under similar working conditions less deviation might be expected with reduced numbers of lifting flights.

Feed Rate 1.48 $ft^3/(ft^2)(hr)$

Hold-up %	4	8
	Deviation %	
8 Flights	4.21	4.70
6 Flights	3.91	4.15
4 Flights	3.78	3.94

One test on dispersion was carried out during drying trials by barley grain. Some dyed grain was used as tracer in a technique identical to that described for the P.V.C. granules. A plot of cumulative discharge Vs time on probability paper was non-linear above 50% tracer discharged and is included in the Appendix, Fig.64.

The Drying of Vegetable Materials

Introduction

The work described in this section deals mainly with the rotary drying of selected vegetable materials. Three substances of considerably different physical characteristics were studied, viz. brewers' spent grain, barley grain and granulated cork. Other materials which were tried and found unsuitable included polished rice and diced potato. The surfaces of these became coated with starch paste and the individual pieces adhered to the walls of the drying tube.

Both the barley grain and the cork exist in definite discrete particles whose size and shape were unaffected by passage through the drier, while the spent grain is a fibrous and crushed material resulting from the extraction, pressing and mechanical handling processes of the brewing industry, which breaks up further during drying. Each dries in a different manner and optimum conditions for each varied considerably. While a fairly high temperature and a longer retention time was necessary for the barley, the cork dried much more rapidly - a much lower temperature and retention time being adequate for a reasonable amount of drying to occur. The spent grain dries fairly readily to low moisture contents and conditions were adjusted to allow for this wherever possible.

Apart from work on simpler materials such as sand[80] or Fullers[79] earth, most published data on rotary driers quote at

most inlet and outlet moisture contents and temperatures. These seldom give any indication of the drying or transport mechanism along the drier and the effects of the controlling design factors on the drying rates of more complex materials has not yet been investigated. The experimental work described below was designed to determine the efficiency of the rotary drier as it affected the drying rates of the three materials. For comparison the results obtained from the through circulation drying of single layers have been referred to where applicable.

The method of evaluating the effects of the variables studied is essentially simple. One test was chosen as standard, the slope, feed rate, air mass flow and temperature, and rate of rotation being selected to produce an intermediate drying rate. To determine the effects of each factor it was possible to vary all in turn. The percentage slope of the drier was, however, maintained at a constant value for each material, as this variable is not thought to affect the drying rates directly but merely by alteration of hold-up, which is covered by the feed rate tests.

Unfortunately, alteration of any one factor may affect the percentage hold-up, which is normally controlled by the feed rate and the rate of rotation where the slope is constant. Friedman and Marshall[80] maintained that the hold-up was the main design factor affecting heat transfer rates and drying, and as such should be treated as a separate variable. With two of the materials studied, however, there was a wide variation in material velocities

along the drier, and it is thought that any value of the percentage hold-up based on the total retention time would be meaningless. To provide some comparison, however, a few tests were conducted where the feed rate was increased with the speed, and these are detailed in the appropriate section.

A feature of this type of work is the somewhat limited range of each variable studied. The working conditions of a rotary drier are critical and wide variation is seldom possible while still achieving satisfactory operation. This is most noticeable in airflow tests, where, for example, the studied range in the spent grain trials was from 290 to 510 $lb/(ft^2)(hr)$. Through circulation tests permitted a range of airflow of from 6.63 to 22.2 $lb/(ft^2)(min.)$, a considerably wider range.

Rates of feed and rotation are limited by the desirability of altering only one variable at a time. Each may be varied by a factor of about $2\frac{1}{2}$ without seriously over or underloading the drier. During tests on spent grain, for example, the speed of the drier was varied from 6.3 to 16.5 R.P.M. Tests at 4.1 and 26.5 R.P.M. were only possible by respectively decreasing and increasing the feed rate.

The limit of 8 on the maximum number of flights fitted was imposed by the size of the drier, and limits of air temperature were set at 200° to $220^{\circ}F$ to limit thermal strain on the glass tube and avoid charring of the feed material.

Brewers' Spent Grain

While the drying of this material has some economic significance owing to its value as a cattle food, its choice here was mainly as a matter of convenience, being readily available in fair quantities. It is representative of the group of light fibrous materials and contains a considerable percentage of water which is not all present as surface moisture.

Some notes on its preservation have been published by Axelsonn[88] and include drying, and a most exhaustive series of tests by Mitchell and Potts[42] details the effects of drying conditions on both shallow and deep beds of this material.

Single layer tests

The results of drying a single layer of a material by through circulation methods can be taken as indicating its basic drying properties. This technique was employed by Van Krevelen et al[40] who stated that it was preferable to the drying of single pieces which might vary in composition and because of size, hinder accurate measurement of moisture removal.

Using the apparatus described above, Fig.4, Mitchell and Potts[42] showed that, apart from short initial and tailing off periods, a semi-logarithmic plot of water ratio (W) vs. time of drying (θ) resulted in a straight line over almost the whole drying period:

$$\text{i.e. } \log_e W = -m\theta + k, \text{ or } \frac{dW}{d\theta} = -mW \quad \ldots\ldots\ldots\ldots \quad 15$$

It was further shown that m increased markedly with the inlet air temperature and to a lesser degree increased with higher air mass flow.

$$\text{Log}_{10}m = \frac{T - 303}{178} \quad \ldots\ldots\ldots\ldots \quad 48$$

Where T is the inlet air temperature, ^{o}F and $m \propto G^{0.75}$ 49

Where G is air mass velocity, $lb/(ft^2)(min.)$.

Hence, as also found by Simmonds et al[39] on comparable work on wheat grain, the drying rate of a single layer is given by a simple expression relating time to the moisture content and a rate constant which can be correlated with temperature and airflow. The results for the spent grain are based on the total moisture content, as distinct from the "free" moisture content, the difference between the actual and the equilibrium values, used by Simmonds et al.

Equation 15, based on the assumption that the drying rate is proportional to the moisture content, has been developed by Treybal[89] for general application in the falling rate period. Attempts to relate the drying rate in this period to either heat or mass transfer coefficients have met with limited success owing to the change of internal resistances during drying.

Rotary Drying of Brewers' Spent Grain

The drying tests were carried out on the apparatus illustrated in Fig.5. The tests were performed as has already been described in the section on apparatus and experimental procedure.

To minimise kiln action and maintain movement by flights at high loadings, 8 lifting flights were used throughout the main portion of the work. Although 12 flights could be accommodated in the drier, it was felt that the close spacing of $1\frac{1}{4}$" which resulted was out of scale with larger units.

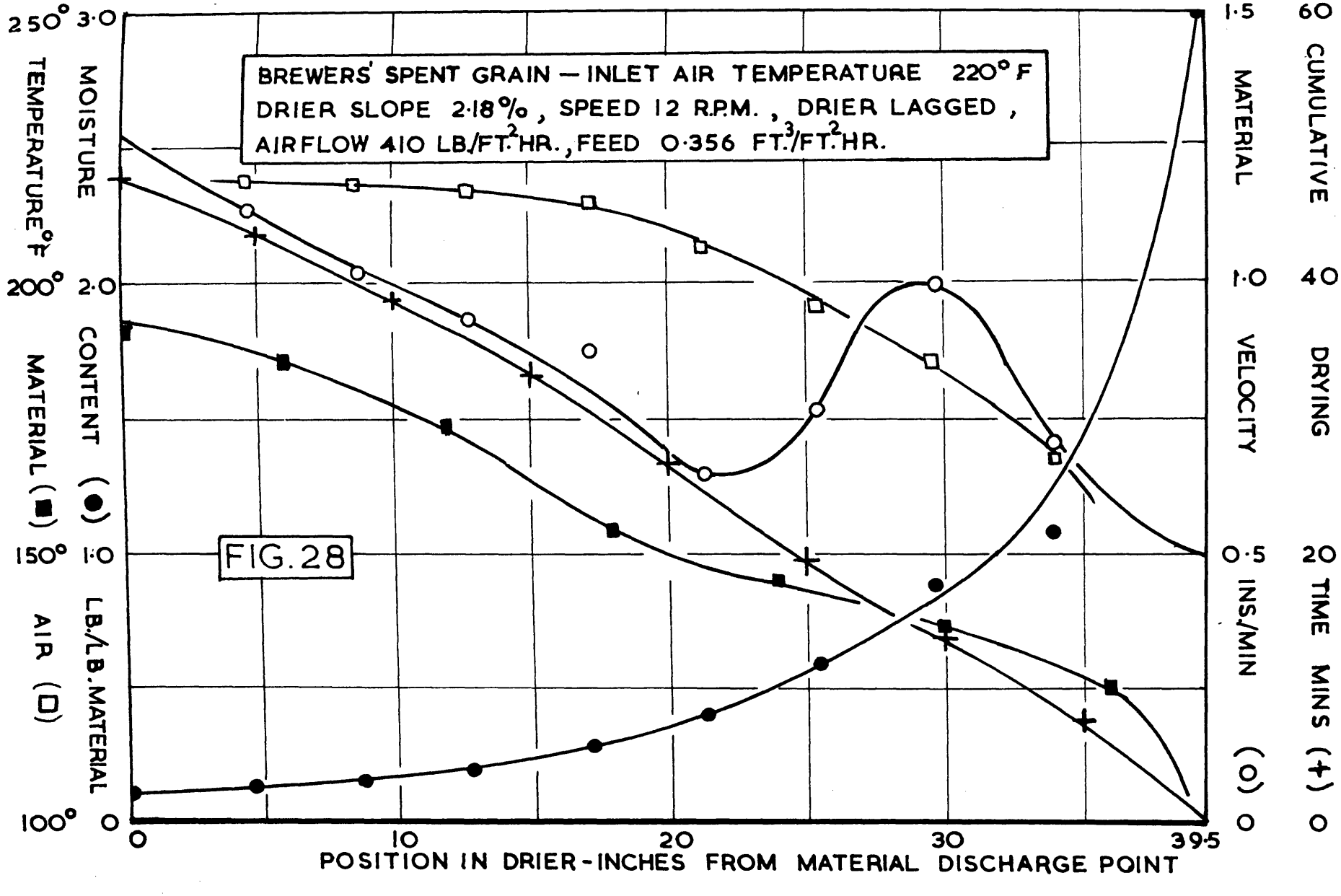
An initial series of 25 runs was carried out with the glass drier tube unlagged. An example of one of the tests is illustrated in Fig.28, and all moisture contents, temperatures and other data obtained during the test are shown.

The velocity of the material in the drier was obtained as follows:

If feed rate = f gm. Bone dry solid/min., and loading at any point in the drier = M gm. B.D.S./min.,

then velocity at that point = $\frac{f}{M}$ ins./min.

The average velocity over each 5" section of the drier from the discharge end was found from the velocity/position curve, and the time spent by the material in each 5" length was calculated. From this a cumulative time curve could be drawn against position in the drier, and by cross reference the drying time elapsed at different moisture contents was determined. This allowed a plot of moisture content Vs time to be constructed, comparable with curves obtained by simpler methods for through circulation drying. An example of one of the drying curves is shown in Fig.29. The data for this test are presented in detail in Appendix 11 .


BREWERS' SPENT GRAIN — INLET AIR TEMPERATURE 220° F
DRIER SLOPE 2·18%, SPEED 12 R.P.M., DRIER LAGGED,
AIRFLOW 410 LB./FT.²HR., FEED 0·356 FT.³/FT.²HR.
FIG. 28
TEMPERATURE °F
MOISTURE CONTENT (●) LB./LB. MATERIAL
MATERIAL (■) AIR (□)
MATERIAL VELOCITY INS./MIN (○)
CUMULATIVE DRYING TIME MINS (+)
250°
200°
150°
100°
3·0
2·0
1·0
0
1·5
1·0
0·5
0
60
40
20
0
0
10
20
30
39·5
POSITION IN DRIER - INCHES FROM MATERIAL DISCHARGE POINT

Considerable variation in material velocity was observed along the drier. As the material passed through it first gathered speed and then slowed down gradually as it dried, became less dense and was more affected by the counter-current airflow. As it approached the open discharge end of the drier, the gradient formed by the material itself produced a fairly rapid increase in velocity right up to the point of discharge.

It was originally hoped that all the drying runs could be carried out in the unlagged drier. There are many advantages in being able to check visually the variation in loading along the drier, the action of the flights and to watch for material caking on the drier shell. Although the drier performed satisfactorily, no consistent basis was found for estimation of the drying rates.

While a regular and systematic variation in total drying achieved was observed, the lack of a regular or definable drying curve prevented ready comparison of runs other than merely by quoting drying times between fixed limits - a most unsatisfactory method when the drying is irregular. Semi-logarithmic plots of the moisture content Vs. the drying time produced only a very limited linear section.

Both mass and thermal balances were calculated over the drying tube. While the mass balances were generally consistent, showing that airflow measurements were accurate, thermal measurements indicated that a fair amount of heat was passing from the jacket,

through the wall of the tube, to its contents. Typical values indicated that about 20% of the total heat, measured from $0^{\circ}F$, leaving in the moist air and dried, heated material, had passed through the drier tube wall. Attempts to express results on a heat transfer basis were hampered by this "excess" heat.

Air temperatures along the drier were estimated by conducting a series of nine thermal and mass balances in the sections of the drier used for calculation purposes. The starting point was taken as the air inlet end where its humidity and temperature were known accurately. The balances allowed calculation of the enthalpy and the moisture content of the air leaving each section, and from these the temperature was found by reference to a standard psychrometric chart[90].

It was found, however, that the calculated exit air dry bulb temperature was consistently a few degrees above the value which was observed by placing a shielded thermometer in the outlet air stream - the increase being attributable to the heat passing in from the jacket. It was assumed that the observed temperature was correct and that the amount of heat passing from the jacket would be proportional to the difference between this and the jacket temperature. The ratio

$$\frac{\text{difference between jacket and actual air temperature}}{\text{difference between jacket and theoretical air temperature}}$$

was known at the outlet, and intermediate values of the theoretical air temperature from the mass balances were raised in the same

proportion.

The weakness of this method is its assumption of constant specific heat of the air stream, but over most of the drier the correction has only a limited effect on the thermal potential between air and solid in the drier. Air temperature fell only slowly through most of the tube, much of the total drop occurring in the few inches of the drier adjacent to the feed conveyor.

McEwan et al[39] suggested that when a material dries in the falling rate period, its ability to receive heat and lose moisture gradually decreases and a relation between the apparent heat transfer coefficient and the moisture content may be formulated. This initially showed some promise with the results from the rotary drier, and values for heat transfer coefficients at different values of inlet air temperature are shown in Fig.29. Subsequent tests involving other factors produced wide and unpredictable variations, and the results for the same material when the drier was finally lagged with asbestos showed no consistent variation and the method was discarded.

A major defect of this approach is that, even if the apparent heat transfer coefficients are known, the actual drying rates still cannot be calculated unless it is assumed that the material will remain at a steady temperature, often assumed as the wet bulb temperature of the drying air, and that all the heat will be employed towards evaporation of the moisture. While this, Friedman and

Marshall[80] have shown, may be true of wet sand, this assumption is often unjustified. Pearse et al[20] have observed that actual surface temperatures are usually above the air wet bulb temperature and in a rotary drier a further rise in temperature may be produced by unavoidable radiation from flights and the drier walls. The tests on spent grain showed no period over which the temperature of the material was at all constant.

For these reasons few quantitative results were obtained from the unlagged drier, but a summary of the tests is given below. The standard test was conducted at an air inlet temperature of 180°F and mass flow G of 355 lb/(ft^2)(hr.). The feed rate was maintained at 0.35ft^3/(ft^2)(hr) and the drier speed at 12 R.P.M. The slope of the tube was 2.18% and 8 angled lifting flights were fitted.

Inlet air temperature

Rising air temperature increased limits of drying, the final moisture content being lowest at the highest temperature employed, viz. 220°F. As has already been noted in the section dealing with the conveying properties of the rotary drier, increased air temperature had considerable effect on the retention times, and this accounts in part for the lower product moisture contents.

No general relation between drying rates, moisture contents and time was observed.

Inlet temp.°F.	160	180	200	220
Final W. lb/lb B.D.S.	0.35	0.26	0.12	0.08
τ mins.	26.9	33.0	37.9	38.6

Air mass flow

Retention times increased from 37 minutes to 54 minutes as the airflow was increased from 285 to 410 lb/(ft^2)(hr). Product moisture content was not, however, affected greatly.

"G"	285	350	410
Final W	0.26	0.25	0.22
τ mins.	36.1	47.3	54.3

Feed rates

Low feed rates produced longer retention times and a much drier product. The increased drying efficiency at low feed rates appears to be due in part to increased drying rates.

F $ft^3/(ft^2)$(hr)	0.70	0.47	0.35	0.28
Final W	0.54	0.48	0.27	0.19
τ mins.	43	39	47	70

Speed of drier

The complex operation of the rotary drier is well illustrated by the effects of speed of rotation on the drying of this material. While the retention time generally decreases with increasing R,P.M. and it appears that the driest product will be obtained at the slowest operating speed, increase in drier speed again finally lowers the product moisture content.

Speed, R.P.M.	23.1	16.9	13.4	10.7	8.5
Final W.	.22	.26	.25	.20	.12
τ	40	38	47	74	85

Number of flights

Increasing the number of equally spaced flights raised the retention time and resulted in a substantially drier product.

No. of Flights	2	4	6	8
Final W	0.70	0.42	0.35	0.25
τ	12.9	21.5	32.0	47.3

Temperature of jacket

With the drier tube unlagged and the air jacket maintained at inlet air D.B.T., heat was transferred to the contents of the tube, and the air outlet temperature was above the theoretical. With the jacket unheated, the reverse was true, and much of the heat of the drying air was lost to the surroundings and the temperature of the outlet air dropped below the theoretical value for no heat loss. It was hoped to adjust the jacket to some temperature which would produce an air outlet temperature equal to that predicted from an estimate of the dry product temperature, the only other unknown factor, and a thermal balance. With conditions as described for the standard, this temperature was shown to be 152°F. It was felt afterwards, however, that this produced a false set of working conditions where heat was still passing inwards through the shell where the air and material were colder at the material feed end, and outwards at the dry product end.

It was accordingly decided to forego the advantages of visibility for a thick layer of insulation.

Tests with the lagged drier

A one inch thick layer of asbestos rope was wound over the exposed part of the drier tube.

When the jacket was maintained at the air inlet dry bulb temperature, thermal balances showed that only a negligible amount of heat now passed through the walls of the tube. Material and air temperatures along the drier again indicate that this will be confined mainly to the few inches adjacent to the feed conveyor.

A second series of tests was conducted with the spent grain and the lagged drier. To counteract the decreased drying rates the inlet dry bulb temperature of the air was increased to 200°F for most tests. A few were conducted at 140°F for comparison with the results at the higher temperature. In these runs the material was often discharged still containing a substantial amount of moisture but sufficient drying was usually accomplished to allow measurement of the drying rate.

Procedure

The procedure adopted was identical with that used before with the unlagged drier.

Results

Several methods of correlation of experimental results were tried.

Air temperatures along the drier were calculated as before. Heat transfer coefficients showed considerable variation with inlet air temperature. The values obtained, plotted against moisture content, are included in Fig.30. These showed so little promise that the method was discarded.

The average water vapour partial pressure P_a in the drying air in each section of the drier was calculated from the known variation values of the relative humidity and temperature. It was assumed that the water vapour pressure of the material would be equal to that of a free water surface at the same temperature and mass transfer coefficients were calculated on a basis of drier volume:

$$k_g = \frac{w.f}{p.dL.\frac{\pi D^2}{4}} \quad \ldots\ldots\ldots \quad 50$$

where w = change in material moisture content over section, lb./H_2O/lb. B.D.S.

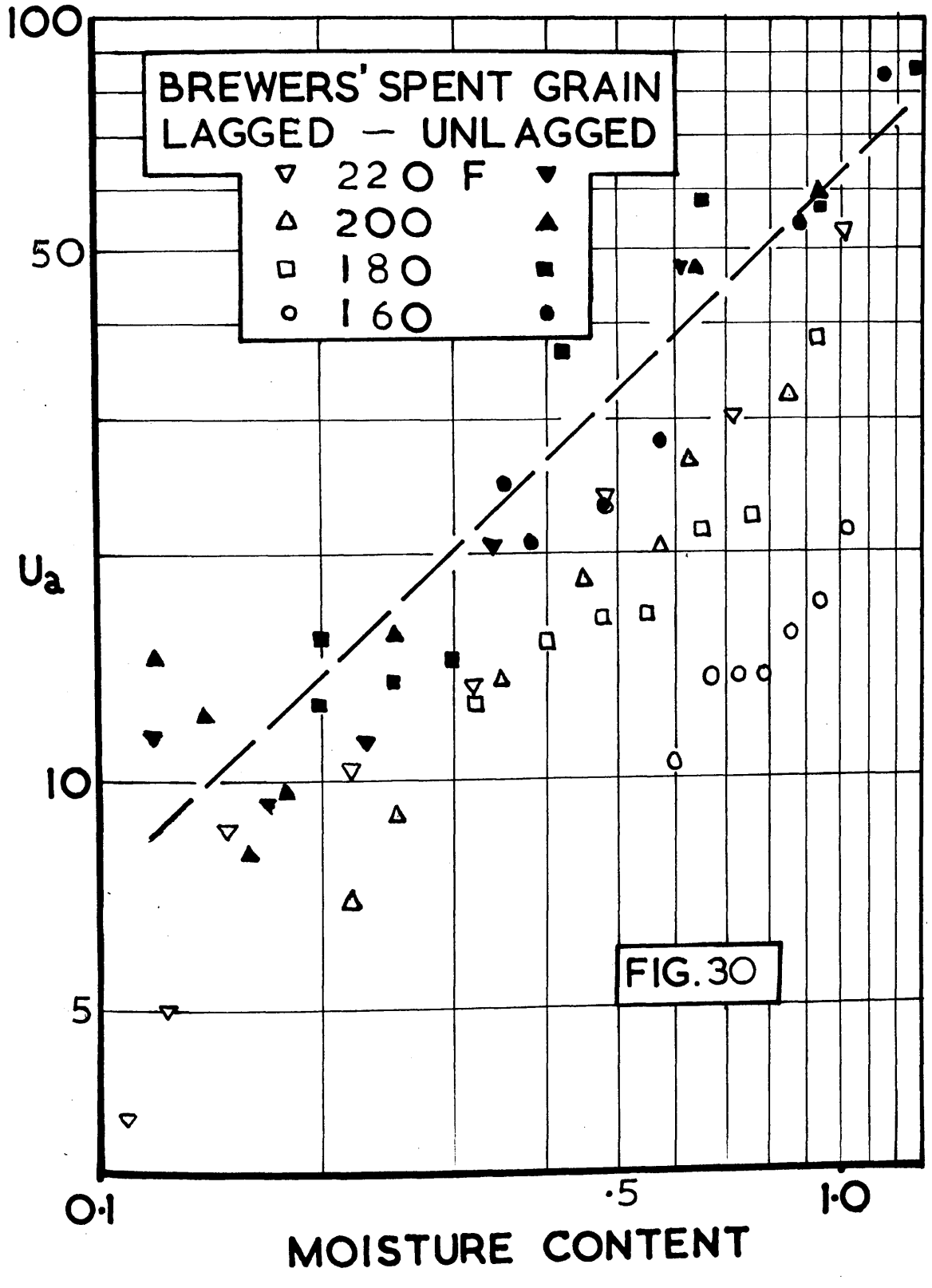
f = drier feed rate, lb. B.D.S./hr.

p = $p_w - p_a$, atmospheres

dL = length of drier section, ft.

k_g = mass transfer coefficient, lb./(atmosphere)(ft^3)(hr).

Plots of k_g against W were constructed but no consistent form of relation was obtained and all results showed strong dependence on air inlet temperature and other operating factors. As with heat transfer coefficients, the utility of the results obtained by this method depends on an ability to predict the temperature of


BREWERS' SPENT GRAIN
LAGGED — UNLAGGED
220 F
200
180
160
100
50
10
5
U_a
0·1
·5
1·0
MOISTURE CONTENT
FIG. 30

the material at all points along the drier. In the second series of trials, as in the first, no "constant material temperature" drying period was observed, and it was felt that further efforts in the field of transfer coefficients would not be justified.

The most satisfactory estimate of the performance of the drier was found simply from the plot of material moisture content against time of drying. When allowance was made for the considerable variation in material velocities along the drier, a plot of $\underline{W}$ against θ indicated that, over most of the drying period observed.

$$\text{Log}_e W = -m\theta - k, \text{ or } \frac{dW}{d\theta} = -mW \quad \ldots\ldots\ldots\ldots 15$$

which is of the same form as has already been observed for the single layer through circulation drying of this material.

Variation in the performance of the drier was observed and estimated by comparison of the value of $\underline{m}$ obtained from each test.

Suitable intermediate values of the operating conditions were again chosen for a standard test, and the effects of each factor investigated by systematic variation. The drier slope was maintained at 2.18% throughout the series, and standard conditions adopted were inlet air temperature of 200°F and mass flow 410 lb./(ft^2)(hr.), drier speed of 12 R.P.M. and feed rate of 0.356 ft^3/(ft^2)(hr). 8 lifting flights were employed in the majority of runs.

Inlet air temperature

Air inlet temperature was varied from 140° to 220°F. Drying rates, as expressed by the value of the falling rate constant, m, were found to vary considerably. All tests produced consistent linear plots on semi-logarithmic scales, Fig.31 and resultant values of m appeared best related by an expression illustrated in Fig.32 of the same type as has already been encountered in single layer work,

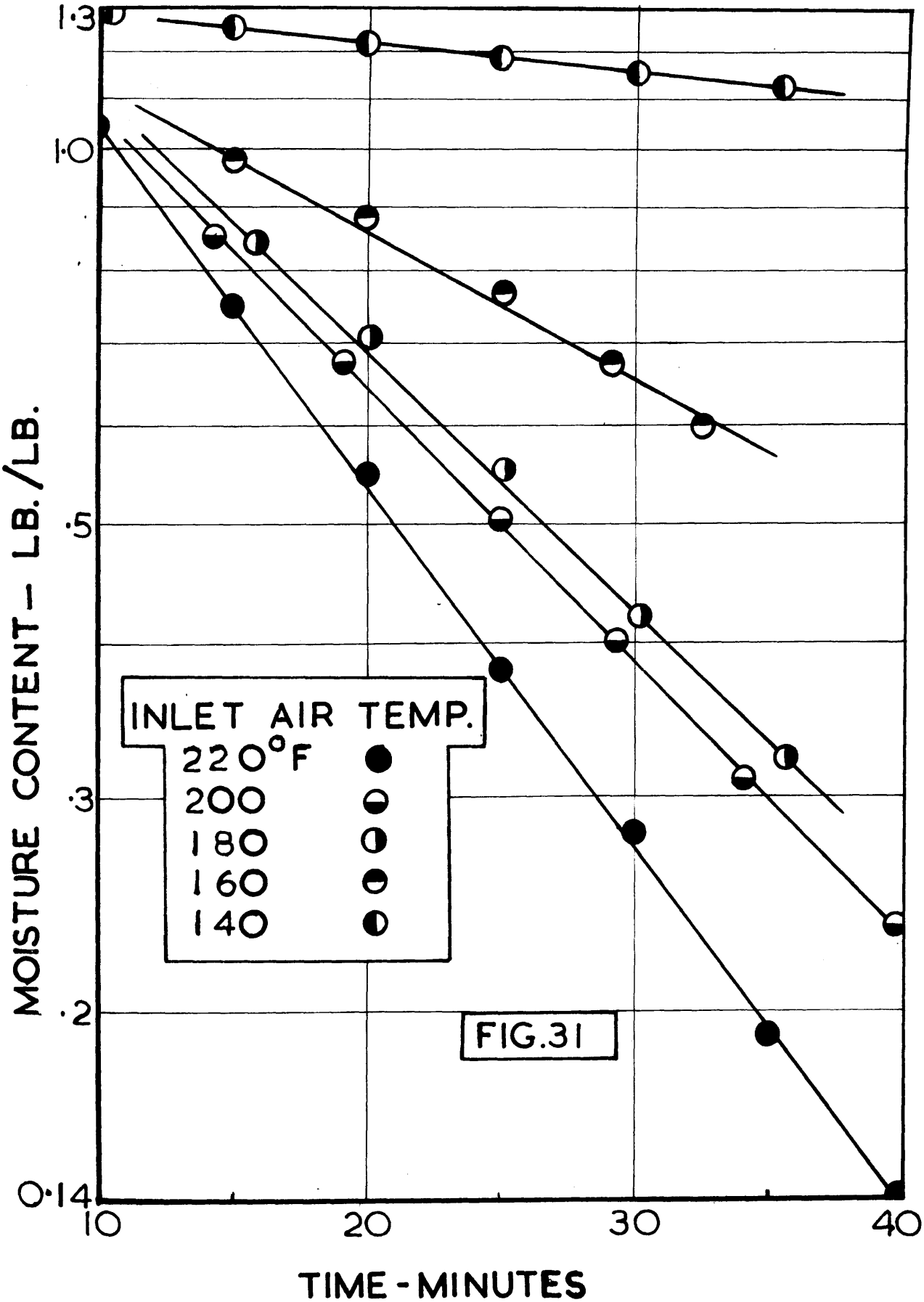
$$\text{Log}_{10} m = \frac{T - 487}{228} \quad \ldots\ldots\ldots\ldots \quad 51$$

Temperature °F	140	160	180	200	220
m	.0054	.0375	.0478	.0496	.0674

The value of m obtained from the test at 140°F was very much lower than is indicated by the above equation. Accordingly, while the majority of tests conducted on other variables were carried out at 200°F, some were repeated at 140°F for comparison.

Air mass flow

The useful range of air mass velocities effective in the drying of this material was found to be somewhat restricted. The lower limit of 290 lb/(ft^2)(hr) was set both by the fairly large amount of water to be evaporated from the material and by difficulties in maintaining drier temperatures at lower values. This lower limit represents an actual linear air velocity of only 1.10 ft/sec. Above 460 lb/(ft^2)(hr) "dusting", the entrainment of part of the feed became very pronounced, and the effective feed rate, necessary for the calculation of retention times, became impossible to


1·3
1·0
·5
·3
·2
0·14
MOISTURE CONTENT – LB./LB.
10
20
30
40
TIME - MINUTES
INLET AIR TEMP.
220°F
200
180
160
140
FIG.31

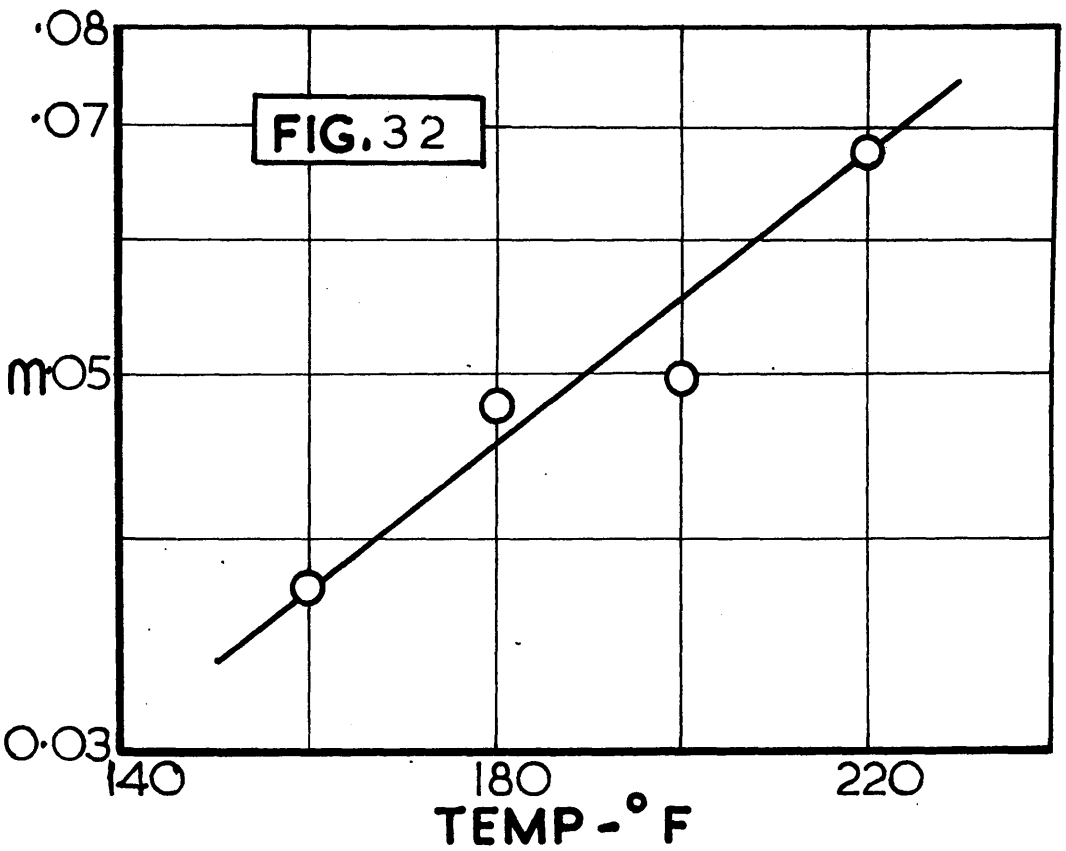


FIG. 32

estimate with any degree of satisfaction. Results from a test at G = 510 lb/(ft^2)(hr) are anomalous and cannot be explained.

Drying rates increased with rising air flow, and final moisture contents were influenced both by this and by the increased retention times

G lb/(ft^2)(hr)	290	350	410	460	510
m	.0330	.0380	.0395	.0475	.0169

The variation of m is illustrated in Fig.33, and over the range studied, the expression

$$m = 0.000531.G^{0.73} \quad \ldots\ldots\ldots \quad 52$$

appears to hold. For the through circulation drying of single layers of this material, Mitchell and Potts[42] suggested the relation

$$m \propto G^{0.75} \quad \ldots\ldots\ldots\ldots \quad 49$$

and it appears that the index of G is similar for the two types of drier.

Tests at 140°F under otherwise similar conditions produced no useful results. Air mass flow of 510 lb/(ft^2)(hr) again produced excessive dusting, and at 290 lb/(ft^2)(hr) the limited evaporative capacity of the cooler air produced a most erratic drying curve.

Feed rate

The feed rate was varied from 0.239 to 0.515 ft^3/ (ft^2)(hr), and drying rates were found to be considerably affected.

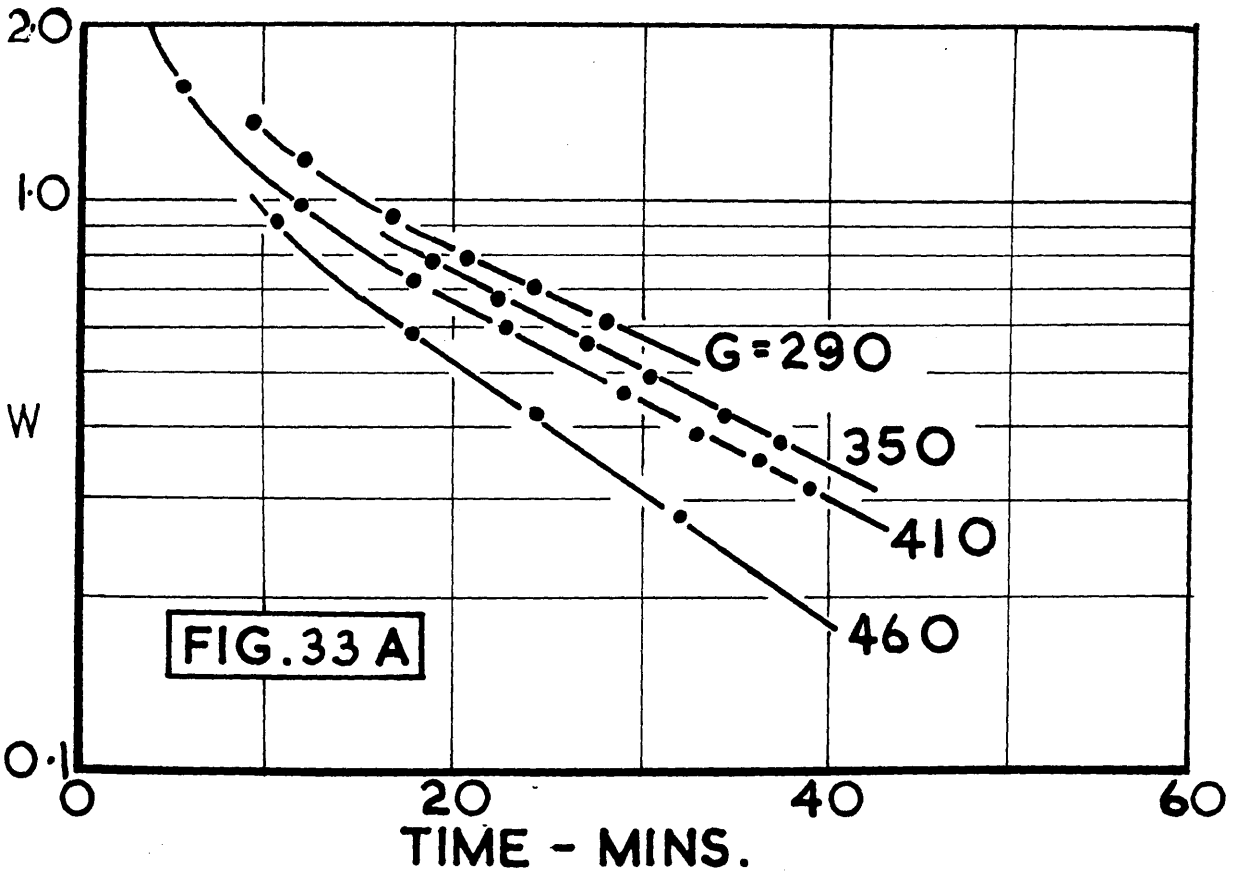


FIG. 33 A

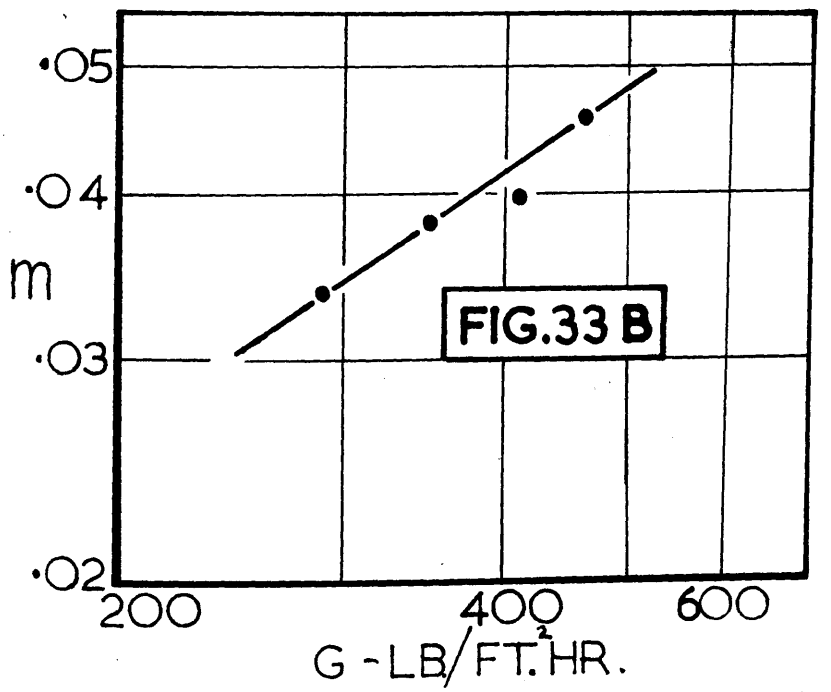


FIG. 33 B

F $ft^3/(ft^2)(hr)$	0.239	0.356	0.403	0.515
m	.0377	.0318	.0256	.0180
τ	52.39	43.26	40.12	35.4

Lower drying rates attended increase in the feed rate. The resulting moisture content of the material in the drier was then higher at high feed rates, the retarding action of the air would be less, producing higher velocities and longer retention times.

At 200°F the relation between m and feed rate, illustrated in Fig.34, is

$$\frac{1}{m} = 126.F - 9.2 \quad \ldots\ldots\ldots\ldots \quad 53$$

Conditions at 140°F again proved critical. At a feed rate of 0.4 $ft^3/(ft^2)(hr)$ most unsatisfactory working resulted - moisture contents along the drier were erratic and drying was apparently very slow. At 0.24 $ft^3/(ft^2)(hr)$ m appeared to be 0.0163, which is three times greater than the value obtained at 0.35 $ft^3/(ft^2)(hr)$. It appears that, under conditions of very wet material and low temperatures, a very precise balance must be struck between feed rates and airflow to permit effective drying.

Speed of drier

Satisfactory working conditions were attained over a reasonable range of drier speeds at both 140°F and 200°F. Other operating variables were maintained as for the standard comparison test.

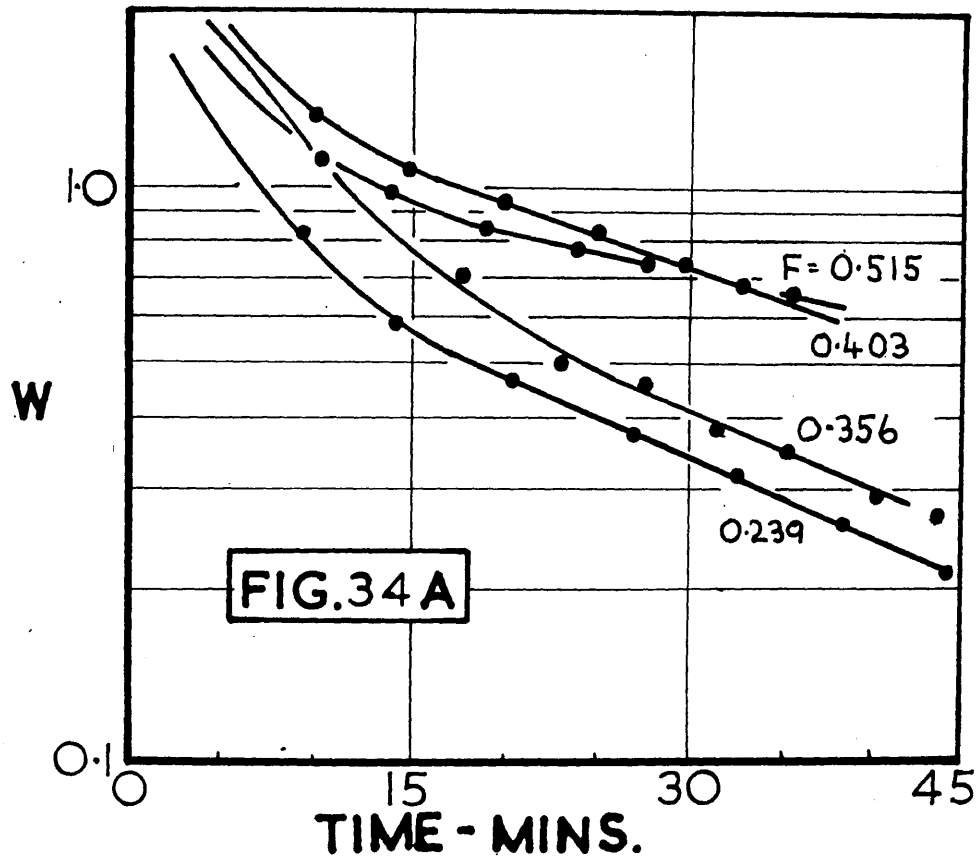


FIG. 34 A

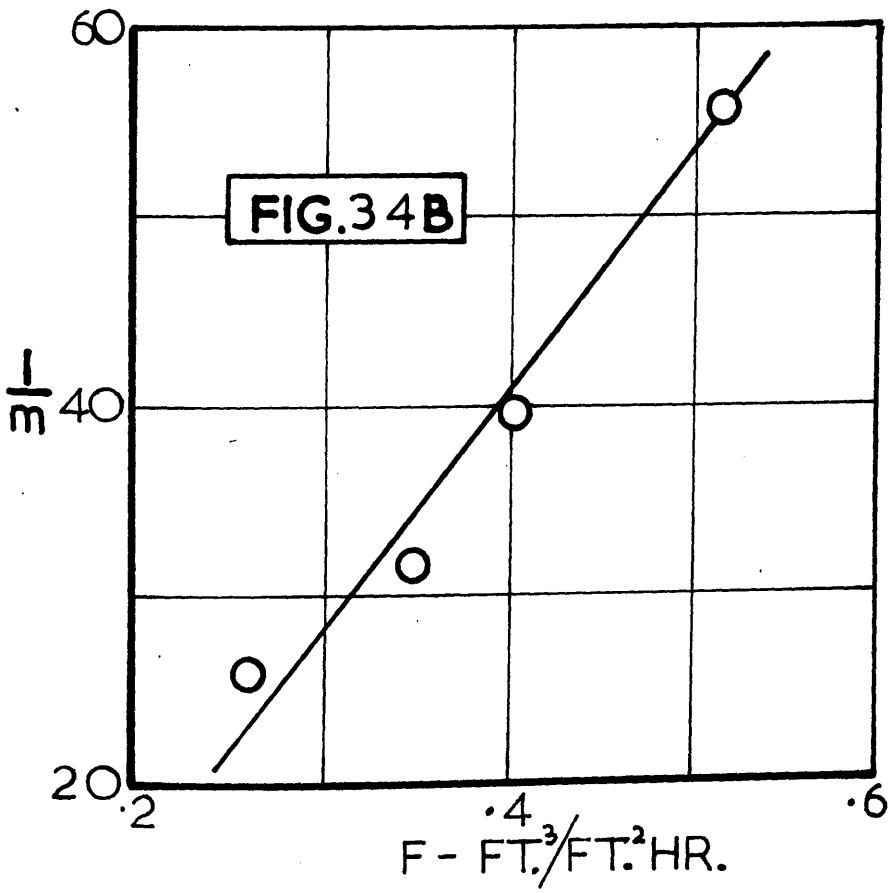


FIG. 34 B

At 200°F increase in the drier speed from 6.3 to 16.5 R.P.M. resulted in a fair increase in the drying rate constant. A linear relation, illustrated in Fig. 35.

$$m = 0.00196.N - 0.0127 \quad \ldots\ldots\ldots \quad 54$$

holds over the range of the tests.

As increase in speed will also decrease the loading or hold-up of the drier, a factor which by variation of the feed rate has already been shown to affect the drying rate, a few tests were conducted where the feed rate was altered as $F \propto N^{0.9}$. According to the general conveying relation, equation 25, proposed for dry material, this should result in constant hold-up conditions. With the large variation in velocity, and consequently loading, along the tube, the assumption of constant loading is not truly justified, but the tests should provide some indication of the effects of rate of rotation alone.

Increase in drier speed under these conditions again raised the values of m, the increase being linear according to the equation also shown in Fig.35:

$$m = 0.000908.N - 0.025 \quad \ldots\ldots\ldots \quad 55$$

Increase in speed from the standard test, when F was varied asabove, therefore produced less increase in m than when the feed was held constant. The difference may be attributed to the effect of the increased hold-up. A similar effect is apparent at lower speeds where the constant feed rate tests produce lower values of

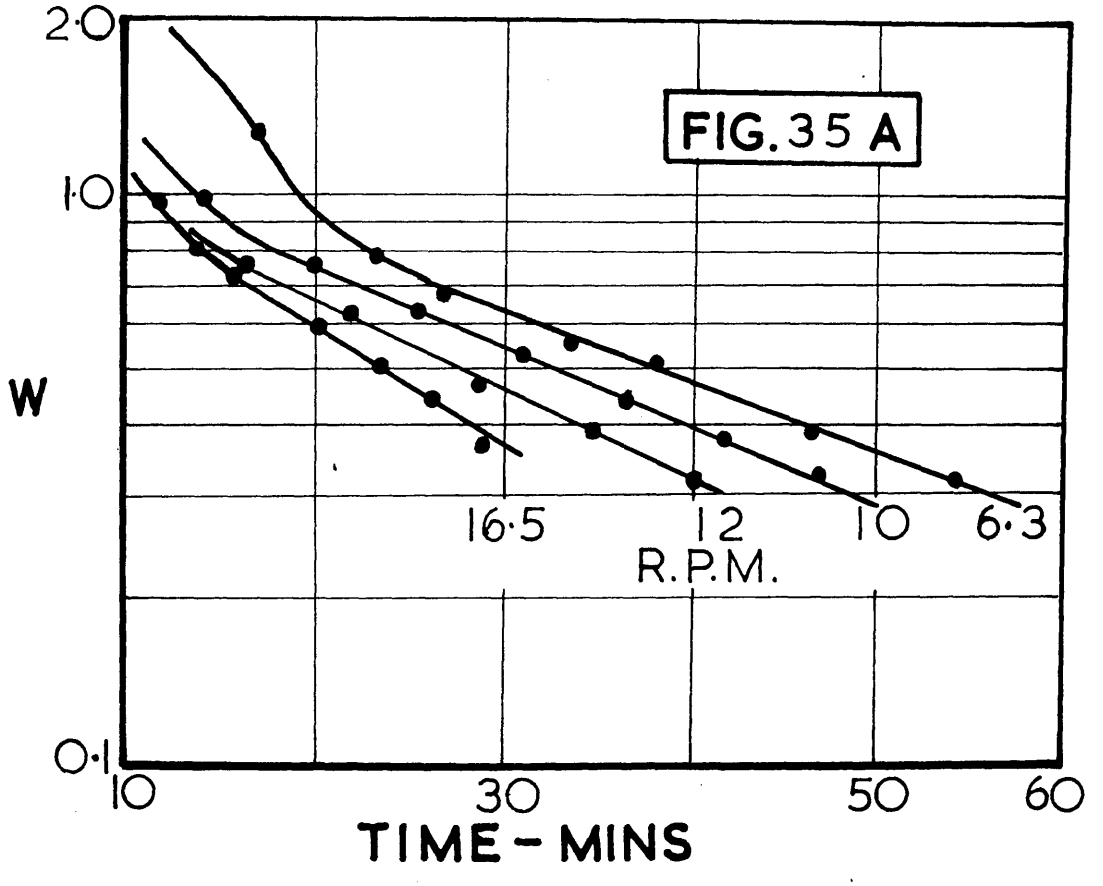
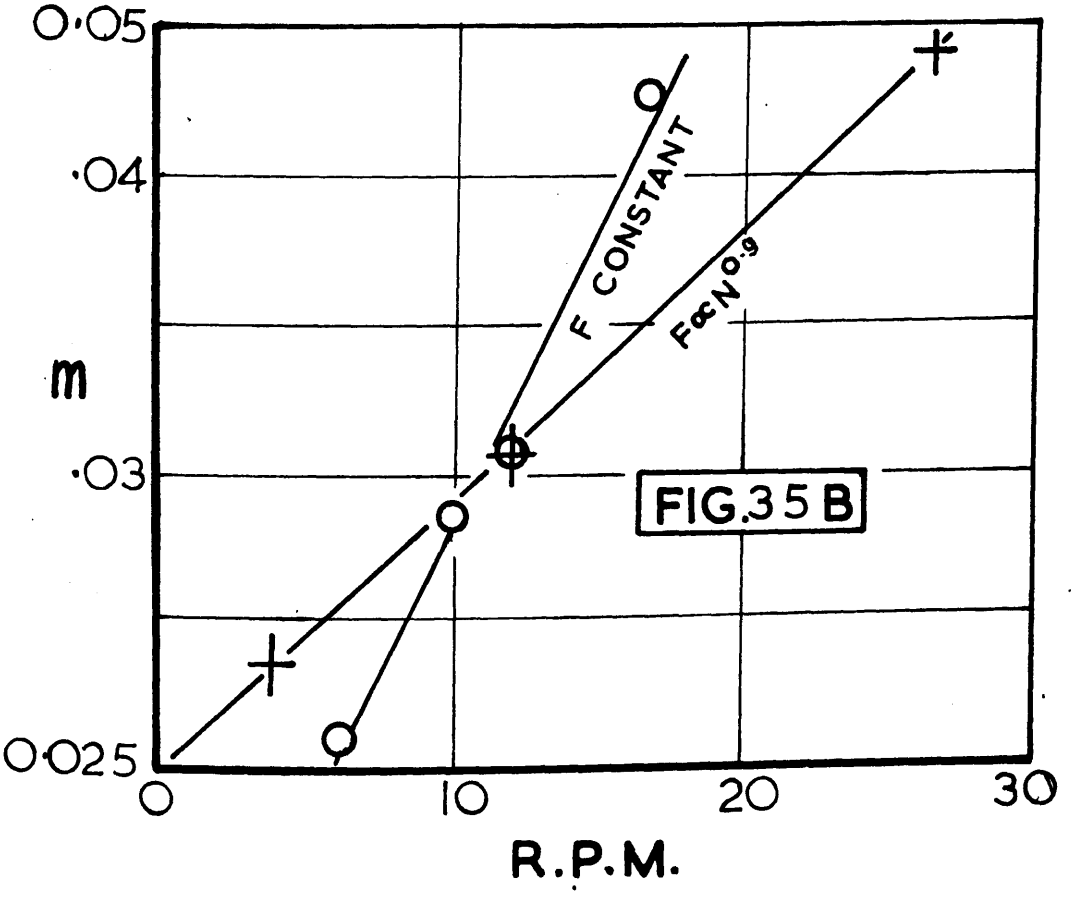


FIG. 35 A
2·0
1·0
0·1
W
16·5
12
10
6·3
R.P.M.
10
30
50
60
TIME - MINS


0·05
·04
·03
0·025
m
F CONSTANT
F∝N^0.9
FIG. 35 B
0
10
20
30
R.P.M.

m owing to heavier loading.

At 140°F increase in drier speed again resulted in higher values of m, both when the feed rate was maintained at 0.35 $ft^3/(ft^2)(hr)$, and when varied as F∝ $N^{0.9}$. The relation between m and N was not strictly linear, proportional increase in N producing a somewhat larger rise in the falling rate constant. The effects of hold-up appear similar to those experienced at the higher temperature, as will be seen from the following table:

	Constant feed rate			Feed rate∝ $N^{0.9}$		
Speed R.P.M.	6	12	16.5	6	12	16.5
Feed 0.356 $(ft^3)(ft^2)(hr)$	0.356	0.356	0.356	0.243	0.356	0.454
m	0.0038	0.0050	0.0079	0.0042	0.0050	0.0075

Number of flights

The number of flights was decreased by stages from 8 to 2 at both 200°F and 140°F.

The data of Miller et al[79] did not correlate results at 6 and 12 flights, but Friedman and Marshall[80] reported that, although a practical maximum was soon reached, heat transfer and therefore drying rates increased with the number of flights fitted. The results suggest that the drying of spent grain is indeed influenced by the number of flights, but that the effect is in the reverse direction. Values of m increase steadily as the number of flights

was decreased from 8 to 2, both for 200°F and 140°F. (Fig.36).

Closer examination of the drying curves, Figs.37 and 38, reveals however, that initially the drying rates are higher with the higher numbers of flights, apparently before the material enters the falling rate period. The effect is most apparent at 140°F where the drying rates are considerably lower, and the time to reach the start of the falling rate period represented by the equation

$$\text{Log}_e W = -m.\theta + k \quad \ldots\ldots\ldots \quad 15$$

correspondingly longer.

To assist clarity, only the linear portion of the curve for 4 flights has been included in Fig.38.

	n_f	8	6	4	3	2
200°	m	.0261	.0275	.0446	.0495	.1048
	R. time min.	47.0	44.3	33.7	30.39	16.56
140°	m	.00525	.00696	.0161	.0276	.080
	R. time	35.26	32.86	19.5	23.1	16.42

Barley Grain

Barley grain appeared suitable for study in the rotary drier. Its uniform particle size make its handling properties almost ideal.

Barley is largely used in the brewing industry for the preparation of malt products. Other uses are as a foodstuff and for stock feeding. McCance and Widdowson[91] give the following analysis:

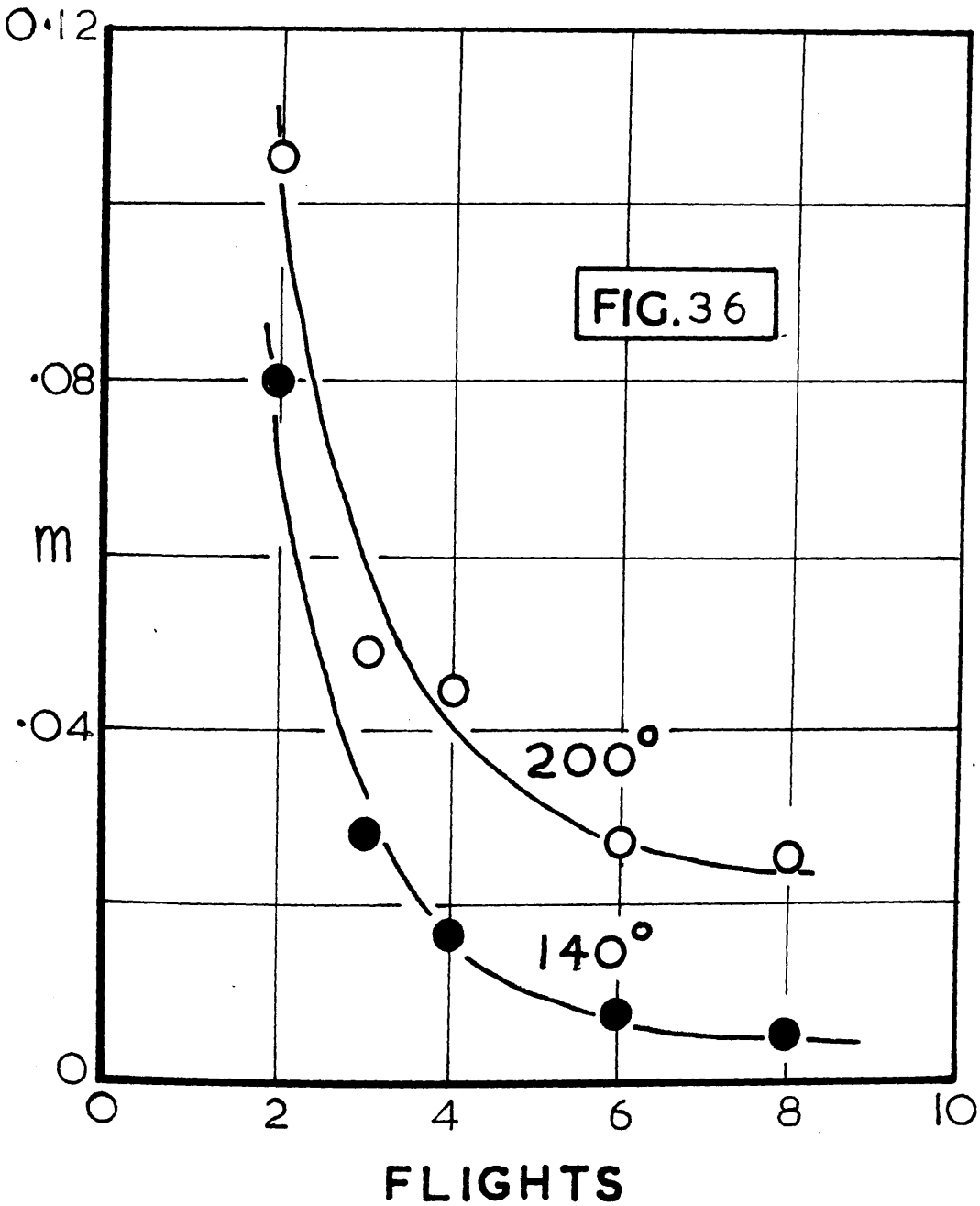


FIG. 36

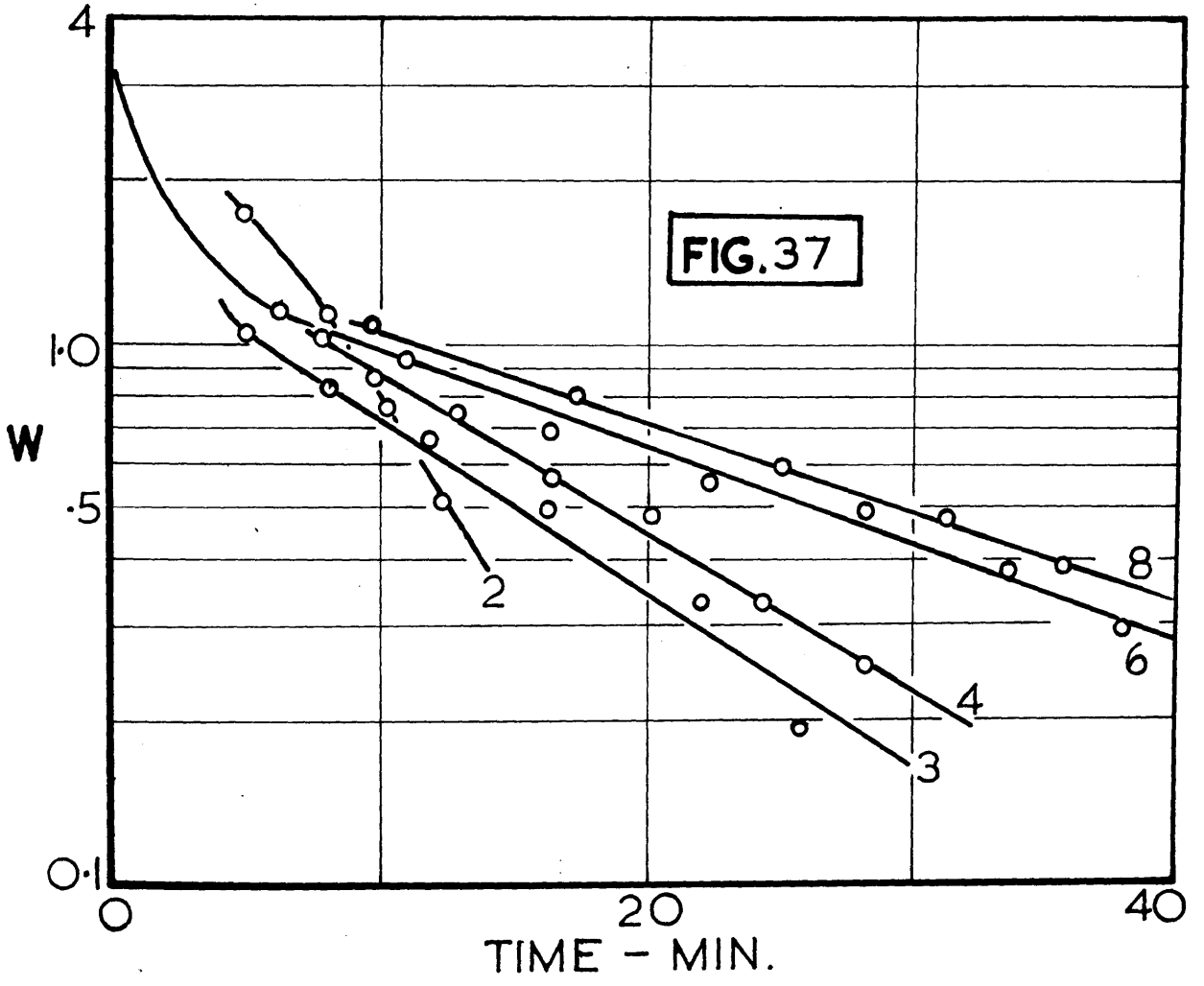


FIG. 37

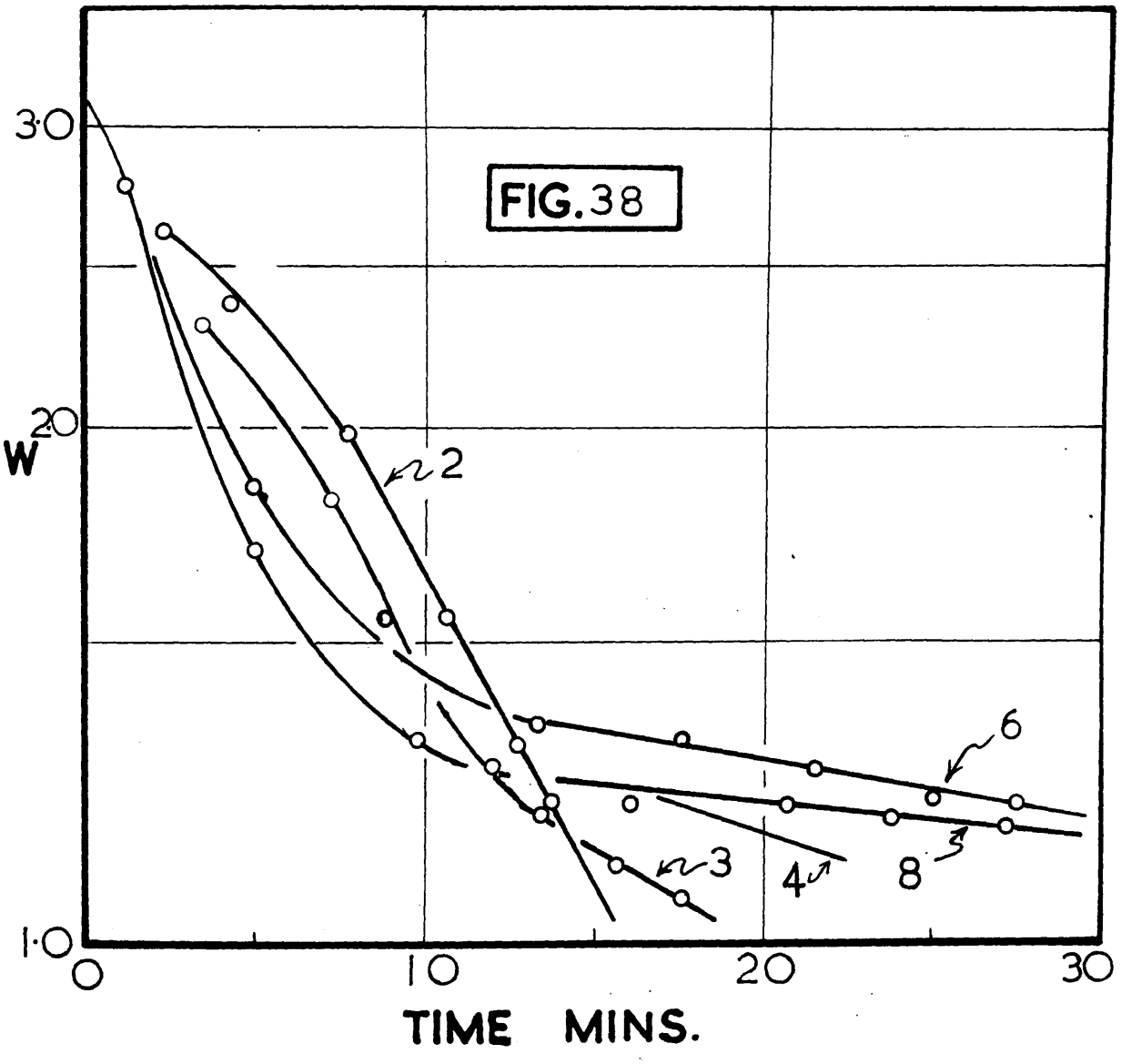


FIG.38
3·0
2·0
1·0
W
0
10
20
30
TIME MINS.
2
3
4
6
8

Water 10.6, Sugar (as invert) trace, Starch and dextrins (as glucose) 81.3, Total Nitrogen 1.35.

Dehydration of barley for use in brewing is important where even germination is desirable and a low moisture necessary to give safe storage of the grain.

Single layer through circulation drying

The through circulation drying of barley has been investigated throughly by Hughes and Mitchell[43] using the apparatus and technique described above, Fig.4. Over the range of moisture contents studied, the drying rates of single layers were shown to be proportional to the total moisture content of the material.

$$\text{i.e. } \frac{dW}{d\theta} = -m.W \text{ , or } \text{Log}_e W = -m.\theta + k \quad \ldots\ldots\ldots \quad 15$$

Both air mass flow and temperature were found to have a marked effect on m, and a method was given for predicting the drying times of deep beds, based on the results from the shallow layers.

The relation between m and drying air temperature was shown to be

$$\text{Log}_{10} m = \frac{T - 241}{70} \quad \ldots\ldots\ldots\ldots \quad 56$$

and in the range of air mass flow from 5 to 10 lb/(ft^2)(min.), the proportionality

$$m \propto G^{0.77} \quad \ldots\ldots\ldots \quad 57$$

was observed.

Rotary drying

The barley used in these tests was obtained from the same source as the material used in the through circulation experiments.

The grain was soaked in water for 24 hours in darkness, and was allowed to drain for a few minutes before use in the drier. This method of preparation is identical with that of Hughes and Mitchell[43], who reported that reconstitution of used material for further tests was most undesirable, as each resoaking and drying operation considerably altered the drying properties of the material. Fresh grain was accordingly used for each run.

A technique similar to that already used for the spent grain was adopted for the barley. Trial and error methods were used to determine a suitable set of intermediate conditions which would produce satisfactory drying, and these were adopted as the "standard" comparison test. Barley dries much more slowly than the spent grain and conditions had to be chosen to produce a much longer retention time to achieve a measurable drying effect.

Conditions for the standard test were an air inlet temperature of 200°F and mass flow of 500 lb/(ft^2)(hr), a feed rate of 0.49 ft^3/(ft^2)(hr) and a drier speed of 6 R.P.M. The slope of the drier was maintained at 0.3% and 8 lifting flights were employed for the majority of tests.

Procedure

The experimental techniques employed in these trials were identical to those used before in the drying of spent grain.

Results

A considerable variation of material velocities was observed along the drier. This appears to be a complex function of change in density and surface properties of the grain as it dries. The velocity of the grain was consistently observed to increase slightly from the point of feed, then decrease slowly as it became drier and less dense and consequently more affected by the counter-current airflow. After reaching a minimum the velocity then increased markedly to the point of discharge. The initial increase in speed is thought to be due to the removal of surface moisture decreasing the angle of repose, the grain falling earlier from the flights. The effect on the material near the discharge end is produced by the gradient formed by the material in the drier. This will have greater overall effect in this series of trials where the actual slope of the drier is small.

The values of the falling rate constant were again used to compare the results. When allowance was made for the variation in material velocity, a semi-logarithmic plot of moisture content against time of drying showed a linear relationship over most of the drying period. Each series of tests produced a group of curves which

allowed convenient estimation of the effects of the variable under investigation.

Air inlet temperature

As in through circulation drying, increase of air inlet temperature had a marked effect on the drying rate. The drying curves obtained are shown in Fig.39. Moisture contents below 0.25 appeared to deviate slightly from the linear relationship described above, and were ignored in construction of the mean straight lines.

Increasing air temperature does not appear to have any significant effect on the overall retention times. The amount of water evaporated per lb. of dry solid

Inlet air temp. ^{o}F	140	160	180	200	220
Retention time, mins.	50	57	55	50	54
$\underline{m}$	0.0096	0.0117	0.0157	0.0176	0.0216

is considerably lower than, for example, spent grain, and the relative effects of the decrease in density on air entrainment will be smaller.

The final moisture content is hence controlled mainly by the value of the falling rate constant. A plot of $\underline{m}$ against inlet air temperature, Fig.40, suggests the relation

$$\mathrm{Log}_{10} m = \frac{T - 585}{219} \quad \ldots\ldots\ldots\ldots \quad 58$$

This is of the same general form as the relation proposed for the through circulation drying of single layers (Eqn. 56).

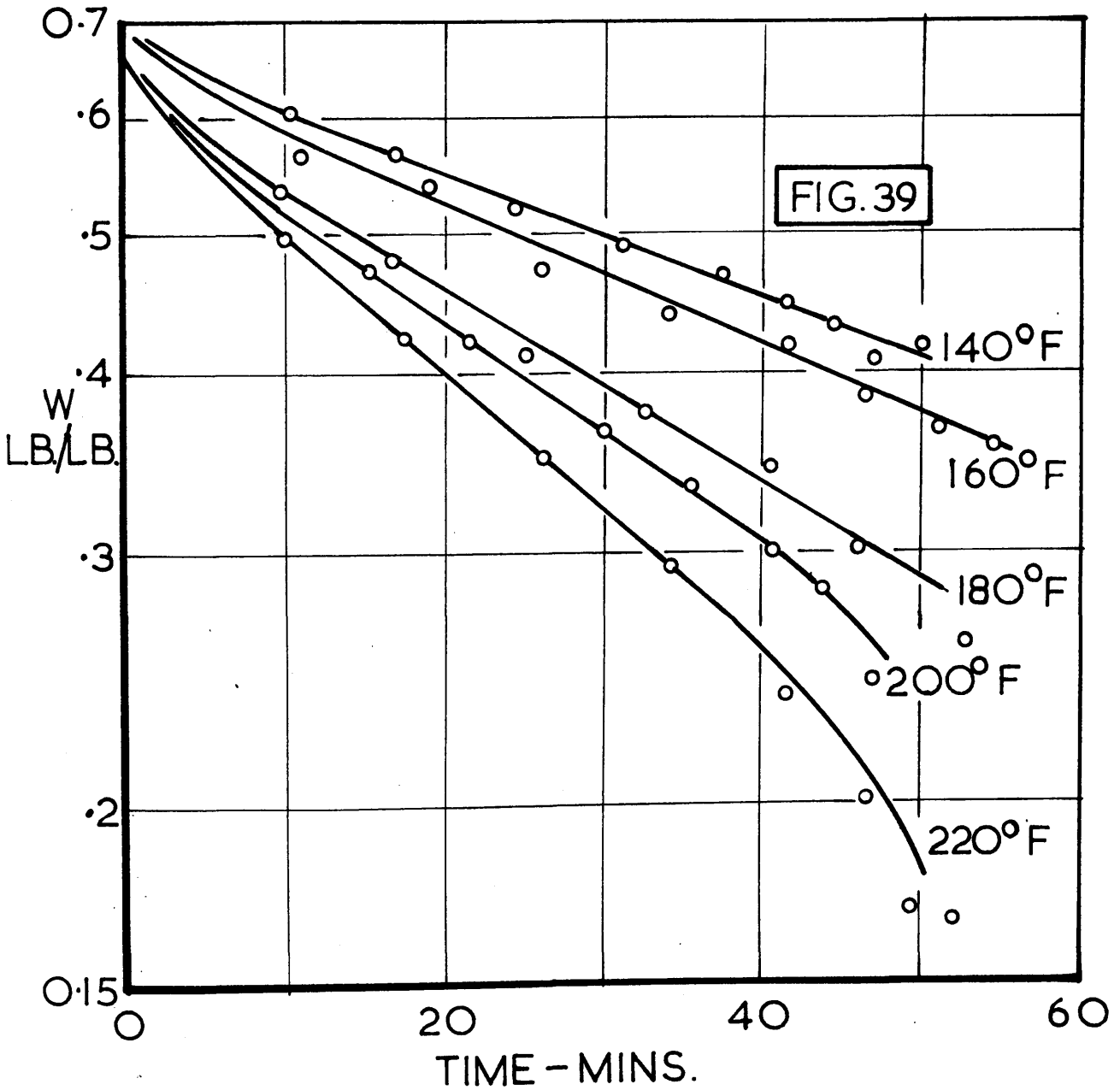


FIG. 39
0·7
·6
·5
·4
·3
·2
0·15
W
LB./LB.
140°F
160°F
180°F
200°F
220°F
0
20
40
60
TIME - MINS.

Air mass flow

The effects of air velocity on the rotary drying of this material were estimated by varying the air mass flow from 410 to 710 lb/(ft^2)(hr). At the highest air velocity used, an estimate of the amount of feed entrained was made continuously during the test, and the actual feed rate was increased by this amount to maintain a constant effective feed rate over the series.

The general effect of increase of air velocity, as is shown in Fig.41, was to increase the drying rate. The actual moisture content of the product was lowered by the increasing retention times at higher airflows, and further slightly by more evaporation near the feed end of the drier. This effect generally displaced downwards the start of the observed falling rate period, although somewhat anomalous results were obtained at the lowest airflow employed.

The value of the falling rate constant was calculated for each set of experimental conditions. This generally rose steadily throughout the series. Following earlier work on single layers, a log/log plot of m against G was prepared, and is shown in Fig.42. Over the range of the tests, the relation

$$m = 0.000117.G^{0.81} \quad \ldots\ldots\ldots \quad 59$$

appears to provide a satisfactory correlation.

The corresponding index of G in the through circulation work is


FIG. 41
0·7
6
4
2
0·1
W – LB./LB.
0
20
40
60
TIME–MIN.
G = 500
410
570
650
715

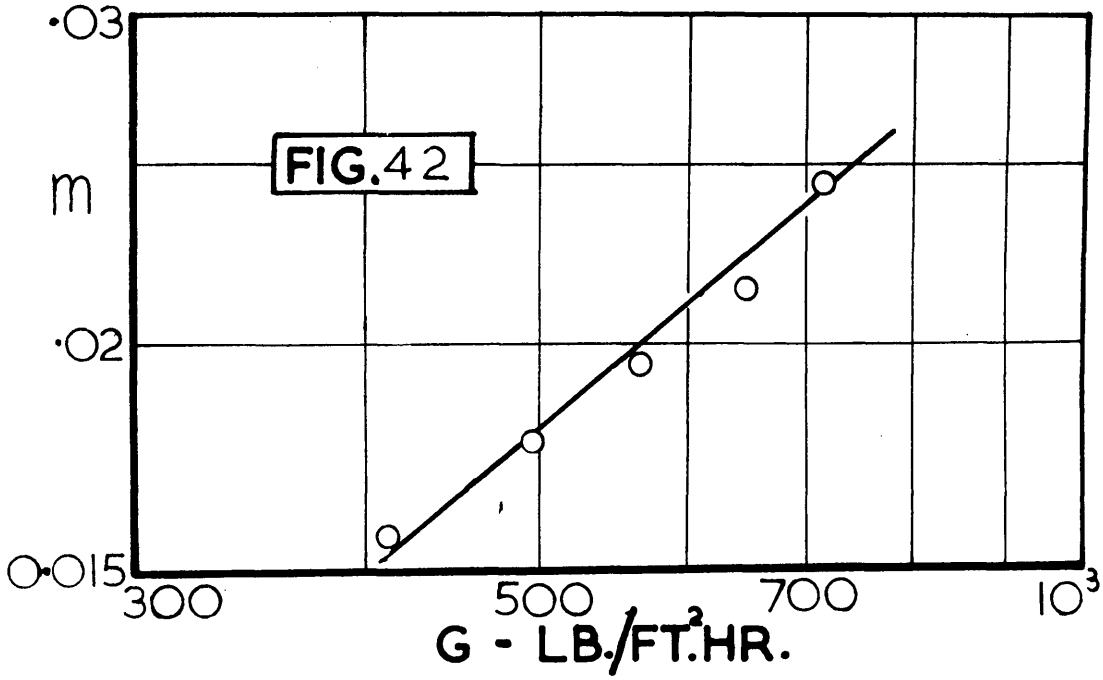


FIG. 42
·03
m
·02
0·015
300
500
700
10³
G - LB./FT.²HR.

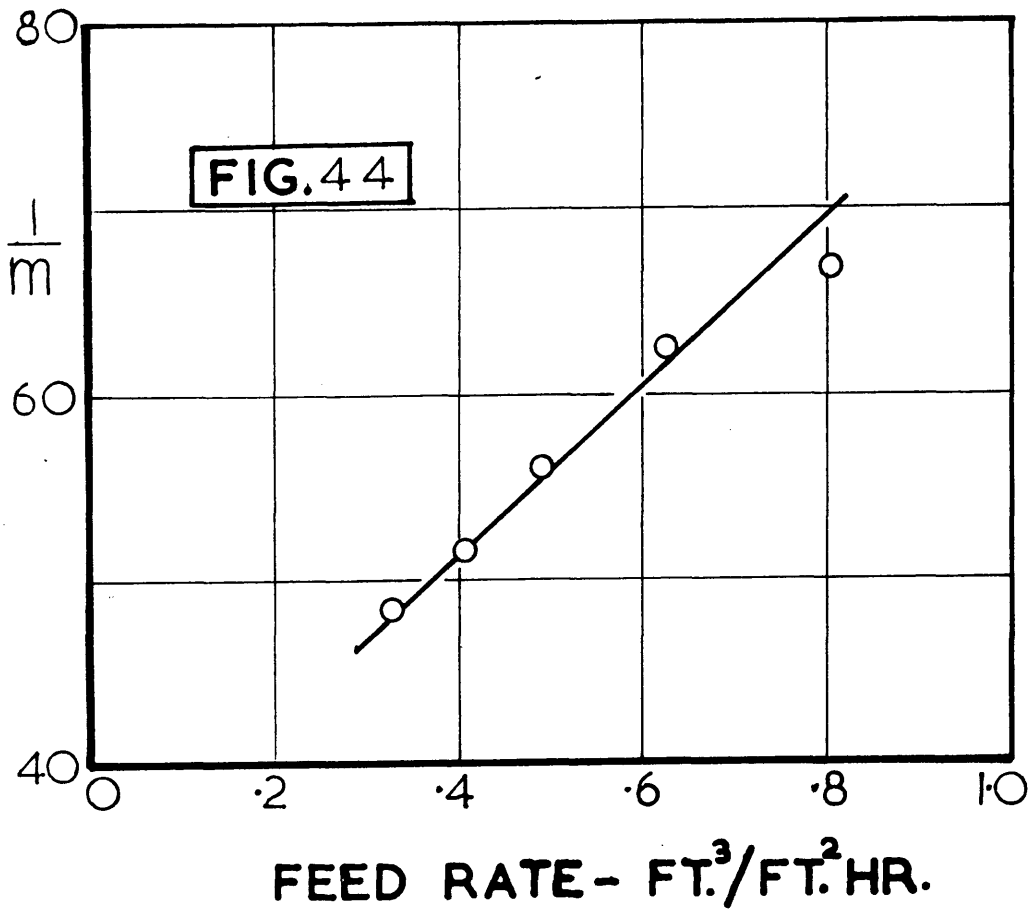


FIG. 44
80
1/m
60
40
0
·2
·4
·6
·8
1·0
FEED RATE - FT.³/FT.²HR.

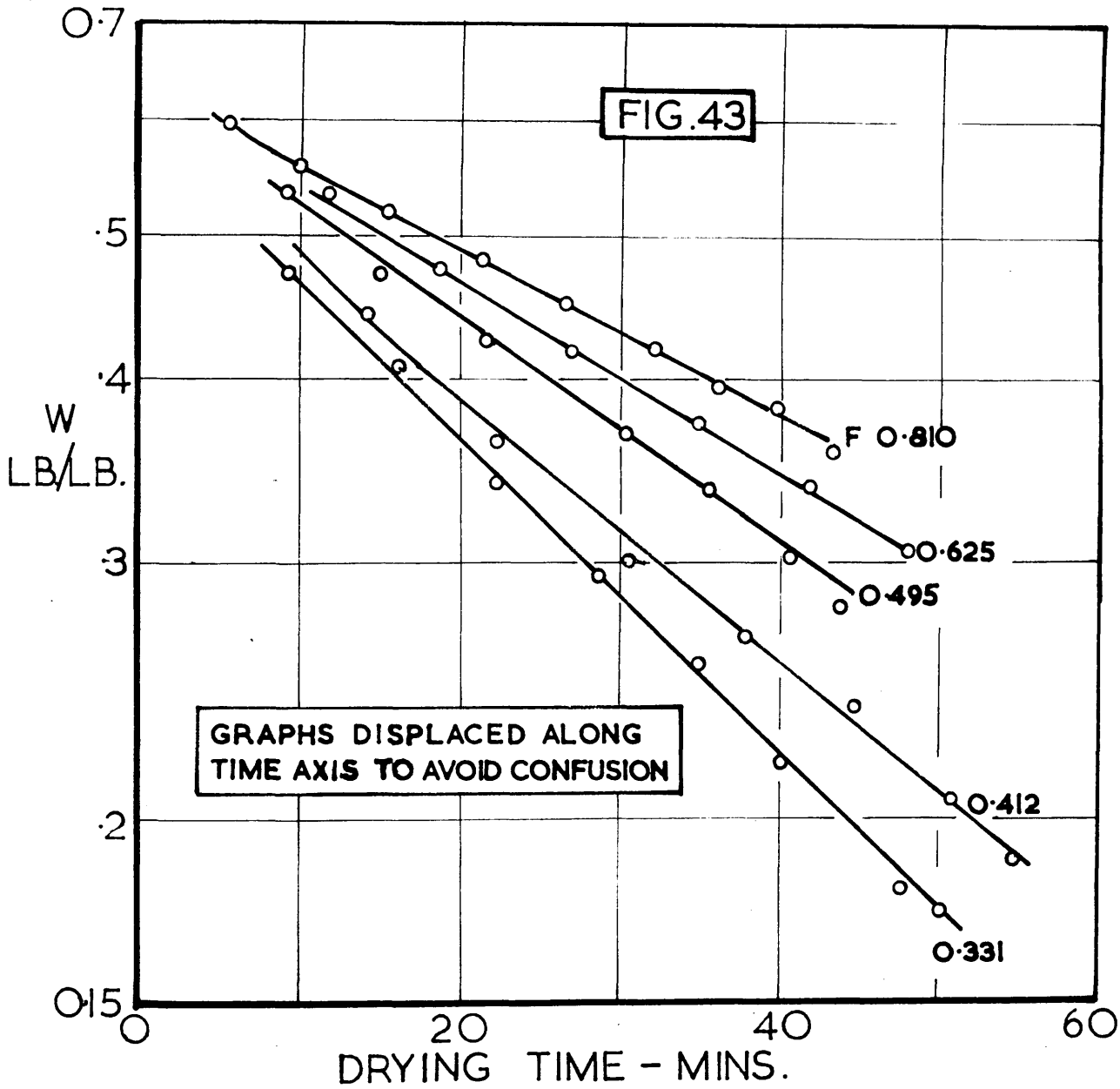


FIG.43
0·7
·5
·4
·3
·2
0·15
W
LB/LB.
F 0·810
0·625
0·495
0·412
0·331
GRAPHS DISPLACED ALONG
TIME AXIS TO AVOID CONFUSION
0
20
40
60
DRYING TIME - MINS.

The actual moisture content of the product is considerably lower than the theoretical, predicted from the retention time and the mean straight line. The drier always runs more lightly loaded at the discharge end of the tube where material gradients produce higher velocities. This lower loading will be accompanied by higher values of m than would otherwise be anticipated, resulting in a tendency for the drying curves to become concave downwards towards the end. This is quite noticeable in several runs, especially where higher feed rates produce higher loadings and more pronounced material gradients.

In the majority of runs, however, the semi-log. plot was linear to the discharge time. Where there was any "tailing off" the falling rate constants were determined from the first, linear, section.

Speed of rotation

The effect of speed of the drier tube may be twofold. The increase in speed decreases the time of passage and therefore the time available for drying, but material will receive more agitation per unit time. With constant feed rate, increase in tube speed produces lower loading, a result similar to that which may be obtained simply by decreasing the feed rate, a factor which has already been shown to affect the drying rate.

The experimental results indicate that increase in the drier

speed increases the drying rate constant. The drying curves are illustrated in Fig.45. Over the range of speed studied, from 4 to 16.5 R.P.M. the relation between the rate constant and speed of tube appears to be

$$m = 0.00117.N + 0.0112 \quad \ldots\ldots\ldots\ldots \quad 61$$

as illustrated in Fig.46.

Data outside the range of speeds quoted were impossible to obtain as limits of drier loading were approached at these speeds.

As both speed of rotation and the feed rate affect the loading of the drier, some tests were conducted where the feed rate was increased as $F \propto N^{0.9}$ to maintain, theoretically, a constant value of the percentage hold-up.

The values of the rate constant obtained and their variation with drier speed are shown in Fig.47. The data are fairly well represented by the mean straight line which has the equation:

$$m = 0.00093.N + 0.0123 \quad \ldots\ldots\ldots \quad 62$$

It appears that, with increased speed, the difference between the rate constant for fixed feed and feed varied with speed as indicated, will grow steadily larger. With the fixed feed rate, decreasing loading with speed will exhibit higher values of $\underline{m}$. The difference between equations 61 and62,

$$m = 0.00024.N - 0.0011 \quad \ldots\ldots\ldots \quad 63$$

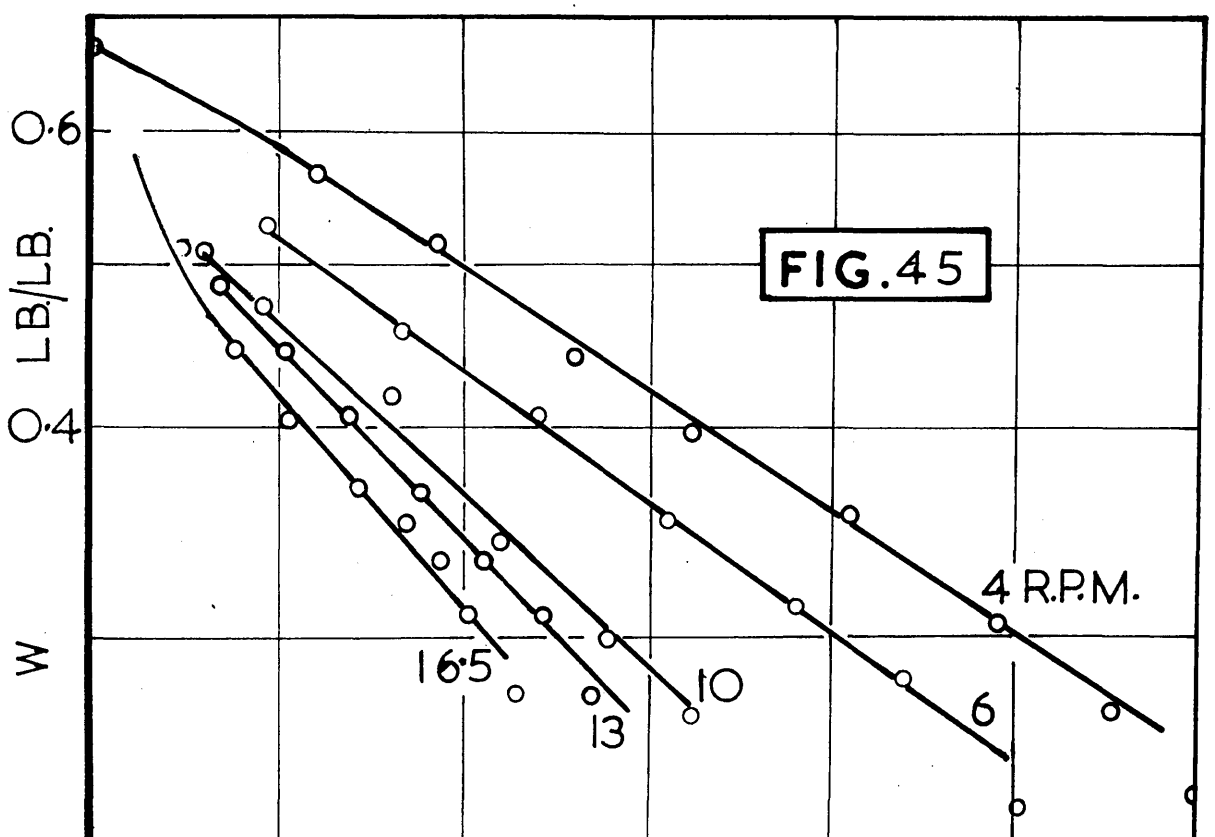


FIG. 45
0·6
0·4
0·2
W LB./LB.
0
20
40
60
TIME — MINS.
4 R.P.M.
6
10
13
16·5

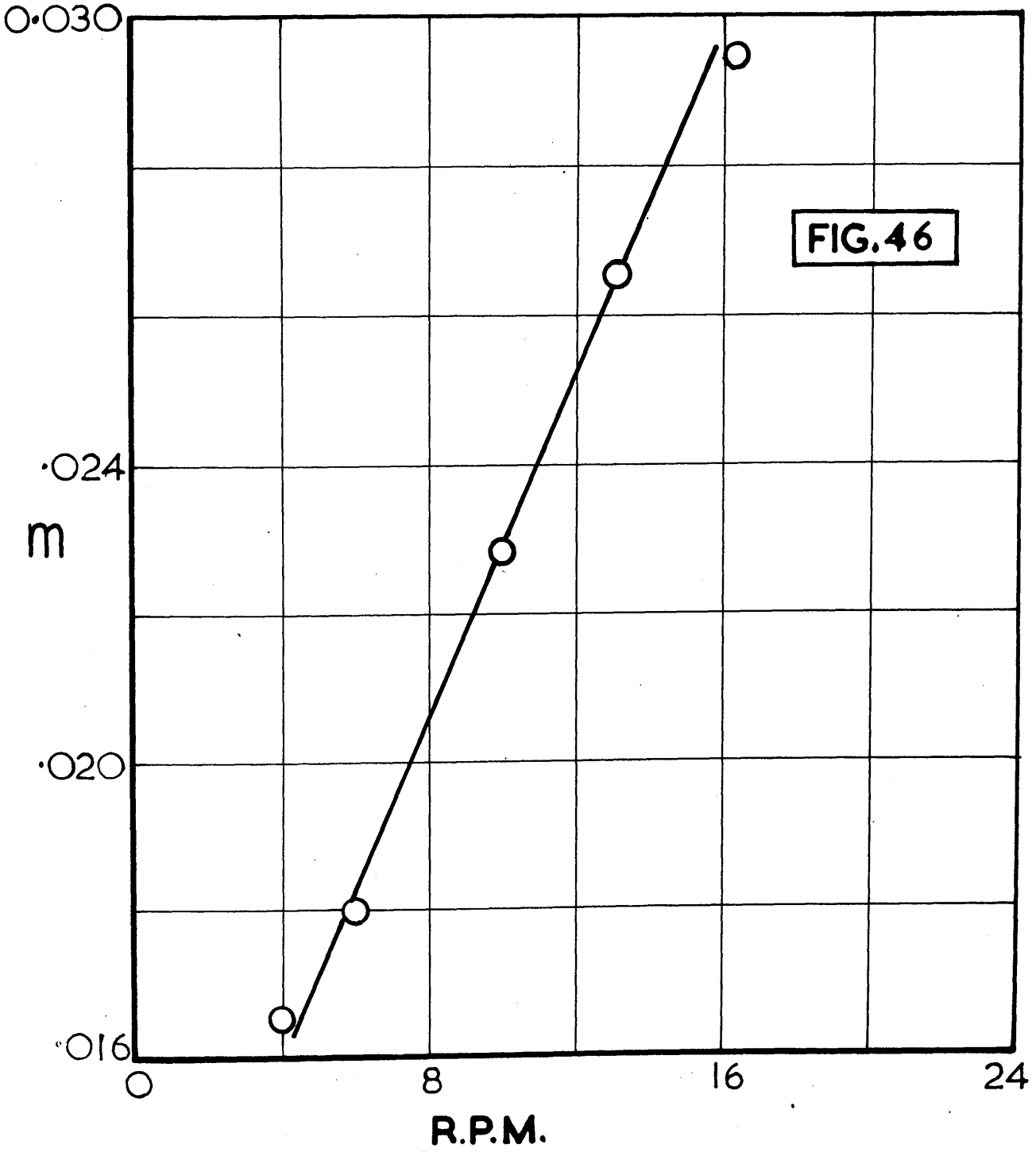


FIG. 46

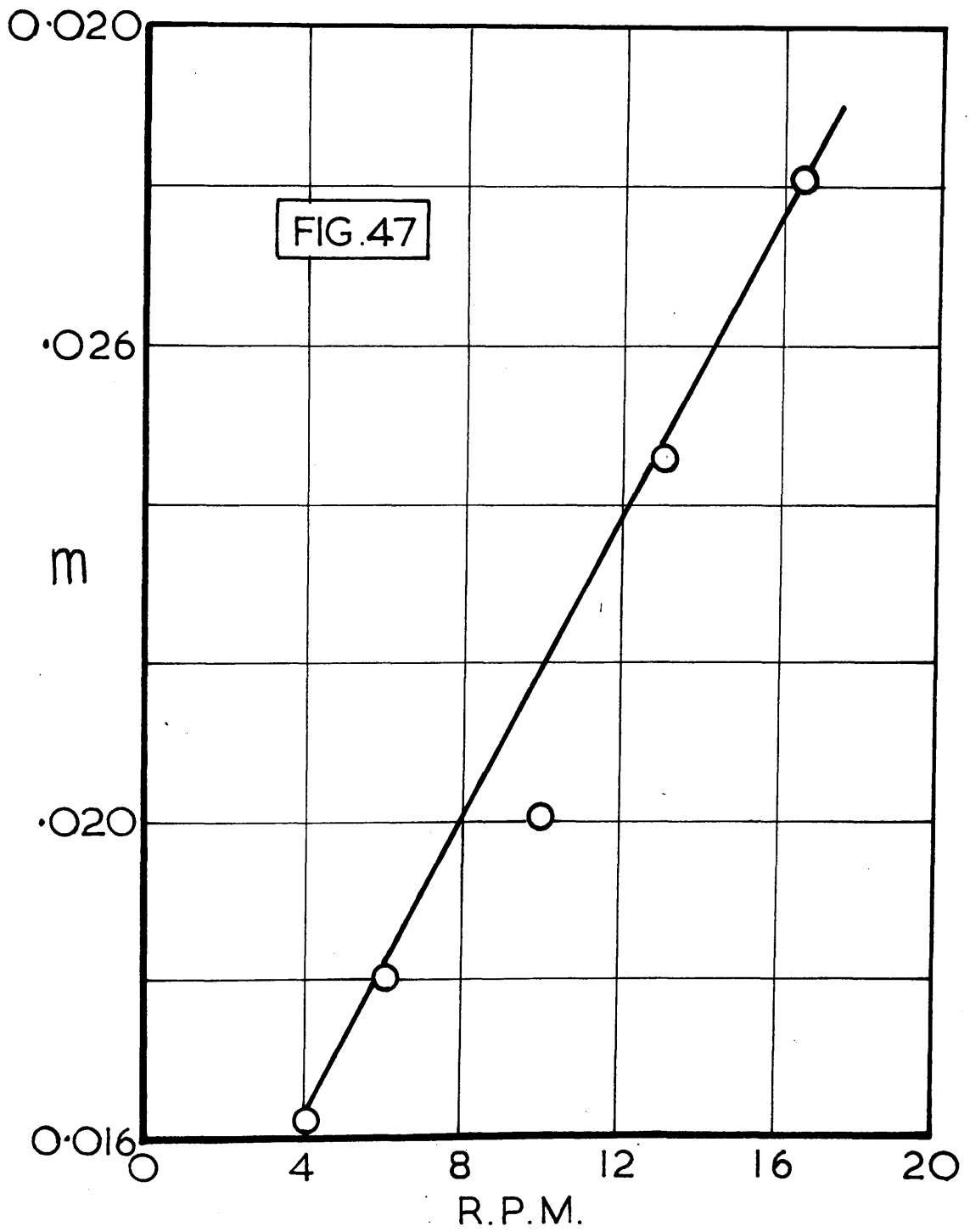


FIG.47
0·020
·026
m
·020
0·016
0
4
8
12
16
20
R.P.M.

will represent the increase in m produced by the decrease in hold-up caused by the increase in drier speed, and should not include the effect of increased agitation at higher speeds. Feed rate and equation 63 cannot be directly related, however, as with this material, the large velocity changes often referred to above render a correlation of either with hold-up impracticable. Increase of the drier speed by 50% from the mean value of 6 R.P.M. to 9 R.P.M. produced an increase m due solely to decreased hold-up, of 0.00106, from equation 63. The value of m obtained from the standard test was 0.0194, so the increase is only about 6%. As an approximation, F may be varied almost as N to produce constant hold-up, and decrease of 33% in F from the standard test alters the value of m by 0.0028, an increase of approximately 14%. The discrepancy between the two figures serves as an illustration of the difficulties which may be encountered in interpretation of the results.

Number of Flights

The number of flights fitted was decreased gradually from 8 to 2 and the effects on the drying of the barley determined.

In addition to altering the amount of drying accomplished by changing the retention time, the number of flights had a considerable effect on the rate constant, m. The results are somewhat scattered, being illustrated in Fig.48, but it appears that, in general, fewer flights result in higher values of m, and conse-

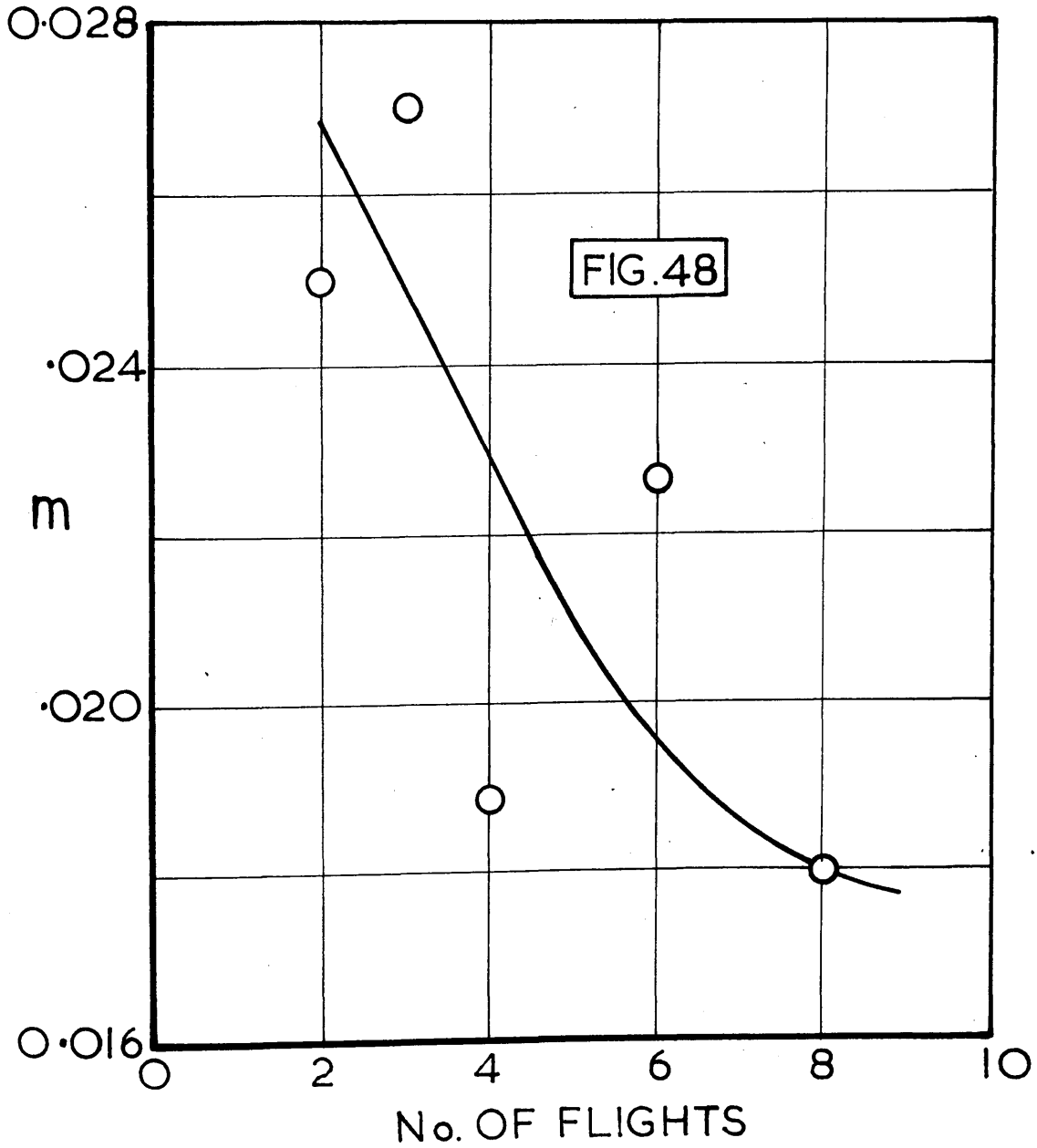


FIG. 48

quently in faster drying.

No. of flights	8	6	4	3	2
m	.0180	.0226	.0188	.027	.025
Retention time min.	49.0	28.1	38.0	27.02	27.45

Cork

As the third material suitable for both single layer through circulation drying and rotary drying, granular cork was used for a series of laboratory tests.

Cork is a resilient cellular substance much employedon account of its useful properties of low density and high thermal resistance. The cells are small, there being about 2×10^6 per inch, and are bonded together by a natural resin. Capillaries are formed in the substance and are found mainly in the darker parts.

Kirk Othmer[92] notes that the air filled apace of the material is 4/5ths of the total volume. If the true density of the cork be taken as that of cellulose, 1.35, complete filling of all spaces would produce a maximum water ratio of 3.1. In the current series of tests, soaking resulted in a material of moisture ratio averaging 1.6, so that about $\frac{1}{2}$ of the air space available in the material was filled with water. This suggests that the water must penetrate some distance into the interior of the granules, and slices of the wet material indeed showed obvious moisture penetration to the centre.

Brown, Panshin and Forsaith[93] list possible methods of moisture movement in wood and similar substances. From these it appears that passage of moisture through cork will be through transient cell wall capillaries and by intercommunicating cell cavities. The same

workers suggest that there will be two stages in the drying process after an initial constant rate. The first will be controlled by the movement of water by a concentration gradient set up between the surface and the inner cells. This gradient is produced by the properties of the cell walls which are always wetted to an equilibrium value down to what is termed the "fibre saturation point". The second stage is reached after this is passed and will be controlled by diffusion of water vapour across cell cavities now filled with air, and the passage of liquid water through cell walls by transient capillaries.

The cork used in the current series of experiments was sieved to pass a 1/3" mesh and to be retained by a 3/32" mesh. It was found that this resulted in a fairly uniform feed for the trials as most impurities were much finer dust and considerably larger particles. The sized granules were somewhat irregular in shape and therefore would present a fairly large average surface area.

Before use in the tests the cork was soaked in almost boiling water two or three times to remove any remaining traces of tannin and other solubles.

Two series of experimental tests were carried out with this material - firstly single layer through circulation tests to determine the effects of airflow and temperature on the basic drying rates of the material itself, and secondly on the rotary drier to study

the effect of these two and other factors affecting the operation of this type of equipment.

Through Circulation Tests

After sieving, washing and air drying, the material for each test was soaked by enclosing it in a porous bag and immersing this and its contents in distilled water. As the quantity required for each test was small, a fresh sample from the main bulk was used each time.

It was anticipated that the much larger quantities required by the rotary drier would entail some re-use of the dried material, and several initial single layer runs were carried out to investigate the effect of re-use on the drying rates. It appears, Fig.49, that some re-use of the material is possible as the drying rates change but little, and subsequent tests on the other unit were based on this premise.

Procedure

The through circulation drier described on page 41 was employed for these trials. They were conducted on a bed of material $\frac{1}{4}$" deep and the drying air was at average atmospheric humidity. The standard procedure already described for through circulation tests was adhered to, and calculation of the results from the series of weighings is illustrated in Appendix I.

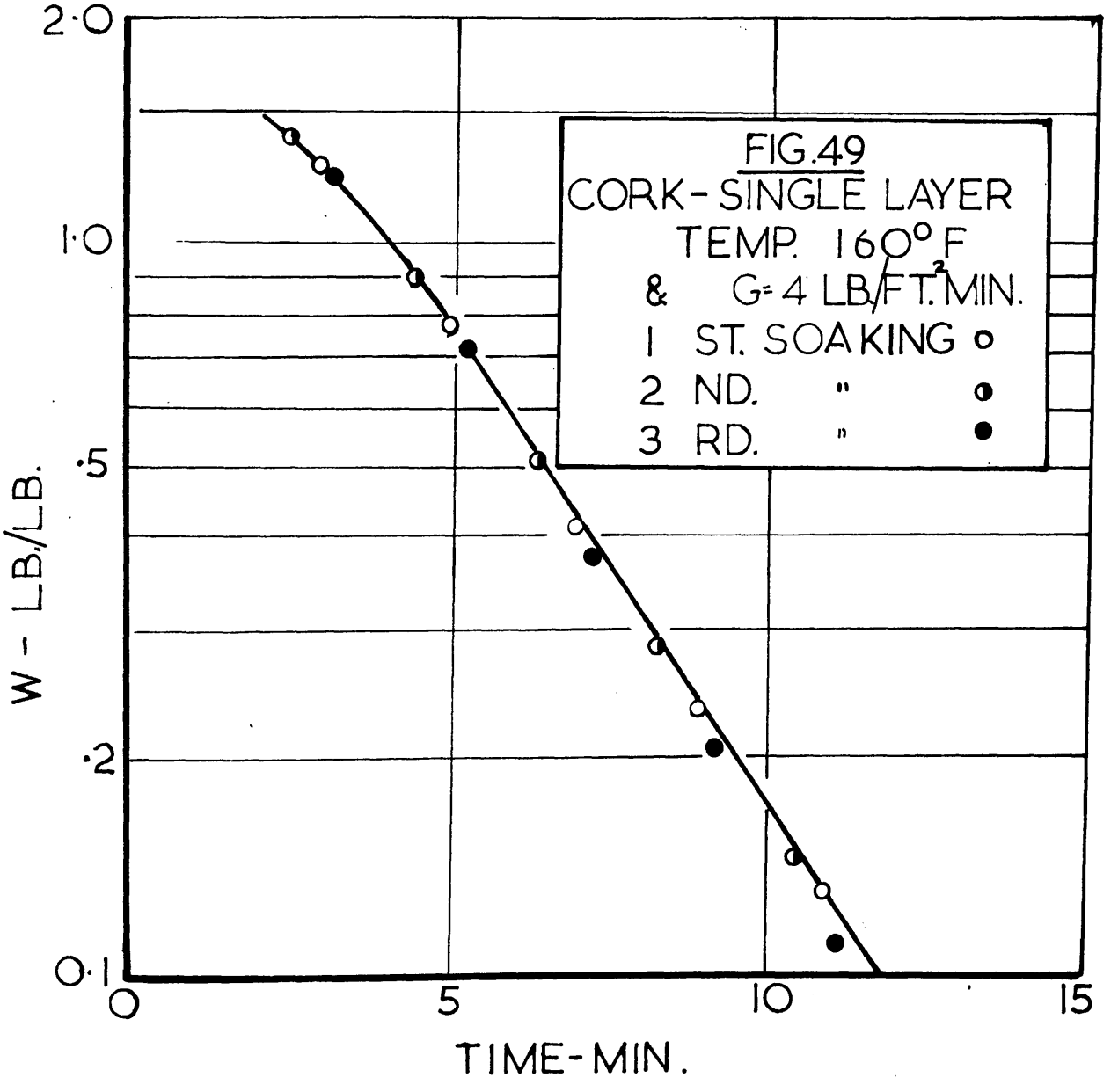


FIG.49
CORK - SINGLE LAYER
TEMP. 160° F
& G = 4 LB/FT.² MIN.
1 ST. SOAKING
2 ND. "
3 RD. "
2·0
1·0
·5
·2
0·1
W - LB./LB.
0
5
10
15
TIME - MIN.

Tests on air temperature and mass flow were carried out in two series.

Air inlet temperature

The air inlet dry bulb temperature was varied from 120°F to 200°F, and the airflow maintained at 4 lb/(ft^2)(hr).

It was observed that increasing air temperature markedly raised the drying rates. After a very short building-up and limited constant rate period, the drying rate steadily decreased, as is shown in Fig.50. This indicates two distinct falling rate periods, where

$$\frac{dW}{d\theta} = -mW \quad \ldots\ldots\ldots\ldots \quad 15$$

as suggested by Brown[93] et al. The two appear to merge at higher temperatures, the separate values of m then becoming equal. In general, drying from a moisture content of 1.0 to 0.1 lb. Water/lb. B.D.S. can be taken as predicted by the value of the falling rate constant observed for the first of the two periods.

The first falling rate constant increases with temperature, the relation being, Fig.51,

$$\text{Log}_{10} m = \frac{T - 216}{128} \quad \ldots\ldots\ldots\ldots \quad 64$$

an equation of the general form already encountered for the other materials employed.

Air mass flow

Satisfactory operation of the drier limited the lowest airflow

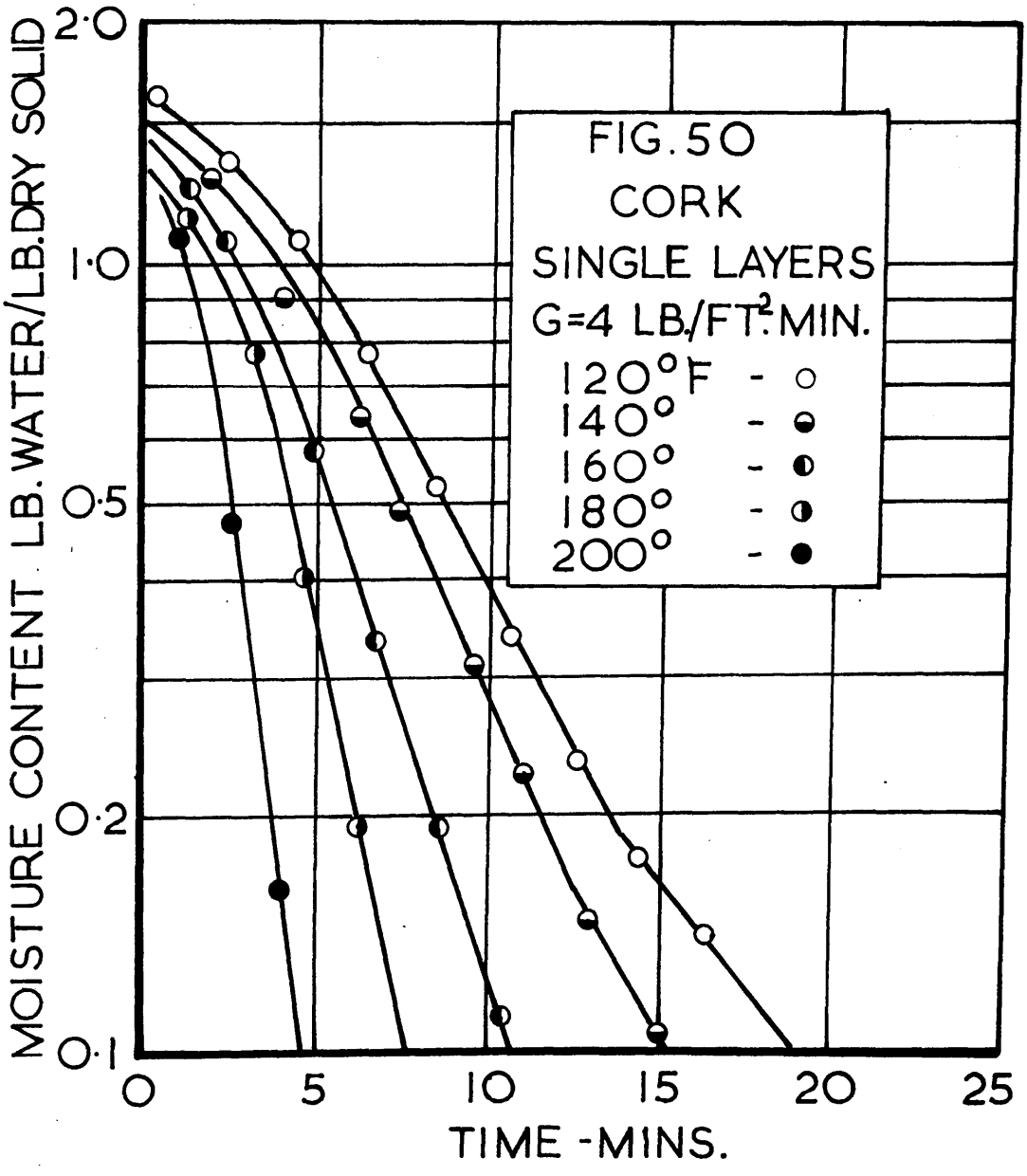


FIG. 50
CORK
SINGLE LAYERS
G=4 LB./FT.²MIN.
120°F -
140° -
160° -
180° -
200° -
MOISTURE CONTENT LB. WATER/LB. DRY SOLID
2·0
1·0
0·5
0·2
0·1
0
5
10
15
20
25
TIME - MINS.

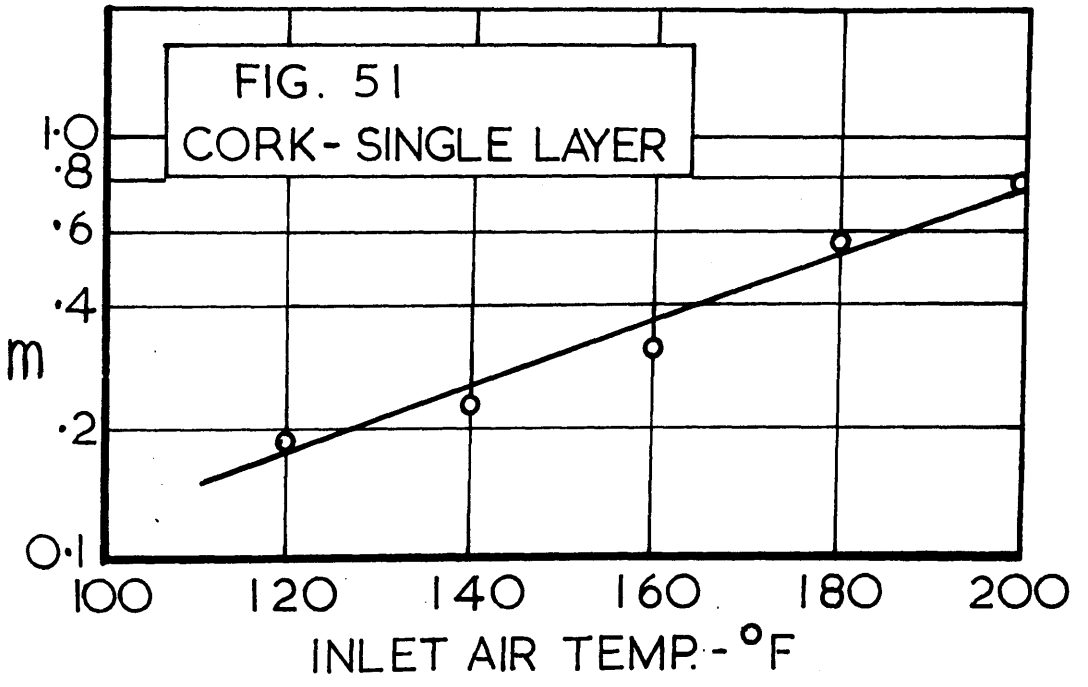


FIG. 51
CORK - SINGLE LAYER
1·0
·8
·6
·4
m
·2
0·1
100
120
140
160
180
200
INLET AIR TEMP. - °F

employed to 3 lb/(ft^2)(min). At 7 lb/(ft^2)(min) blowholes developed in the bed and material tended to become airborne as it dried. Tests were therefore carried out at "G" equal to 3,4,5 and 6 lb/(ft^2)(min), the inlet temperature being maintained at 160^{o}F

A short constant rate period was observed but most of the time taken to dry to low W was accounted for by the falling rate period. The drying curves over the range required for further study, W = 1.0 to 0.1 are illustrated in Fig.52. The relation

$$\frac{dW}{d\theta} = -mW \quad \ldots\ldots\ldots\ldots \quad 15$$

holds quite consistently.

Over the range studied, increase in air mass flow led to slightly increased drying rates. The amount of the increase was, however, small, and the corresponding values of m show only a small rise.

"G"	3	4	5	6
"m"	0.272	0.308	0.315	0.326

The data may be expressed by the relation

$$m \propto G^{0.12} \quad \ldots\ldots\ldots\ldots \quad 65$$

This may be compared to the expressions obtained for the other materials used, when the index of G was of the order of 0.8. This secondary dependence of rates in the falling rate period on airflow has been observed with some other vegetable materials, including beetroot, turnip and sugar beet[42].

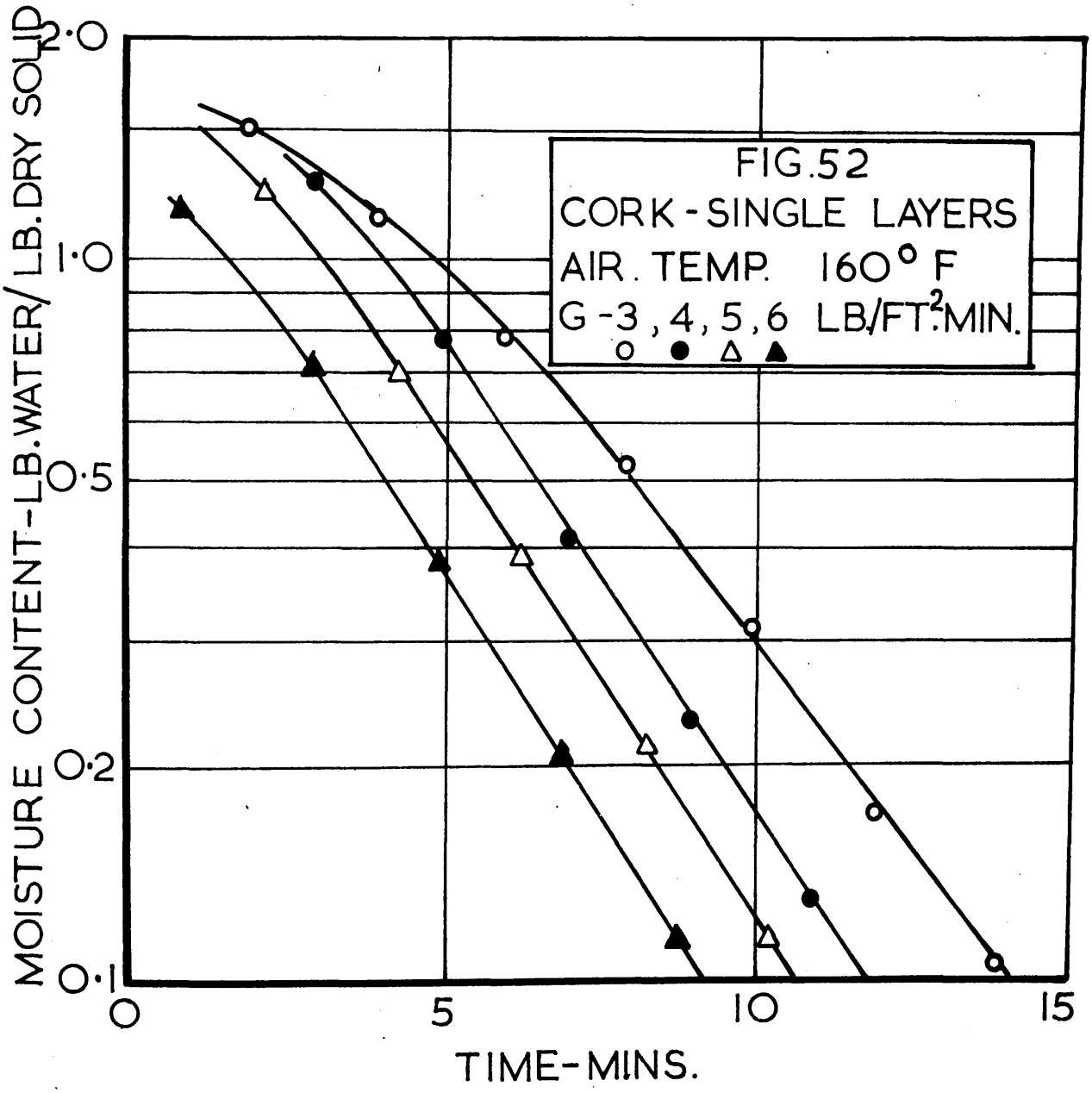


FIG.52
CORK - SINGLE LAYERS
AIR. TEMP. 160° F
G - 3, 4, 5, 6 LB./FT.²MIN.
MOISTURE CONTENT - LB. WATER/ LB. DRY SOLID
1·0
0·5
0·2
0·1
0
5
10
15
TIME - MINS.

Rotary drying of Granular Cork

A series of tests was carried out to determine the effects of the variables controlling the operation of the rotary drier on the drying of this material. Factors investigated included air mass flow and temperature, feed rate, rate of rotation of the drier and the number of lifting flights fitted.

As before a "standard" set of test conditions was chosen to aid comparison between the runs. To allow for the faster drying characteristics of the cork granules, these conditions were chosen to produce a shorter retention time than had been employed with the other two materials. The reference test was conducted at an inlet air temperature of 160°F and mass flow of 288 $lb/(ft^2)(hr)$. The feed rate was 0.484 $rt^3/(ft^2)(hr)$ and the rate of rotation of the tube 6 R.P.M. The slope of the drier was maintained at 3.5% and 8 flights were fitted for the majority of tests.

Procedure

The methods already described for the rotary drying of the other materials were employed in these tests.

The actual feed for the drier was prepared by submerging an open weave sack containing the granules in water for 3 to 4 hours before use.

Results

Calculation of heat transfer coefficients showed no promise. In addition, material temperatures during drying rose continuously a feature which has already been noted as rendering application of any tentative values of apparent heat transfer coefficients almost impossible.

Drying rates were once again adopted as the basis for comparison. Plots of moisture content against drying time, calculated as for the other materials, produced consistently linear relationships on semi-log, paper, indicating the general equation.

$$\frac{dW}{d\theta} = -mW \text{ , or } Log_e W = -m\theta + k \quad \ldots\ldots\ldots \quad 15$$

With generally lower retention times than encountered when drying the other two materials, the average velocity of the cork granules in the drier was considerably higher. Much less variation in the velocity was observed along the drier than before, a reasonably high slope being employed and material gradients would have proportionally less effect. A general rise in velocity was, however, still observed towards the outlet.

Inlet air temperature

Increase in air temperature from 120°F to 200°F resulted in a much drier product. The effect on retention times was small and the increase in the amount of drying was due mainly to the increase

in the drying rate as measured by the rate constant m.

The drying curves are shown in Fig.53 and the resultant variation in m is shown in Fig54. Over the range of the tests, it appears that m can be expressed by

$$\text{Log}_{10} m = \frac{T - 674}{392} \quad \ldots\ldots\ldots\ldots \quad 66$$

This is of the same general form as has been observed for both single layer through circulation and rotary drying of the other materials tested.

Air mass flow

Air mass flow was varied from 250 to 392 lb/(ft^2)(hr), other conditions being maintained as for the standard comparison test.

The effects of airflow variation, which is one of the factors directly comparable with the single layer work, were perhaps somewhat unexpected. The values of m calculated from the drying rate curves decreased fairly rapidly with increasing air mass flow, the reverse of the effect encountered in single layers. It seems that the overall effect may be the resultant of two factors:

(a) actual effect of airflow on the drying rate

(b) effect of increased loading, produced by the higher airflow, on the drying rate.

In Fig.55 are plotted the values of m obtained, and the average

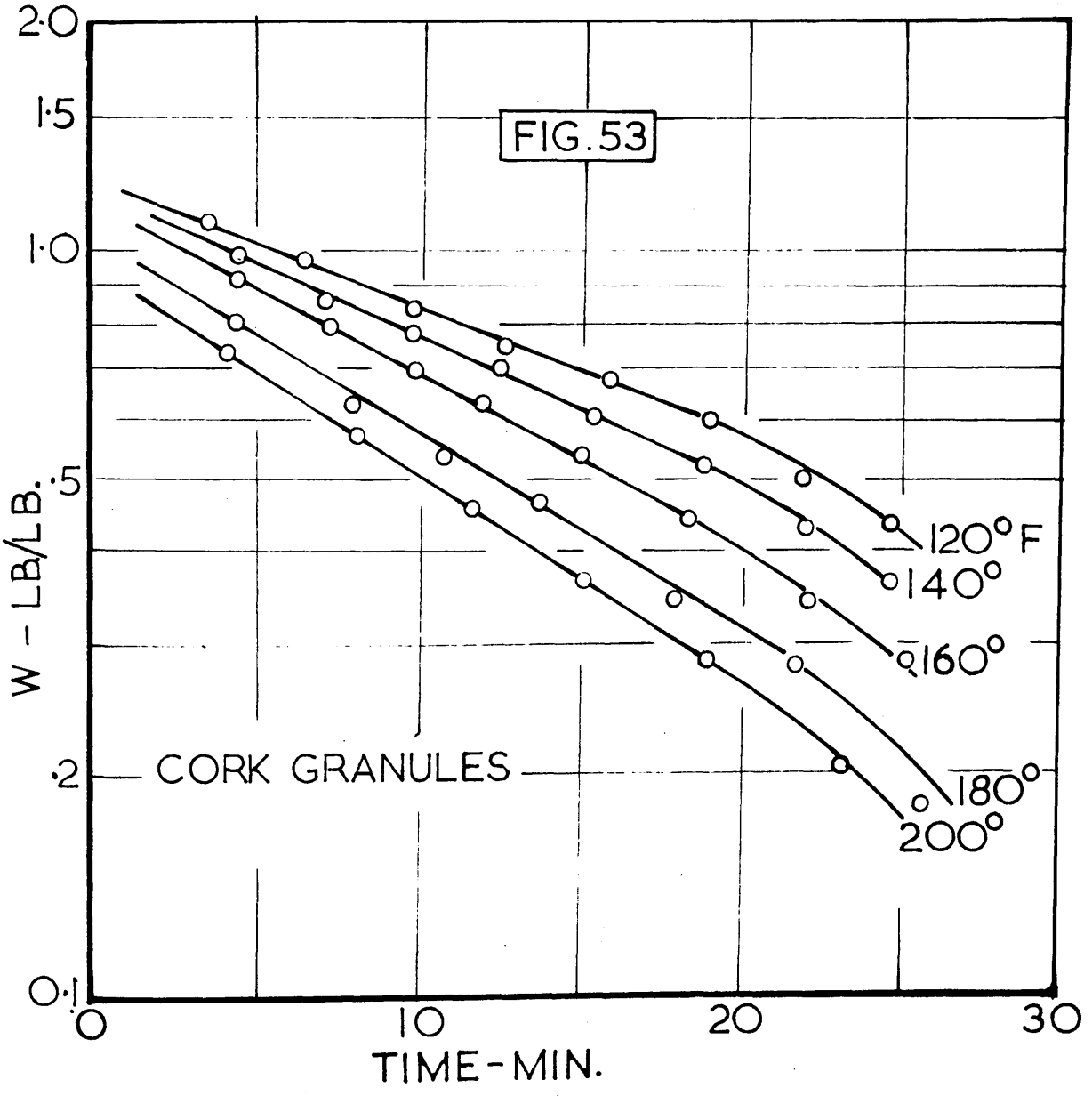


FIG. 53
2·0
1·5
1·0
·5
·2
0·1
W - LB/LB.
CORK GRANULES
120° F
140°
160°
180°
200°
0
10
20
30
TIME - MIN.

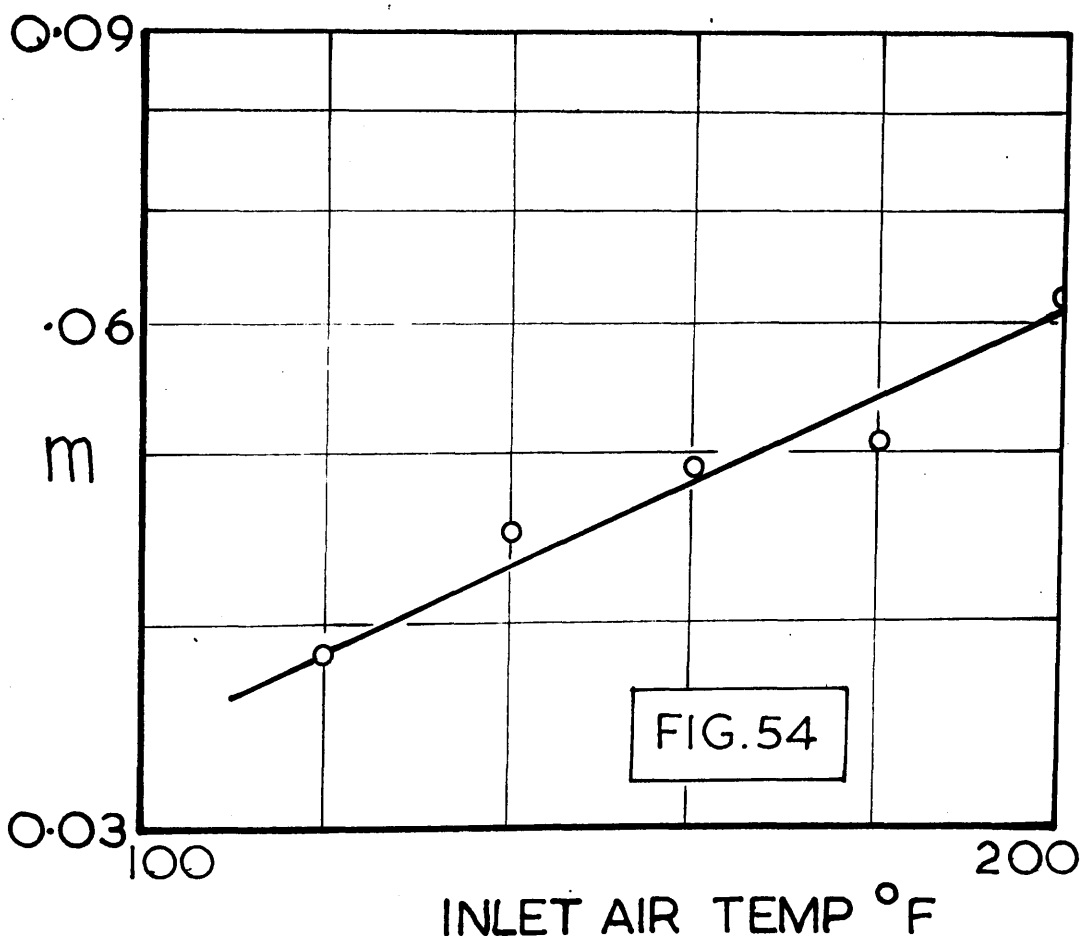


FIG.54

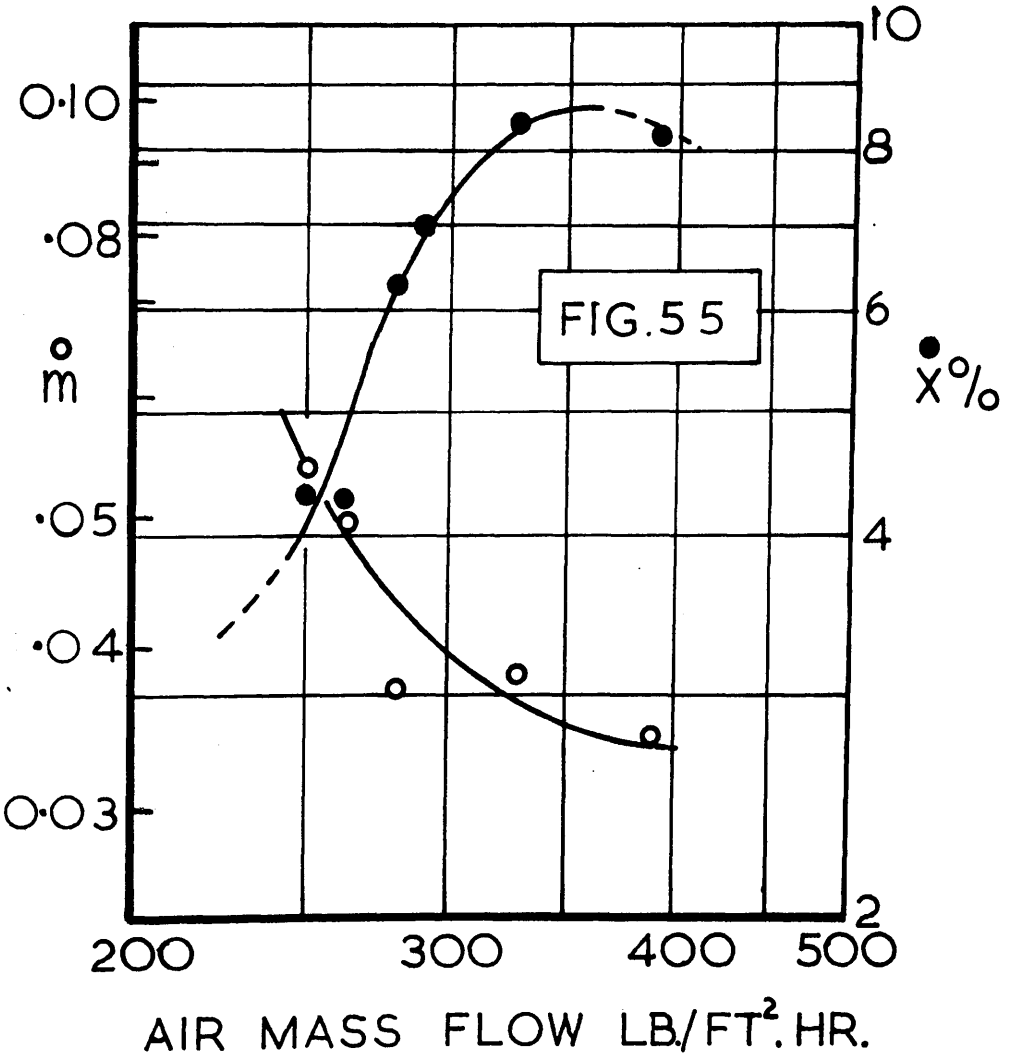

0·10
·08
·05
·04
0·03
m
10
8
6
4
2
X%
200
300
400
500
AIR MASS FLOW LB./FT². HR.

FIG. 55

percentage hold-up, calculated from drier dimensions, retention time and the feed rate against air flow. The use of an average percentage hold-up is considered justified here because of the smaller changes in material velocities.

With a material such as the granulated cork which has low density and a fair particle size, the effect of increase in airflow on loading is considerable. The critical velocity, above which material will be virtually airborne, is low, and considerable dusting or blow-back of some of the feed may be encountered. In the current tests, feed rate at the higher airflows was increased slightly to counteract this and maintain an effectively constant feed rate, but total hold-up tended to fall above airflow of 350 lb/(ft^2)(hr)

G	250	263	278	324	392
m	0.0518	.0473	.0346	.0358	.0322
%X	4.35	4.19	6.26	8.47	8.19
$\frac{1}{m}$	19.3	21.3	29.0	28.1	31.2

Feed rate

The effects of variation of feed rate from 0.157 to 0.682 ft^3/(ft^2)(hr) were investigated at constant values of the other variables.

Increasing feed rate produced higher loading, and resulted in slower drying and decrease of the falling rate constant. Over the range of the experiments, the variation in m can be expressed as

$$\frac{1}{m} = 34.8\ F + 13.5 \quad \ldots\ldots\ldots\ 67$$

the relation illustrated in Fig.56.

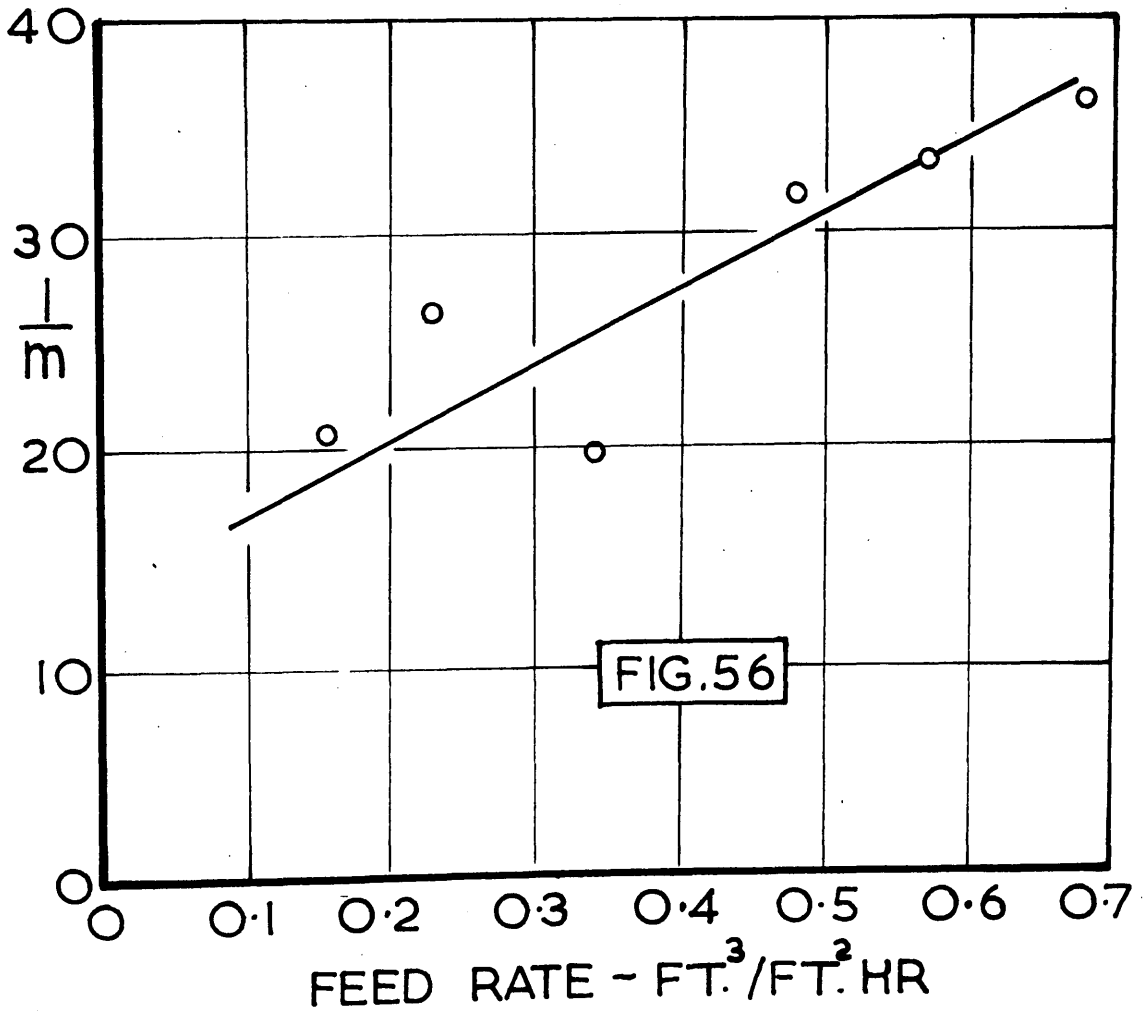


FIG.56

Increase in the feed rate also produced a linear variation in the volumetric hold-up, according as

Fig.57, $X = 11.3.F + 1.8$ 68

This is essentially of the same form as the general correlation equation 25 verified earlier in this work. The figure 1.8 refers to the increase in hold-up produced by the standard test airflow of 288 $lb/(ft^2)(hr)$. If this is deducted from all experimental values of $\frac{F}{s_d \cdot N^{0.9}}$, reasonable agreement with the general correlation is obtained with this material, illustrated in Fig.20.

Equations 67 and 68 suggest a new approach to the treatment of airflow effects. Combination of the two result in

$\frac{1}{m} = 3.60X - 7.35$, and that $\frac{d(\frac{1}{m})}{dX} = 3.6$ 69

values of $\frac{1}{m}$ obtained in the air mass flow trials are shown against actual hold-up in Fig.58. From values shown it appears that with air mass flow producing a hold-up of 4%, the value of $\frac{1}{m}$ will be circa 19.5. If equation 69 is assumed to hold, then the effect on $\frac{1}{m}$ produced by the increase in hold-up will be represented by the line shown. The tendency for the tests at higher airflow and therefore higher hold-up to produce values below this line can be ascribed to the slightly increased basic drying rates with air velocity which might be expected from the single layer tests.

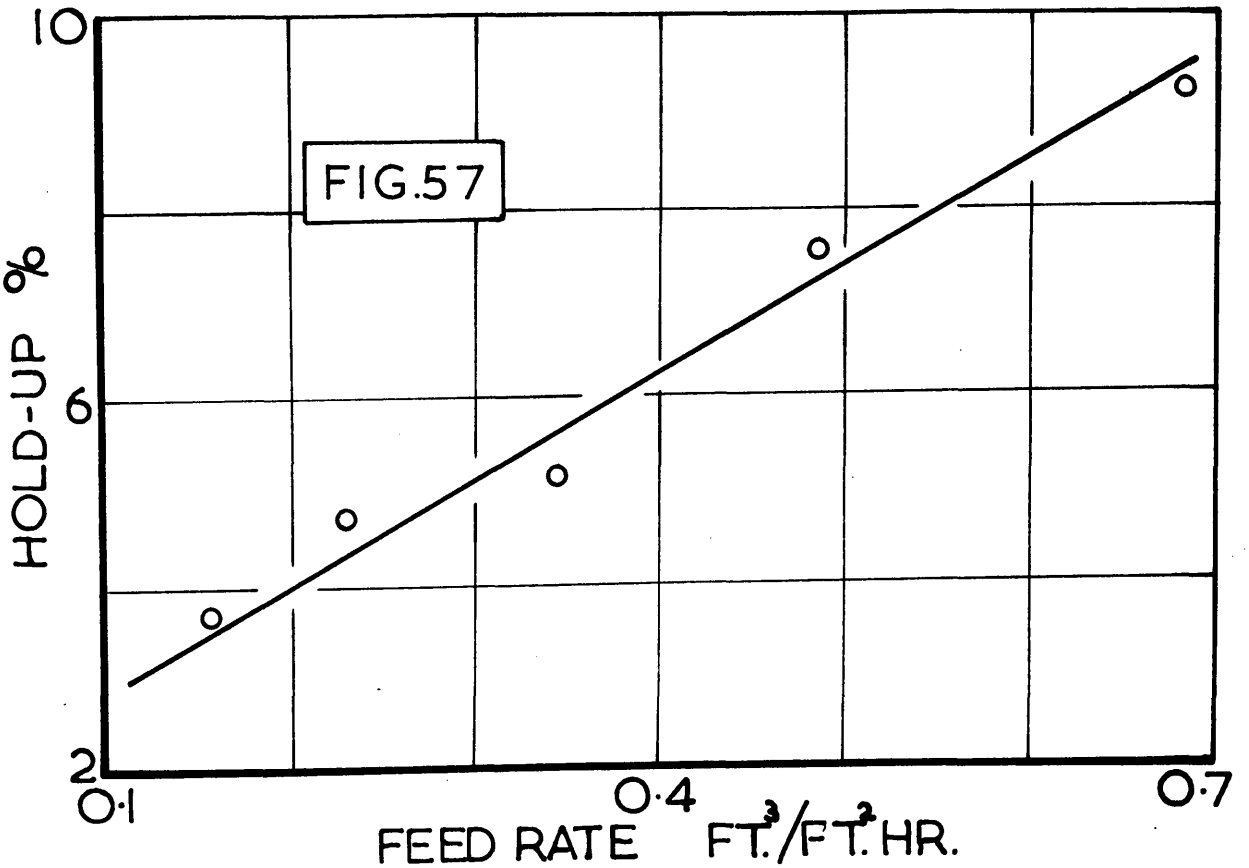


FIG.57
10
6
2
HOLD-UP %
0·1
0·4
0·7
FEED RATE FT.³/FT.²HR.

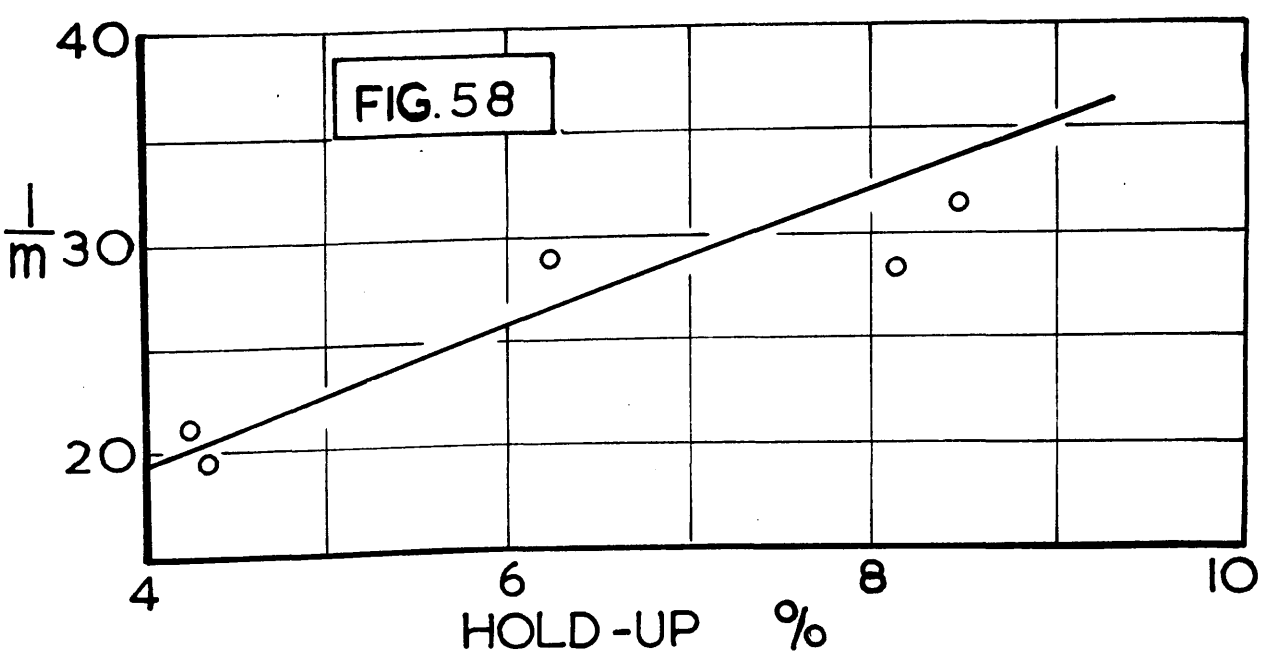


FIG.58
40
30
20
1/m
4
6
8
10
HOLD-UP %

F	0.682	.573	.550	.484	.344	.229	.157
$\frac{1}{m}$	36.1	33.1	16.1	31.9	19.6	26.5	20.9
X	9.20	7.57	7.26	7.57	5.14	4.73	3.67

Speed of rotation

Effects of rate of rotation were investigated at tube speeds from 4 to 21 R.P.M.

The effect of increased speed on retention time is covered by the relation

$$X = 213.N^{-0.95} \quad \ldots\ldots\ldots\ 45$$

discussed above, p. 70 .

Drying rates rose steadily as the speed was increased. $\underline{m}$ appears almost directly proportional to $\underline{N}$, the relation illustrated in Fig.59 being

$$m = 0.00706.N - 0.00575 \quad \ldots\ldots\ldots\ 70$$

Increase in $\underline{m}$ with $\underline{N}$ may be due to both

(a) decrease in hold-up

(b) increase in contacting efficiency produced by improved agitation.

The results may be compared with the feed rate trials. Combining equations 45 and 70,

$$\frac{1}{\Psi} = \frac{0.434}{\frac{0.494}{X^{1.10}} - 0.0025} \quad \ldots\ldots\ldots\ 71$$

which is illustrated in Fig.60a.

At $\frac{1}{m} = 100$, X = 8.8% and N = 4.3 R.P.M. and if relation

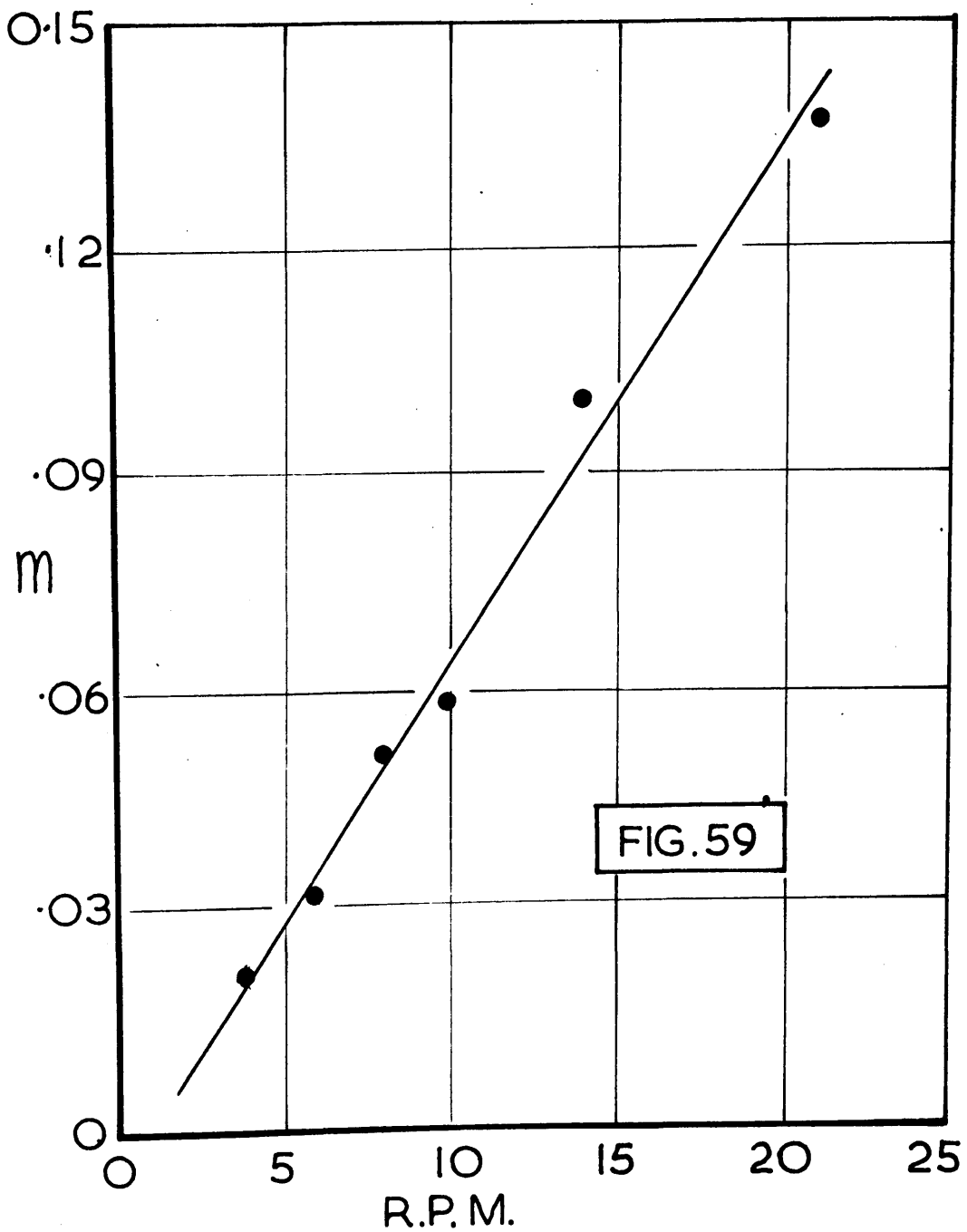


FIG. 59

$$\frac{d\frac{1}{m}}{dX} = 3.6 \quad \ldots\ldots\ldots \quad 69$$

is assumed, then a further series of values of $\frac{1}{m}$, independent of drier speed can be shown. These are consistently lower than the actual values and the difference may be ascribed to the improved contacting efficiency alone at the higher speeds. In Fig.60b this difference is plotted against the drier speeds producing corresponding values of hold-up. The actual value of $\frac{1}{m}$ in this is proportional to the actual reduction in drying time to any limit of moisture content which attends increase in drier speed from 4.3 R.P.M. to the values shown.

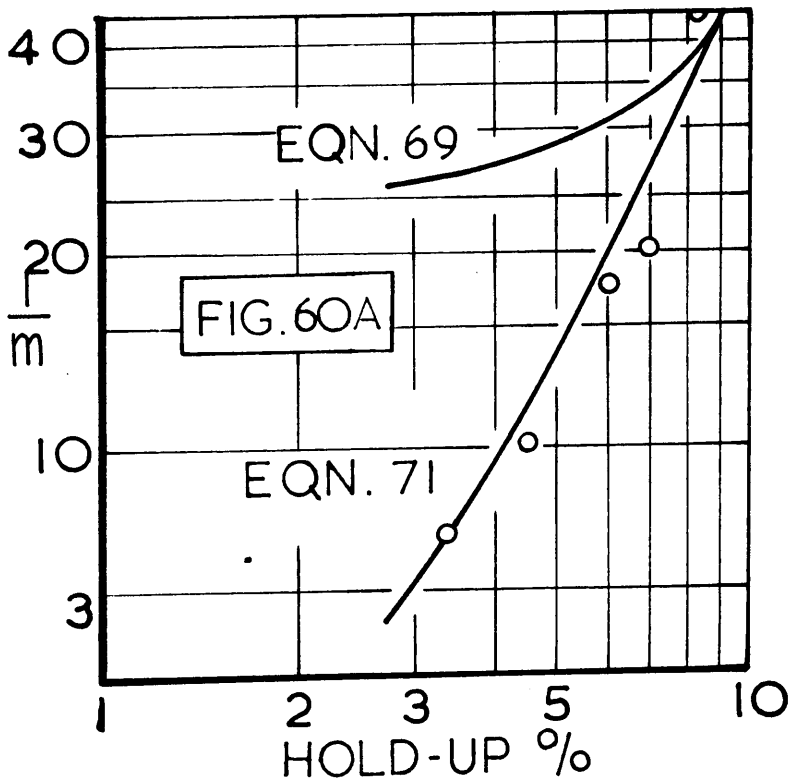
The tendency for the rate of increase of $\frac{1}{m}$ to fall off at high speeds is comparable with a similar trend in heat transfer coefficients reported by Friedman and Marshall.

R.P.M.	4	6	8	10	14	21
X	8.3	7.1	7.0	6.1	4.6	3.4
m	.02270	.0323	.0524	.0592	.1008	.137

Number of flights

The number of flights fitted to the drier was decreased in stages from 8 to 2. Other operating factors were maintained as for the standard comparison test.

Over the range studied, the number of flights affected both


40
30
20
10
3
1/m
EQN. 69
FIG. 60A
EQN. 71
1
2
3
5
10
HOLD-UP %

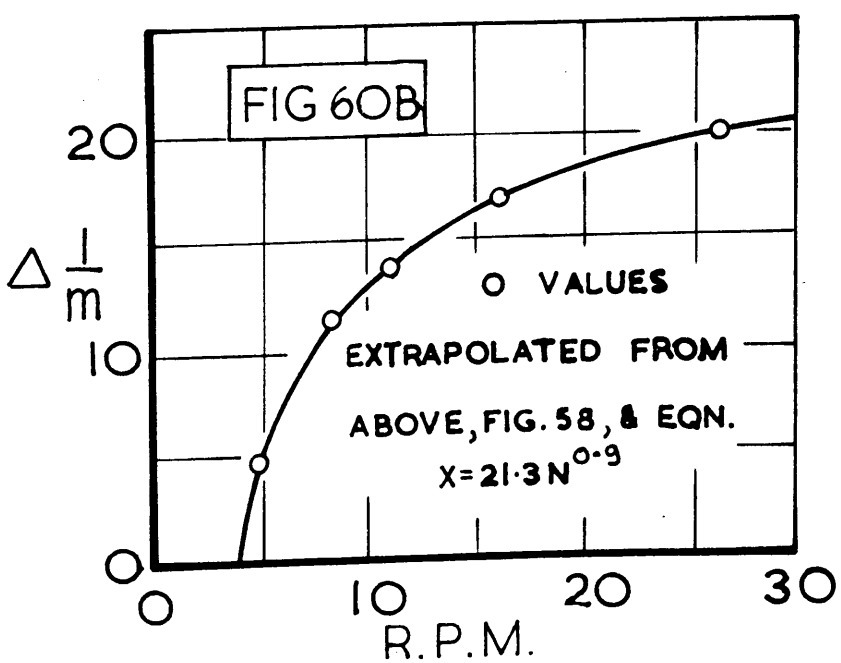


FIG 60B
20
10
0
Δ 1/m
O VALUES
EXTRAPOLATED FROM
ABOVE, FIG. 58, & EQN.
X = 21·3 N^0·9
0
10
20
30
R.P.M.

the hold-up and the drying properties. Drying rates as expressed by the values of m increased as the number of flights was decreased, the variation being illustrated in Fig. 61.

No. of flights	8	6	4	3	2
m	0.0318	0.0341	0.0628	0.0485	0.0740
%X	7.0	5.4	3.92	3.06	2.65
Retention time mins.	25.87	21.7	14.8	16.5	10.9

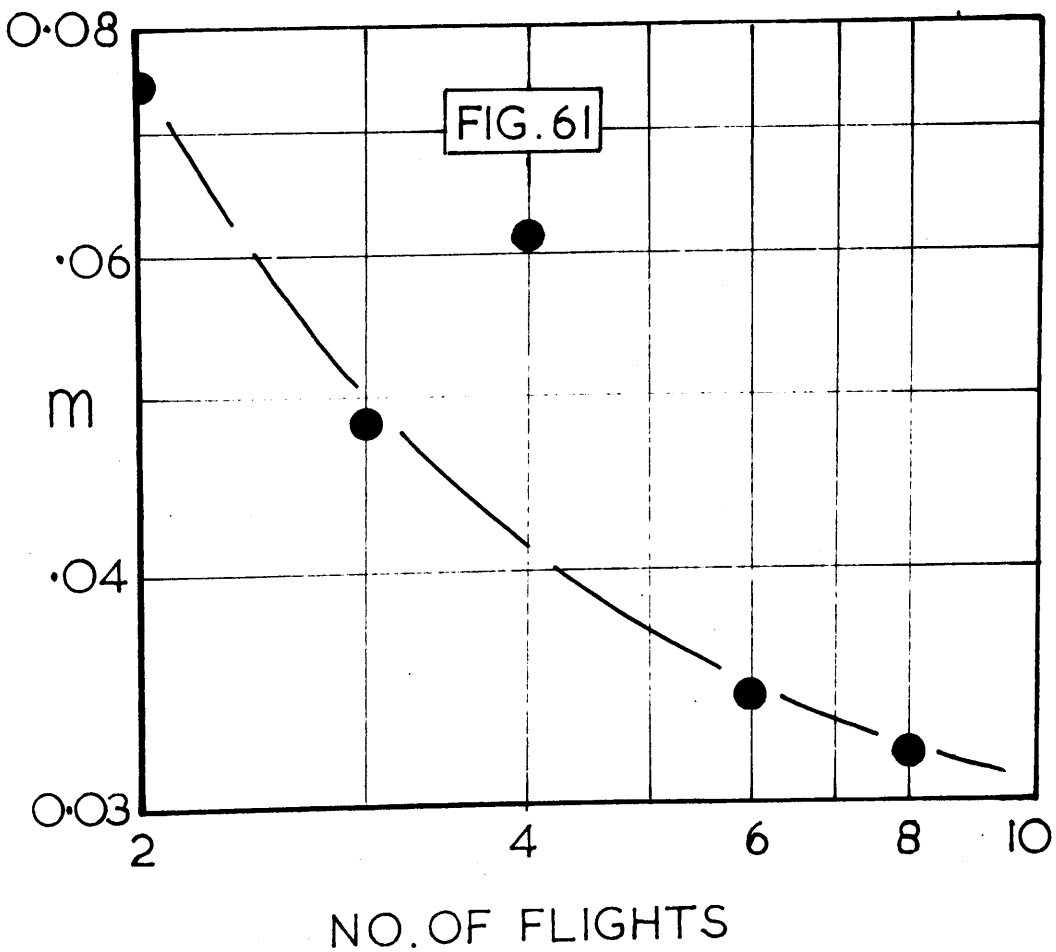


FIG. 61
0·08
·06
m
·04
0·03
2
4
6
8
10
NO. OF FLIGHTS

DISCUSSION OF RESULTS.

Discussion

Introduction

Most published work on rotary driers has dealt essentially with heating sand or a simple dry inorganic salt, or with the drying of a material containing only surface moisture, such as wet sand or Fullers' earth. While a few results for more complex materials are available, no details of any systematic series of tests on these appear to exist and the effects of the factors controlling the operation of the rotary drier on such materials do not seem to have been intensively studied. The tests described in this work have been concerned with the variation of operating conditions of a given drier, and not with the drier dimensions. The interest lay not so much in the materials being dried but in the way the rotary drier affected their drying. Actual design of a drier from the data presented is therefore not feasible, as one factor in particular, the drier diameter, had of necessity to be kept constant. Some general points which apply to the design of a unit are apparent, however, and will be made after a discussion on the effects of each factor investigated.

Satisfactory working of a rotary drier may usually be obtained over a comparitively narrow range of operating conditions, and where the effects of some factors are

slight, difficulty may be experienced in interpretation of the results. A feature of much work on rotary drying has been the scattering of experimental results, an unfortunate and annoying characteristic of a system which is affected by so many variables.

The effects of various factors in rotary drying

The operation of a rotary drier is controlled by many factors including temperature, direction and mass velocity of the airflow, drier dimensions, speed and slope, the number of lifting flights and, of course, the nature of the material being dried and its feed rate. The most effective method of investigating such a system controlled by several variables is to hold all but one constant and systematically vary this one, repeating the procedure with each. This has occasionally proved difficult with the rotary drier, as most factors have some influence on each other, but no alternative was available. The results are from a planned series of tests on several materials, intended to cover a fair range of working conditions.

With all three materials containing internal moisture studied in the drying trials, drying rates were considerably below predictions from published heat transfer coefficients for the evaporation of surface moisture. Apparent volumetric heat transfer coefficients were found unsuitable for

prediction or design work because of the gradual but steady rise in material temperatures encountered along the length of the diameter.

Drying Rates

Single layer tests on the materials dried in this investigation indicated that the drying could be expressed by

$$\frac{dW}{d\theta} = -mW \qquad \text{15}$$

a relation suggested by diffusional theory and already reported to apply to a considerable number of both vegetable and other materials. It appears when allowance is made for any variation in material velocities along the tube of the rotary drier, that a similar relation also holds for this type of equipment. Values of m, the rate constant which indicates the speed at which the material dries under a particular set of working conditions, are affected by the factors which control the operation of the drier. The variation in material velocity along the tube appeared considerable with both the spent grain and the barley grain. This effect has been noted before and Smith[72] mentions a German attempt to correct this and improve material distribution over the drier by having plain flat flights at the wet feed end, followed by angled flights as the material becomes less moist. Several patents[50] have been concerned mainly with flight design

to allow for the gradual changes in material properties, but it was felt that it would be unrealistic to include altering flight designs through a drier only 40" long.

All the drying tests were conducted with counter-current airflow and it was noted that air temperatues along the drier dropped slowly through most of the tube, falling but a few degrees below inlet temperature, and dropped rapidly only in the last two or three inches of the tube before discharge. Tests where inlet air temperatures are equal may therefore be justifiably compared with each other.

Materials with free surface moisture

Values for the heat transfer coefficients at the wet feed end of the drier approached the figures predicted by Friedman and Marshall[80], viz., 60 B.T.U./ft^3.hr.$^\circ$F. Where the material was very moist and contained a fair amount of surface water, effects of the variables studied agreed with the observations of these workers. The point at which all the free surface moisture is evaporated and drying enters the falling rate period is defined as W_c, the critical moisture content of the material. As in through circulation drying, it is obviously desirable to be able to calculate W_c, i.e. the point at which Friedman and Marshall's volumetric heat transfer coefficients become invalid. Broughton[94] has studied materials which dry in this manner and has put forward a series of rules for its prediction,

but Mitchell and Potts[42] have shown that varying degrees of agitation, by exposing fresh surface, may alter W_c considerably. No proposals can be made as a result of current work on prediction of this factor as the experimental conditions were generally intended to allow material to enter the falling rate period fairly rapidly, to permit more accurate study of this type of drying.

Drying in the rotary drier was much slower than in the through circulation drier, values of $\underline{m}$ at the same temperatures and airflow being about $\frac{1}{4}$ to $\frac{1}{20}$th lower.

Standard test conditions, & T=180°F, G=800 lb/(ft²)(hr)	Spent grain	Barley Grain	Cork
Through circulation drier	0.1450	0.1114	0.550
Rotary drier	0.0460	0.0134	0.0534

The values of $\underline{m}$ quoted for the rotary drier are at different values of speed, slope, feed rate, and of course, loading. Use of average loading data has been avoided for the spent grain and the barley. If it is assumed, however, that the average hold-up X_a is proportional to $\frac{F}{T}$, from equation 16 , and that the values of $\underline{m}$ will vary with X_a in the same manner as the experimental equations 53, 60, and 67 linking $\underline{F}$ with $\underline{m}$, then values of $\underline{m}$ at 180°F and $\underline{G}$ = 400 may be calculated which would produce the same hold-up as in the tests on barley which taken as a standard. The standard speed in the tests on the spent grain was 12 RPM., and if the value of dm/dN from equation 55 is employed,

a value at 6 R.P.M., the standard speed of the other two, may be calculated. The resultant values of m and the relations with the static tests are given below:

	Spent grain	Barley grain	Cork
m rotary	0.036	0.0134	0.0615
$\frac{\text{m rotary}}{\text{m single layer}}$	0.234	0.121	0.1125

Conveying properties and dispersion effects

The variables studied generally affected m, conveying properties, and dispersion effects. These will be considered in turn.

The conveying tests on dry materials show results in agreement with the data of Friedman and Marshall[67]. The observations from the drying tests were often considerably different from experimental results with the dry materials, and while these could be explained in the light of prevailing working conditions, no satisfactory method of calculation the difference between wet and dry feed can be suggested. The effect of each variable is, however, discussed below and influence on drying noted.

The "deviation" trials on dry material were not generally repeated with wet feed during the drying runs, One test, however, conducted with barley, using some dyed grain as tracer, was carried out, and the plot of cumulative percentage leaving V_s time, Fig.64, shows that dispersion effects will probably be more marked with wet feed and

counter-current airflow. That portion of the feed which, by chance effects of flight action and bouncing remains in the drier for longer than the average time, will become still further dried and retarded by the airflow owing to its reduced density.

Inlet air temperature

Increasing air temperature generally raised the retention times in the drying tests, a result which may be ascribed to the greater retarding effect which the air has on the much drier material produced in the high temperature runs.

As with the through circulation tests, increasing air temperature raised drying rates in the rotary drier according to the general equation

$$\log_{10} m = \frac{T - a}{b} = \frac{T}{b} - \frac{a}{b} \quad \ldots \ldots \quad 48$$

The variation of $\log_{10} m$ with temperature depends on b, and it appears that increasing air temperature has not an equal effect on all three materials studied. Although varying conditions of feed rate, material velocities and loadings make direct comparison between the materials impossible, it was originally hoped to be able to compare the rate of variation of m with temperature for both static and kinetic drying. While it appears that increased temperature affects barley grain most in both driers, temperature affected the spent grain more than the cork in rotary drying, the reverse

of the case in through circulation trials. For comparison, the % increase in $\underline{m}$ as the inlet temperature was raised from 140°F to 200°F is listed below

		Cork	Spent Grain	Barley
% increase $\underline{m}$ 140°F to 200°F. $_b$	Rotary drier	45	68	83
	T. circ. drier	196	116	680
	Rotary drier	392	228	219
	T. circ drier	128	178	70

Air mass flow

When dry feed was used and where reasonably constant velocity along the drier, as in the drying tests on cork, permitted estimation of loading with wet feed, the increase in hold-up with counter-current airflow was proportional to $\underline{G}^c$ where $c > 1$. The tests on cork at higher airflows showed that as a limiting value of $\underline{G}$ was approached and some material became airborne, hold-up dropped as dusting increased.

When average hold-up could not be estimated with any degree of accuracy, it was observed that increasing airflow raised the retention time.

With all materials, the limiting velocity above which the drier became unworkable was lower than the maximum velocity which could be used in single layer through circulation work without disturbing the bed.

	Barley	Spent grain	Cork
	G - lb./ft². hr.		
Rotary drier	710	510	392
Through drier	900	1200	420

The greatest difference was apparent with the spent grain where through circulation drying results in a layer of material bonded together by the fibres. If this bed is agitated or broken, the highest airflow which may be passed through without disturbing the material becomes about 12 lb/(ft^2)(min) or 720 lb/(ft^2)(hr). It appears therefore, that air velocity in rotary drying should be kept considerably below the maximum possible with through circulation drying.

Where the effects of airflow on the drying rates could be found with satisfaction, as in the spent grain or barley trials, drying rate constants m were found proportional to almost the same index of G as in through circulation tests. In the trials on cork, where single layer tests indicated that airflow had only a secondary effect on the drying rates, the decrease in drying rates with increased airflow was shown to be produced by higher drier loading. The effects of airflow are complex, involving drier loading and retention time, and final moisture content of material will be affected by both these and the value of m.

Friedman and Marshall's[80] results for "constant rate" or heat transfer limited drying indicate a lower dependence on airflow, viz, $G^{0.16}$. It appears that, where indicated by single layer trials, falling rate drying in rotary drier will be much more affected by airflow variation than

where surface moisture only is being evaporated, although actual drying rates will be much lower.

Feed Rate

Results with dry feed agreed with published data, hold-up being directly proportional to feed rate, inferring an independence of retention times. In drying trials, however, increasing feed rate generally lowered retention times, the effect being most marked with the spent grain where density variation through the drier was considerable. With the other two materials, threefold increase of feed rate decreased retention times by about 25%.

The affect of feed rate on deviation is dependent on retention time and may be deduced from the general correlation, fig.26 and corresponds values of α

Eg. At 10% X, $\frac{D}{T}\alpha = 8.0$ and $\alpha = 0.49$

2 x feed rate at 20% X, $\frac{D}{T}\alpha = 2.0$ and $\alpha = 0.80$

hence $\frac{\text{Deviation at 20\% hold-up}}{\text{Deviation at 10\% hold-up}} = \frac{1}{4} T^{0.31}$, < 1 where $T < 88$ mins.

i.e. as T is normally below 88 minutes, deviation at 20% x produced by double the feed rate is lower than at 10% in this case.

Alteration of feed rate had a considerable effect on the drying of all three materials. Decrease in the drying rates of surface wet materials would be anticipated from the results of Friedman and Marshall who suggested that, while overall

heat transfer coefficients increase slowly with hold-up, increased drier loading produces proportionately more material in each section of the drier to take up the available heat, and, although the total amount of moisture evaporated is higher, the drying rate decreases.

In current work, relations of a similar type were obtained for all three materials, that for cork was, e.g.,

$$\frac{1}{m} = 80\ F + 31 \qquad \ldots\ldots\ldots\ldots\ 67$$

Under other conditions as for the standard test, a feed rate of 0.3 $ft^3/(ft^2)(hr)$ indicates a value of 0.0182 for m, and for F = 0.6, m = 0.0127. The time to dry from W = 1.0 to 0.1 would be 126.5 and 181 minutes respectively. If the retention time of the unit be adjusted by slope to 126.5mins., then at the higher feed rate the final moisture content would rise to 0.2 or 0.1 greater than before, but the actual unit of moisture evaporated would have increased by 55.5%.

Speed of Tube

In all runs where drier speed was increased, retention times fell, and under constant feed rate conditions hold-up deceased proportionally where this could be measured. With cork, average hold-up could be determined and was related to speed of the general formula for dry material, equation 25. The value of the index n was 0.95, which

indicates greater dependence on speed than was found with dry material. This is probably due to the properties of the more dense wet material rather than the drier, as dry potato cubes which also possessed a high angle of repose had a low value for $\underline{n}$, viz. 0.71. The dynamic angle of repose of dry cork was 45°, but that of the wet material up to 55°. Spraul[53] has criticised hold-up relations based on angles of repose, and it appears that his arguments are to a large extent justified. $\underline{n}$, however, decreases with increasing angle of repose, and may therefore be suspect - the adoption of an average value of 0.9 for $\underline{n}$ is equivalent to the assumption of a mean value of the angle of repose. The values indicated by the general hold-up formulae may be taken as a reasonably accurate guide.

The effects of drier speed on deviation are covered by the general correlation suggested for dispersion results.

Increasing drier speed produced higher drying rates, the relation between $\underline{m}$ and $\underline{N}$ being consistently linear. Loading fell with increasing speed and the increased drying effect is due to both the lower loading and improved contacts efficiency of higher speed. Where an accurate estimation of the variation in hold-up could be made, this could be related to the decrease in $\underline{m}$ with the variation in hold-up produced by altered feed rates. The effects of increasing agitation alone may thus be found and it

appears that m increases with speed, although the exact form of the relation is hard to define. Under arbitary "constant loading" conditions produced by increasing the feed rate with drier speed according to dry hold-up relations, tests carried out with the barley infer that this change of m with N is linear, equation 62. Deduction from the tests on cork, Fig.60 suggest that while increase in drier speed alone will raise m, the effect is limiting and the rate of increase of m with N gradually diminishes. These results are somewhat in conflict but it is probable that equation 62 does not refer to true average constant loading conditions due to the velocity variation along the drier with barley, and that increase of N here will also finally reduce $\frac{dm}{dN}$. The observations are comparable with Friedman and Marshall's[80] suggestions that a limiting value of heat transfer coefficient is approached at higher speeds.

Number of Flights

Of necessity the majority of the experimental tests were concerned with the operation of a given drier, dimensions and constructional features being limited by the original design. It was possible, however, to vary the number of lifting flights fitted to the actual drying tube and study their effect on the conveying and drying rates.

With both wet and dry feed, extra flights produced longer retention times, and where these could be determined, higher average hold-up. This may be ascribed to the higher lifting and carrying capacity of the extra flights decreasing kiln action both on the flights themselves and along the bottom of the drier. This agrees with the observations of Spraul[53]. Plots of X vs $F/S_d\ N^{0.9}D$, figure 15, were linear at lower values of hold-up and all flight arrangements. As X increased, however, the relation becomes curved, kiln action producing higher velocities through the drier and decreasing hold-up. The value of the hold-up at which the relations become non-linear increases, as might be anticipated, with extra flights.

Higher deviation from mean retention time was observed in the smaller unit when more lifting flights were fitted. When extra flights are simply added to the drier, hold-up and retention time will increase, and retention appears to be one of the factors producing dispersion. Plots of deviation against actual hold-up for different number of flights, Fig.62, show however that under similar loading conditions, added flights produce higher deviation - presumably by offering a greater choice of routes through the drier. The occurrence of a minimum in the deviation /hold-up relationship has already been discussed in the experimental section, p. 79 , and it appears that gradual

increase in the value of X at which this is found, with numbers of flights, is related to the start of kiln action and the formation of a moving layer of material on the drier bottom.

Friedman and Marshall[80] suggested that the number of flights fitted to the drier affected drying in much the same way as drier speed - i.e. increased heat transfer with improved agitation - but that a practical limit to the number of flights necessary was soon reached. These results are in conflict with the observations of Miller et al[79] whose tests on Fullers earth showed higher drying rates with 6 flights than with 12. The results from this section are of considerable interest and appear to agree with both the above suggestions and explain the apparent anomaly.

Where a considerable amount of surface moisture was present and initial drying rates were low, e.g. the tests at 140° on a spent grain, drying rates initials varied as 8 flights > 6 flights > 4 flights > 3 flights > 2 flights. This is illustrated in Fig.38, and to a lesser extent in the tests at 200°, Fig.37. When the material had entered the falling rate period, however, the effects of the flights were completely reversed, and with all materials, the slowest drying rate was observed with the largest number of flights employed.

No completely satisfactory explanation can be offered for this phenomenon. Fewer flights, under otherwise similar operating conditions, decreased retention times and loading, a factor already shown to affect drying rates. The increase in drying rates with fewer flights cannot, nevertheless, be attributed solely to this as, Fig.36 a very large variation in $\underline{m}$ was encountered.

As the M.C. of the product depends on both $\underline{m}$ and τ it appears that, for a given drier, feed rate, speed and air conditions, there will be an optimum number of flights to produce the driest material - e.g. with barley grain, other conditions being as for the standard test, 3 flights appear most suitably. It is not suggested that this figure will apply to as drier, the inference is that there will be an optimum number of flights for any particular situation.

Hold-up and retention time

Hold-up and retention time are themselves separate operating factors. While the primary object of the conveying trials was the elucidation and study of the factors controlling these two, it was observed that both have a not inconsiderable effect on drying and dispersion. The effects of hold-up or loading on drying rates has been covered by the trials on feed rate, and retention time must be used in conjunction with the falling rate constant, $\underline{m}$, to estimate the limits to which the material is dried.

The effects of hold-up and retention time on deviation are covered by the general correlation proposed, Fig.26.

Suggestions for Design

No satisfactory basis for the actual design of a rotary drier intended to operate on materials which dry in the falling rate period has as yet been proposed. The only published data on this is that of Gutzeit and Spraul[95], who suggested that as a basis for design work, an outlet gas temperature from pilot plant tests should be determined, and material and air rates adjusted to produce this with the larger unit. Where material is not available in sufficient quantity for pilot plant studies, Spraul suggests that these be conducted on substances "which have similar constant drying and falling rates" - and presumably, critical moisture contents.

The present state of knowledge is therefore somewhat vague in this field, but the following general suggestion on counter-current rotary driers are made as the results of the work described in this thesis:

(a) Hold-up and retention times. In general the correlation of Friedman and Marshall[67] should be accepted but values obtained must be located with caution where large changes in material handling characteristics may be encountered. Allowance should then be made for generally longer retention times.

(b) Air temperature. The falling rate constant observed in the rotary drier may be about one tenth of that in single layer static tests. Variation in $\underline{m}$ with drier temperature will not be so marked, but it is suggested that $d \log_{10} m/dT$ be assumed 1/3rd of the static value.

(c) Air mass flow. In counter-current drying, air mass flow which can be safely employed should be below 80% of the maximum possible with a thin static bed. Care should be taken to note whether the material binds together in single layer tests, when velocity in the rotary drier should be still lower. The effects of air mass flow on drying rates are comparable to those encountered in the static trials, but where the material is very light and hold-up may be considerably affected by airflow, care must be taken to allow for altered loading.

(d) Feed rate. The feed rate affects drying mainly by alteration of % hold-up and should therefore be adjusted to produce a definite loading or conversely, the drier diameter should be chosen to produce the desired hold-up with a given feed rate. Where a heat sensitive material is being treated, the hold-up should not be excessing, to avoid large deviation, and should preferably be at a minimum of the deviation/hold-up relationships. Where feed rate is increased a wetter

product may be expected in resulting from both decreased retention time and drying rate.

(e) Speed of drier. The range of drier speeds is limited by mechanical considerations, and the suggested values [83] of peripheral shell speeds should be adhered to. A reasonably high speed will, however, produce highest drying rates, in direct proportion to drier speed, and should be allowed for if possible. Hold-up may be maintained at the optimum value by alteration of the drier slope.

(f) Number of flights. Where an initial constant rate period may be encountered, a section with a fair number of flights should be employed, and flight designs should be varied with the properties of the material. When material enters the falling rate zone, the number of flights should be reduced to the minimum value which will still produce a reasonably high retention time.

Suggestions for future work

Further experimental work is desirable, both with other materials which dry in the falling rate period and with driers having tubes of a different diameter. The question of scale-up is important but cannot be studied with the present apparatus. In scale-up operations a transfer

coefficient, or other design factor, may often be related to some variable dependent on the dimensions of the unit, but in the present work no obvious relation between m and the drier diameter is apparent, and further work with both larger and smaller driers is advised.

Falling rate constants for materials may be found readily in single layer through circulation tests, which may be carried out with fairly simple apparatus. It is considered that a design method, based on falling rate constants determined in this way, might be established for counter-current rotary driers.

Nomenclature.

Except where the results of other workers are involved, the following system of nomenclature is employed.

D' - average height of fall, a function of the drier diam., D.
F - feed rate, $ft^3/(ft^2)(hr.)$.
f - experimental feed rate, gm./min.
G - air mass flow, by convention $lb/(ft^2)(min.)$ in through circulation drying, $lb./(ft^2)(hr.)$ in rotary drying.
N - speed of drier, R.P.M.
n - a factor relating hold-up and speed of drier.
X - loading of rotary drier, normally on a volumetric basis, ft^3/ft^3 %.
L - length of drier. ft.
T - air temperatures, ^oF.
t - material temperatures, ^oF.
S_d - slope of rotary drier tube, ft./ft.
- mean retention or residence time, min.
Θ - drying time, min.
U_a - overall volumetric heat transfer coefficient, $B.T.U./(ft^3)(^oF)(hr.)$
m - rate constant predicting drying in the falling rate period, min^{-1}.
k - integration constant related to above m.
n_f - number of flights fitted to the drier.
D_t - in deviation trials, a factor expressing deviation from the mean retention time, usually min./min.,%.
α - a function of hold-up and deviation.
V - velocity of the material along the rotary drier, ins./min.
W - moisture content of the material being dried, lb. water/lb. dry solid.

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Appendix

I. Single layer test, granulated cork.

II. Rotary drying test, brewers' spent grain.

III. Tables of conditions and results for drying tests.

IV. Specimen histogram and cumulative discharge graphs for deviation trials.

Granulated cork, through circulation drying test.

Single layer of material, inlet air temperature 140°F and mass flow 4 lb./ft.^{2}min.

Drying time, min.	Weight of bed, lb.	M isture content, lb.water/lb.dry solid.
2	0.556	2.09
4	0.484	1.69
6	0.407	1.26
8	0.340	0.89
10	0.290	0.61
12	0.255	0.42
14	0.234	0.242
16	0.220	0.222
18	0.209	0.161
20	0.204	0.132
22	0.200	0.111
24	0.196	0.089
26	0.194	0.078
28	0.191	0.061
30	0.190	0.055
32	0.189	0.050

Moisture content of sample of bed taken after 32 min. drying = 4.53 %.

Hence dry weight of bed = $0.189 \times \frac{100 - 4.53}{100} = 0.180$ lb.

Rotary drier - Specimen results and calculation,

Brewers' spent grain. Drier slope 2.18% and speed 12 R.P.M., 8 flights, and material feed rate of 0.356 $ft^3/ft^2.hr.$, i.e., 2.38 gm. dry solid per minute. Inlet air temperature 220°F and air mass flow 410 $lb./ft^2.hr.$ Jacket maintained at inlet air temperature, i.e. 220°F, and tube lagged.

Temperature readings taken 3hrs. 20 mins. after start of test, moisture samples taken after 4hrs. 30 mins.

Sample point	A	B	C	D	E	F	G	H	I	J
	Product									Feed
Ins. from dischge.	0	4.5	8.6	12.7	17.0	21.3	25.4	29.7	33.9	39.5
Moisture content lb./lb.	0.1	.11	.145	.196	.266	.370	.553	.881	.962	3.21
Loading gm/inch	-	1.18	1.32	1.44	1.53	2.09	1.76	1.34	1.89	-
					Material feed rate = 2.38 gm.dry solid/min.					
Velocity ins/min.	-	1.13	1.01	0.93	0.87	0.64	0.76	1.00	0.71	-

5" sections of drier: measured from dry product end,

Distance	0"	5"	10"	15"	20"	25"	30"	35"	39.5"
Average velocity ins/min.	1.20	1.05	0.93	0.76	0.67	0.92	0.80	0.60	
Time in section, minutes.	4.16	4.76	5.40	6.45	7.45	5.40	6.25	7.50	
Cumulative time from feed end, minutes	47.4	43.2	38.4	33.0	26.6	19.1	13.7	7.5	0

Extrapolated values of time and material moisture content:-

Time(min.)	0	5	10	15	20	25	30	35	40	45
W (lb/lb)	3.22	1.77	1.09	.75	.55	.38	.28	.19	.14	.11

The results for this test are illustrated in Fig.(28) & (29).

Heat Transfer Calculations for preceding data:

Feed rate = 0.31 lb.dry solid/hr. Average temperature of solid material in drier approx. 150°F., i.e. latent heat of evaporation = 1009 B.T.U./lb.

Section	A	B	C
Average moisture content in section, lb./lb.	0.110	0.125	0.150
Difference in moisture content in section, lb./lb.	0.015	0.025	0.050
Wt. of water passing through section, lb./hr.	0.0341	0.0387	0.0465
Wt. of water evaporated in section, lb./hr.	0.00465	0.00775	0.0155
Heat to the dry material in section, B.T.U./hr.	0.72	0.675	0.900
Heat to liquid water in section, B.T.U./hr.	0.273	0.290	0.465
Difference in material temp. in section, °F.	8	7.5	10
Heat effectively lost by airstream, B.T.U./hr.	0.993	0.965	1.365
Heat lost by each lb. of air passing thro' drier.	0.031	0.0321	0.0455
Heat evaporating water in section, B.T.U./hr.	4.7	7.2	15.6
Total heat transferred in section, B.T.U./hr.	5.693	8.165	16.965
Water evaporated in sectn. per lb. of air passing, lb.	0.000155	0.000258	0.000516
Moisture content of air, lb./lb.	0.0092	0.009355	0.009613 0.01013
Enthalpy of air, B.T.U./lb.dry air.	64.0	64.0	64.0 63.9
Air temperature, from psychrometric chart, °F.	220	219	218 217
Temperature difference between air and material, °F.	25	31	38 47
Average temperature diff. in section, °F.	28	34.5	42.5
Volume of section, ft³.	0.0562	0.0469	0.0463
Heat transfer coefficient B.T.U./ft³.hr.°F.	3.62	5.05	8.60

Heat transfer specimen calculation, continued.

Figures in columns as on preceding page: figures between columns refer to conditions between sections of drier.

D	E	F	G	H	I
0.22	0.32	0.48	0.71	1.02	1.90
0.08	0.12	0.20	0.25	0.39	2.0
0.0682	0.0991	0.1490	0.22	0.316	0.589
0.0248	0.0372	0.0620	0.0775	0.121	0.62
1.35	0.81	0.495	0.45	0.675	4.32
1.02	0.89	0.82	1.10	2.37	28.2
15.0	9.0	5.5	5.0	7.5	48
1.37	1.70	1.315	1.55	3.04	32.5
0.0465	0.0566	0.0438	0.0516	0.101	1.08
25.0	37.6	62.6	78.2	122.0	625.0
26.37	39.30	62.91	79.25	123.0	657.5
0.000826	0.00124	0.00206	0.00258	0.00404	0.0206
0.01013	0.0109	0.0122	0.0143	0.0168	0.0209	0.041
63.9	63.9	63.8	63.7	63.65	63.55	62.45
217	214	207	196	186	167	-
47	58	61	56	52	43	-
52.5	59.5	58.5	54	47.5		
0.0491	0.0491	0.0463	0.0491	0.0475	0.0424	
10.2	13.4	23.6	30.1	54.6	-	

Summary of drying tests. 1.

Brewers' spent grain, unlagged drier, S_d = 2.18%

No. of flights	R.P.M.	Feed rate. $ft^3/ft^2.hr.$	Air flow. $lb./ft^2.hr.$	Air temp. ^oF	Final M.C.	R.Time min.
8	12	0.35	355	160	0.35	26.9
8	12	0.35	355	180	0.26	33.0
8	12	0.35	355	200	0.12	37.9
8	12	0.35	355	220	0.08	38.6
8	12	0.35	285	180	0.26	36.1
8	12	0.35	350	180	0.25	47.3
8	12	0.35	410	180	0.22	54.3
8	12	0.70	355	180	0.54	43.0
8	12	0.47	355	180	0.48	39.0
8	12	0.35	355	180	0.27	47.1
8	23.1	0.35	355	180	0.22	40.2
8	16.9	0.35	355	180	0.26	37.9
8	13.4	0.35	355	180	0.25	47.0
8	10.7	0.35	355	180	0.20	74.0
8	8.5	0.35	355	180	0.12	85.1
8	12	0.28	355	180	0.19	69.9
2	12	0.35	355	180	0.70	12.9
4	12	0.35	355	180	0.42	21.5
6	12	0.35	355	180	0.35	32.0
8	12	0.35	355	180	0.25	47.3

Falling rate constant m not determined in these trials.

Summary of drying tests. 2

Brewers' spent grain, lagged drier, S_d = 2.18%.

No. of flights.	R.P.M.	Feed rate $ft^3/ft^2hr.$	Air flow $lb./ft^2hr.$	Air temp. ^oF	$\underline{m}$	R. time. min.
8	12	0.356	410	140	0.0054	35.26
8	12	0.356	410	160	0.0375	32.17
8	12	0.356	410	180	0.0478	35.58
8	12	0.356	410	200	0.0496	46.2
8	12	0.356	410	220	0.0674	47.37
8	12	0.356	290	200	0.0330	27.3
8	12	0.356	350	200	0.0380	42.0
8	12	0.356	410	200	0.0395	54.9
8	12	0.356	460	200	0.0475	58.3
8	12	0.356	510	200	0.0169	84.2
8	12	0.239	410	200	0.0377	52.39
8	12	0.356	410	200	0.0318	43.26
8	12	0.403	410	200	0.0356	40.12
8	12	0.515	410	200	0.0180	35.4
8	6.3	0.356	410	140	0.0038	65.0
8	12	0.356	410	140	0.0050	36.0
8	16.5	0.356	410	140	0.0079	20.29
8	6.3	0.243	410	140	0.0042	77.5
8	12	0.356	410	140	0.0050	35.4
8	16.5	0.454	410	140	0.0075	20.29
8	12	0.356	410	200	0.0261	47.0
6	12	0.356	410	200	0.0275	44.3
4	12	0.356	410	200	0.0446	33.7
3	12	0.356	410	200	0.0495	30.39
2	12	0.356	410	200	0.1048	16.56
8	12	0.356	410	140	0.0053	35.36
6	12	0.356	410	140	0.0070	32.86
4	12	0.356	410	140	0.0161	19.5
3	12	0.356	410	140	0.0276	23.1
2	12	0.356	410	140	0.0800	16.42
8	12	0.356	290	140	-	31 approx.
8	12	0.356	410	140	0.0054	35.2
8	12	0.356	510	140	-	-
8	6.3	0.356	410	200	0.0261	78.6
8	10	0.356	410	200	0.0335	59.1
8	12	0.356	410	200	0.0355	46.0
8	16.5	0.356	410	200	0.0477	29.05
8	4.1	0.122	410	200	0.0285	126.0
8	12	0.356	410	200	0.0355	46.0
8	26.5	0.470	410	200	0.0490	14.08
8	12	0.240	410	140	0.0163	31.28
8	12	0.350	410	140	0.0054	35.0
8	12	0.460	410	140	-	37.0

Jacket temperature maintained at air inlet temperature.

Summary of drying tests 3

Barley grain, lagged drier, S_d = 0.3%.

No. of flights.	R.P.M.	Feed rate $ft^3/ft^2hr.$	Air flow $lb./ft^2hr.$	Air temp. ^oF	m	R. time. min.
8	6	0.490	500	140	0.0096	50
8	6	0.490	500	160	0.0117	57
8	6	0.490	500	180	0.0157	55
8	6	0.490	500	200	0.0176	50
8	6	0.490	500	220	0.0216	54
8	6	0.490	410	200	0.0157	50
8	6	0.490	500	200	0.0176	53
8	6	0.490	570	200	0.0193	56.2
8	6	0.490	650	200	0.0212	56.35
8	6	0.490	715	200	0.0242	53.2
8	6	0.810	500	200	0.0150	41.57
8	6	0.625	500	200	0.0160	48.4
8	6	0.495	500	200	0.0179	49.63
8	6	0.412	500	200	0.0193	51.7
8	6	0.331	500	200	0.0207	57.9
8	6	0.490	500	200	0.0180	49.0
6	6	0.490	500	200	0.0226	28.1
4	6	0.490	500	200	0.0188	38
3	6	0.490	500	200	0.0270	27
2	6	0.490	500	200	0.0250	27.4
8	4	0.490	500	200	0.0165	64.2
8	6	0.490	500	200	0.0180	50.1
8	10	0.490	500	200	0.0229	32.6
8	13	0.490	500	200	0.0266	27
8	16.5	0.490	500	200	0.0295	23
8	4	0.340	500	200	0.0162	72.7
8	6	0.490	500	200	0.0180	49.8
8	10	0.695	500	200	0.0202	34.2
8	13	0.845	500	200	0.0246	27.9
8	16.5	1.075	500	200	0.0281	22.7

Jacket temperature maintained at air inlet temperature.

Summary of drying tests. 4

Granulated cork, lagged drier, S_d = 3.5%.

No. of flights.	R.P.M.	Feed rate $ft^3/ft^2hr.$	Air flow $lb./ft^2hr.$	Air temp. ^oF	m	R. time. min.
8	6	0.484	288	120	0.0385	27.7
8	6	0.484	288	140	0.0453	27.5
8	6	0.484	288	160	0.0496	30.3
8	6	0.484	288	180	0.0511	32.7
8	6	0.484	288	200	0.0627	35.5
8	6	0.484	250	160	0.0518	18.1
8	6	0.484	263	160	0.0473	17.1
8	6	0.484	278	160	0.0346	25.9
8	6	0.484	324	160	0.0358	30.7
8	6	0.484	392	160	0.0322	36.5
8	6	0.682	288	160	0.0279	23.69
8	6	0.573	288	160	0.0302	25.8
8	6	0.484	288	160	0.0314	30.3
8	6	0.344	288	160	0.0519	33.3
8	6	0.229	288	160	0.0378	30.6
8	6	0.157	288	160	0.0480	48.9
8	4	0.484	288	160	0.0227	33.5
8	6	0.484	288	160	0.0323	30.31
8	8	0.484	288	160	0.0524	29.5
8	10	0.484	288	160	0.0592	24.5
8	14	0.484	288	160	0.1008	18.9
8	21	0.484	288	160	0.1370	13.4
8	6	0.484	288	160	0.0318	25.9
6	6	0.484	288	160	0.0341	21.7
4	6	0.484	288	160	0.0628	14.8
3	6	0.484	288	160	0.0485	16.5
2	6	0.484	288	160	0.0740	10.9

Jacket temperature maintained at air inlet temperature.

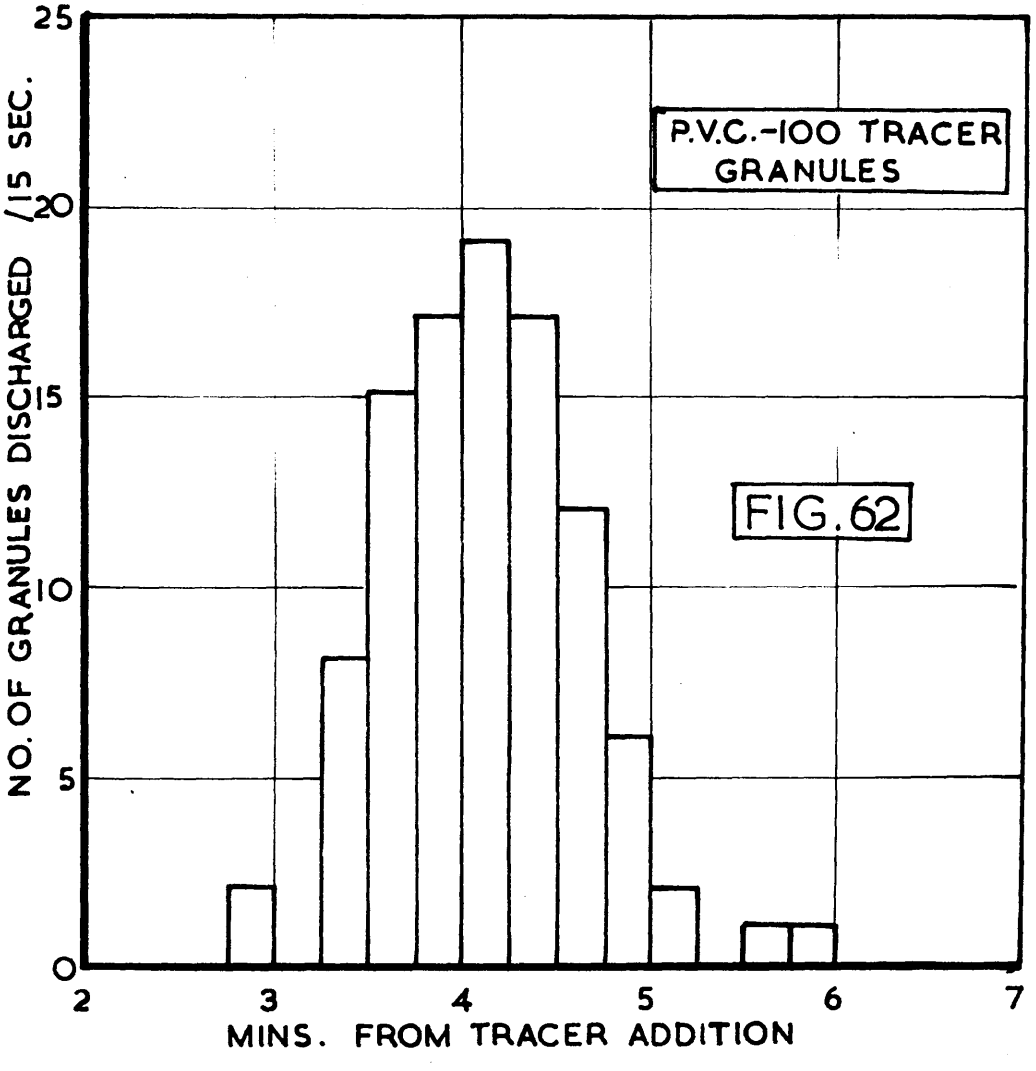
P.V.C.-100 TRACER GRANULES
NO. OF GRANULES DISCHARGED /15 SEC.
0
5
10
15
20
25
2
3
4
5
6
7
MINS. FROM TRACER ADDITION

FIG. 62

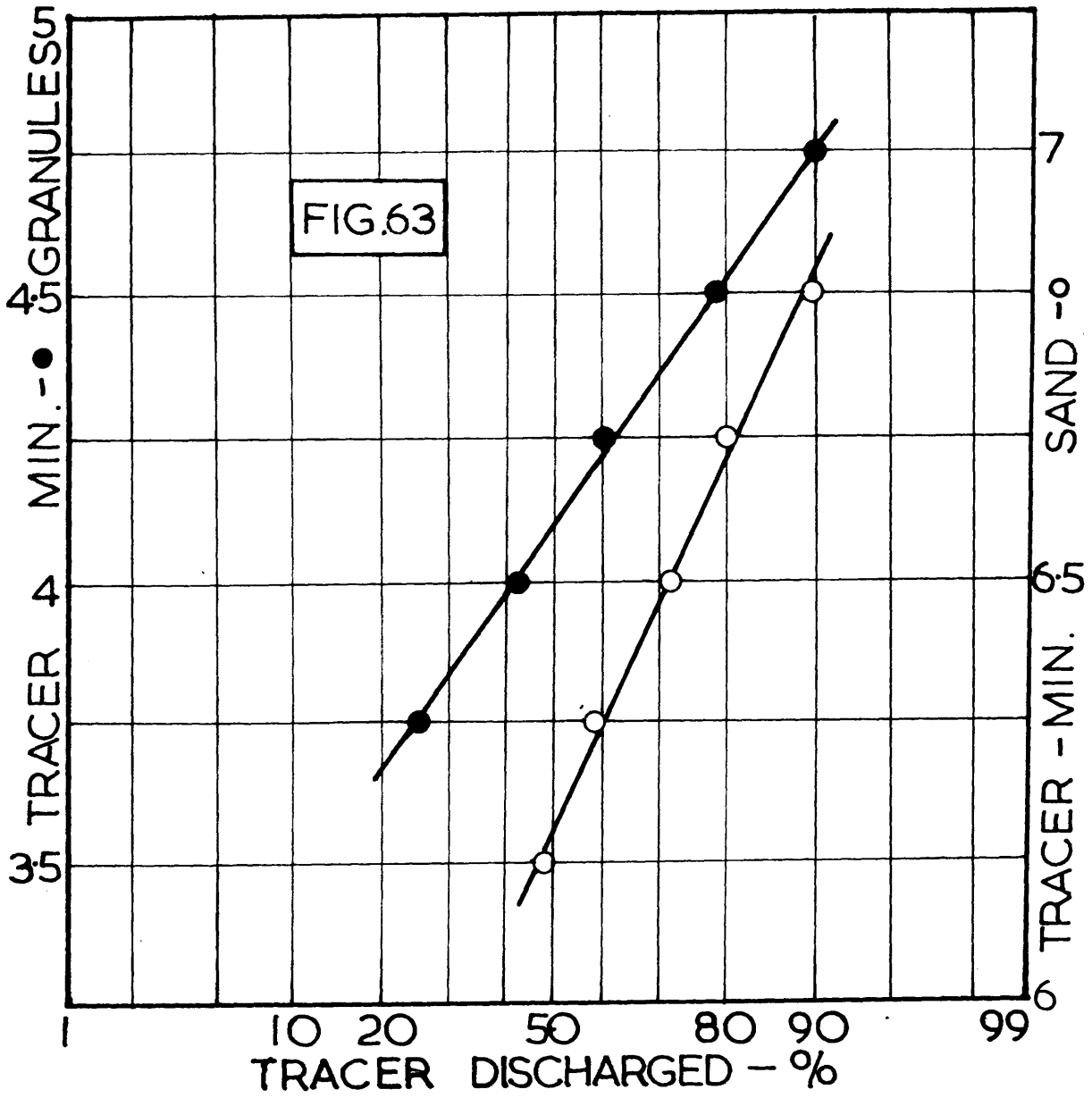
FIG.63
TRACER MIN. - ● GRANULES
TRACER - MIN. SAND - o
3.5
4
4.5
5
6
6.5
7
1
10
20
50
80
90
99
TRACER DISCHARGED - %

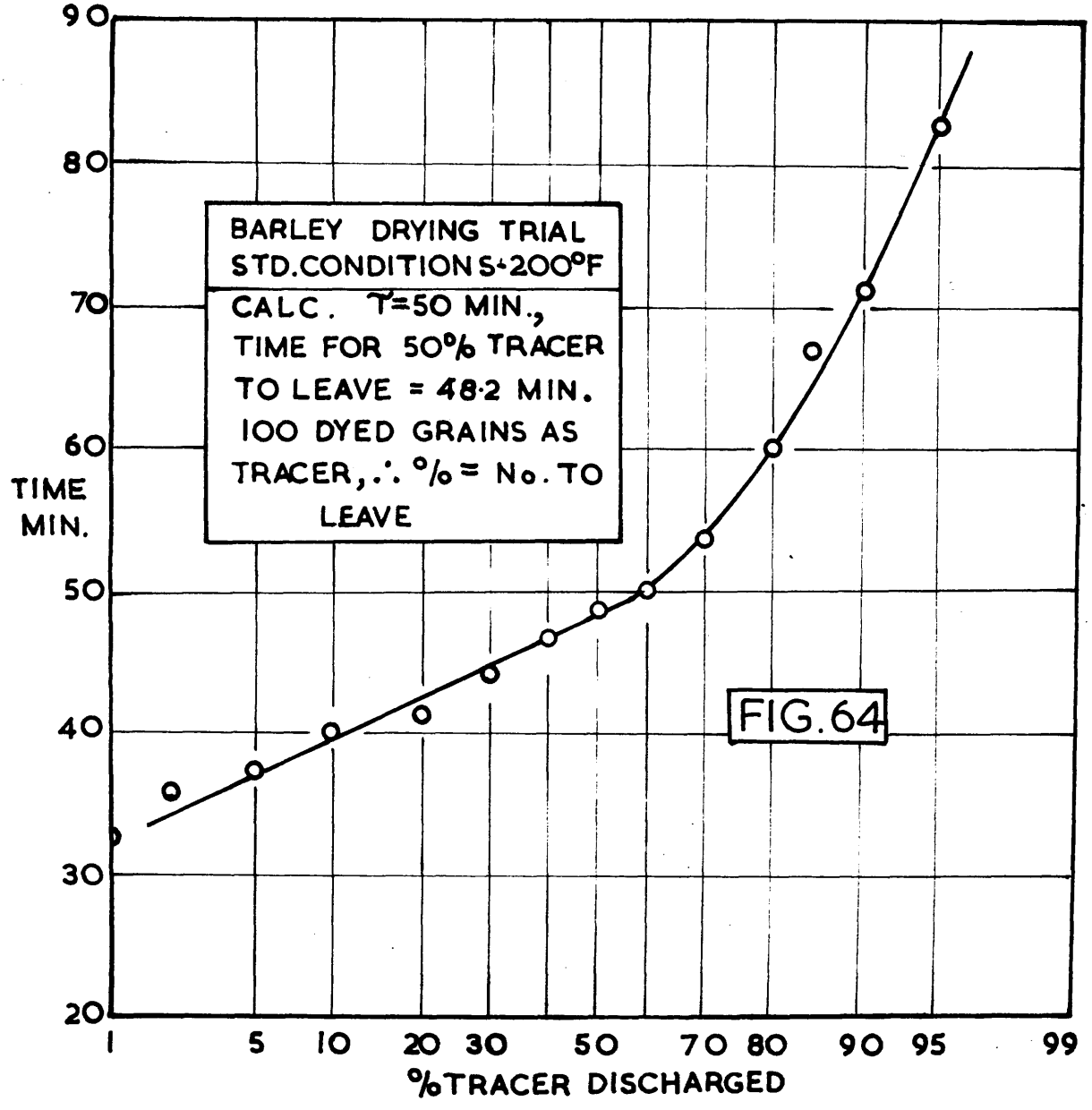
BARLEY DRYING TRIAL
STD. CONDITIONS 200°F
CALC. T=50 MIN.,
TIME FOR 50% TRACER
TO LEAVE = 48·2 MIN.
100 DYED GRAINS AS
TRACER, ∴ % = No. TO
LEAVE
TIME MIN.
90
80
70
60
50
40
30
20
1
5
10
20
30
50
70
80
90
95
99
% TRACER DISCHARGED

FIG. 64

JAMES CALDWELL SMITH.

SUMMARY

Summary

A rotary drier is a rotating cylinder through which passes a steady stream of material which is agitated and showered through hot air by lifting flights to secure efficient heat and mass transfer. Although this drier is now well established in chemical industry, virtually all the design methods and complete operational studies available are restricted to the treatment of materials which have only surface moisture and are therefore easily dried. Vegetable materials are representative of the substances whose drying rates decrease as they lose moisture, i.e. they dry in the so-called falling rate period. They have therefore been chosen to study the counter-current operation of a small rotary drier built for this purpose.

The operation of the drier is controlled by air mass flow and temperature, the speed and slope of the tube, by the lifting flights, and the feed rate of the material being dried. The effects of these on the drying rates of three vegetable materials which were available in bulk, viz. brewers' spent grain, barley grain and granulated cork, were studied, and to allow for the effects of the time of contact in the drier, the conveying properties of the unit were checked with both wet and dry materials. As considerable deviation from an average contact time is possible, which

may lead to scorching and degradation of part of the feed, the effects of some of the operating factors on dispersion were studied in a smaller unit.

Because of the interdependence of many of the factors involved, interpretation of the results was occasionally difficult, but where possible, particularly in tests on inlet air temperature and velocity, drying rates are compared with fundamental or basic figures obtained from through circulation drying of thin layers. After allowance had been made for the considerable variation in material velocity through the rotary drier, in both types of drying the rate of removal of moisture is shown to be proportional to the moisture content of the material, i.e.

$$\frac{dW}{d\theta} = -m.W \quad , \text{ or } \mathrm{Log}_e W = -m.\theta + k$$

The values of m, the falling rate constant, are employed to compare the effects of each of the operating variables on drying rates. Those calculated from the rotary drier are about one tenth of the values obtained from single layers under comparable conditions of temperature and airflow.

Effects of variables controlling rotary drying

Tests on contact, or retention time and loading show that although relations already proposed for dry materials can be generally accepted, with wet feed considerable differences are observed. The effects of the operating

factors are detailed and discussed. A general correlation for deviation from mean retention time has been developed explaining the effects of the factors, viz. flight action and bouncing, which apparently cause this.

Inlet air temperature

In studies in the range 120°F to 220°F, relations between drying rates and temperature are shown to be similar for both types of drying studied, but rising temperature appears to have less effect in the rotary drier.

Air mass flow

The practicable range of air mass flow was limited by the nature of each material, and a relationship between the limiting velocities for each type of drier is suggested. Drying rate constants showed a similar dependence on air-flow in both types of drying.

Feed rate

Drying rates are shown to decrease with increasing feed rate and empirical equations between them are proposed. It is thought that the effects are caused by the variation in drier loading caused by altering the feed rate.

Speed of the drier tube

Increased drying rates were encountered when drier speed was increased. As the effect appears to be due to several factors, the nature of these is discussed and

relations between them are deduced.

Number of lifting flights

As the result of tests on each material where the number of lifting flights was varied between two and eight, it appears that higher values of the falling rate drying constant can be obtained with fewest flights - the reverse of the effect observed where surface moisture only is being evaporated.

General

Some points relating to the general design and operation of rotary driers are proposed. While a considerable amount of experimental work is still necessary with both more materials and different sizes of drier to determine scale effects, it is suggested that the methods detailed in this work, involving the falling rate drying constant which can be determined readily from single layer tests, can form the basis for a general design method for rotary driers.